Free VirtualLab Fusion Seminar in USA, Sunnyvale, 08th of June, 2018 (9am-4pm)

Beyond Ray Tracing: Innovative Optical Simulations with Fast Physical Optics

Hartwig Crailsheim (LightTrans International UG)

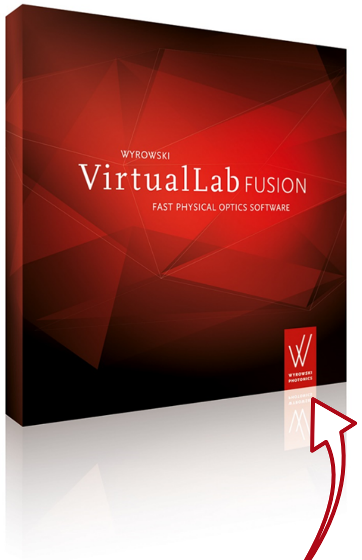
Where – Who – What

Where – Who – What

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

Where – Who – What

All examples shown in this seminar were done with **VirtualLab Fusion** software.(*)



+ partners (world-wide)
cooperations with other international universities and companies for research and development

Wyrowski Photonics
development of fast physical optics software VirtualLab Fusion

(*) except for those of explicit comparison simulations.

Where – Who – What

LightTrans

- distribution of VirtualLab Fusion, together with distributors worldwide
- technical support, generation of examples, seminars and trainings
- engineering projects

Where – Who – What

All techniques shown in this seminar are available in
VirtualLab Fusion software
or/and as
consulting & engineering services!

LightTrans – Short Overview

DNA of LightTrans

Understand and exploit physical optics effects for optical design applications

products and services

Software. Engineering. Prototyping.

core product

VirtualLab Fusion: fast physical optics design & simulation software

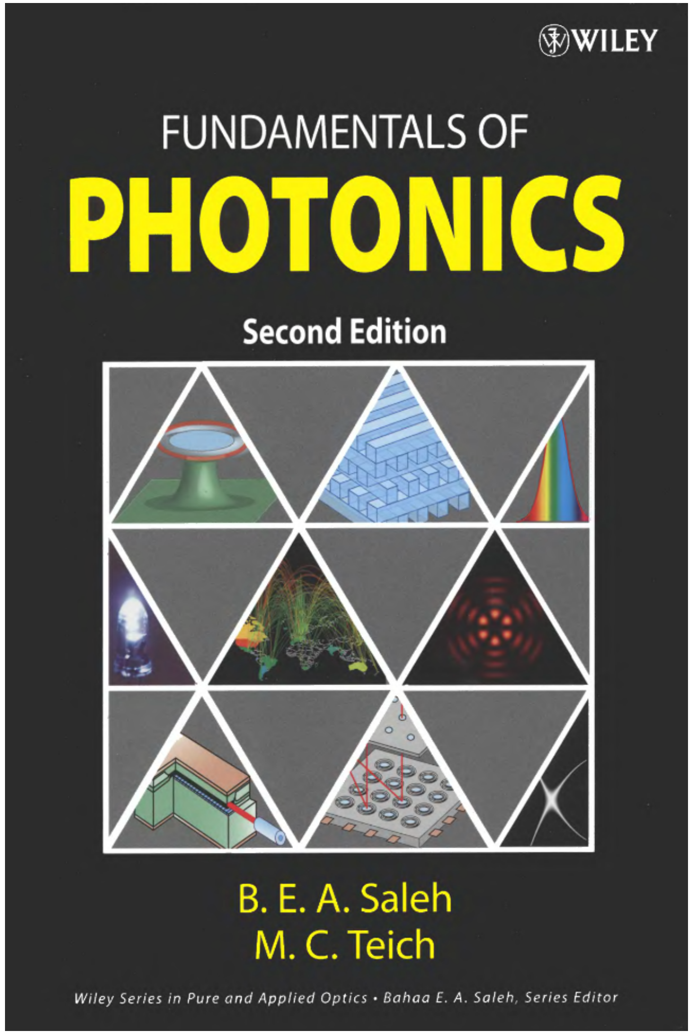
What's Coming Next #1 ...

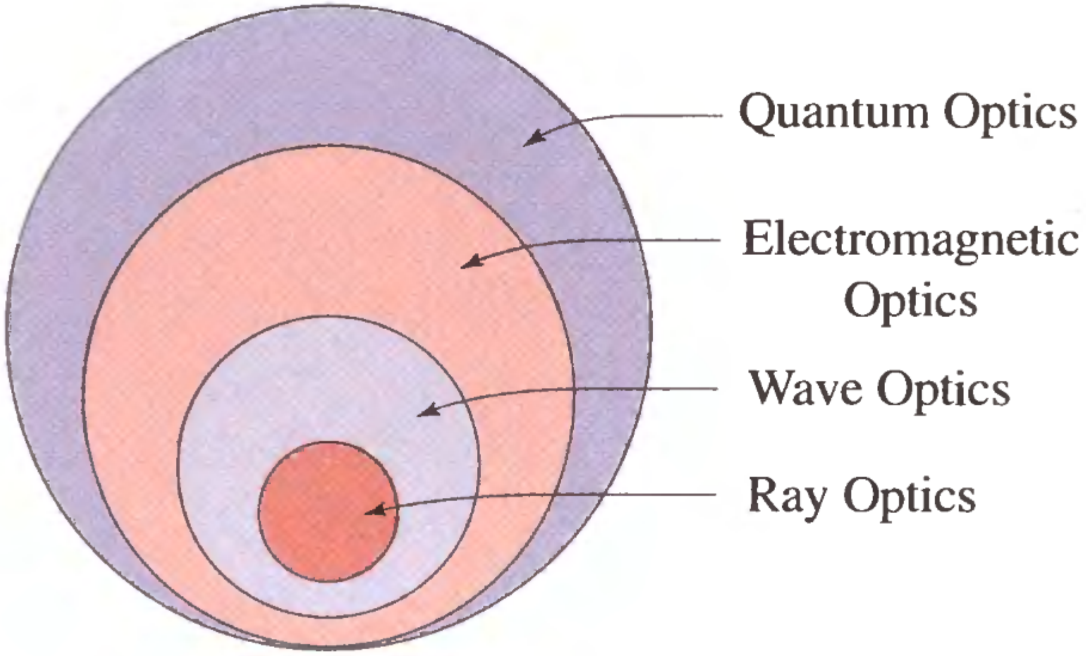
- classification of physical optics vs ray optics
- first demo of VirtualLab and its usage concept
- our view about the demands on an optical simulation & design software
- our basic simulation approach
- limitations of conventional ray tracing

Clarification of the Basics of VirtualLab

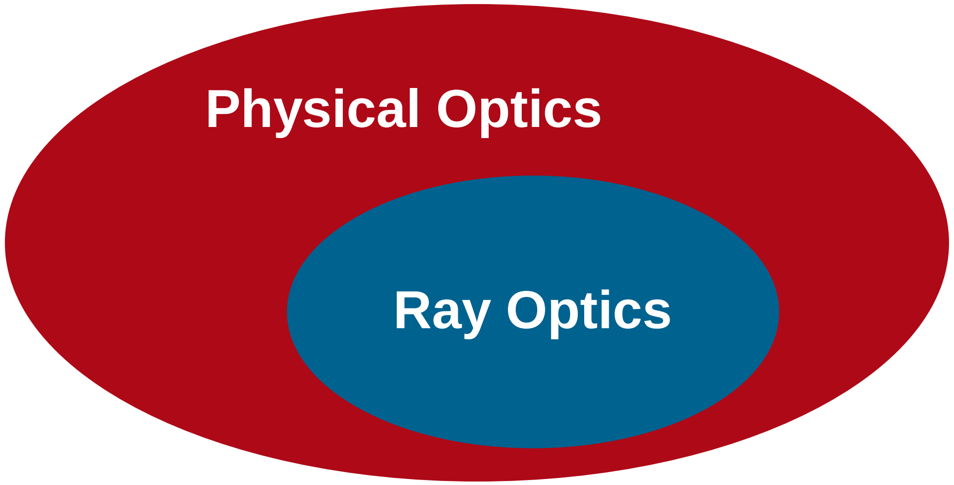
Diffractive and Geometric Branches of Physical Optics

Physical and Geometrical Optics: Traditional Understanding





Physical and Geometrical Optics: Traditional Understanding



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

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

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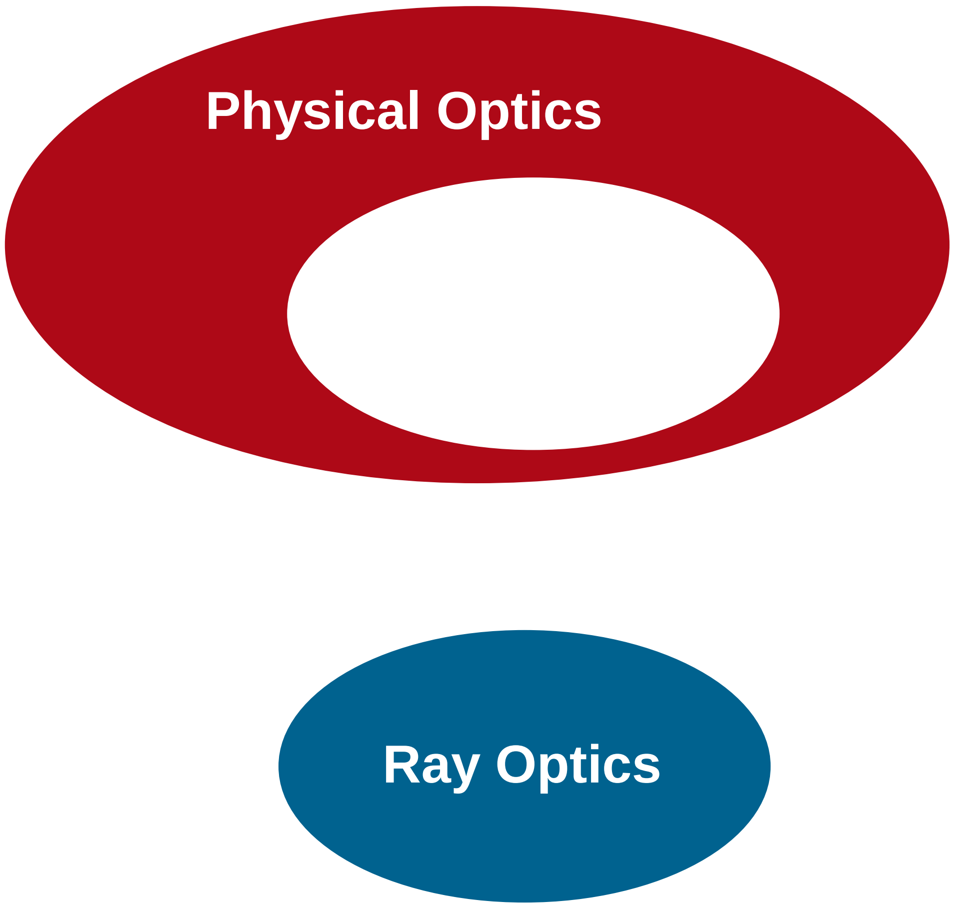

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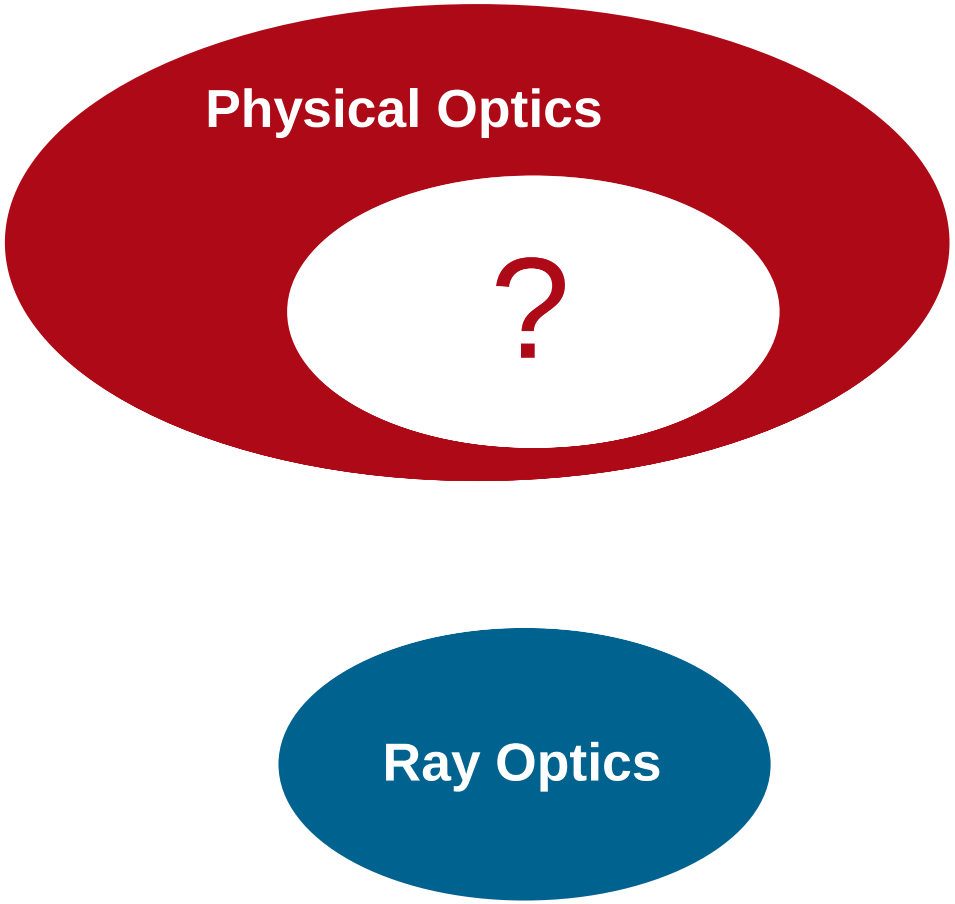

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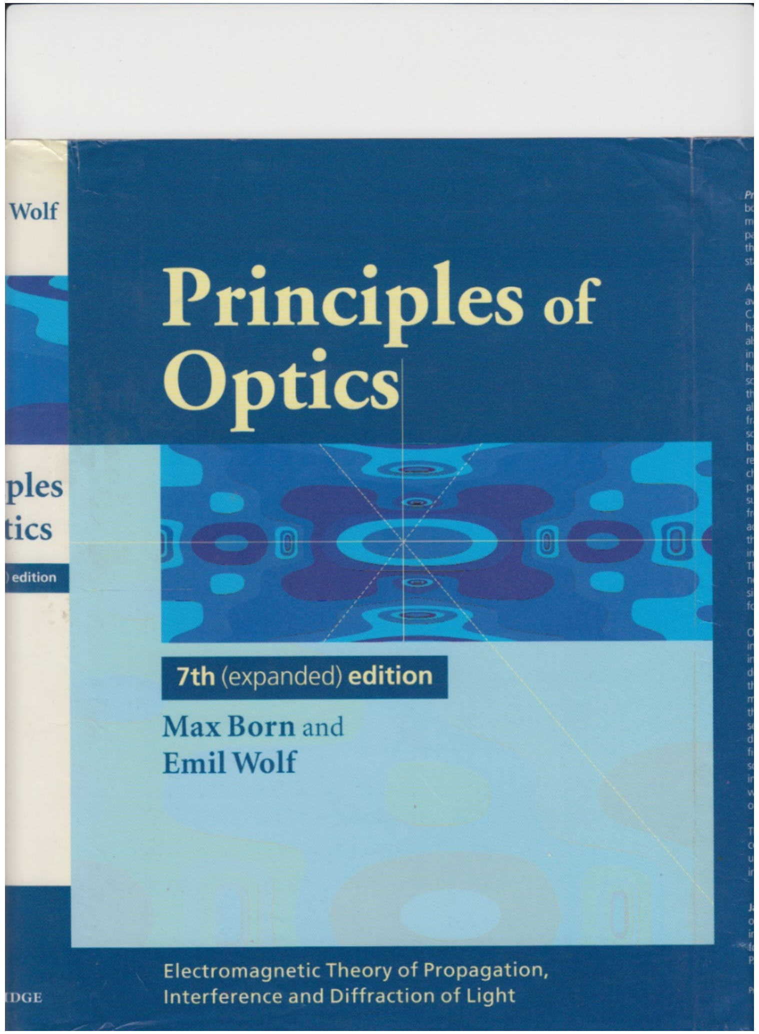
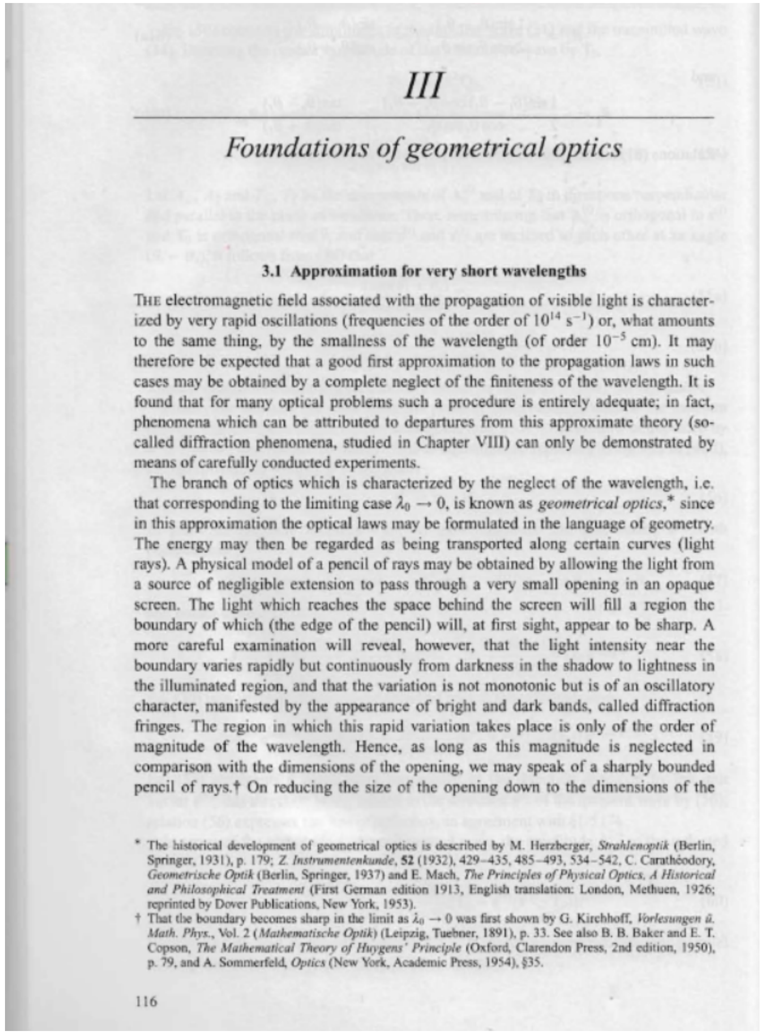
Geometrical Optics for Electromagnetic Fields





III

Foundations of geometrical optics

3.1 Approximation for very short wavelengths

THE electromagnetic field associated with the propagation of visible light is characterized by very rapid oscillations (frequencies of the order of $10^{14}\ s^{-1}$) or, what amounts to the same thing, by the smallness of the wavelength (of order 10^{-5} cm). It may therefore be expected that a good first approximation to the propagation laws in such cases may be obtained by a complete neglect of the finiteness of the wavelength. It is found that for many optical problems such a procedure is entirely adequate; in fact, phenomena which can be attributed to departures from this approximate theory (so-called diffraction phenomena, studied in Chapter VIII) can only be demonstrated by means of carefully conducted experiments.

The branch of optics which is characterized by the neglect of the wavelength, i.e. that corresponding to the limiting case $\lambda_0 \to 0$, is known as *geometrical optics*,* since in this approximation the optical laws may be formulated in the language of geometry. The energy may then be regarded as being transported along certain curves (light rays). A physical model of a pencil of rays may be obtained by allowing the light from a source of negligible extension to pass through a very small opening in an opaque screen. The light which reaches the space behind the screen will fill a region the boundary of which (the edge of the pencil) will, at first sight, appear to be sharp. A more careful examination will reveal, however, that the light intensity near the boundary varies rapidly but continuously from darkness in the shadow to lightness in the illuminated region, and that the variation is not monotonic but is of an oscillatory character, manifested by the appearance of bright and dark bands, called diffraction fringes. The region in which this rapid variation takes place is only of the order of magnitude of the wavelength. Hence, as long as this magnitude is neglected in comparison with the dimensions of the opening, we may speak of a sharply bounded pencil of rays.† On reducing the size of the opening down to the dimensions of the

* The historical development of geometrical optics is described by M. Herzberger, *Strahlenoptik* (Berlin, Springer, 1931), p. 179; *Z. Instrumentenkunde*, **52** (1932), 429–435, 485–493, 534–542, C. Carathéodory, *Geometrische Optik* (Berlin, Springer, 1937) and E. Mach, *The Principles of Physical Optics, A Historical and Philosophical Treatment* (First German edition 1913, English translation: London, Methuen, 1926; reprinted by Dover Publications, New York, 1953).

† That the boundary becomes sharp in the limit as $\lambda_0 \to 0$ was first shown by G. Kirchhoff, *Vorlesungen ü. Math. Phys.*, Vol. 2 (*Mathematische Optik*) (Leipzig, Tuebner, 1891), p. 33. See also B. B. Baker and E. T. Copson, *The Mathematical Theory of Huygens' Principle* (Oxford, Clarendon Press, 2nd edition, 1950), p. 79, and A. Sommerfeld, *Optics* (New York, Academic Press, 1954), §35.

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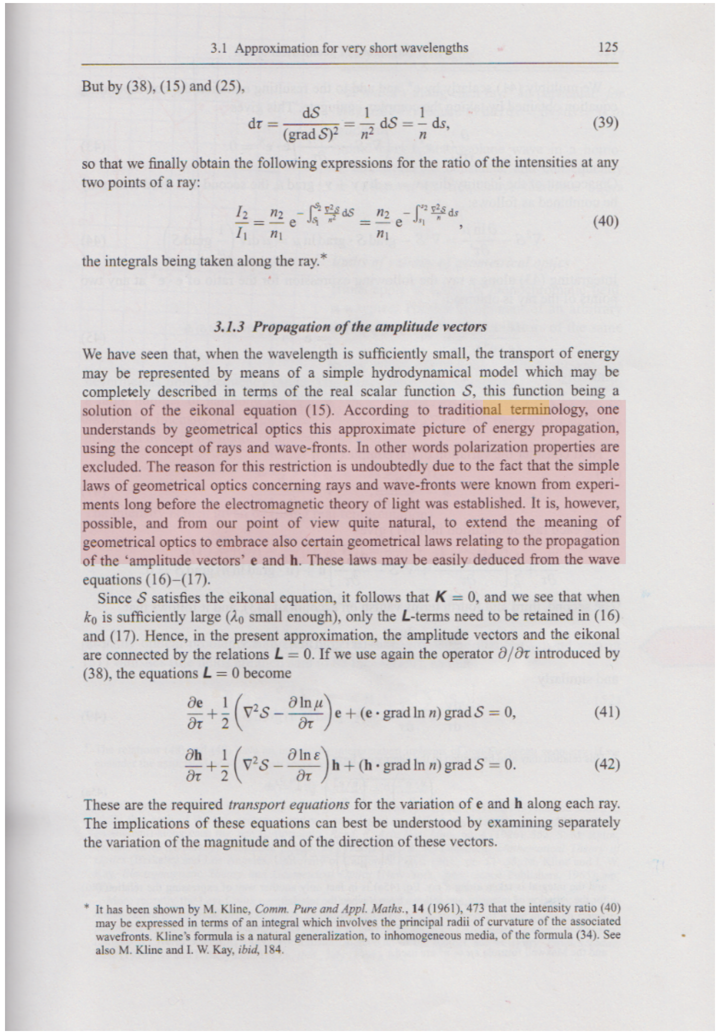
Geometrical Optics for Electromagnetic Fields



3.1 Approximation for very short wavelengths 125

But by (38), (15) and (25),

$$d\tau = \frac{d\mathcal{S}}{(\operatorname{grad}\mathcal{S})^2} = \frac{1}{n^2}\,d\mathcal{S} = \frac{1}{n}\,ds, \tag{39}$$

so that we finally obtain the following expressions for the ratio of the intensities at any two points of a ray:

$$\frac{I_2}{I_1} = \frac{n_2}{n_1}\,e^{-\int_{\mathcal{S}_1}^{\mathcal{S}_2}\frac{\nabla^2\mathcal{S}}{n^2}\,d\mathcal{S}} = \frac{n_2}{n_1}\,e^{-\int_{s_1}^{s_2}\frac{\nabla^2\mathcal{S}}{n}\,ds}, \tag{40}$$

the integrals being taken along the ray.*

3.1.3 *Propagation of the amplitude vectors*

We have seen that, when the wavelength is sufficiently small, the transport of energy may be represented by means of a simple hydrodynamical model which may be completely described in terms of the real scalar function $\mathcal{S}$, this function being a solution of the eikonal equation (15). According to traditional terminology, one understands by geometrical optics this approximate picture of energy propagation, using the concept of rays and wave-fronts. In other words polarization properties are excluded. The reason for this restriction is undoubtedly due to the fact that the simple laws of geometrical optics concerning rays and wave-fronts were known from experiments long before the electromagnetic theory of light was established. It is, however, possible, and from our point of view quite natural, to extend the meaning of geometrical optics to embrace also certain geometrical laws relating to the propagation of the 'amplitude vectors' **e** and **h**. These laws may be easily deduced from the wave equations (16)–(17).

Since $\mathcal{S}$ satisfies the eikonal equation, it follows that $\boldsymbol{K} = 0$, and we see that when k_0 is sufficiently large (λ_0 small enough), only the $\boldsymbol{L}$-terms need to be retained in (16) and (17). Hence, in the present approximation, the amplitude vectors and the eikonal are connected by the relations $\boldsymbol{L} = 0$. If we use again the operator $\partial/\partial\tau$ introduced by (38), the equations $\boldsymbol{L} = 0$ become

$$\frac{\partial\mathbf{e}}{\partial\tau} + \frac{1}{2}\left(\nabla^2\mathcal{S} - \frac{\partial\ln\mu}{\partial\tau}\right)\mathbf{e} + (\mathbf{e}\cdot\operatorname{grad}\ln n)\operatorname{grad}\mathcal{S} = 0, \tag{41}$$

$$\frac{\partial\mathbf{h}}{\partial\tau} + \frac{1}{2}\left(\nabla^2\mathcal{S} - \frac{\partial\ln\varepsilon}{\partial\tau}\right)\mathbf{h} + (\mathbf{h}\cdot\operatorname{grad}\ln n)\operatorname{grad}\mathcal{S} = 0. \tag{42}$$

These are the required *transport equations* for the variation of **e** and **h** along each ray. The implications of these equations can best be understood by examining separately the variation of the magnitude and of the direction of these vectors.

* It has been shown by M. Kline, *Comm. Pure and Appl. Maths.*, **14** (1961), 473 that the intensity ratio (40) may be expressed in terms of an integral which involves the principal radii of curvature of the associated wavefronts. Kline's formula is a natural generalization, to inhomogeneous media, of the formula (34). See also M. Kline and I. W. Kay, *ibid*, 184.

page 125

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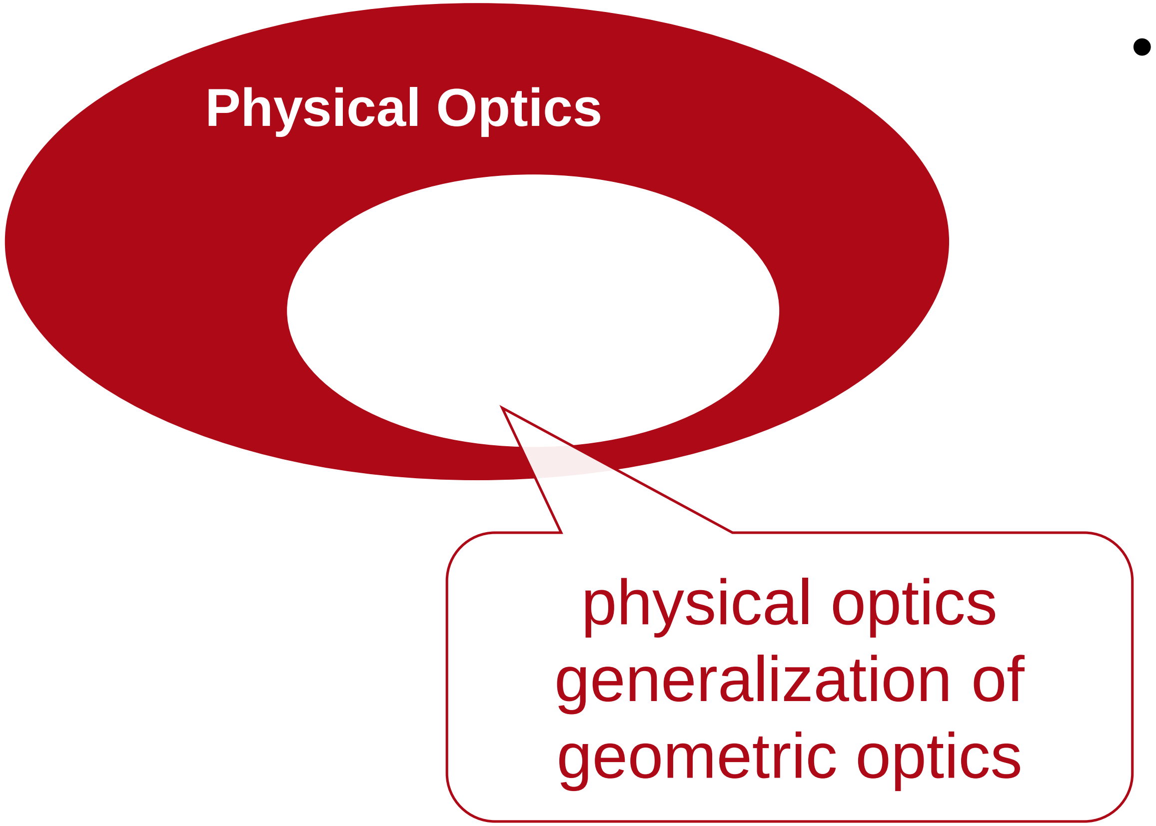
Physical and Geometrical Optics: Unified Theory



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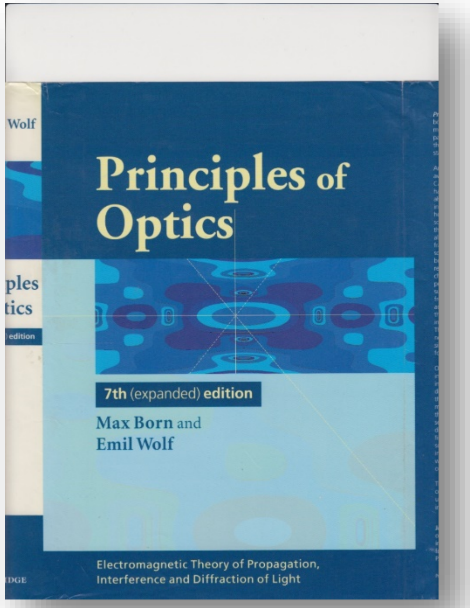

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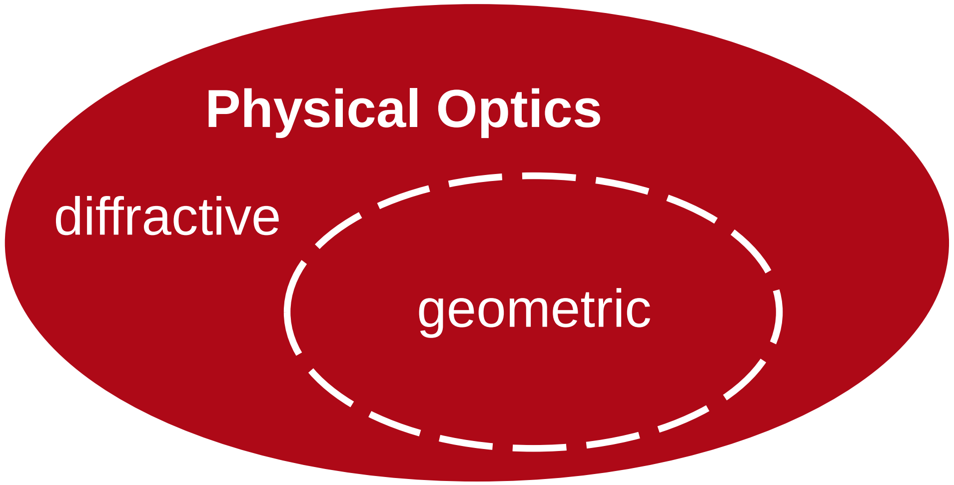

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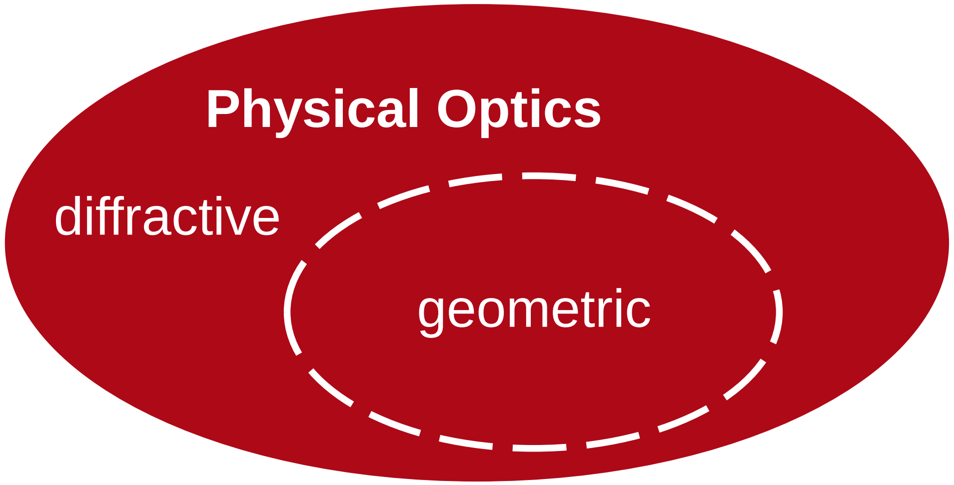

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  - Transition between diffractive/geometric branch fully specified and controlled by mathematical concepts.
    → diffractive and geometric field zones

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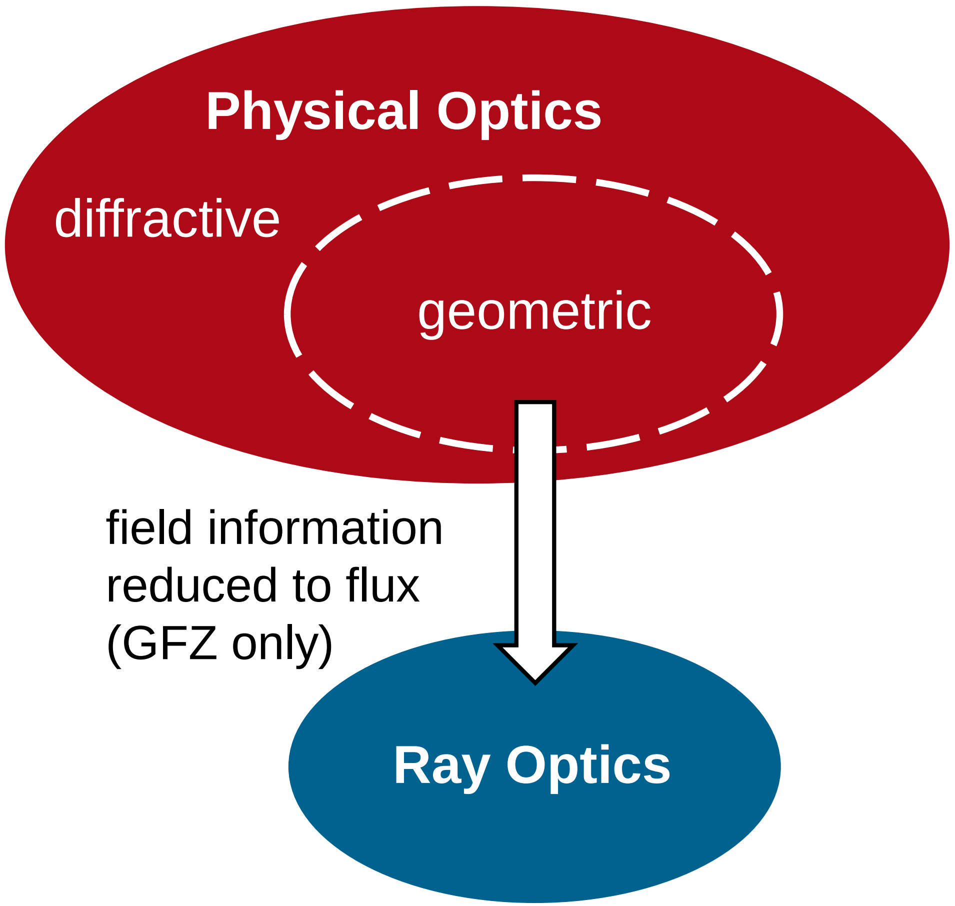

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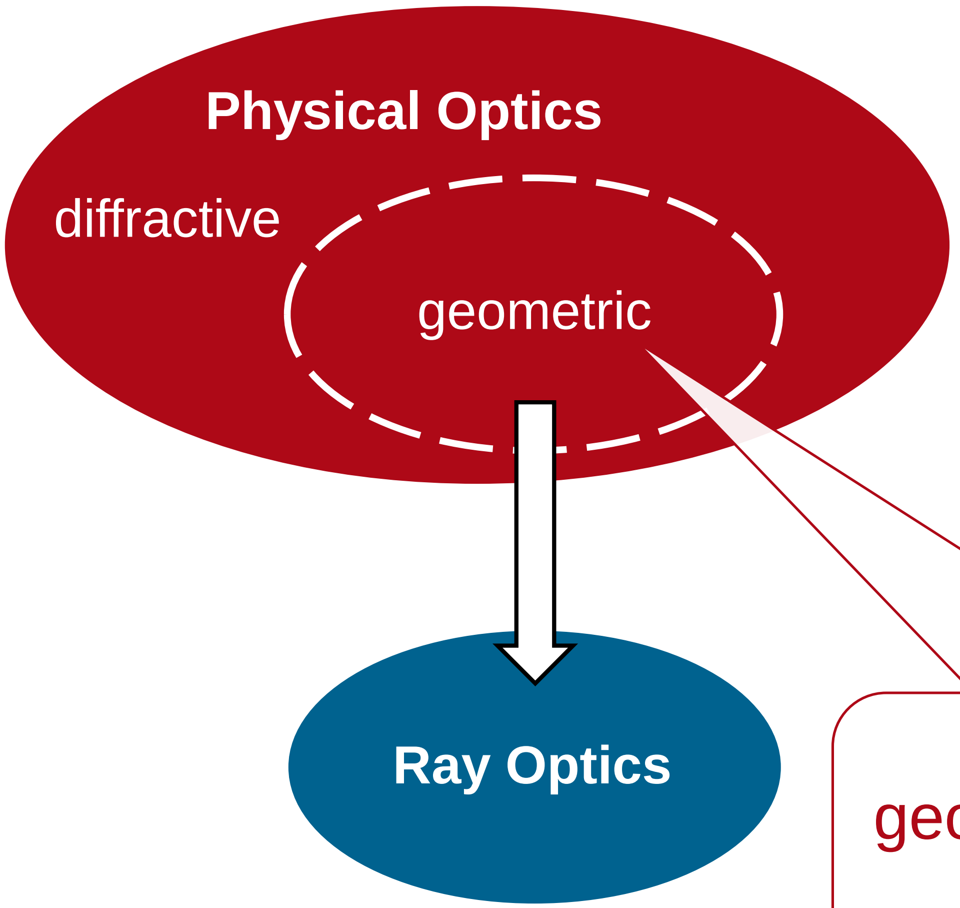

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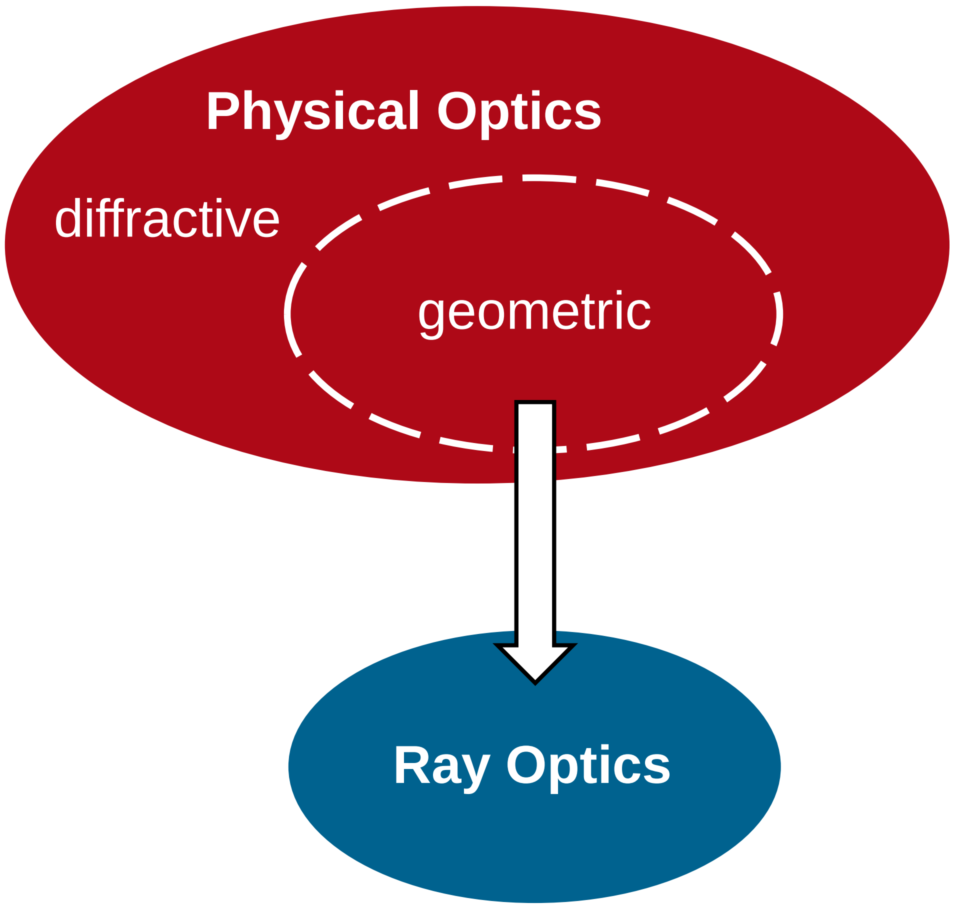
Physical optics in geometric zones can be as fast as ray tracing sometimes even faster!

Physical and Geometrical Optics: Unified Theory



- Physical Optics:
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    → diffractive and geometric field zones
- VirtualLab Fusion deals with the transitions between diffractive and geometric branches of physical optics automatically (steady development).

Modeling and Design with Fast Physical Optics

- Compared to ray tracing no light information is lost by fast physical optics.
- Ray tracing is included in VirtualLab Fusion software on a solid base knowing about the power and the limitations of ray optics.

- **By going beyond ray tracing**
  - You win more information about the light in your system
  - You get better insight into the performance of your system
  - You can include and investigate more effects
  - You can model with higher accuracy
  - You are ready for new optical design concepts and by that for innovative optical solutions

Basics 0004 (v1.1)

Easy Setup & Simulation

Quick & Clear

No matter if it‘s

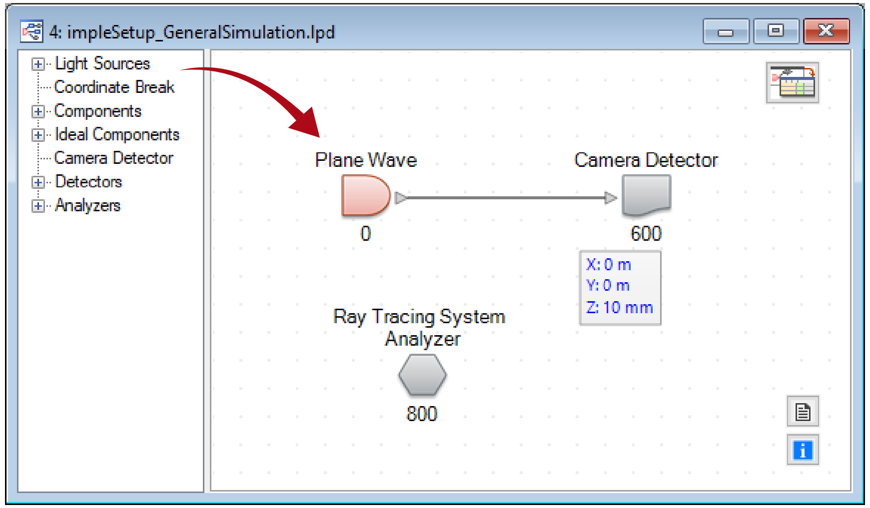
- **Ray Tracing** or **Field Tracing**
- in **2D** or **3D**,

VirtualLab allows an **easy, quick and intuitiv approach** to setting up and simulating optical systems.

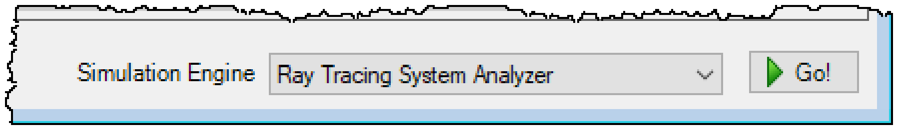
→ Demo example with simple plane wave light source

Optical System in VirtualLab‘s Light Path View

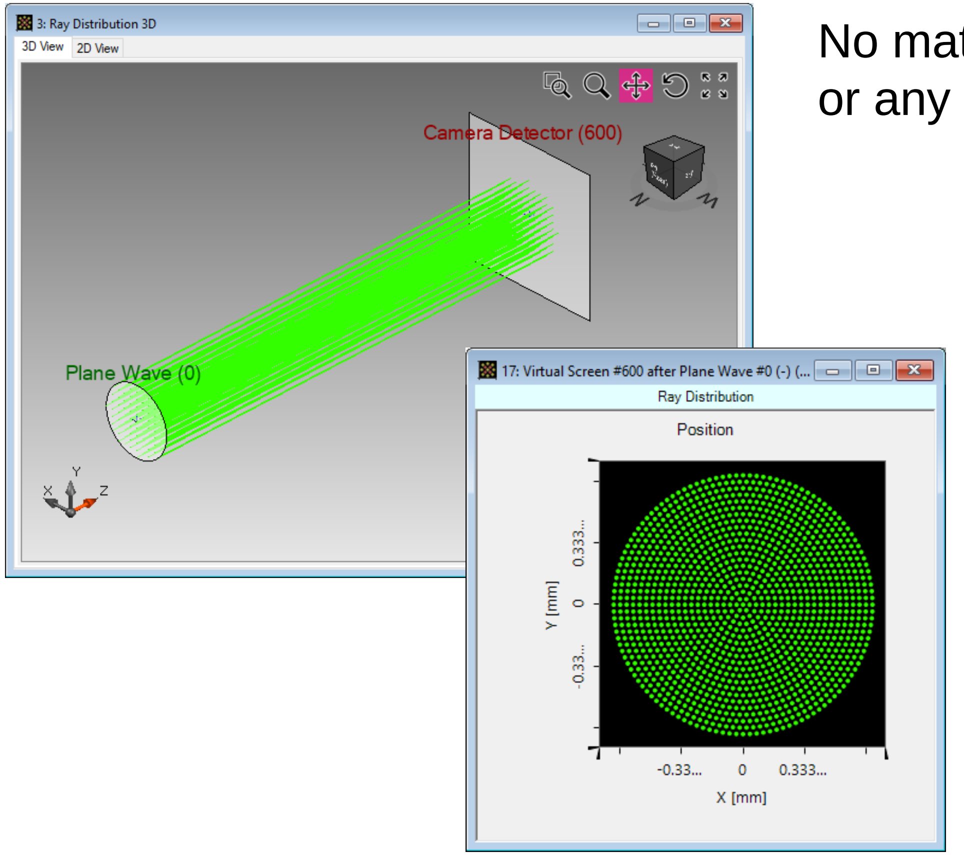
1. To build a system elements are just added via **drag‘n‘drop**.



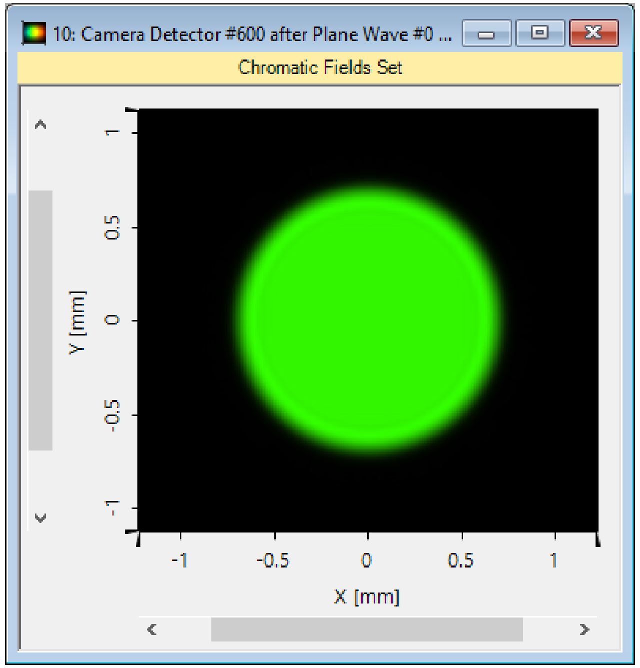
2. To simulate a system the desired simulation engine is chosen, then **Go!**



Simple Simulation Results



No matter, if it's conventional Ray Tracing or any Field Tracing method…



… **VirtualLab** is comparatively **easy to be used**.

Basics 0005 (v1.1)

Requirements for an Optical Design & Simulation Software

What Is to Be Regarded for Optical Simulations?

An optical software programm should be able to model ...

1. ... systems consisting of all kinds of
   a) light sources
   b) optical elements
   c) detectors

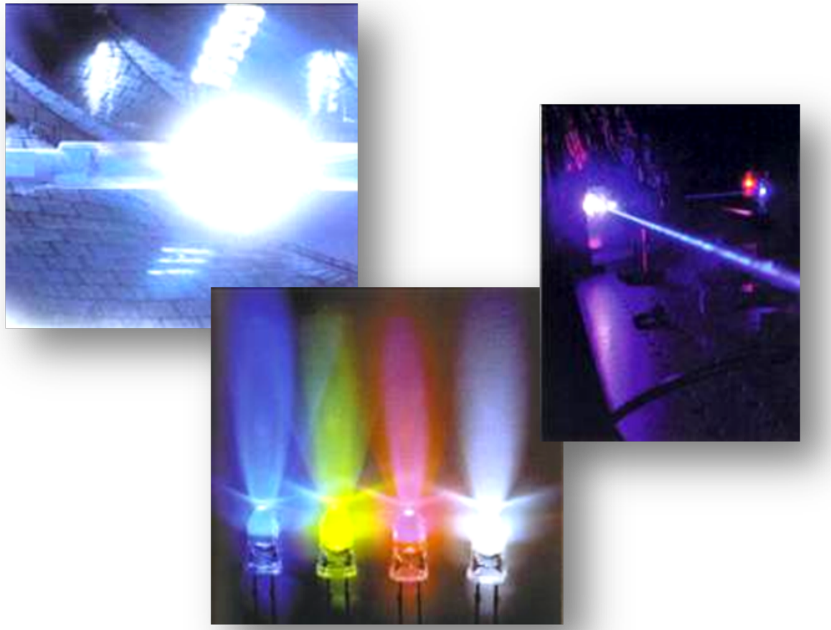
2. ... the light propagation in the different regions of the system.

3. Furthermore, the design and optimization of diverse optical elements or systems is of interest.

→ What does this mean?

1.a Advanced Source Modeling

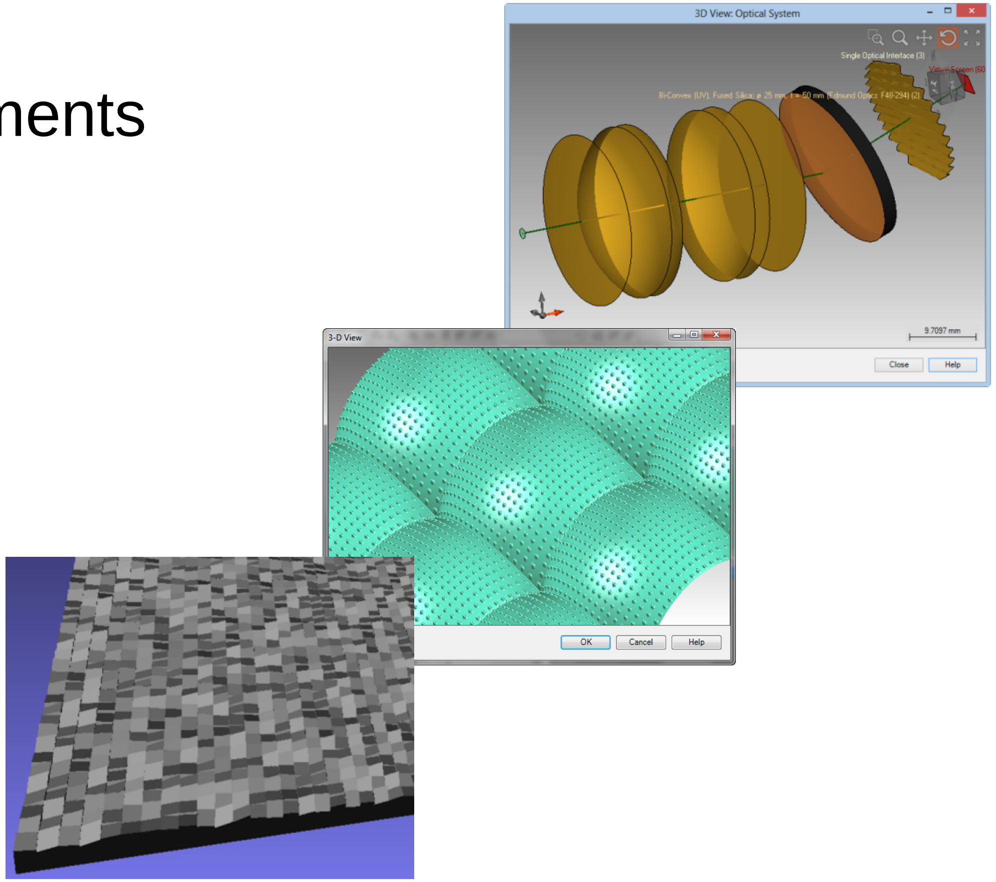
- Coherent laser beam propagation
- Partially coherent source modeling and propagation:
  - Temporal coherence
  - Spatial coherence
- Ultrashort pulse
- Rigorous regard of polarization



1.b Modeling of Elements and Systems

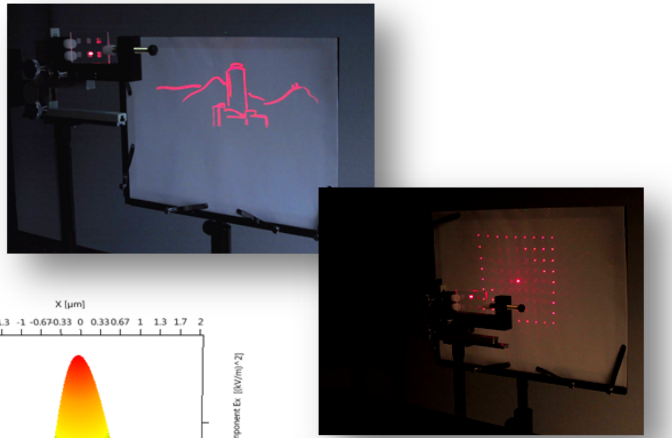
Different elements are differently to be modeled, e.g.:

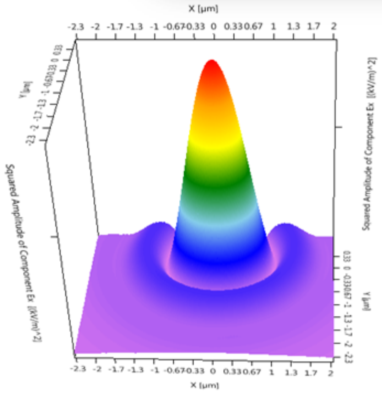
- lenses, prisms, etalons
- micro/nano/diffractive optical elements
- holographic and grin elements
- waveguides
- freeforms and scatterers
- multi-layer structures, gratings
- coatings

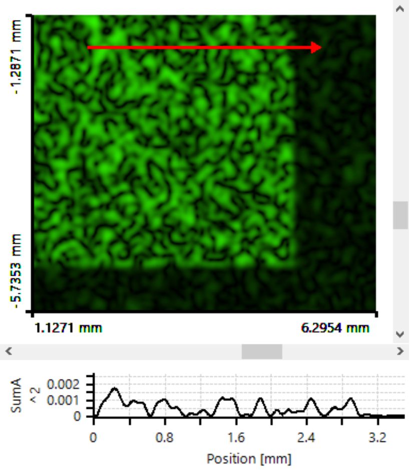


1.c Access to Any Light Field Parameter

- Innovative optical design often requires accurate access to e.g.
  - intensity, amplitude
  - wavefront, phase
  - aberrations (e.g. Zernike & Seidel)
  - beam parameters
  - polarization
  - degree of coherence
  - efficiency, power, stray light
  - poynting vector, energy flow
  - pulse duration, chirp, …
- Definition of customized merit functions
- Export of laser data to Matlab …



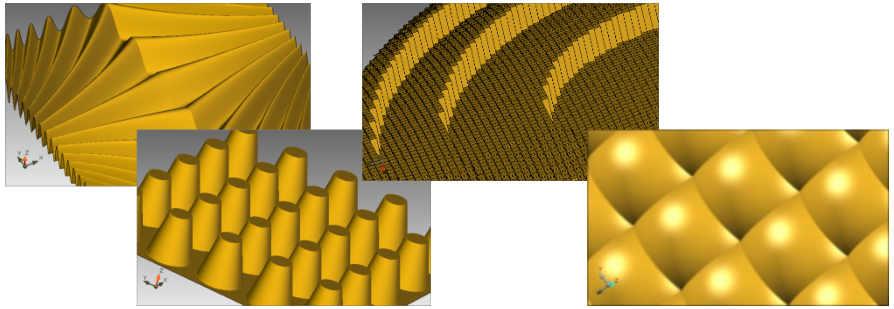




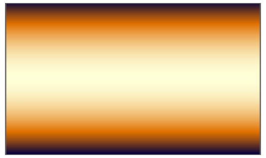
2. Light Propagation

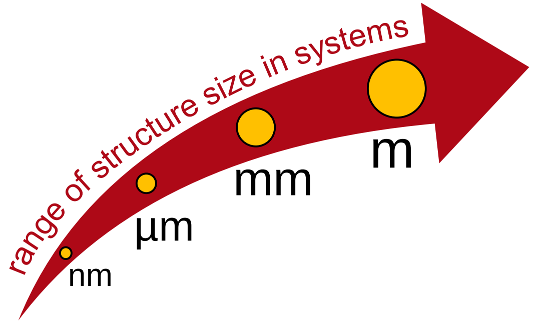
Adequate light propagation models are required for diverse conditions:

- Enormous variety of different types of optical surfaces & media
  - smooth freeform surfaces
  - microstructured surfaces
  - multilevel surfaces
  - miniaturized components
  - inhomogeneous media

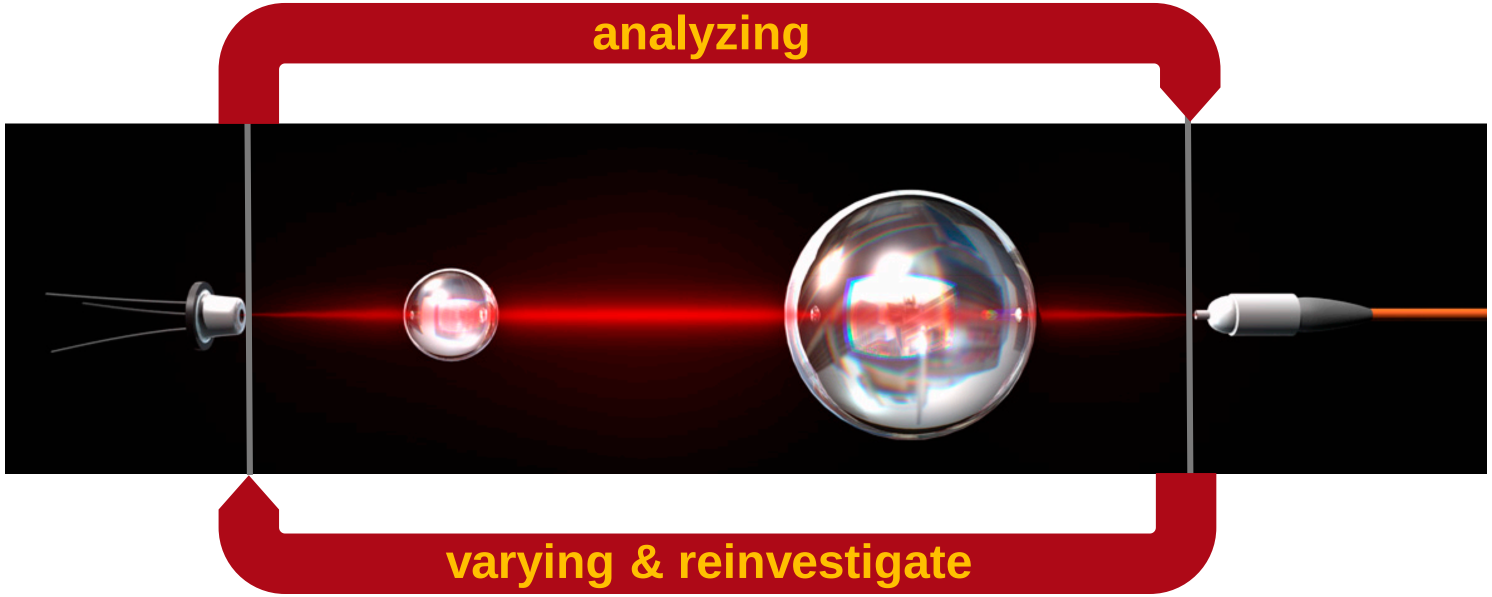


- Simulations of Complex Systems
  - varying sizes and dimensions





3. Design, Optimization & Tolerancing

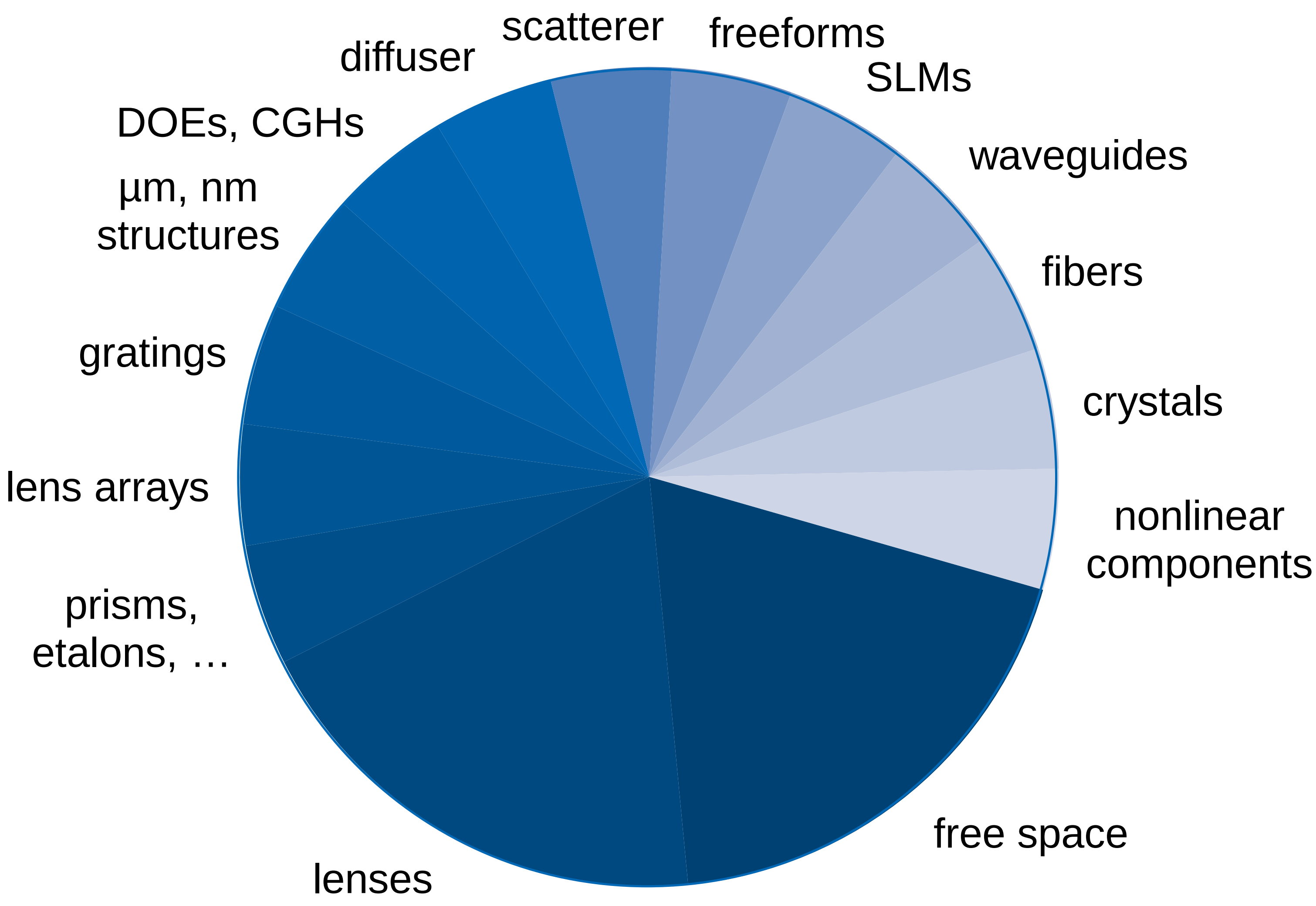


- diverse design approaches (IFTA, inverse design, parametric optimizations, cells array designs, …)
- local and global optimization algorithms
- simulation series by parameter run
- position, tilt and fabrication tolerances
- Monte-Carlo simulations

Basics 0006 (v1.5s)

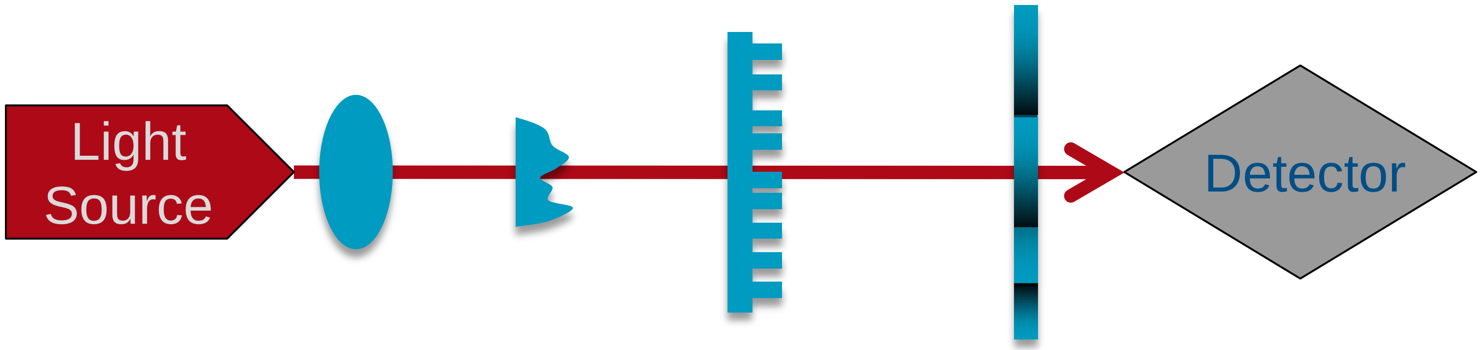
Optical Simulation Approach

Optical Areas of Application



Simulation Approach

One modeling technique for all fields of application?



~~**with Ray tracing?**~~

NO

~~with rigorous electromagnetic solutions of Maxwell‘s equations?~~

NO

…due to diverse limitations

Limitations of Simulation Approaches

Geometric Optical Solutions with Conventional Ray Tracing

- If light is just represented by conventional rays and is propagated by geometric optical rules, several physical optical effects cannot be regarded.
- I.e. diffraction effects (deflection and energy distribution due to sharp/small structures), Fresnel effects (interaction with media interface), polarization effects (cross talk between E_x and E_y) are neglected.

Rigorous Solutions

- Even with today's PC technology: Rigorous modeling is restricted to small volume regards.
- A rigorous modeling of entire systems is not practical!

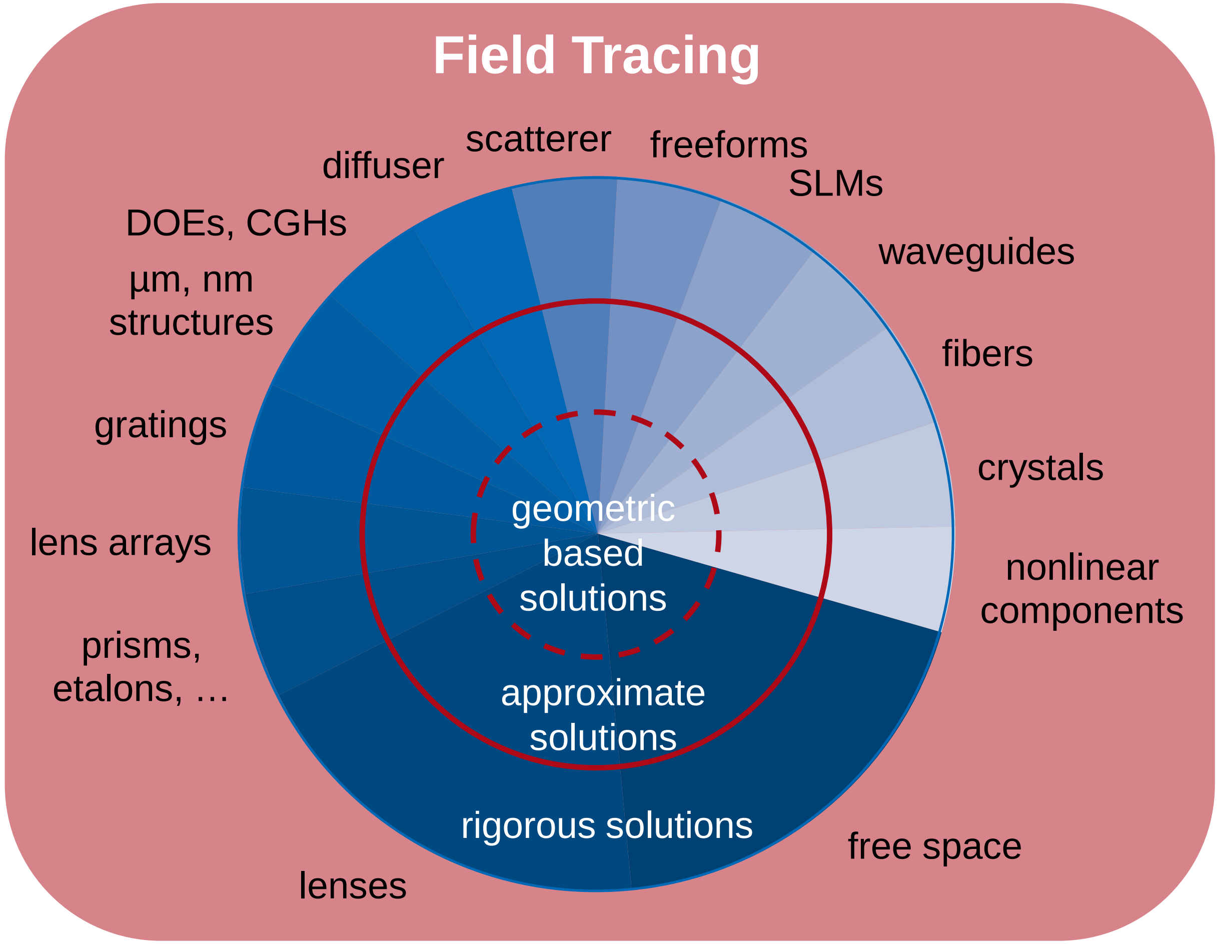
Benefit from All Kinds Of Available Methods

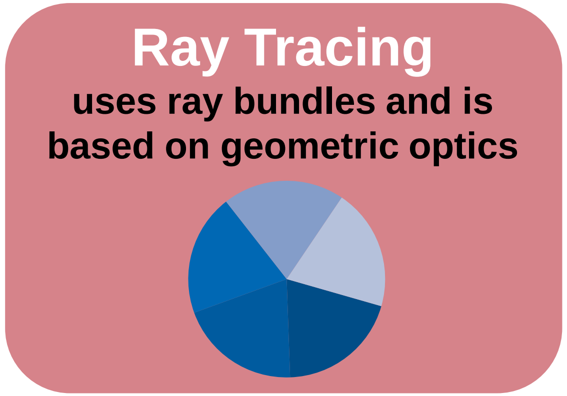
As expected, neither the most approximated nor the rigorous modeling approach alone are suited for many of today‘s applications.

In order to **simulate full optical systems** we need to be able to use **different methods** adapted to the particular regard – within one simulation process.

= VirtualLab‘s Approach

Optical Areas of Application: Approaches





System Modeling and Physical Optics

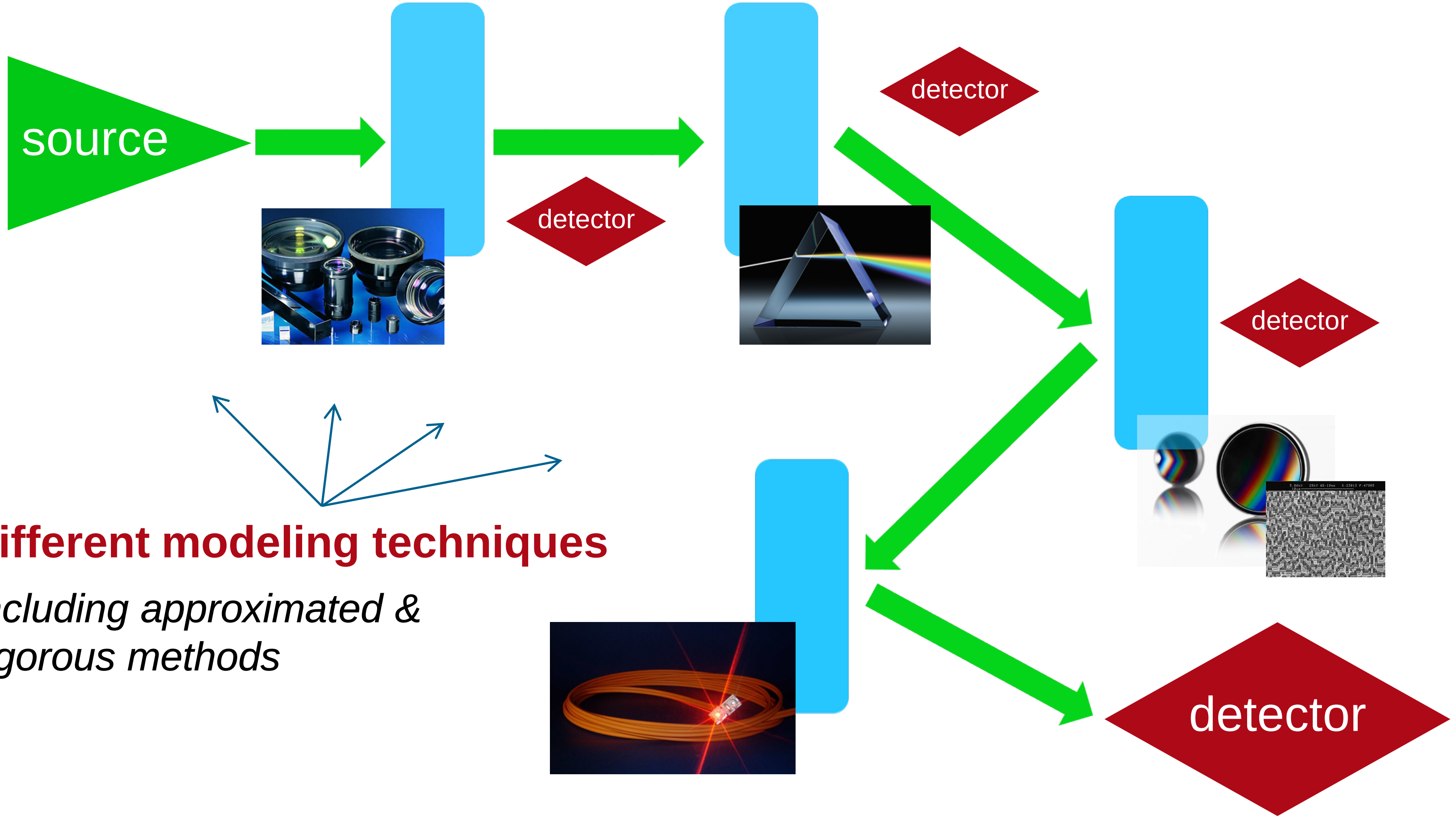
- **Ray Tracing** is based on geometrical optics and often gives a very **good impression** of more complex **systems' behaviour**, too.
- **Field Tracing** and its diverse propagation techniques (from geometrical to physical optical) gives you much more information.

→ **Geometrical optics stays an important basis** and is used if appropriate.

→ **Field Tracing allows to use alternative propagation methods** in case geometrical optics is not accurate enough.

➡ Physical optics and geometrical optics techniques must work smoothly together in modern system modeling and design!

Flexibel Approach for All Kinds of Systems

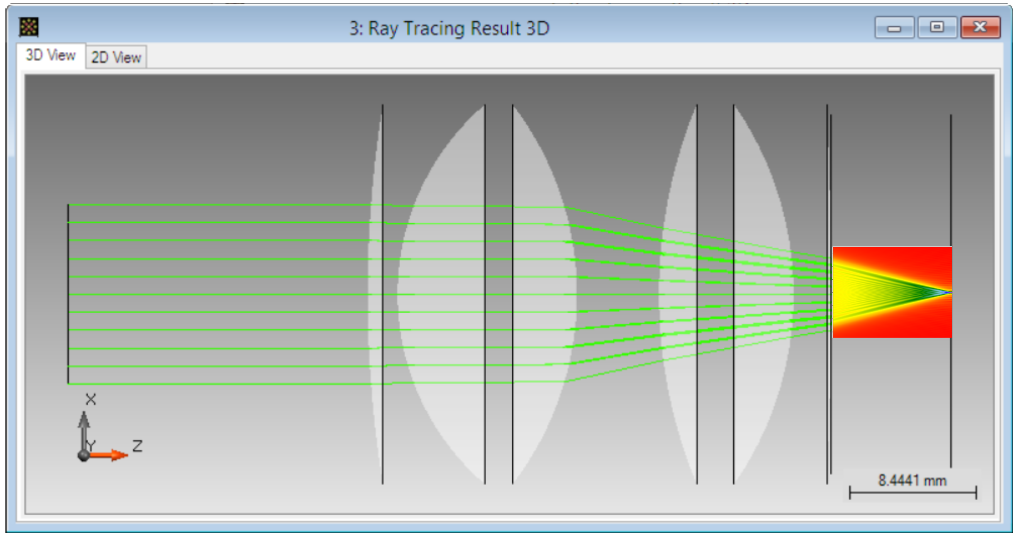


different modeling techniques

including approximated & rigorous methods

+ non sequential propagations (not shown here)

2^{nd} Generation Field Tracing Specifics



Adjacent figure depicts the concept that VirtualLab handles the last propagation to each detector with special regard. Either...

- geometrically
- semi-analytically
- rigorously

The current *2^{nd} Generation Field Tracing* simulation engine is the beginning of a new simulation concept.

Currently it uses geometrical optics rules in most parts of the system except for:

- a Gaussian source
- the last propagation distance

where a diffractional regard is applied if required.

VirtualLab Fusion automatically switches between these different light handling.

Classic Field Tracing Techniques in VirtualLab

1. Free-space propagation
   a. Spectrum of plane wave integral (SPW)
   b. Fresnel integral
   c. Far field integral
   d. Geometrical optics propagation
   e. Automatic selection operator
   f. further specialised methods
2. Rotation operators (electromagnetic fields on arbitrary planes)
3. Rigorous modeling for plane interfaces, prisms, cubes etc.
4. Geometrical optics field tracing
5. Thin element approximation (TEA)
6. Beam propagation method (BPM) (split-step)
7. Fourier modal method (FMM)
8. Finite Element Method (FEM) (with JCMWave)
9. … More are added steadily …

For **Field Tracing 2nd Generation** for many of these methods we use new and more efficient algorithmic approaches.

Benefit from Field Tracing

As the name suggests, **field tracing** allows to regard and evaluate the light as **complex electromagnetic field throughout the system**, thus

- amplitude
- phase

data of the **E** field are stored.

And due to **diverse applicable physical optics algorithms** accurate **investigations of**

- polarisation
- interference
- coherence
- diffraction

effects is made possible and all **other derivable optical quantities can be calculated**.

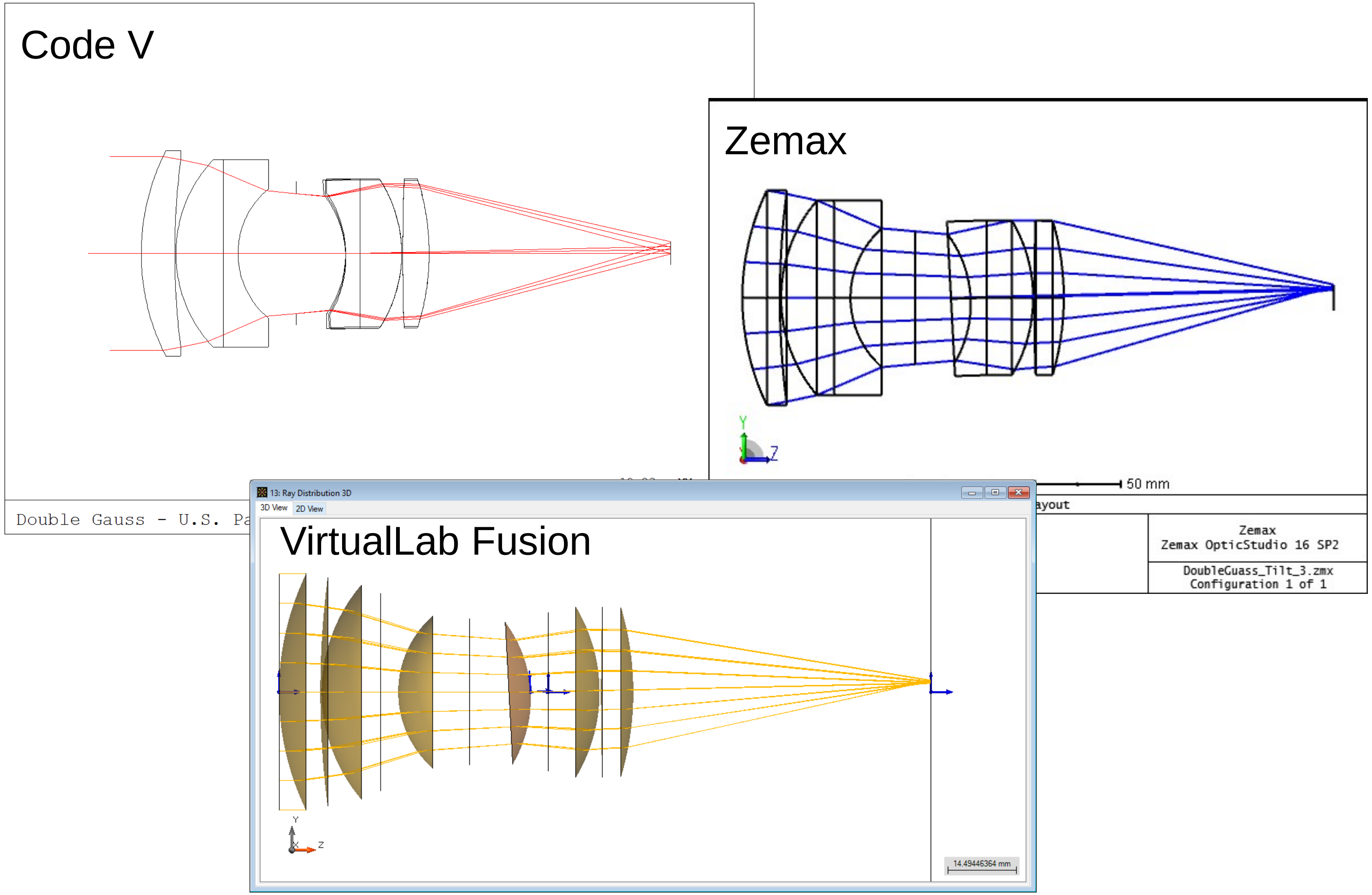
Ray Tracing Engine Comparison: VirtualLab Fusion vs Code V vs Zemax

Zongzhao Wang, Tingcheng Zhang and Irfan Badar

Date: 2017, Dec, 31th

Applied Computational Optics Group, Jena
China Aerospace Science and Technology (CAST) Corporation

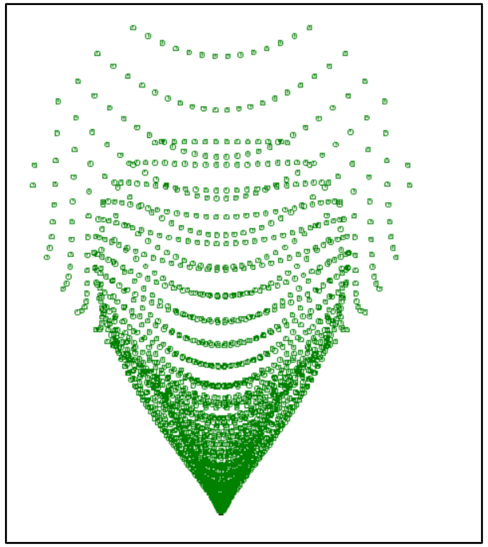
System Illustration (Lens System with Tilted Surface)



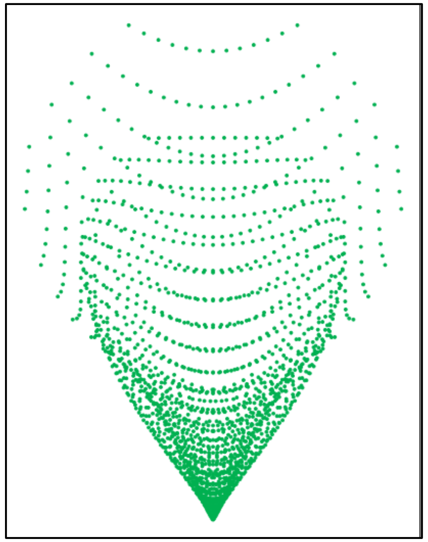
Specification of Simulation Parameters

- working wavelength: 587 nm
- polarization: E_x-polarized
- effective focal length: 100.00049 mm
- NA of System: 0.2499
- diameter of plane input wave (entrance pupil): 50 mm
- field of view (FOV): 0°
- vignetting: 0
- tilt angle of 7th surface about its x-axis: -3°

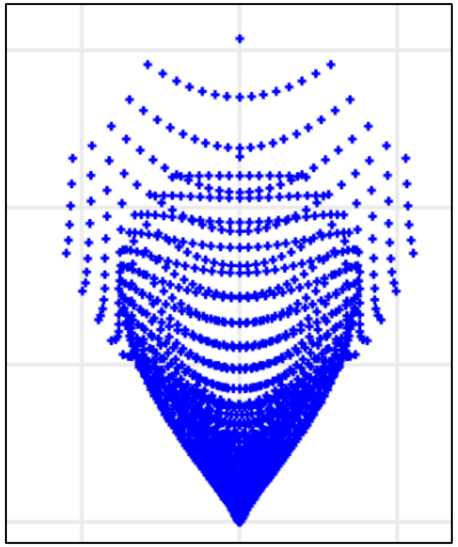
Dot Diagram Comparison: Target Plane



Code V



VLF



Zemax

Precise Comparison: Positions all in Accordance

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)

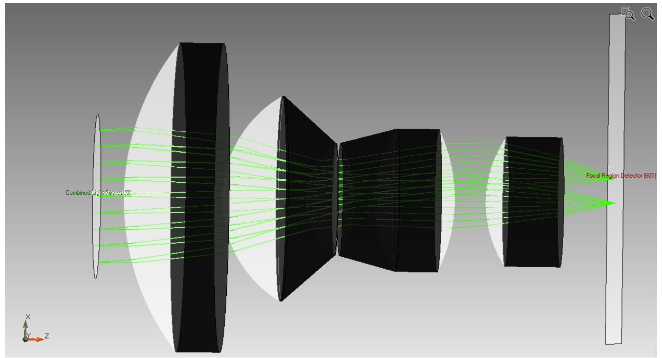
Ray position at imaging plane

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)

Ray Tracing in VirtualLab Fusion

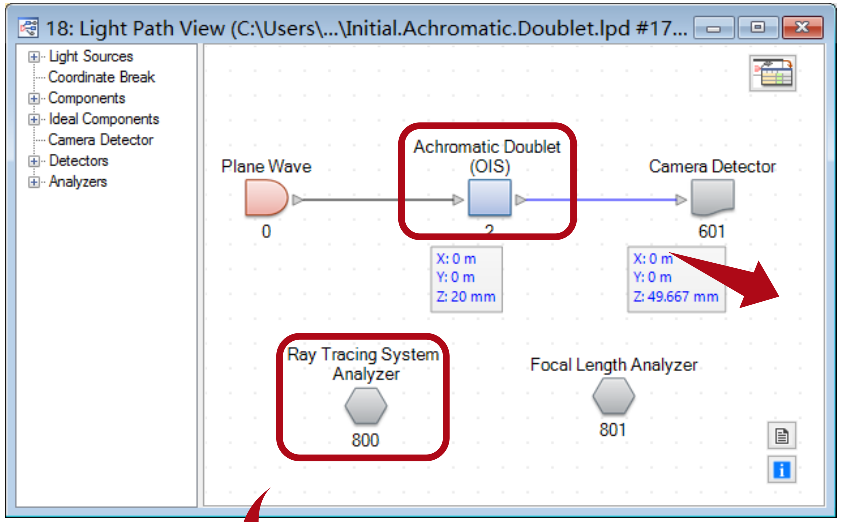
- Ray Tracing System Analyzer

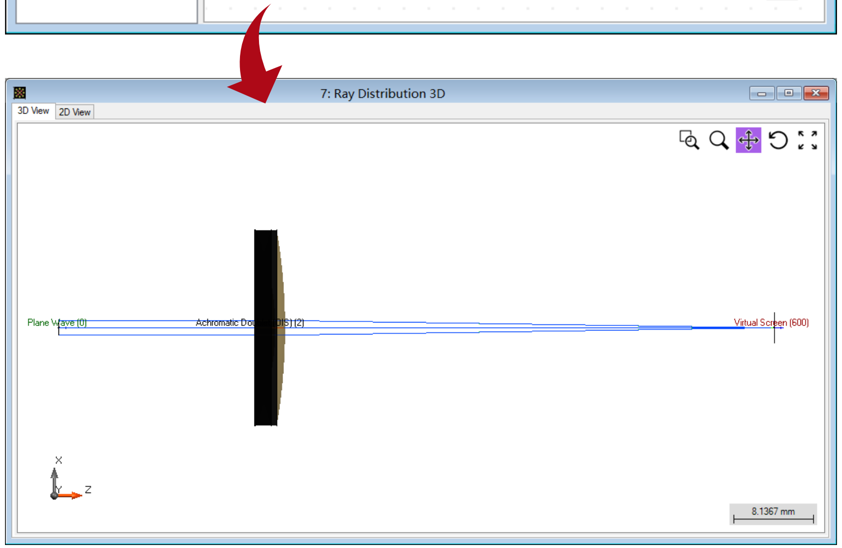
- Detector
  - Spot size
  - Wavefront error (Zernike polynomials)
  - Focal length analyzer
  - …
- Parametric optimization

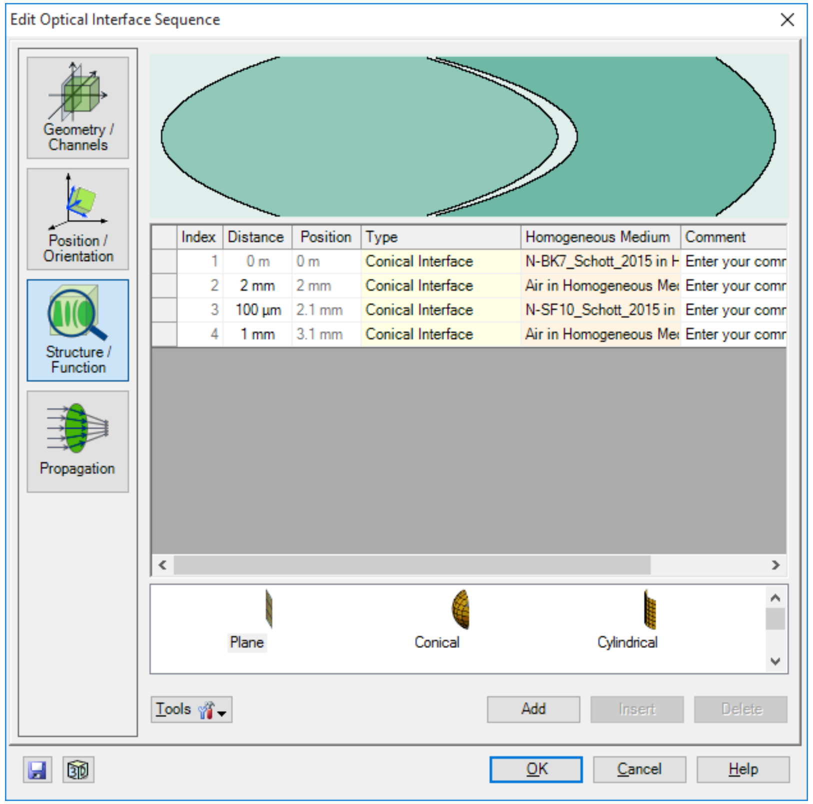


Parametric Optimization of An Achromatic Doublet

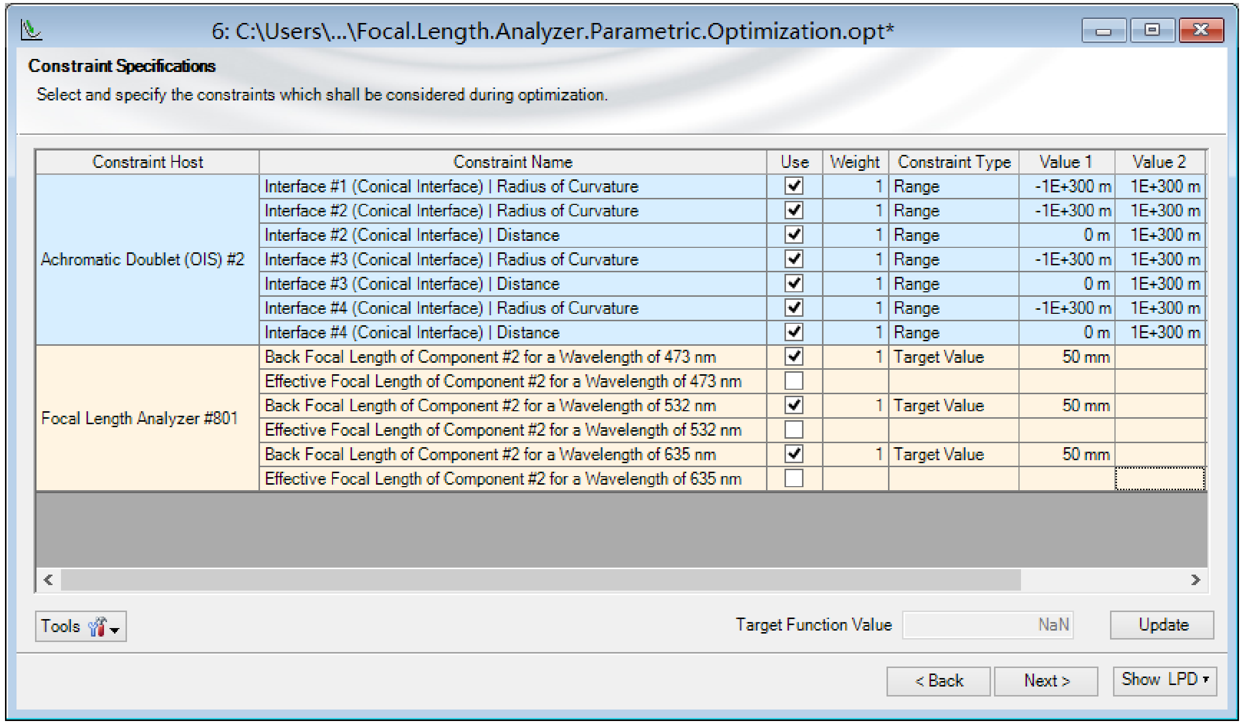
Schematic and Light Path Diagram







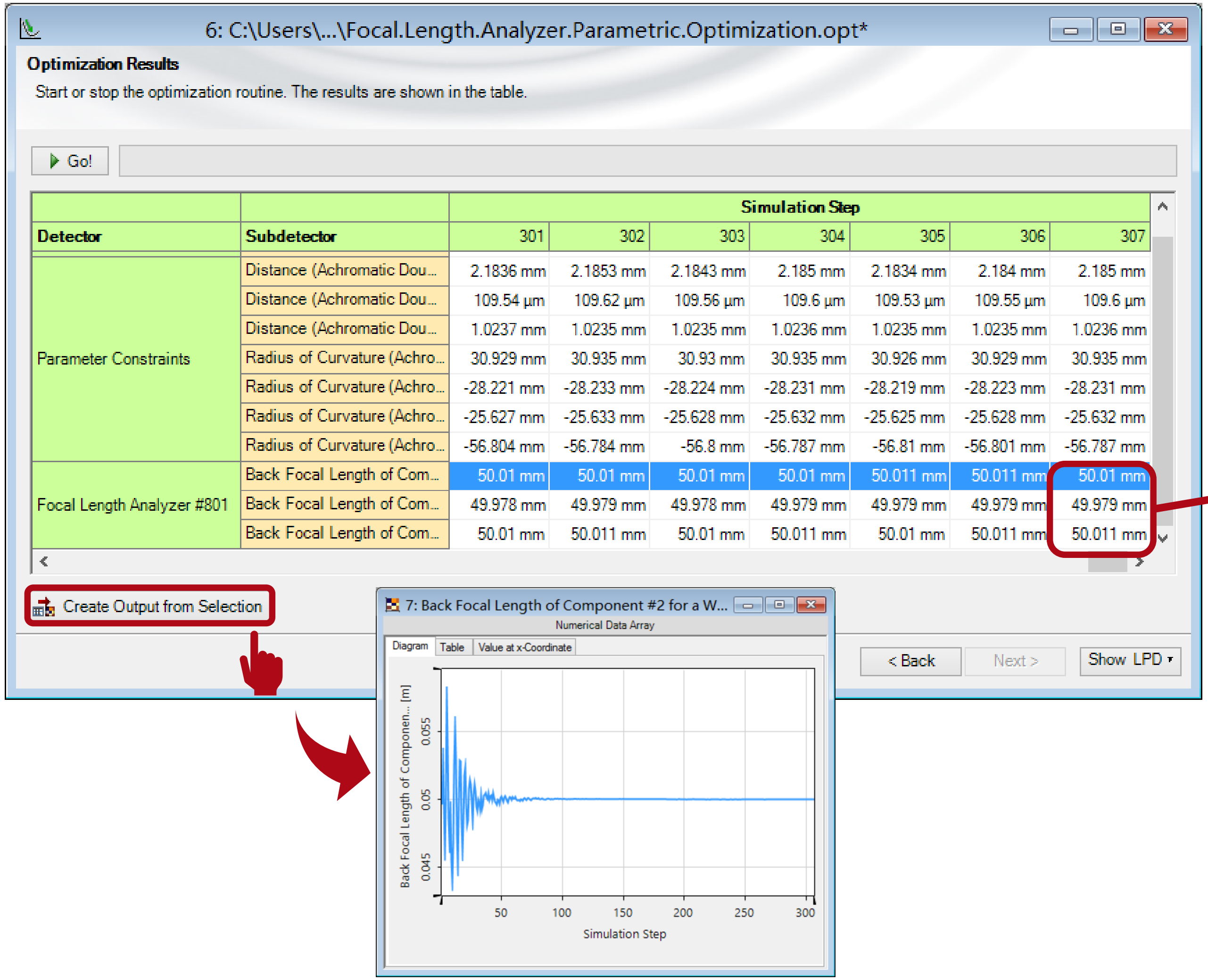
Set Optimization Target



Constraint Host	Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2
Achromatic Doublet (OIS) #2	Interface #1 (Conical Interface) | Radius of Curvature	☑	1	Range	-1E+300 m	1E+300 m
	Interface #2 (Conical Interface) | Radius of Curvature	☑	1	Range	-1E+300 m	1E+300 m
	Interface #2 (Conical Interface) | Distance	☑	1	Range	0 m	1E+300 m
	Interface #3 (Conical Interface) | Radius of Curvature	☑	1	Range	-1E+300 m	1E+300 m
	Interface #3 (Conical Interface) | Distance	☑	1	Range	0 m	1E+300 m
	Interface #4 (Conical Interface) | Radius of Curvature	☑	1	Range	-1E+300 m	1E+300 m
	Interface #4 (Conical Interface) | Distance	☑	1	Range	0 m	1E+300 m
Focal Length Analyzer #801	Back Focal Length of Component #2 for a Wavelength of 473 nm	☑	1	Target Value	50 mm	
	Effective Focal Length of Component #2 for a Wavelength of 473 nm	☐				
	Back Focal Length of Component #2 for a Wavelength of 532 nm	☑	1	Target Value	50 mm	
	Effective Focal Length of Component #2 for a Wavelength of 532 nm	☐				
	Back Focal Length of Component #2 for a Wavelength of 635 nm	☑	1	Target Value	50 mm	
	Effective Focal Length of Component #2 for a Wavelength of 635 nm	☐				

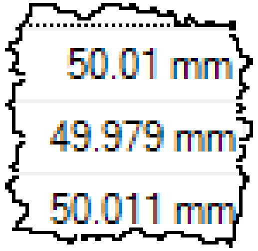
- Focal Length Analyzer
  - Effective Focal Length is set to 50 mm: for all chosen wavelengths

Optimization Result



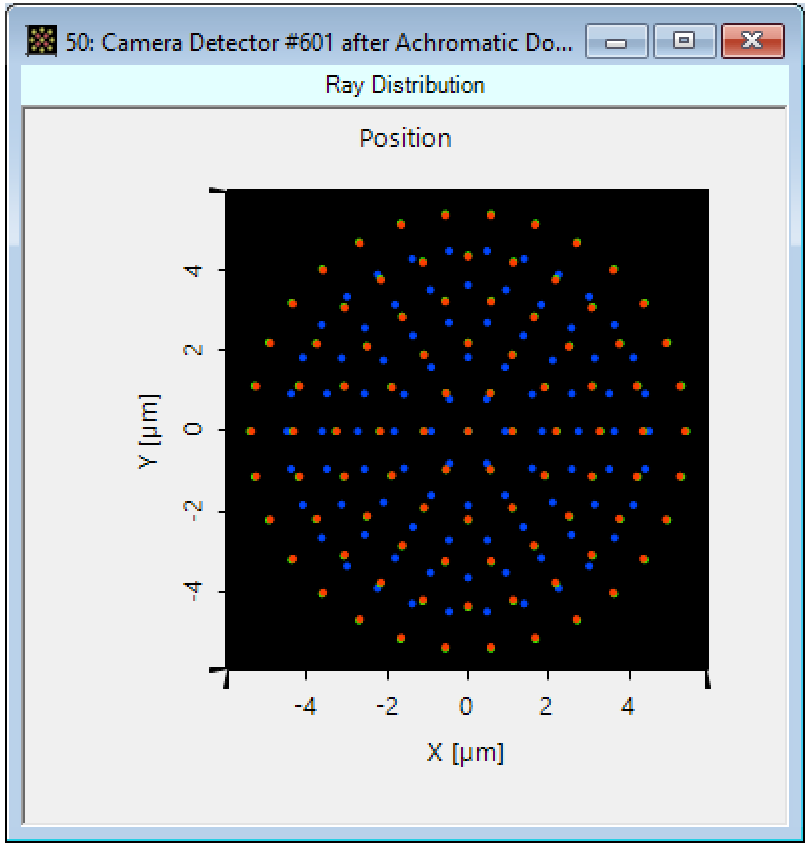
		Simulation Step						
Detector	Subdetector	301	302	303	304	305	306	307
Parameter Constraints	Distance (Achromatic Dou...	2.1836 mm	2.1853 mm	2.1843 mm	2.185 mm	2.1834 mm	2.184 mm	2.185 mm
	Distance (Achromatic Dou...	109.54 µm	109.62 µm	109.56 µm	109.6 µm	109.53 µm	109.55 µm	109.6 µm
	Distance (Achromatic 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

focal length after optimization

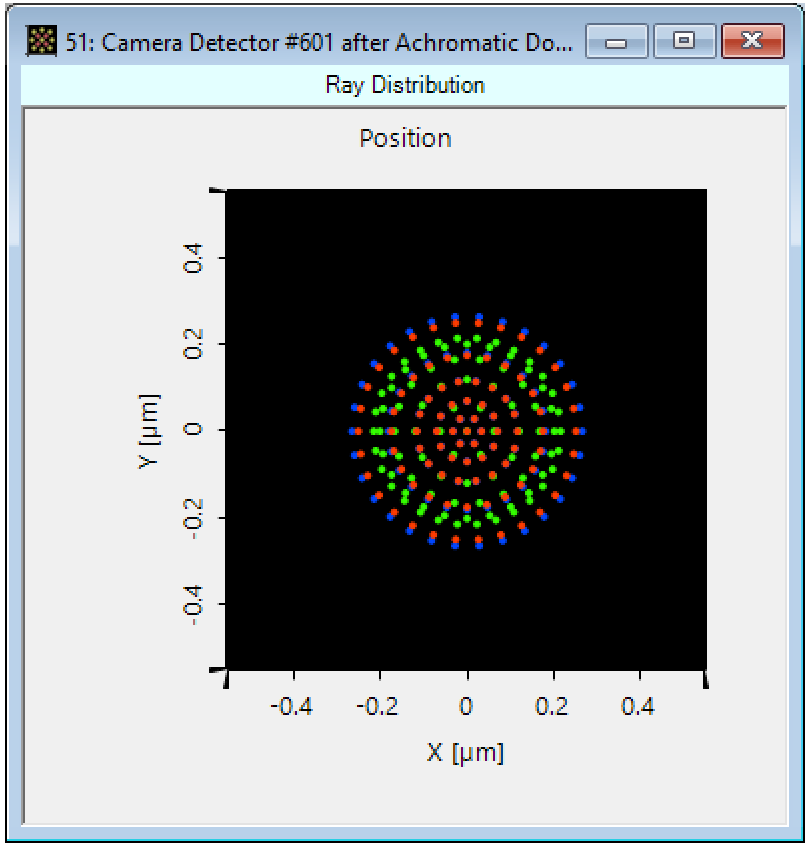


Comparison of Results

Dot Diagram (initial setup)



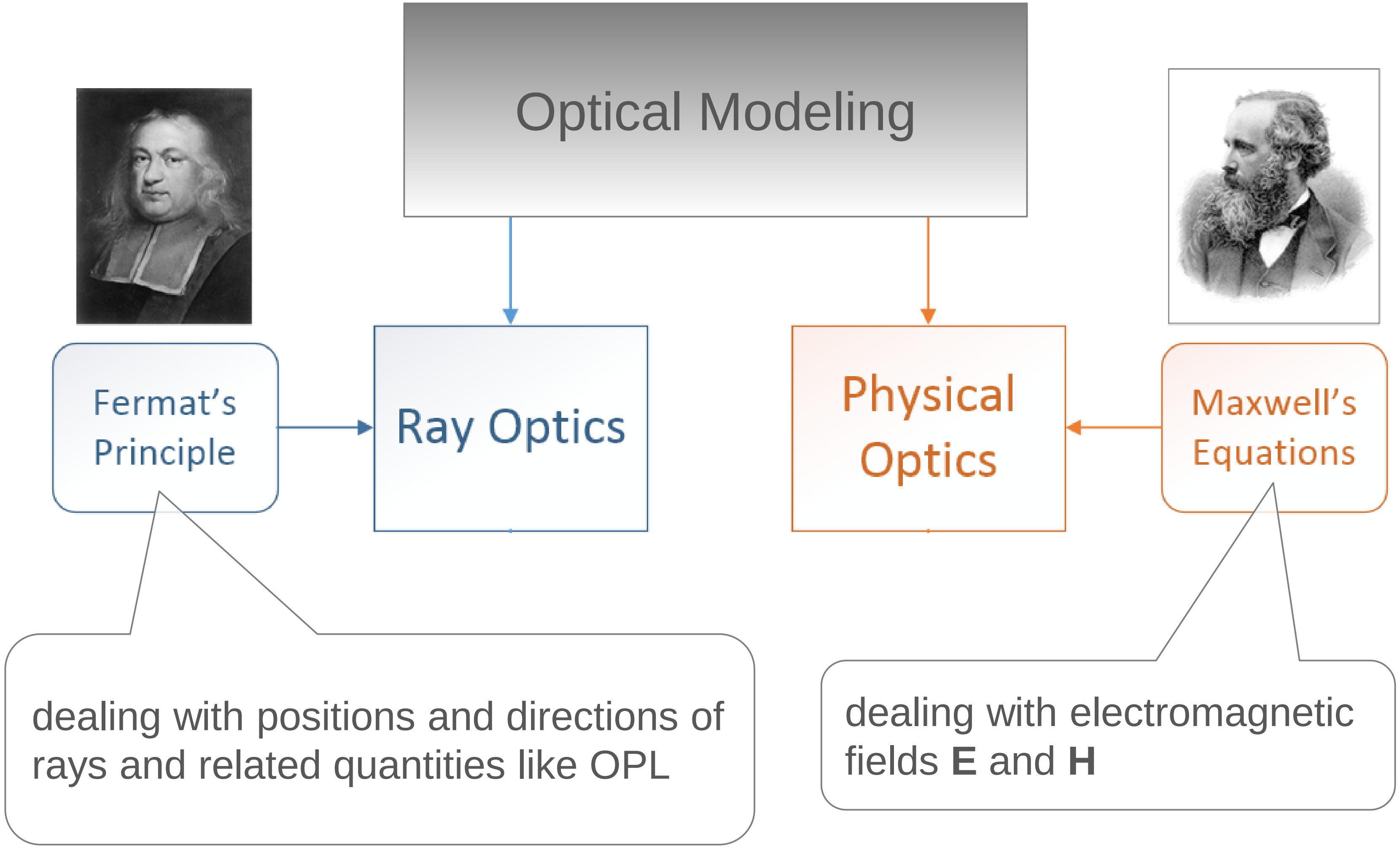
Dot Diagram (optimized)



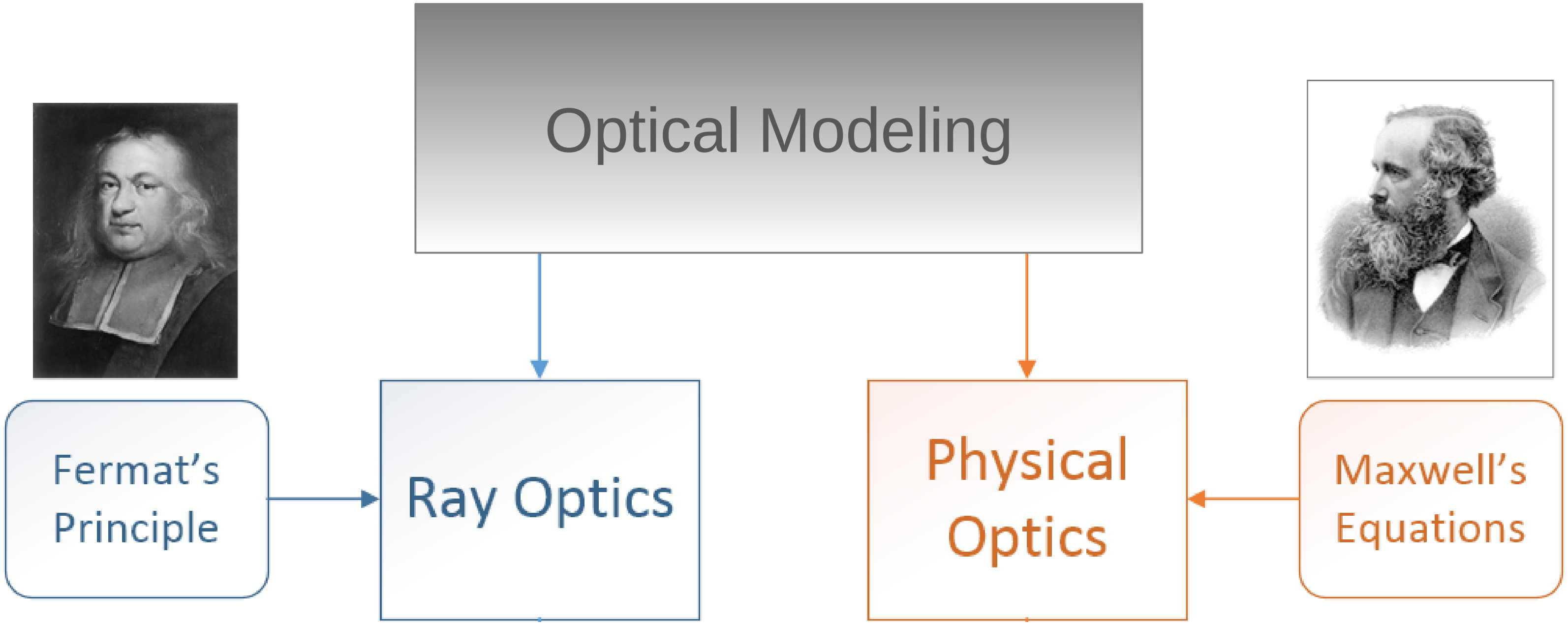
Basics 0008 (1.0)

Limitations of Conventional Ray Tracing

Ray & Field Tracing



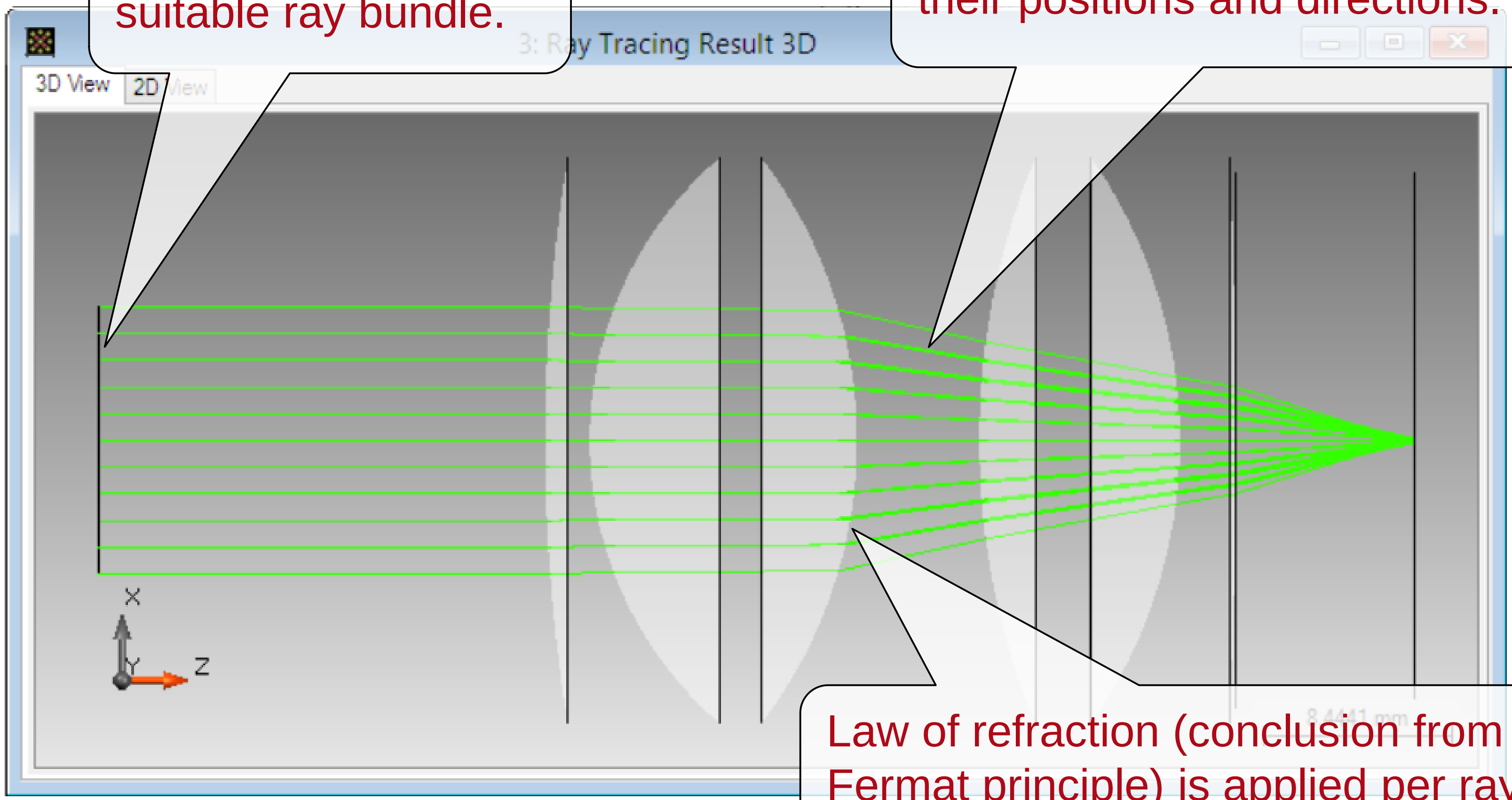
Ray & Field Tracing



Ray Optics Modeling ...

- gives great basic insight into light propagation.
- often sufficient for optical design, e.g. in standard lens design.
- **suffers from serious limitations...**

Ray Tracing Concept

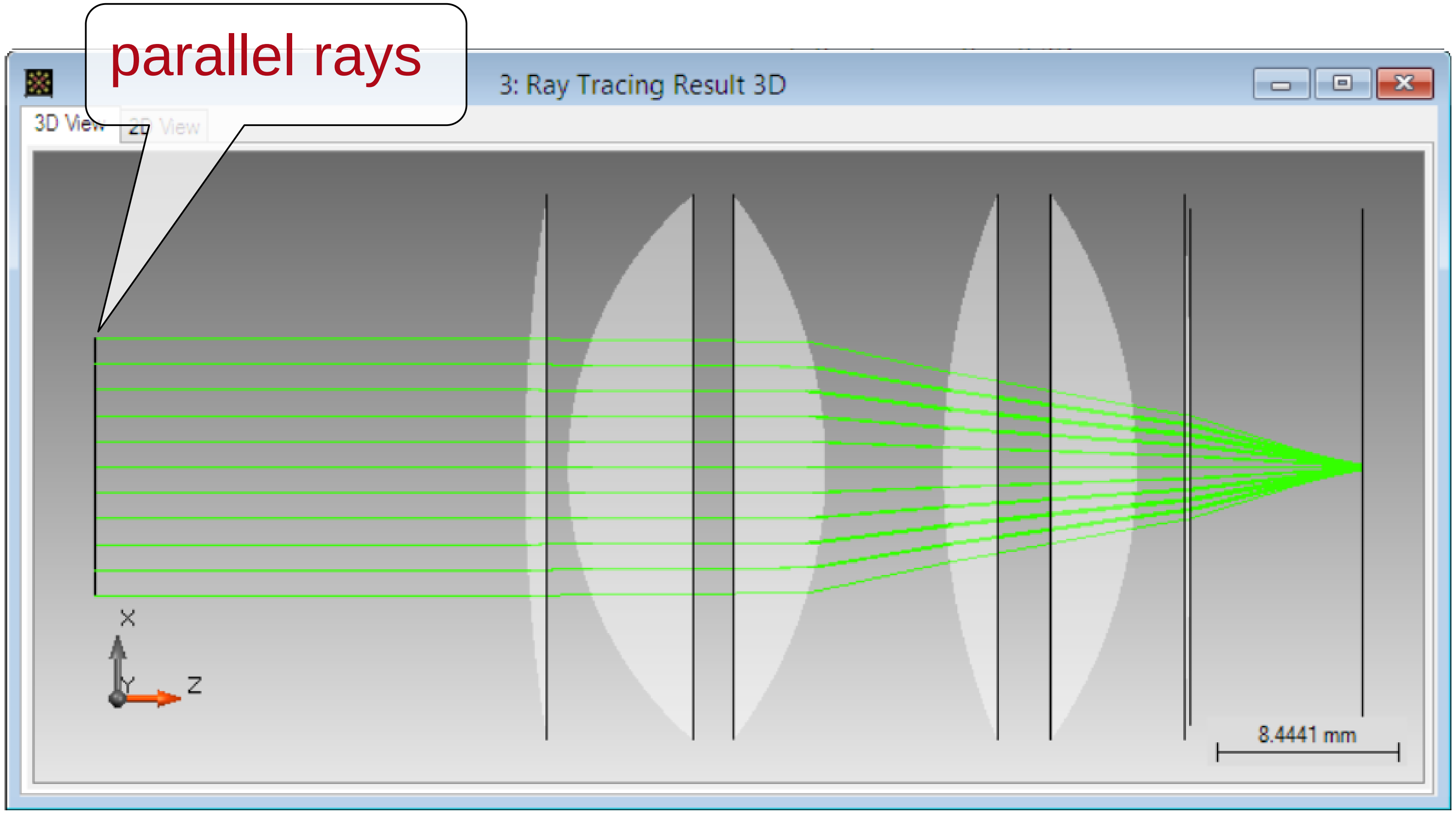


Source modeled by a suitable ray bundle.

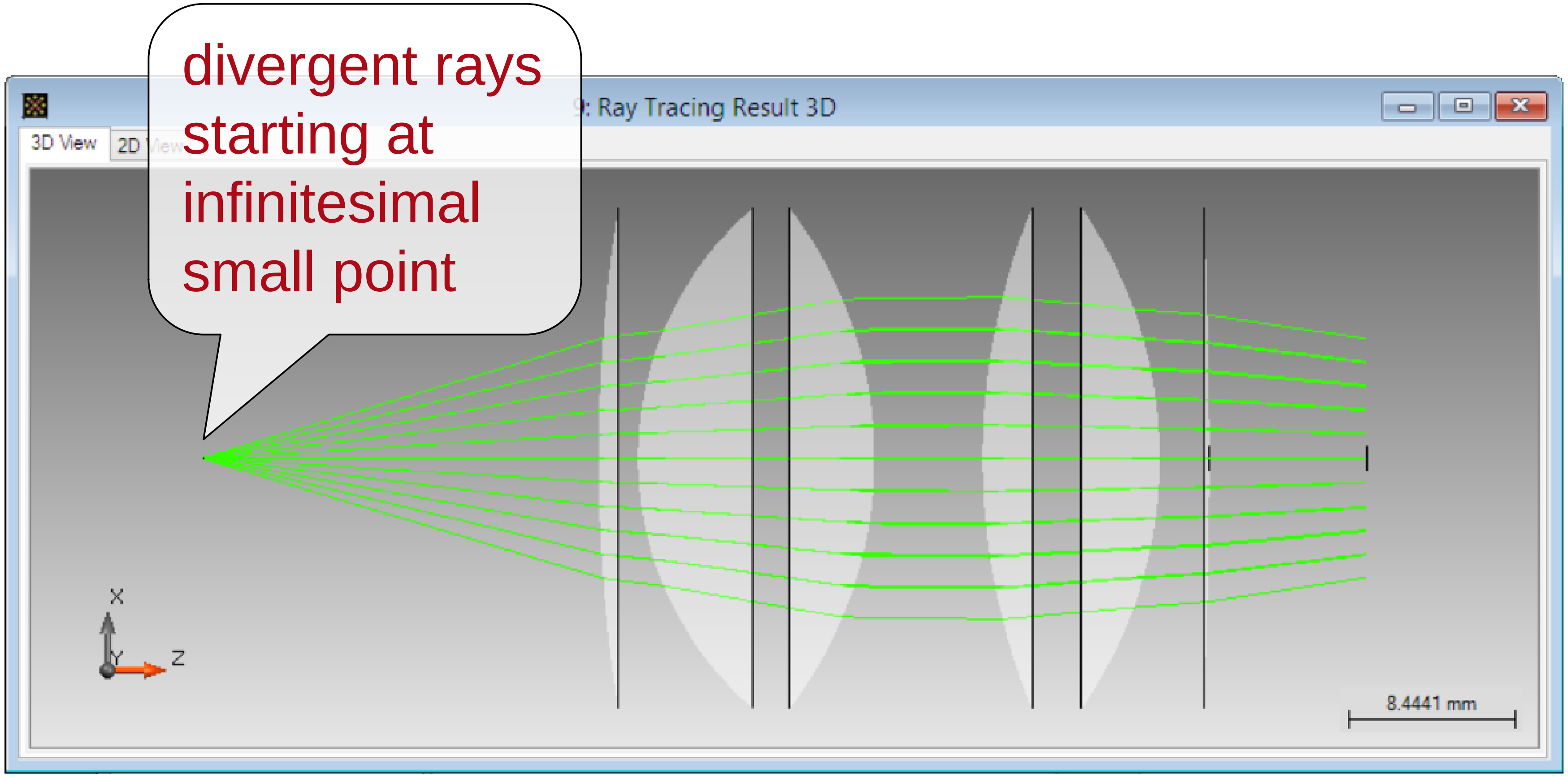
Rays are traced by determining their positions and directions.

Law of refraction (conclusion from Fermat principle) is applied per ray.

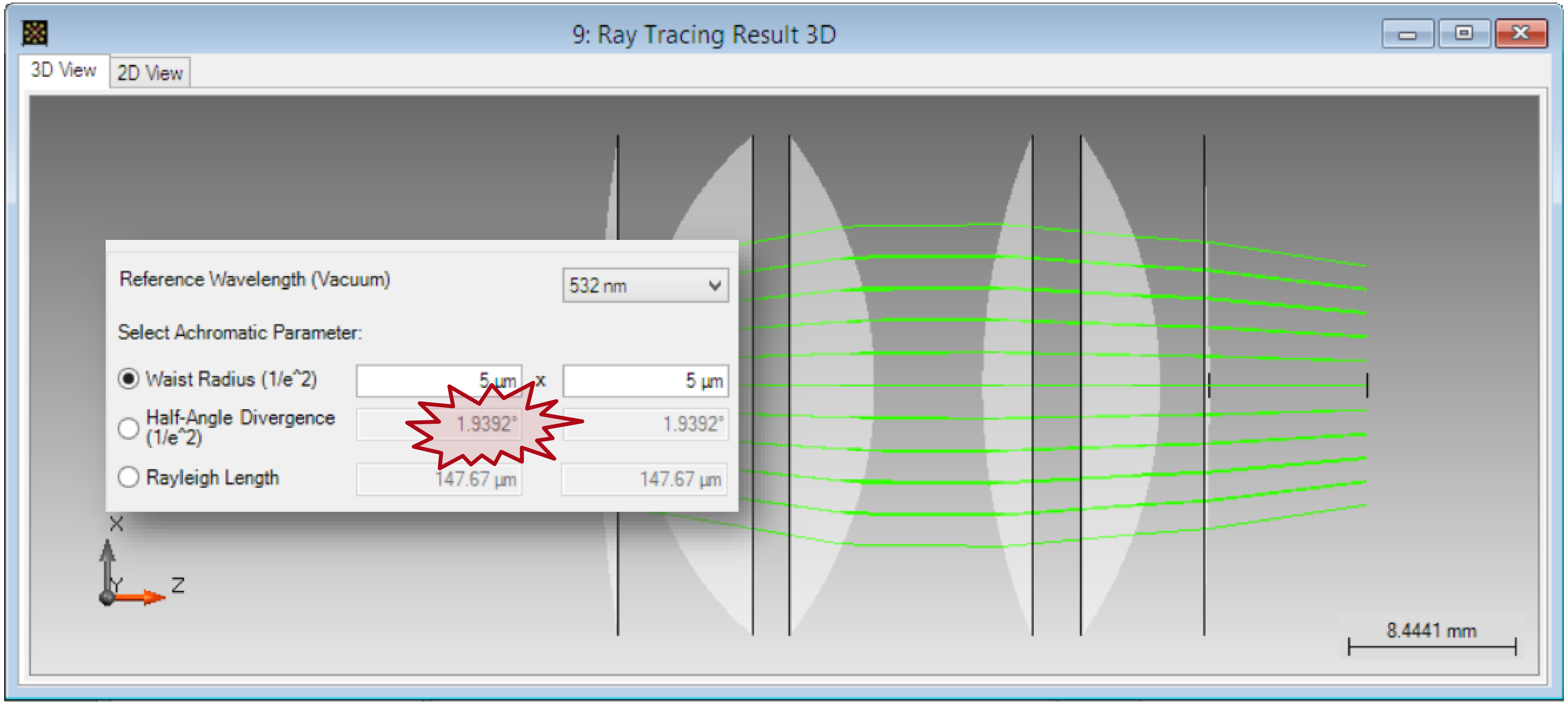
Ray Tracing Concept: Collimated Light



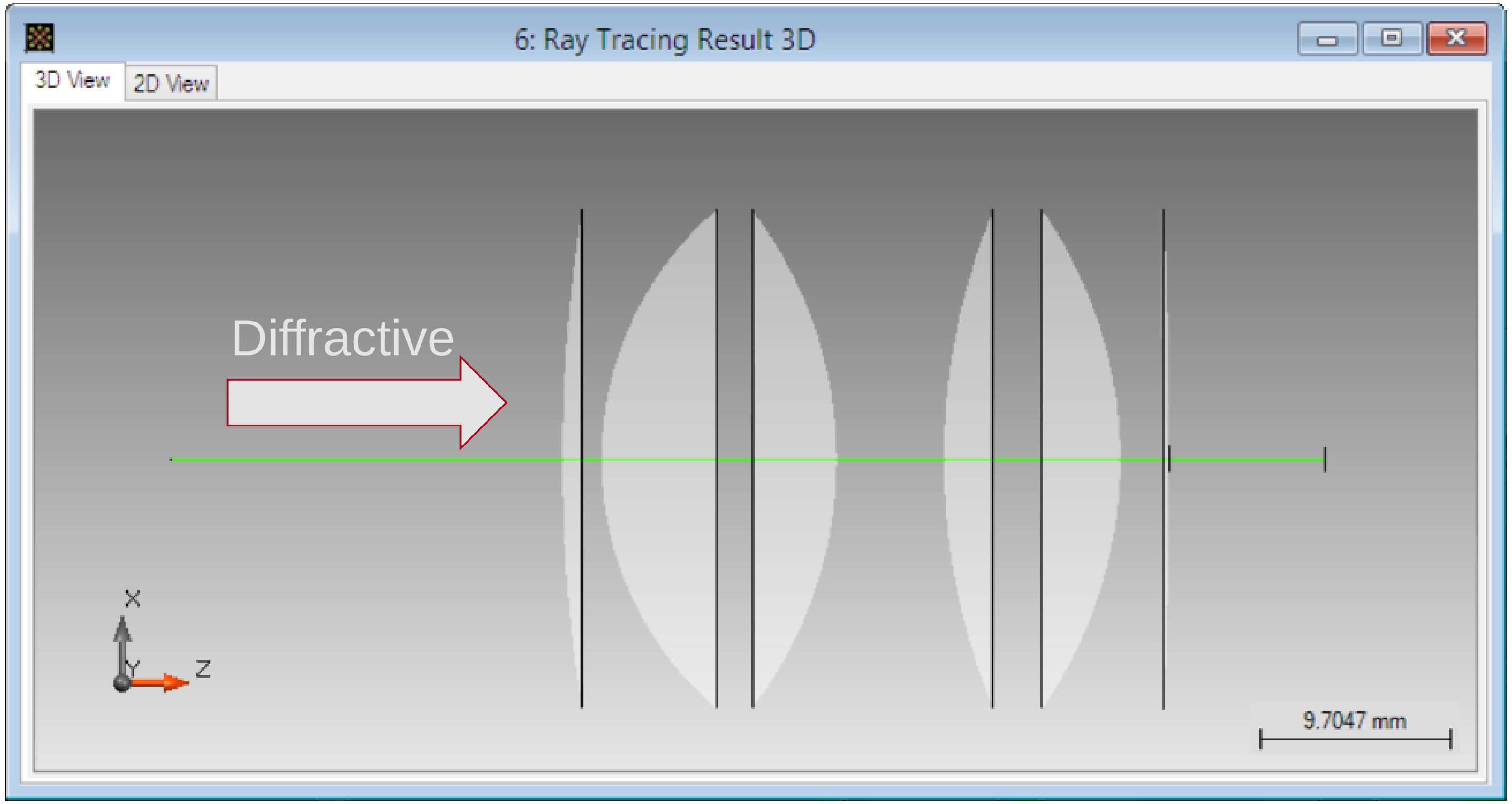
Ray Tracing Concept: Point Source (Spherical Wave)



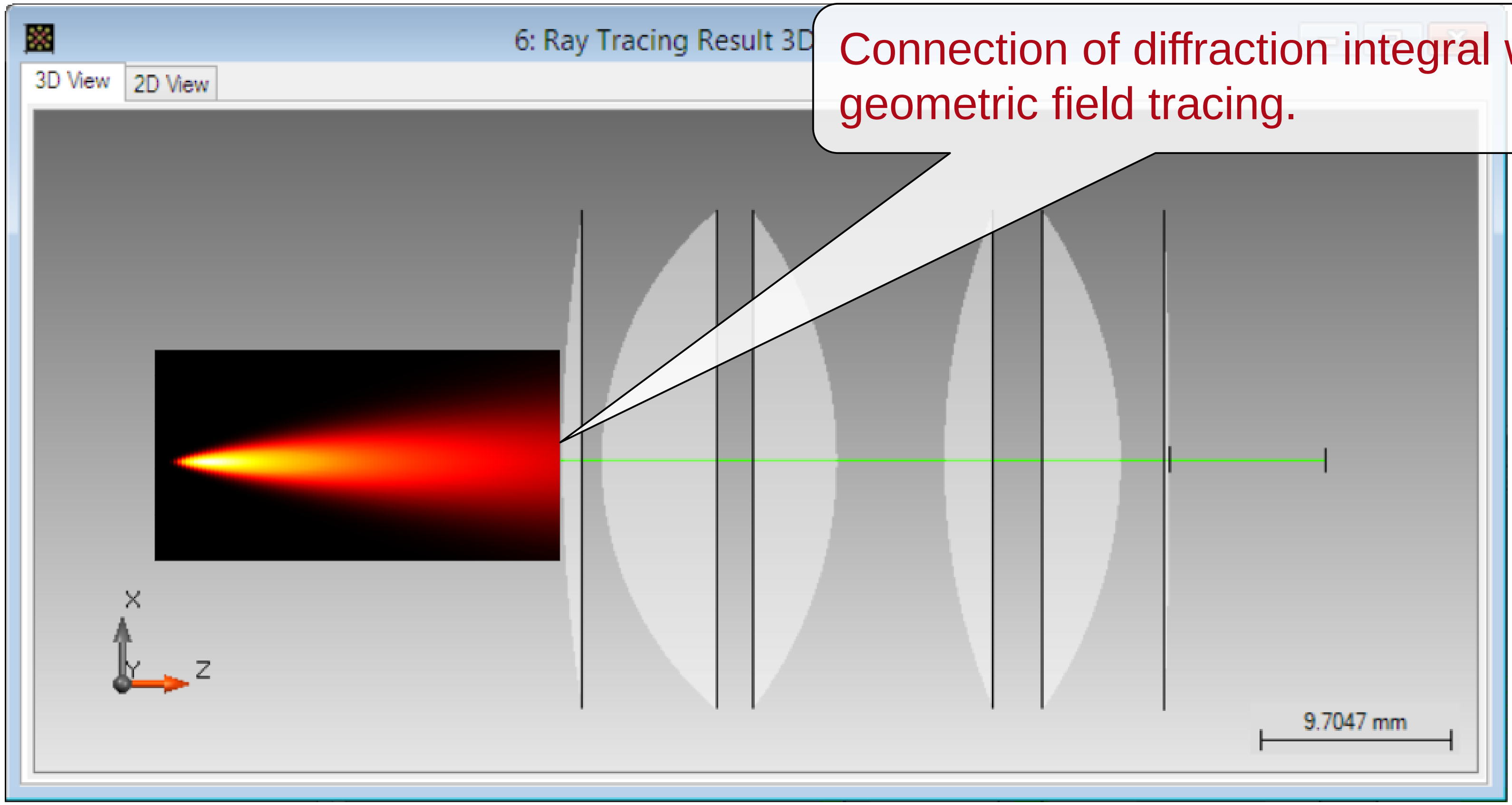
Ray Tracing Limitations: Gaussian Source



Ray Tracing Limitations: Gaussian Source

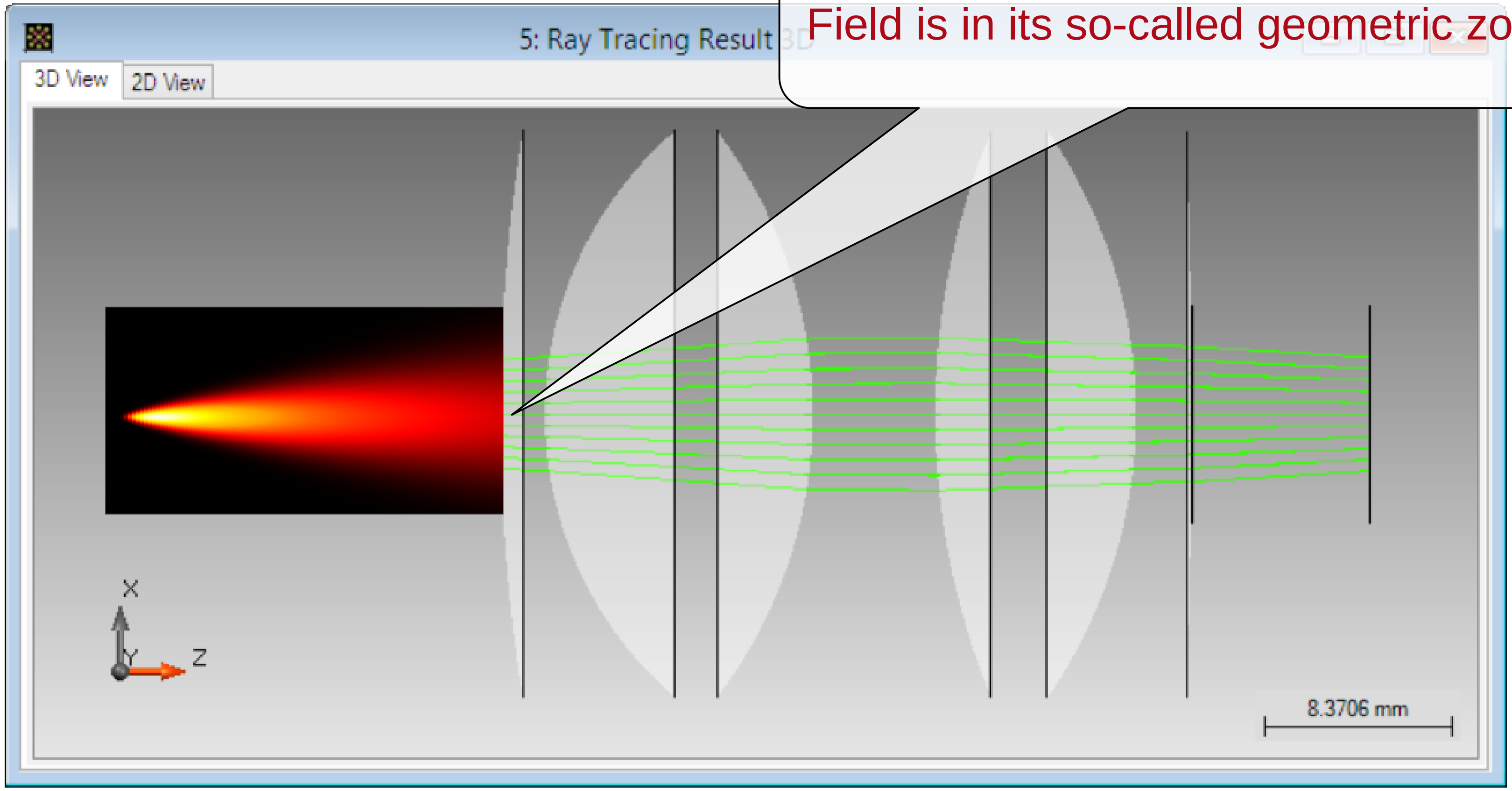


Ray Tracing Limitations: Gaussian Source



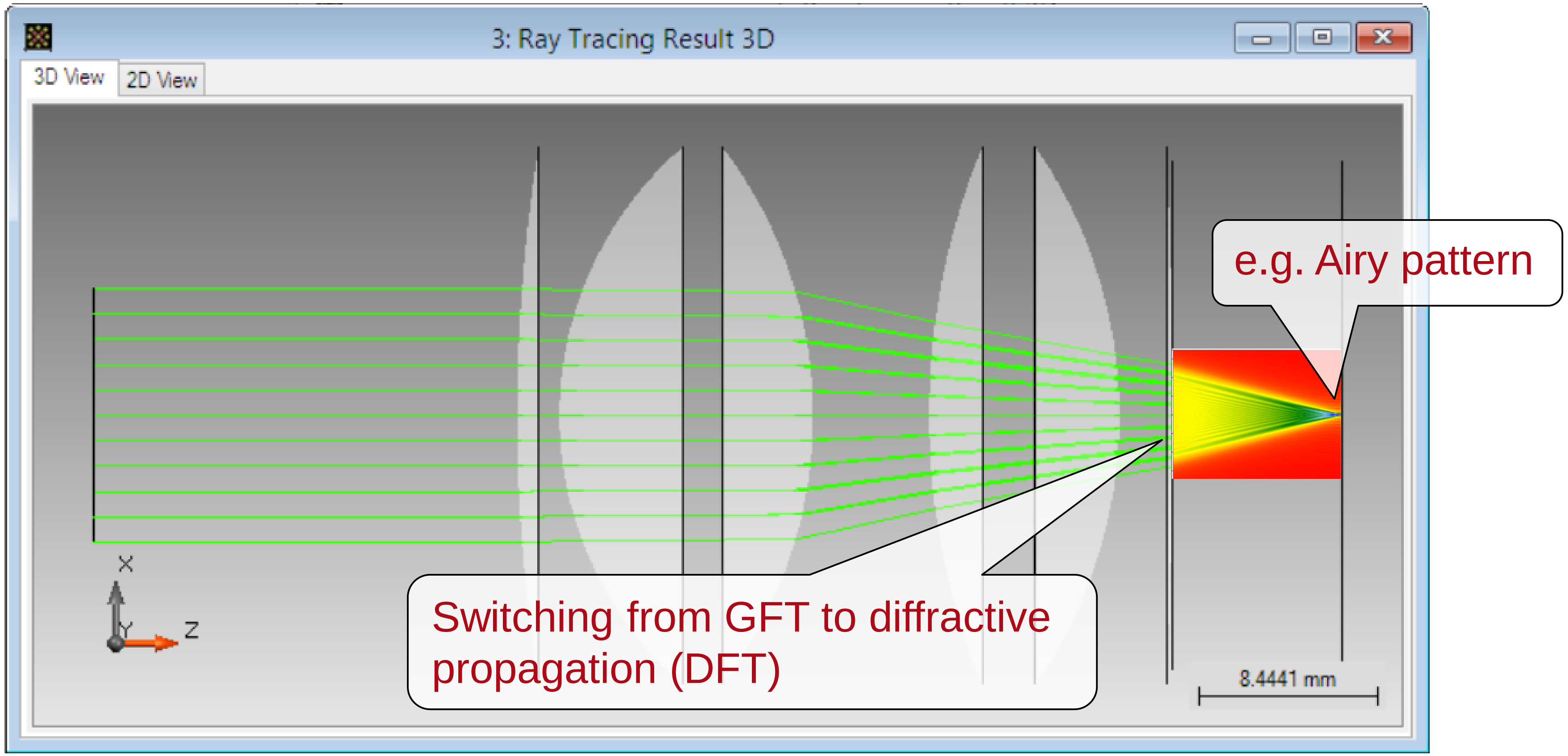
Connection of diffraction integral with geometric field tracing.

Ray Tracing Limitations: Gaussian Source

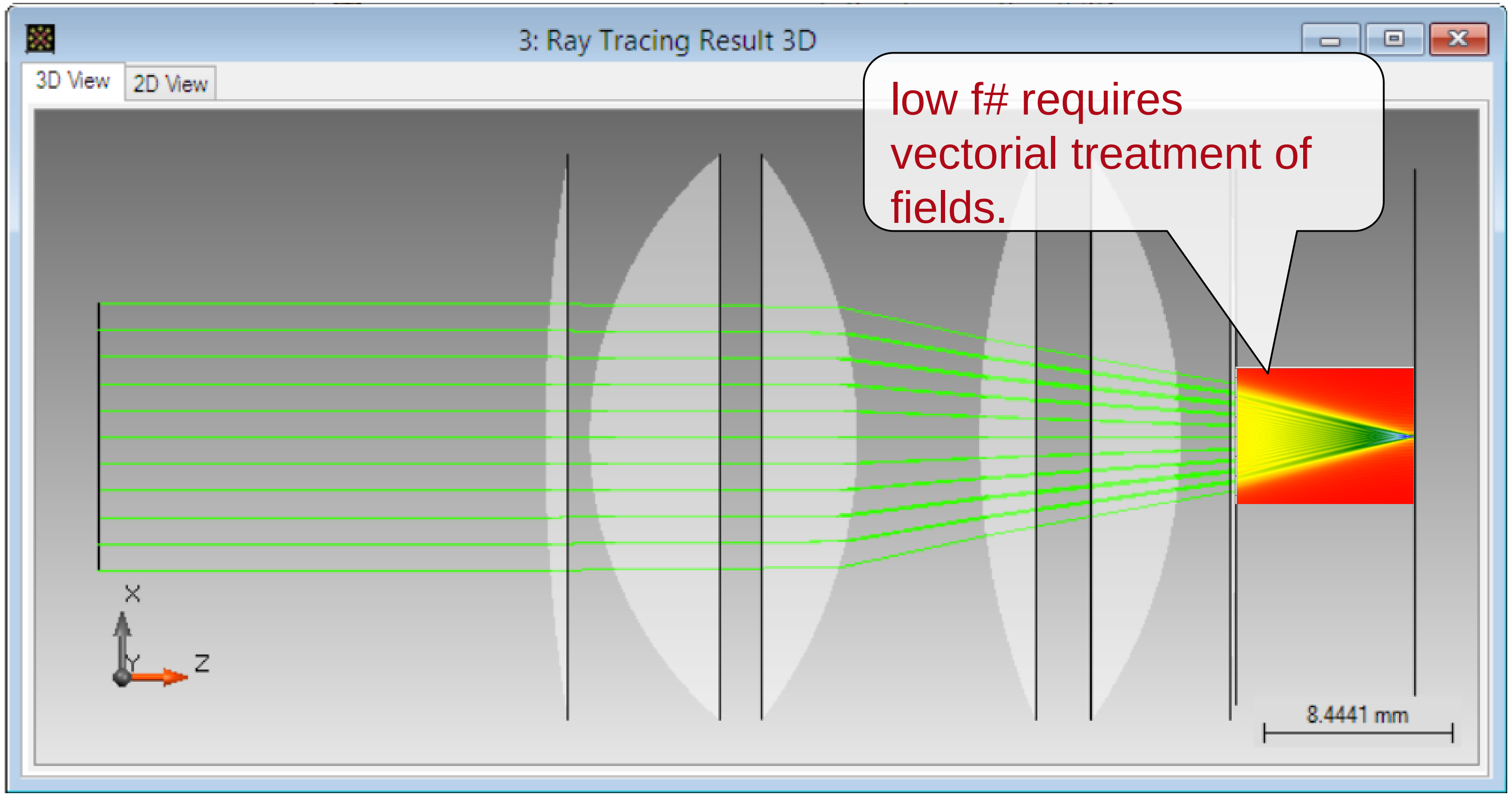


Assumption
Field is in its so-called geometric zone!

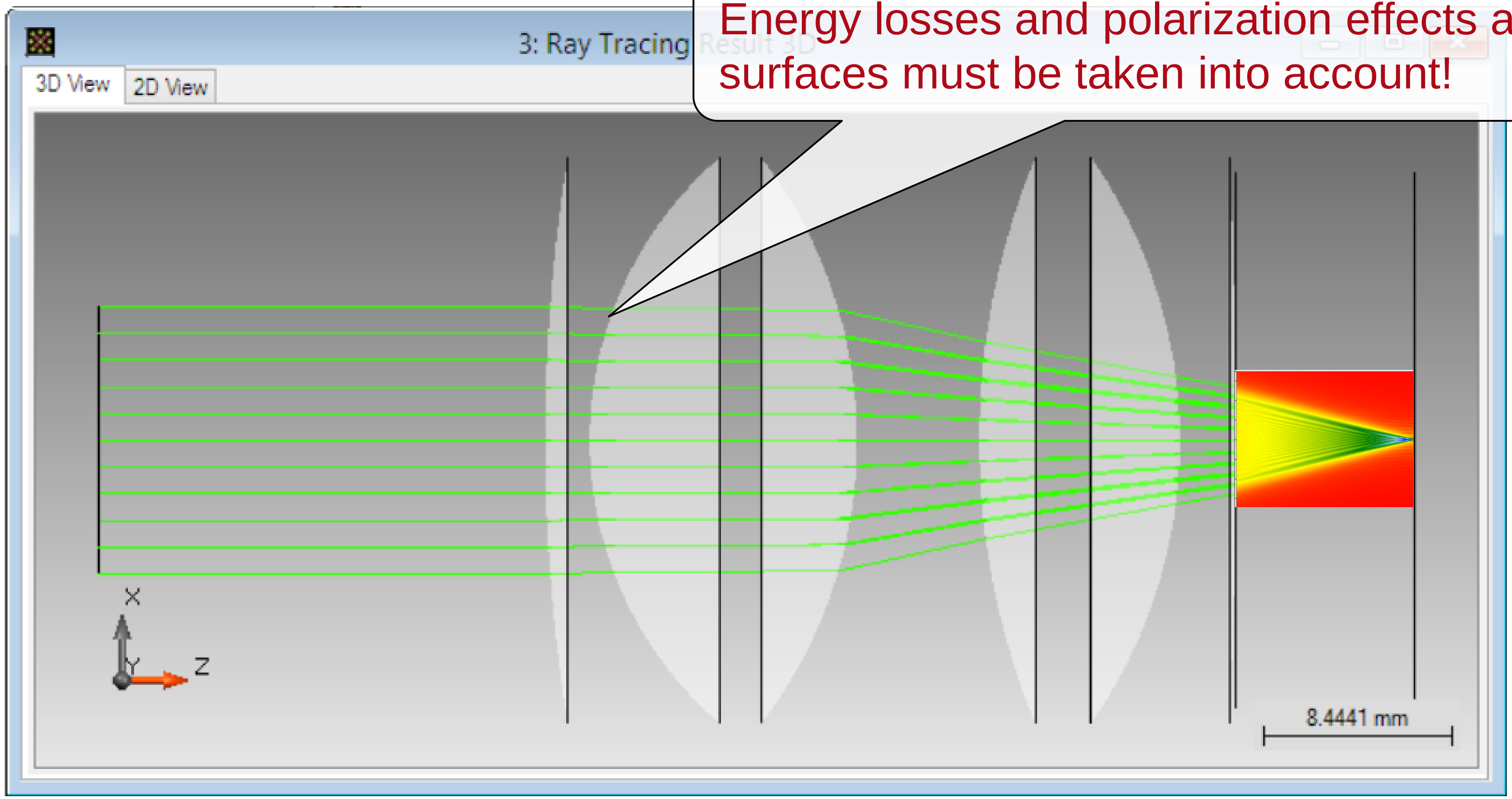
Ray Tracing Limitations: Focusing → Diffractive Zone



Ray Tracing Limitations: Vectorial Modeling

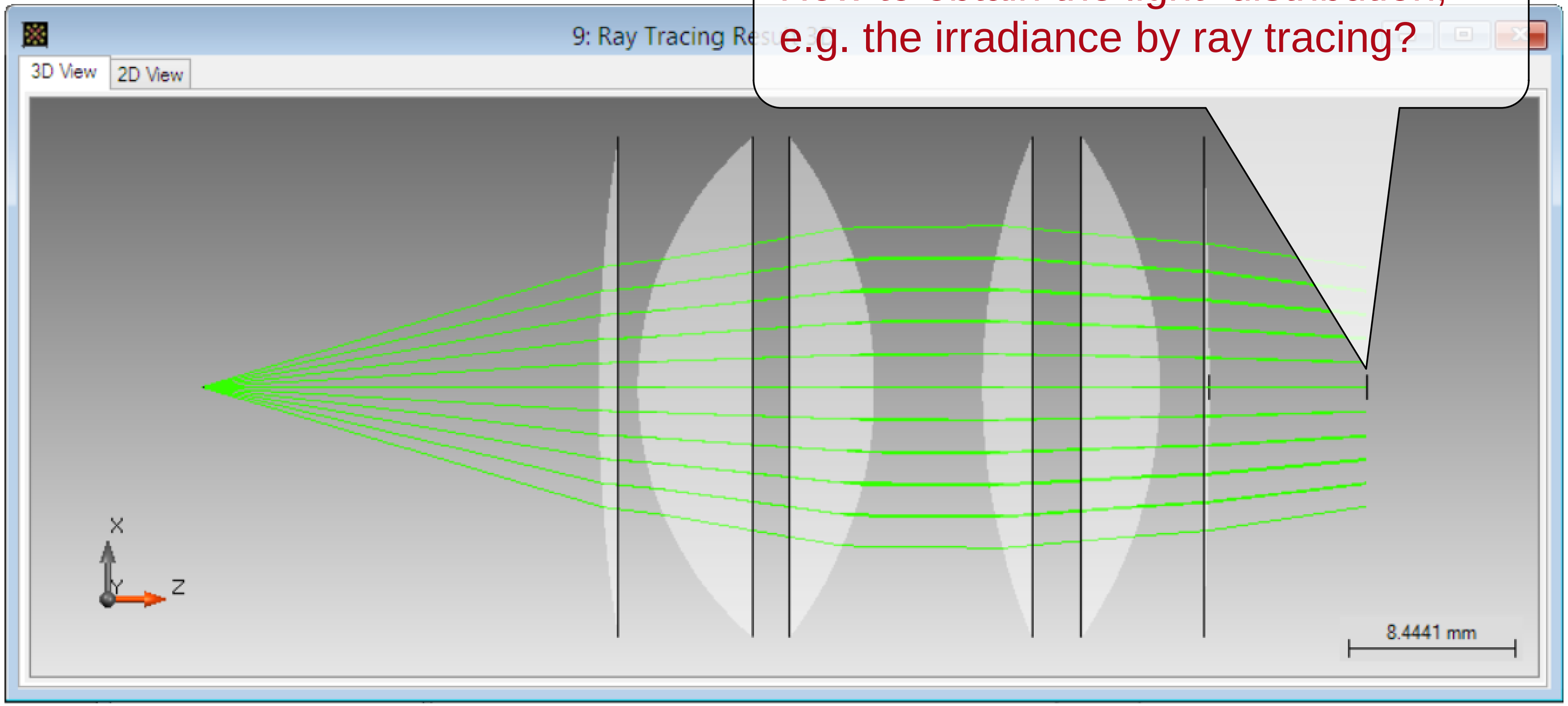


Ray Tracing Limitations: Vectorial Modeling



Energy losses and polarization effects at surfaces must be taken into account!

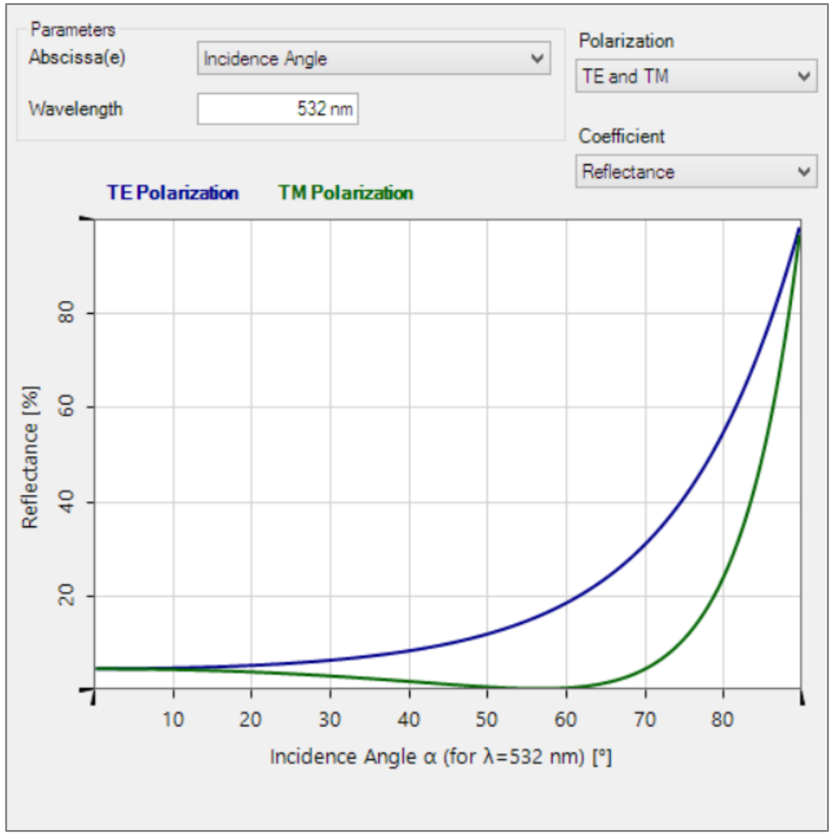
Ray Tracing Limitations: Energy



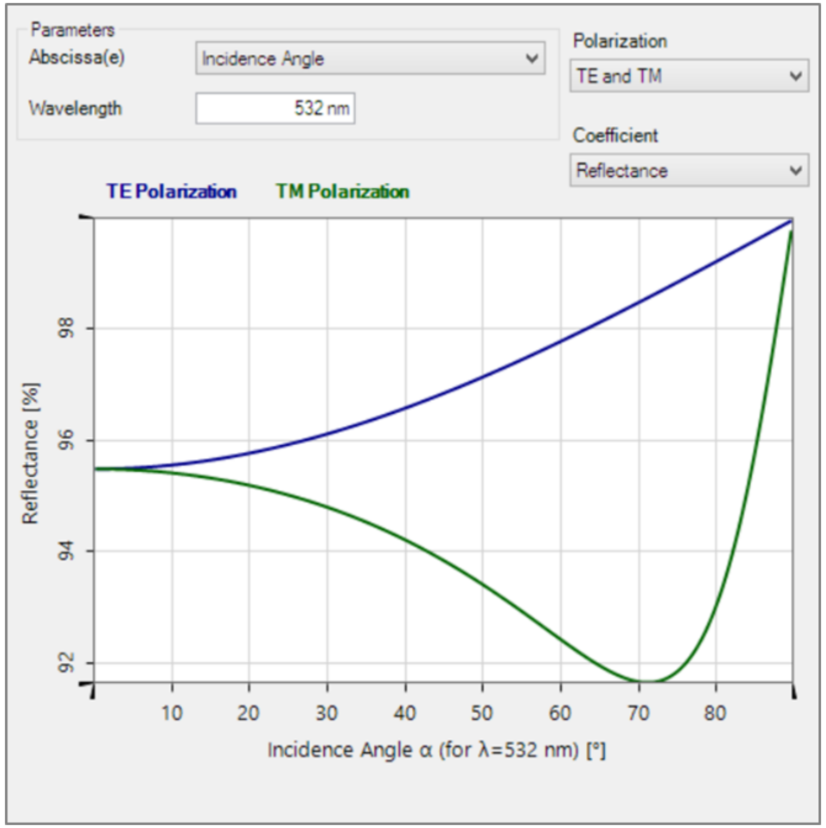
How to obtain the light distribution, e.g. the irradiance by ray tracing?

Fresnel Effect: Reflectance for TE/TM

air vs. BK7 glass

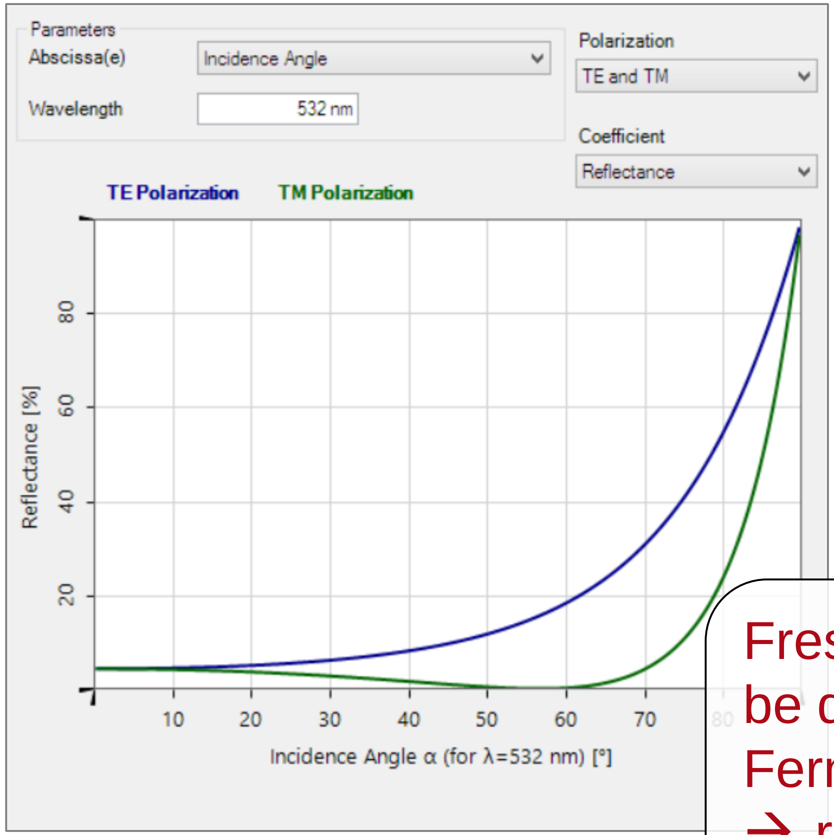


air vs. silver

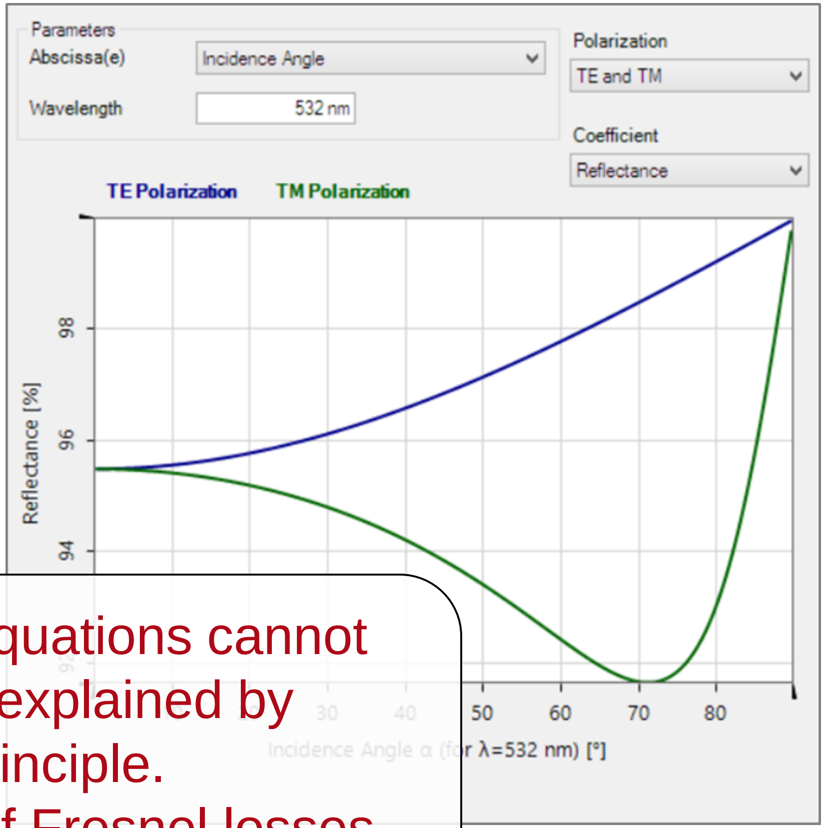


Fresnel Effect: Reflectance for TE/TM

air vs. BK7 glass

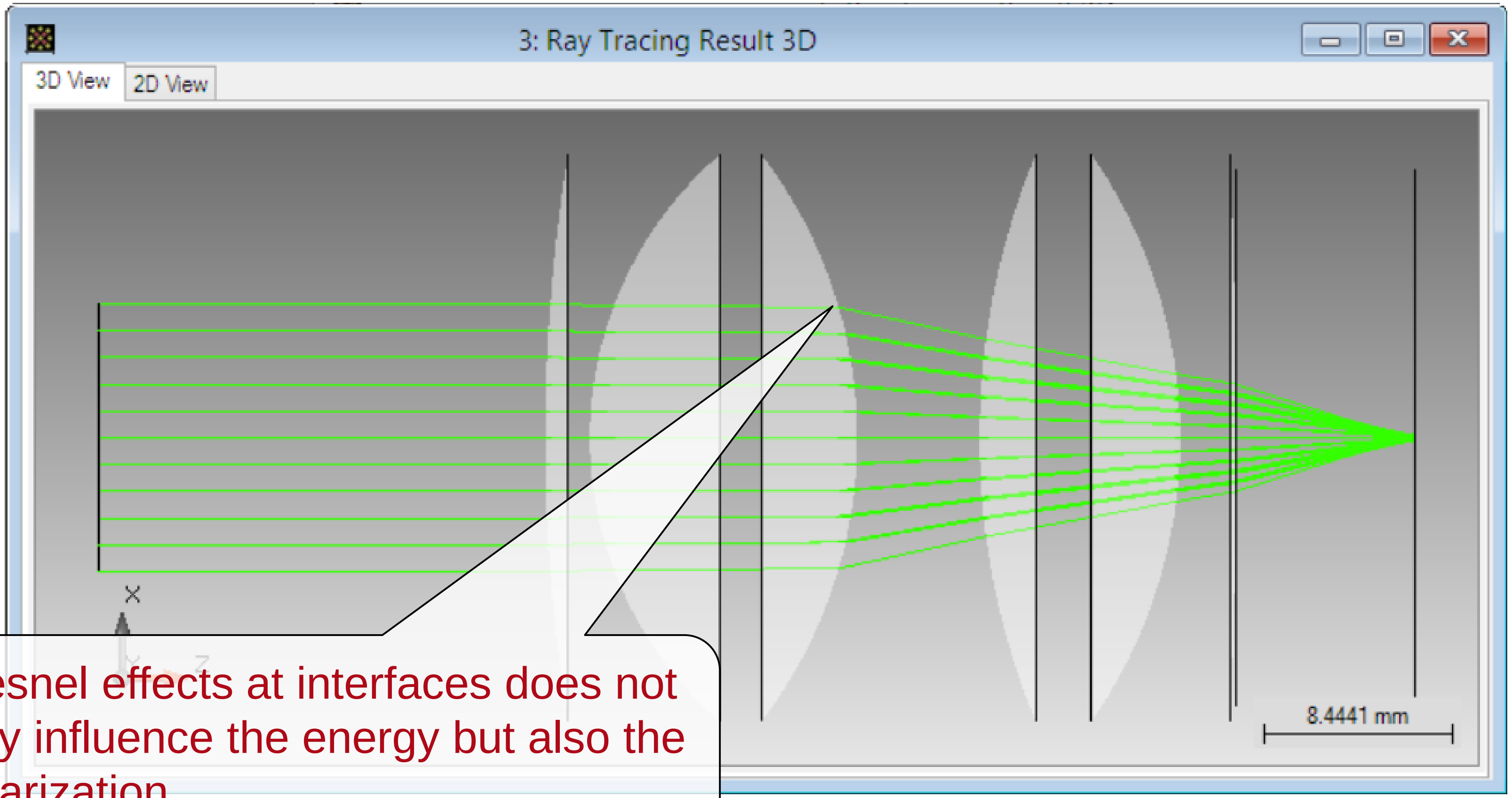


air vs. silver



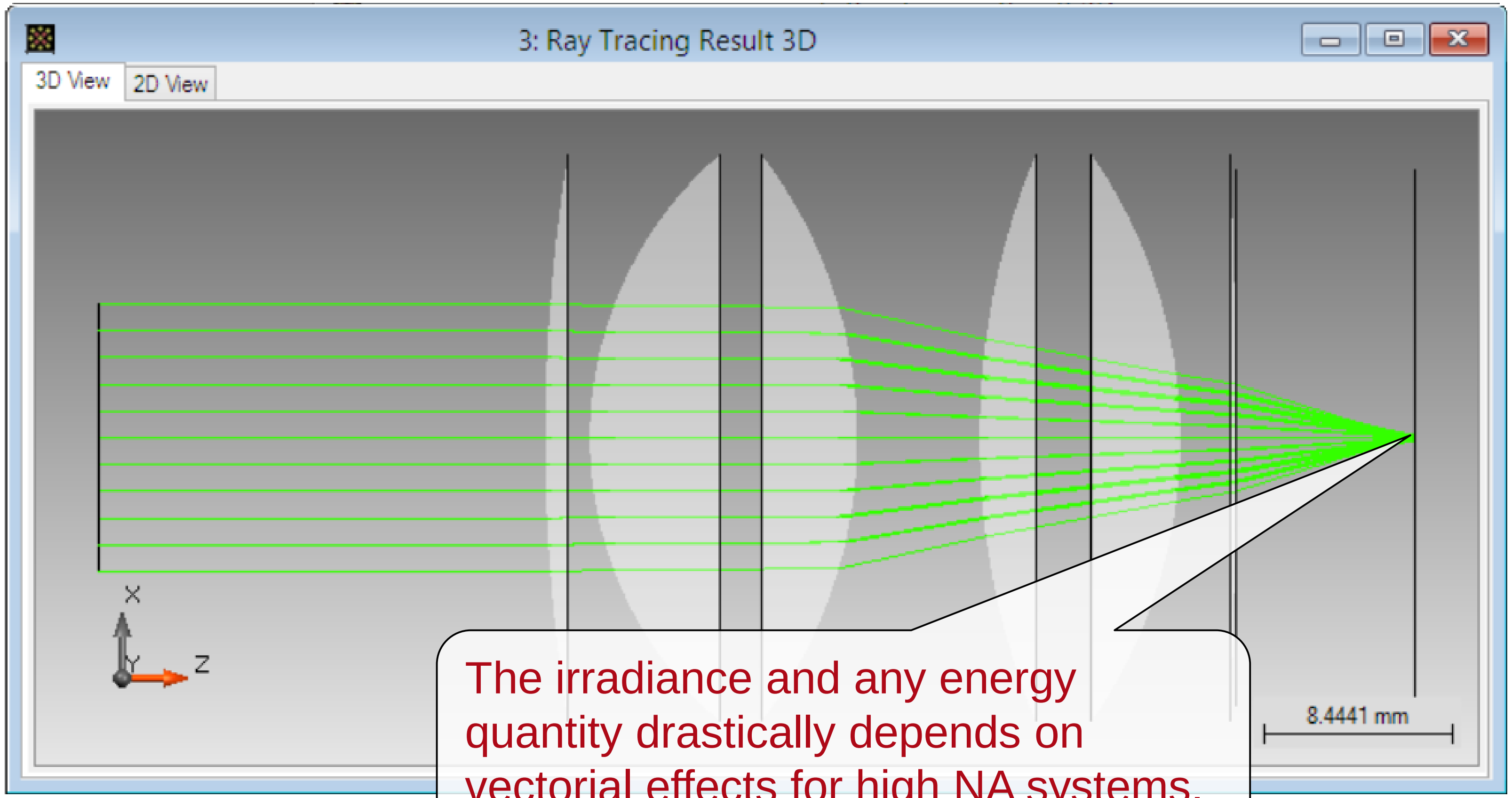
Fresnel's equations cannot be derived/explained by Fermat's principle.
→ regard of Fresnel losses requires physical optics

Ray Tracing Limitations: Polarization Effects



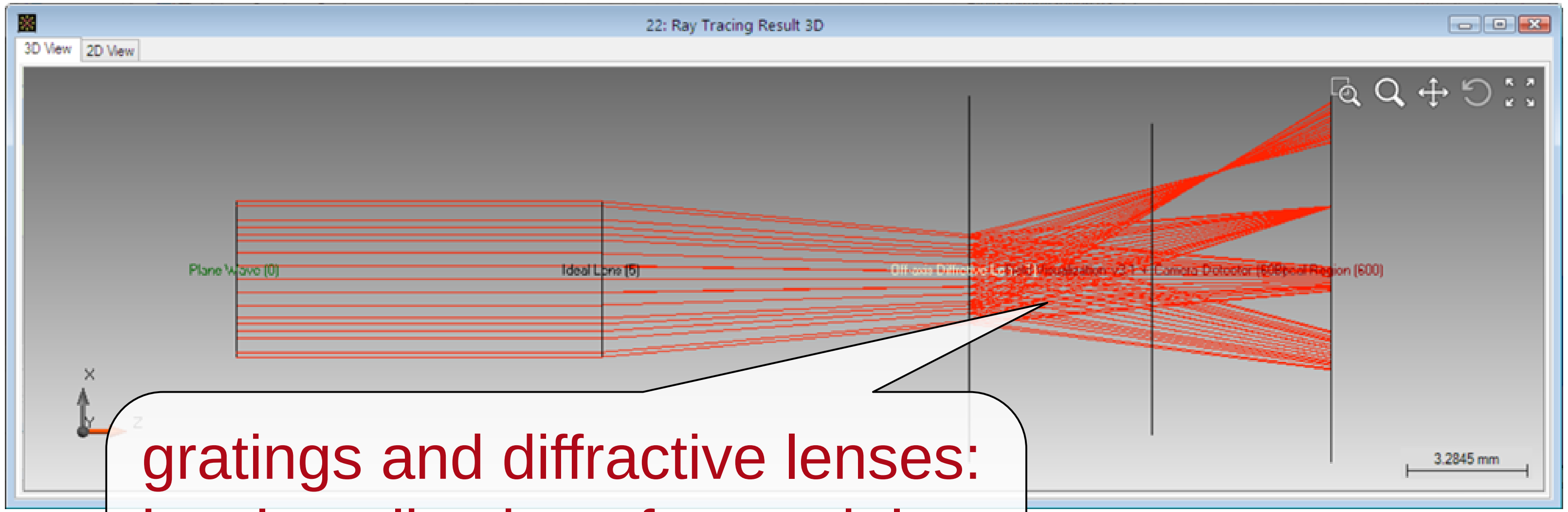
Fresnel effects at interfaces does not only influence the energy but also the polarization.

Ray Tracing Limitations: Polarization Effects



The irradiance and any energy quantity drastically depends on vectorial effects for high NA systems.

Ray Tracing Limitations: Gratings / DOE



gratings and diffractive lenses: local application of vectorial grating response by grating theory

Ray and Physical Optics

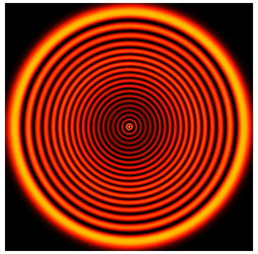
Ray Optics

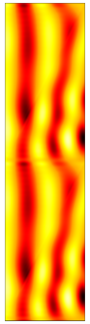
Physical Optics

Ray Optics Modeling ...

- gives great basic insight into light propagation.
- often sufficient for optical design, e.g. in standard lens design.
- **suffers from serious limitations...**

Demand for physical optics modeling and design!





What's Coming Next #2 ...

- different toolboxes of VirtualLab
- non-sequentiality
- fast physical optics

Basics 0013 (v2.0)

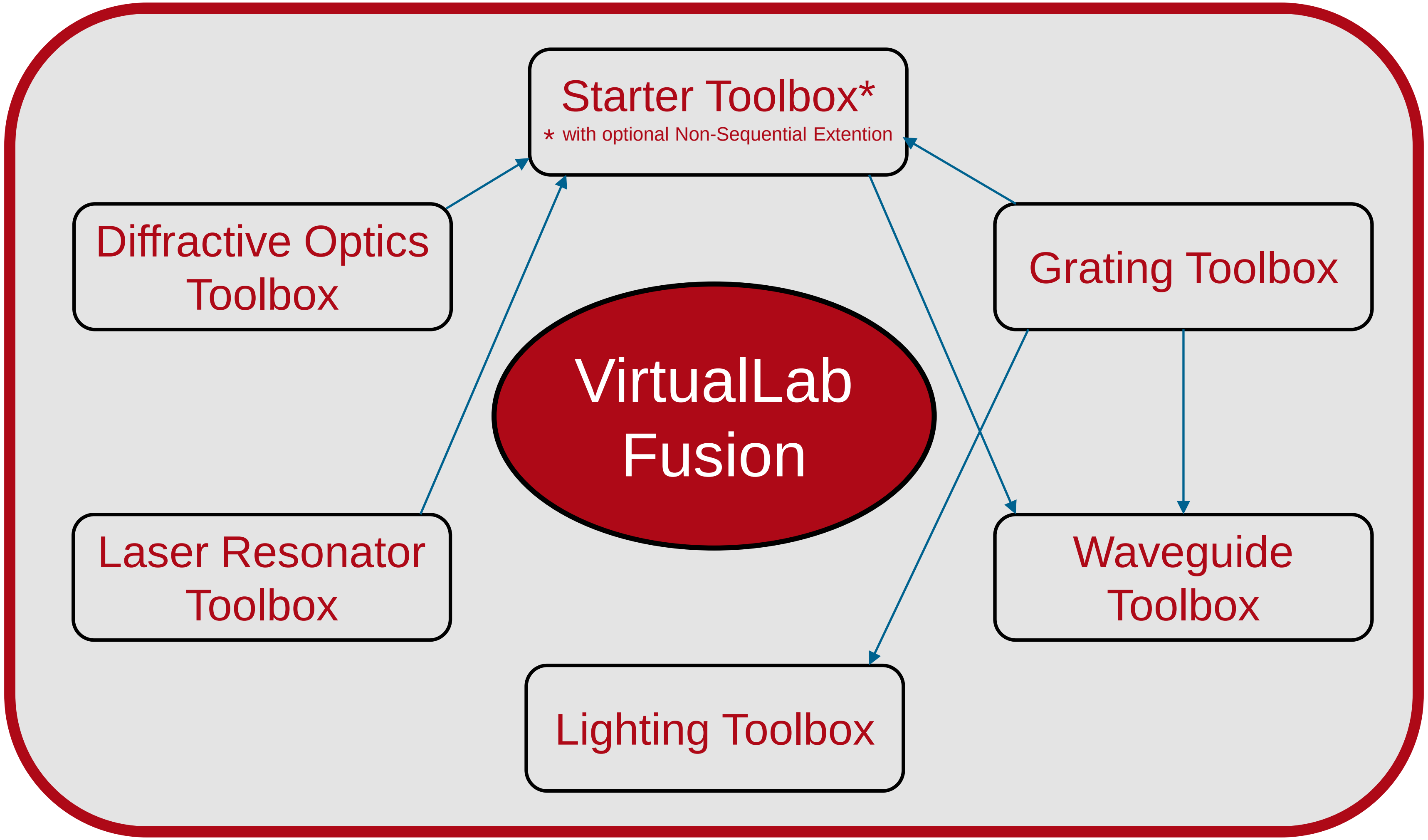
VirtualLab Toolboxes

Overview

Toolboxes

- Different toolboxes provide different functionalities. Users can select those they need.
- Each toolbox adds more tools to your VirtualLab.
- Any toolbox works also as a stand-alone software package, e.g., you may work with the Grating Toolbox without a Starter Toolbox.
- Toolboxes work smoothly together in your VirtualLab.
  Some toolboxes' power is greatly increased if combined with other toolbox(es).
- Typically customers use Starter Toolbox + additional one(s).

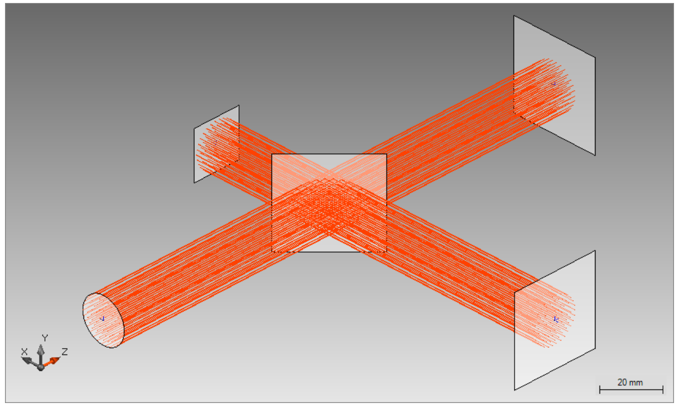
VirtualLab Toolboxes

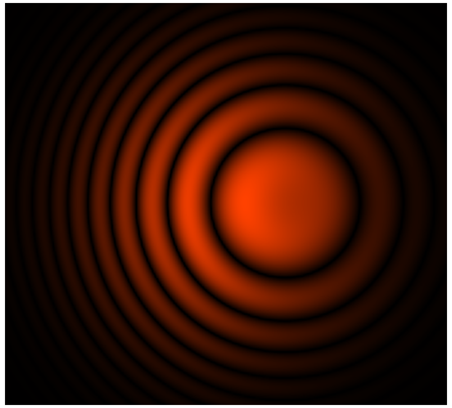


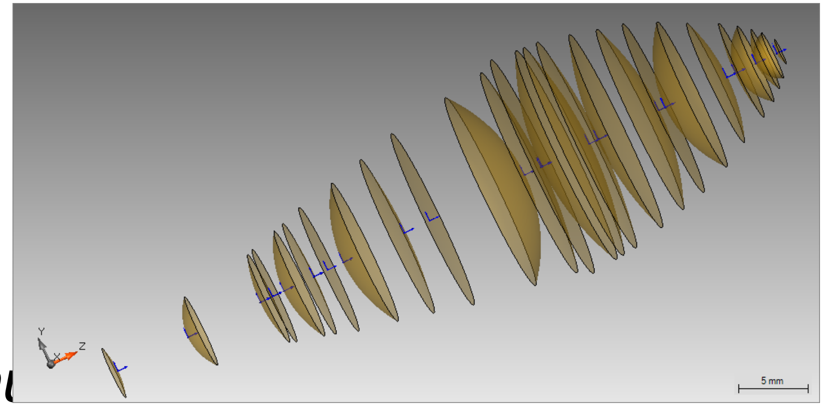
Starter Toolbox (1)

Analysis and parametric optimization of optical systems including:

- refraction
- diffraction
- interference
- polarization
- coherence
- color
- ultrashort pulses (USPs)
- coatings





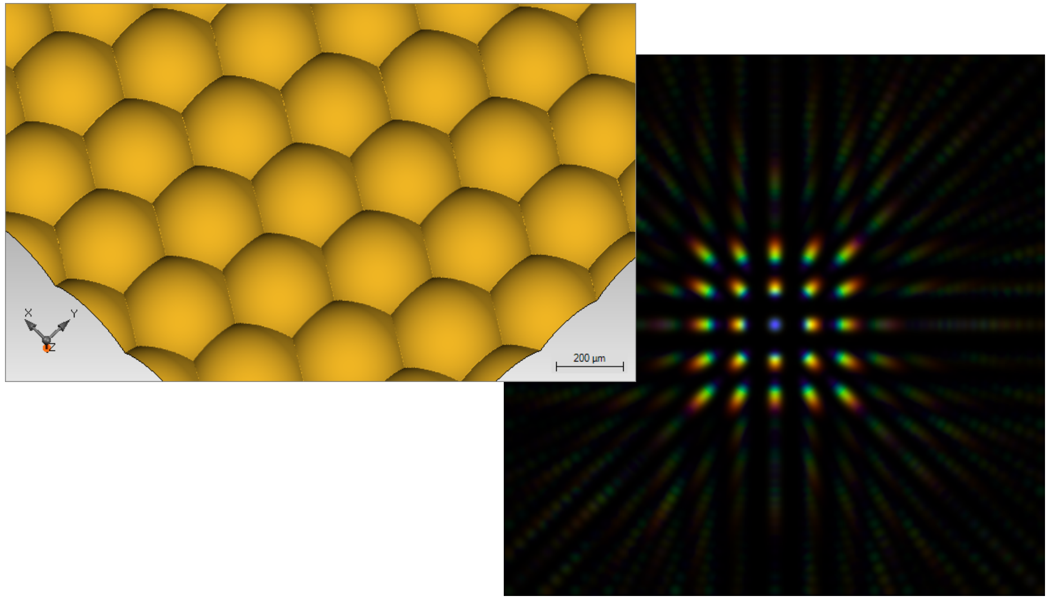


allows sequential and non-sequential simu

Starter Toolbox (2)

You benefit in particular in different optical areas:

- micro and diffractive optics
- laser optics
- partial coherent source modeling, e.g. excimer and LED
- information and Fourier optics
- interferometry
- polarization optics
- near field optics
- high NA optics
- wavefront engineering
- ultrafast optics
- parametric optimization

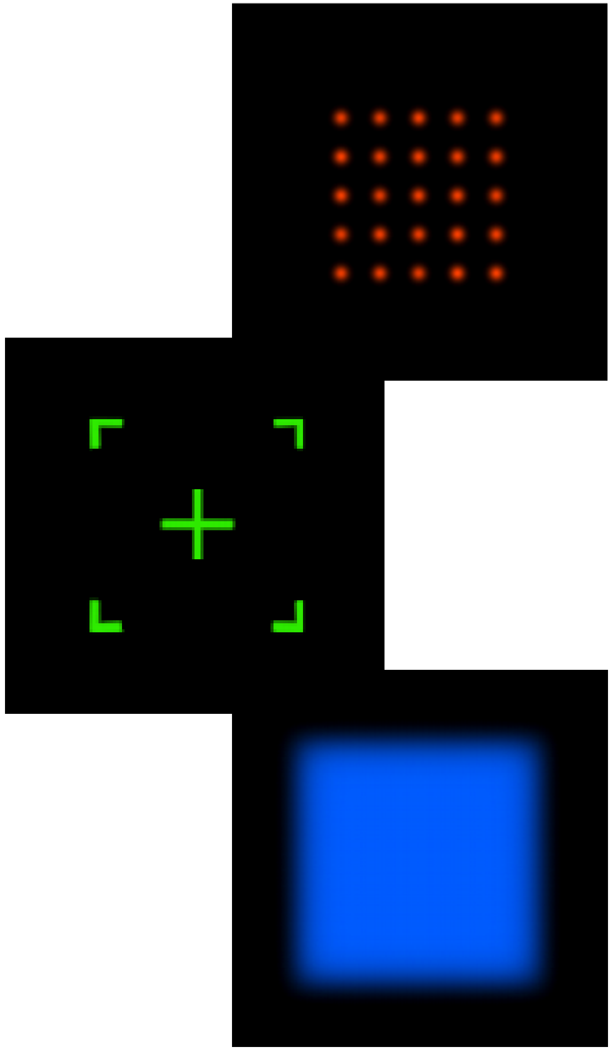


Diffractive Optics Toolbox

design and analysis of

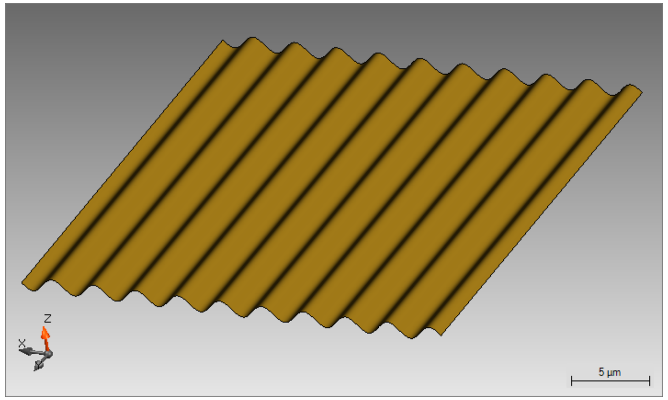
- diffractive optical elements (DOE)
  - Diffractive light diffusers
  - Diffractive beam splitters
  - Diffractive beam shapers

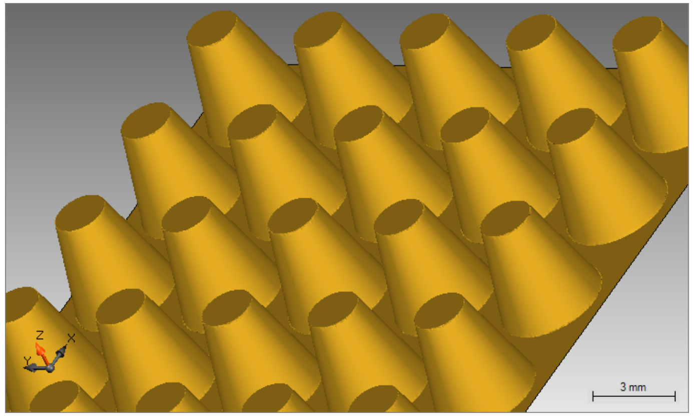
  different common names:
  - *computer generated holograms (CGHs)*
  - *kinoforms*
  - *phase plates*
- refractive beam shapers



Grating Toolbox

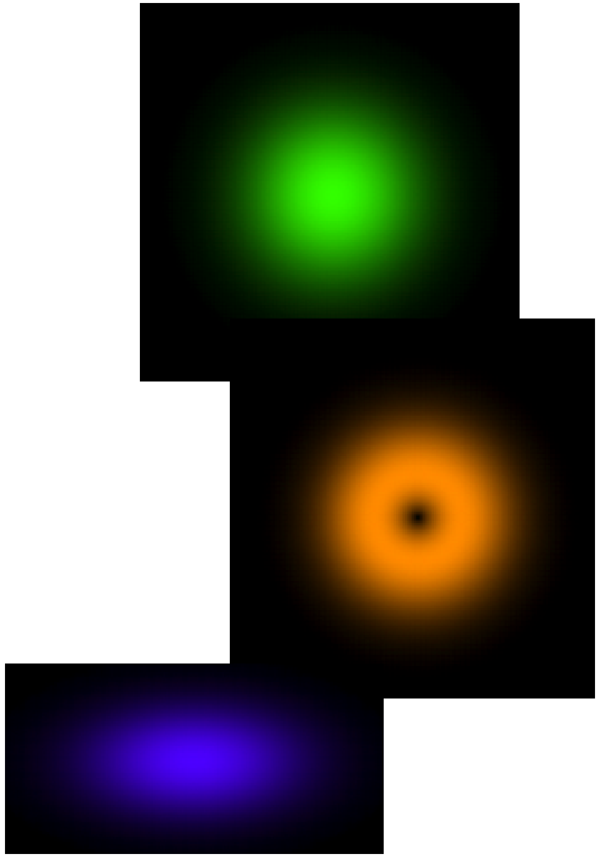
- electromagnetic analysis of periodic structures
  with the Fourier Modal Method (FMM):
  - diffraction efficiency, near field, field inside grating and polarization analysis
  - simulation of 2D & 3D periodic surface and volume gratings
  - analysis of gratings with sub-wavelength features and above
- modular setup concept
- parametric optimization





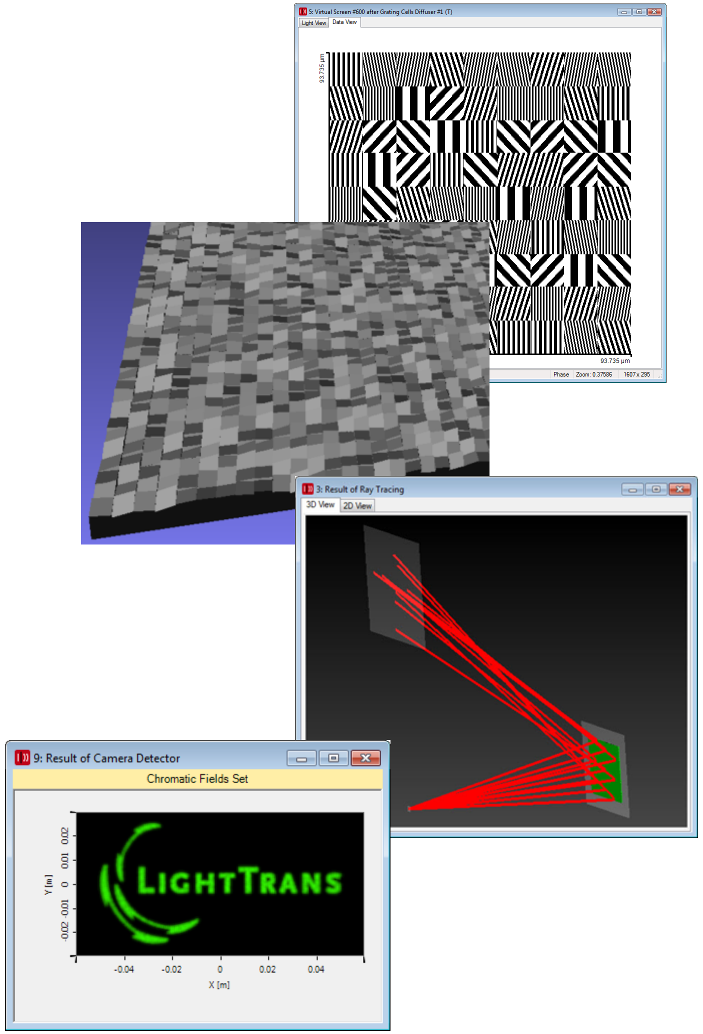
Laser Resonator Toolbox

- analysis of eigenmodes of stable and unstable resonators
- modeling of active media
- simulation of diffraction effects at apertures and micro structures
- investigation of tolerances
- shaping of fundamental mode by micro-structured mirrors
- LASCAD import



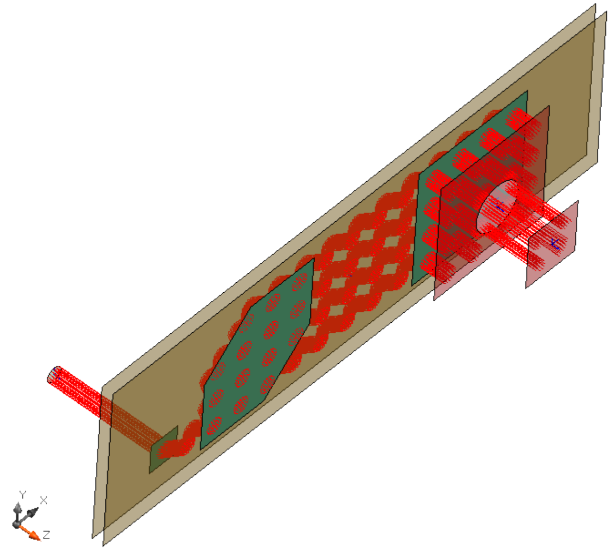
Lighting Toolbox

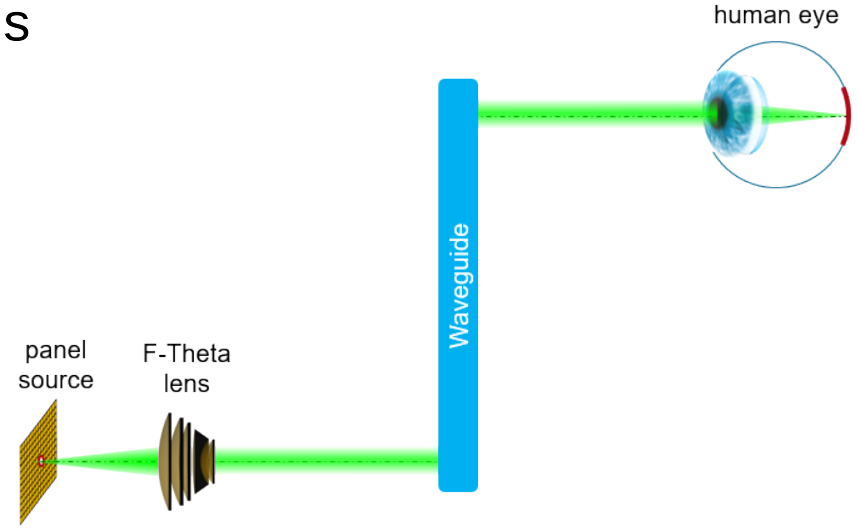
- design and analysis of grating, prism and mirror cells arrays for light deflection:
  - shaping and homogenization of LED light
  - generation of light marks and light patterns
- includes diffraction, interference, and partial coherence effects



Waveguide Toolbox enables ...

- non-sequential simulations
  with many configuration options
- special waveguide component
  - complete control of simulated light paths
  - inclusion of ideal and real gratings
  - rigorously calculated grating efficiencies
  - arbitrarily shaped & positioned grating regions
  - gratings on curved surfaces
- powerful modeling & simulation options
  - allow fully/partially illuminated
    arbitrarily shaped apertures
  - full regard of coherence effects
- ideal for NEDs & HUDs





Non-Sequential Optical Modeling with VirtualLab Fusion

about the Non-Sequential Extension

Non-Sequential Extension (NSE)

Since 2018 VirtualLab introduced the so-called

Non-Sequential Extension (NSE).

VirtualLab *without* NSE also allows non-sequential simulations namely by explicit specification of all light paths of interest.

→ *With* the NSE, **setting up systems and analyzing the different light paths** for investigational purposes **become much easier, intuitive and adjustable.**

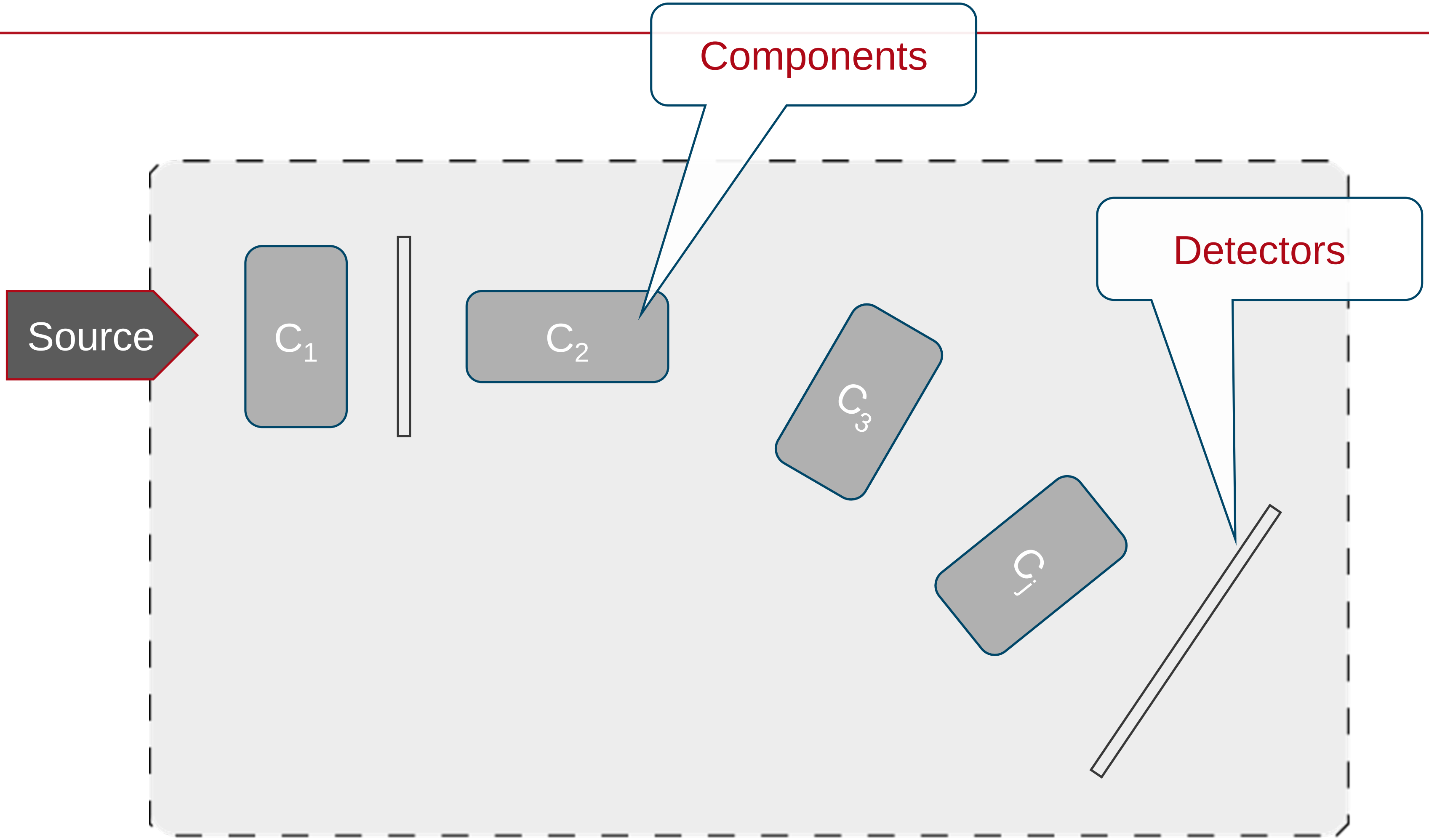
Overview of Content

Two questions are answered and further information and examples are shown.

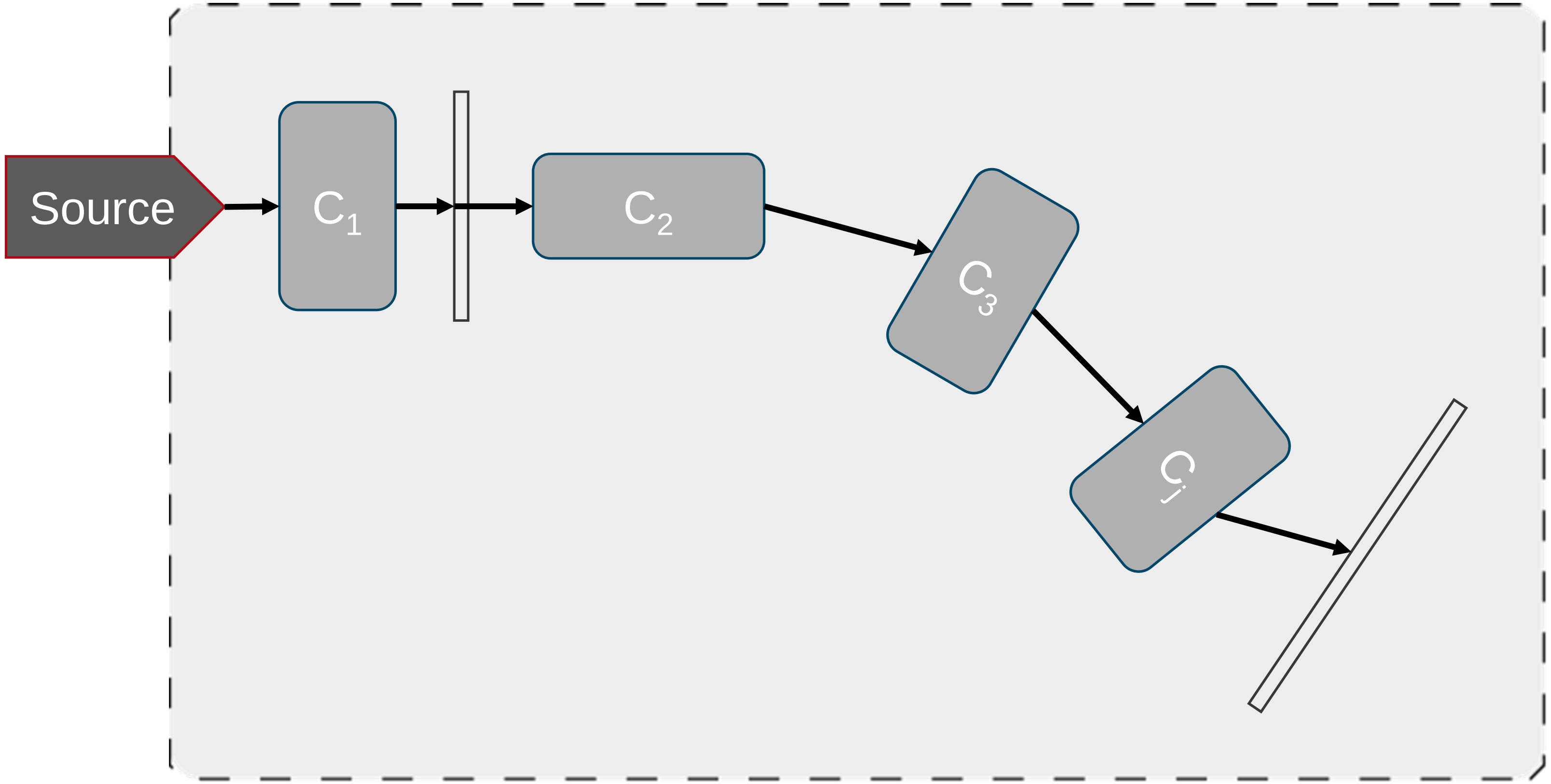
- Q1: What is sequential tracing?
- consequences for setup of systems
- energy regard
- Q2: How to enable & control/specify the non-sequential light paths of interest?
- some examples

Question 1:
What is Sequential and Non-Sequential Tracing?

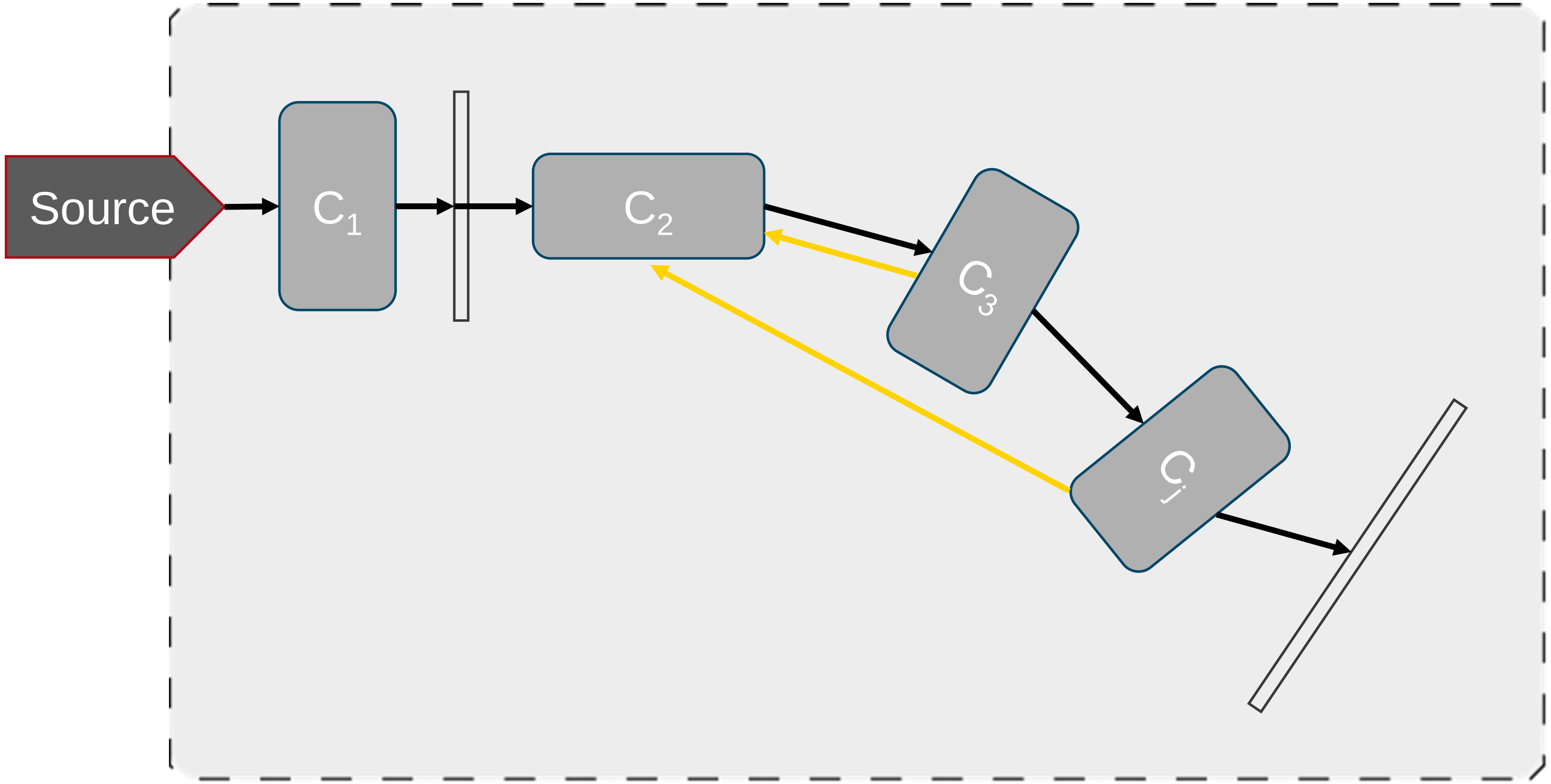
Optical Modeling Task



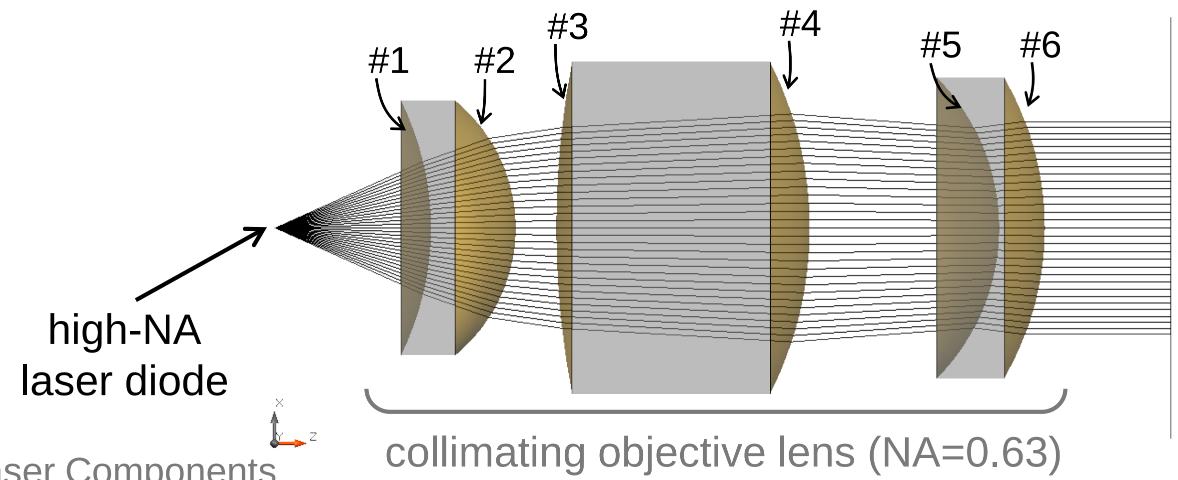
Optical Modeling: Sequential



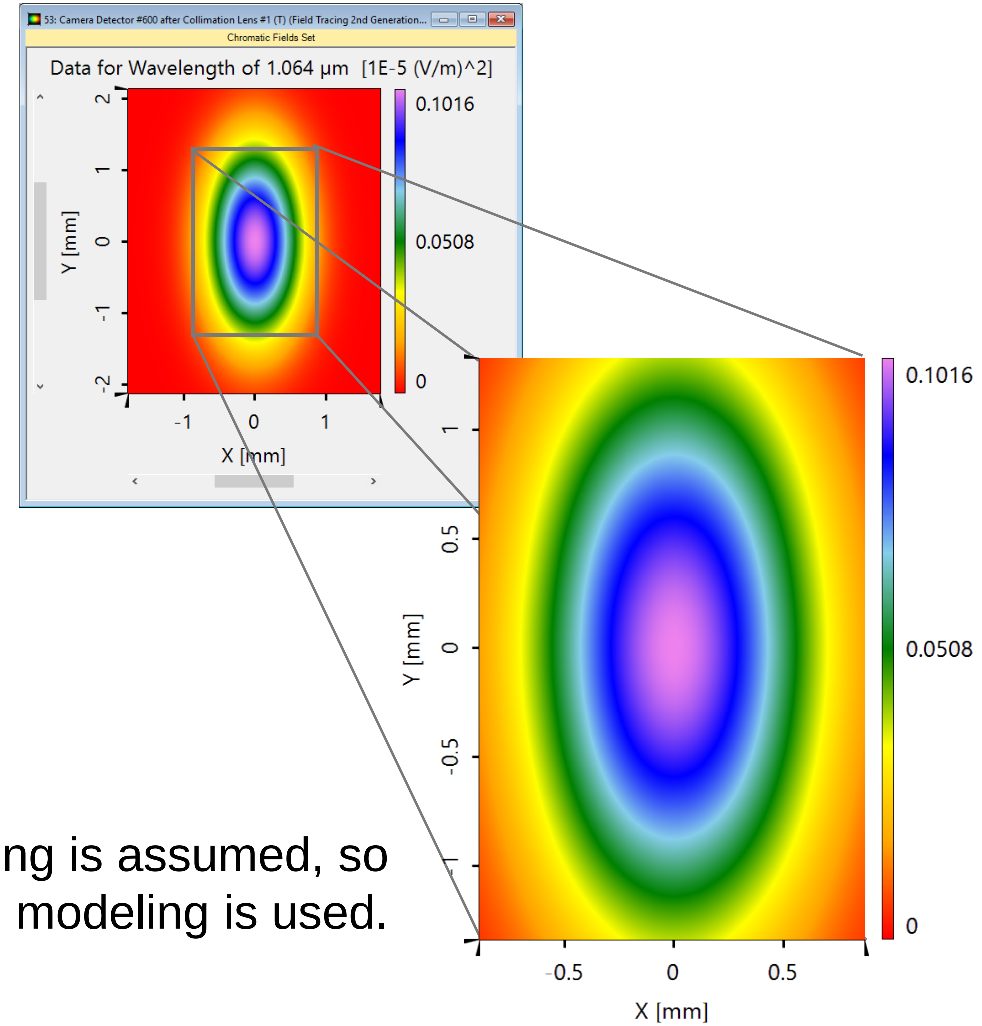
Optical Modeling: Non-Sequential



Collimation System: Sequential Simulation

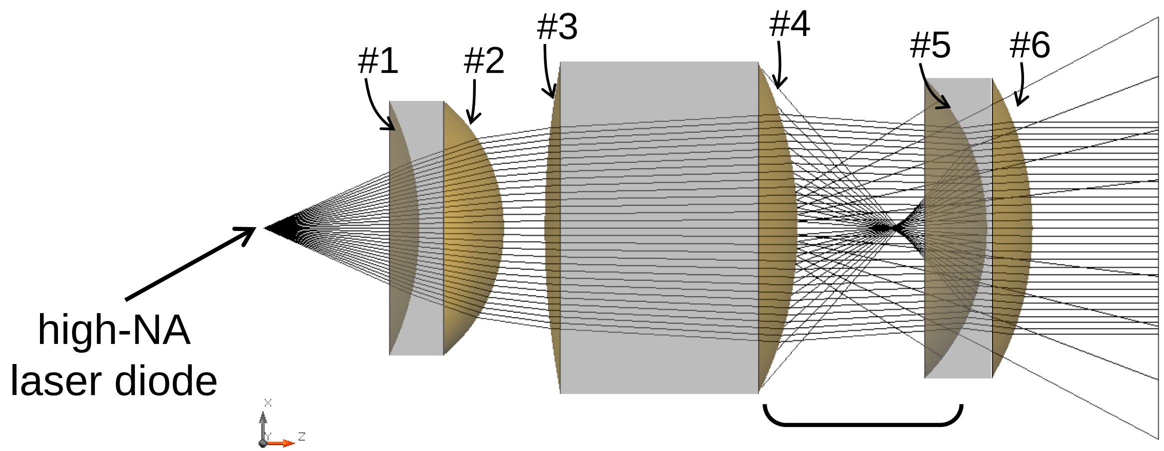


Laser Components
WSLD-1064-050m-1-PD
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20°x10°
- astigmatism 11.6 µm between *x*- and *y*-plane



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

Collimation System: Non-Sequential Simulation



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

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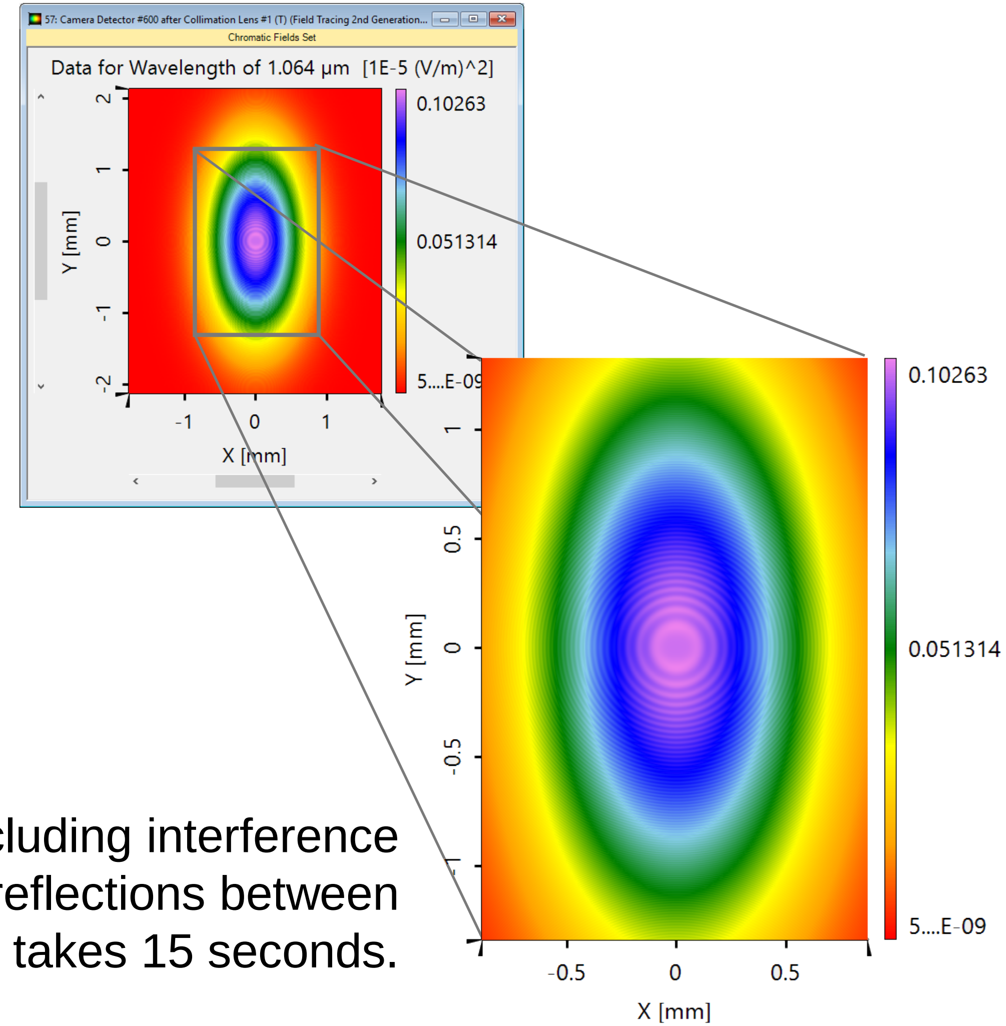
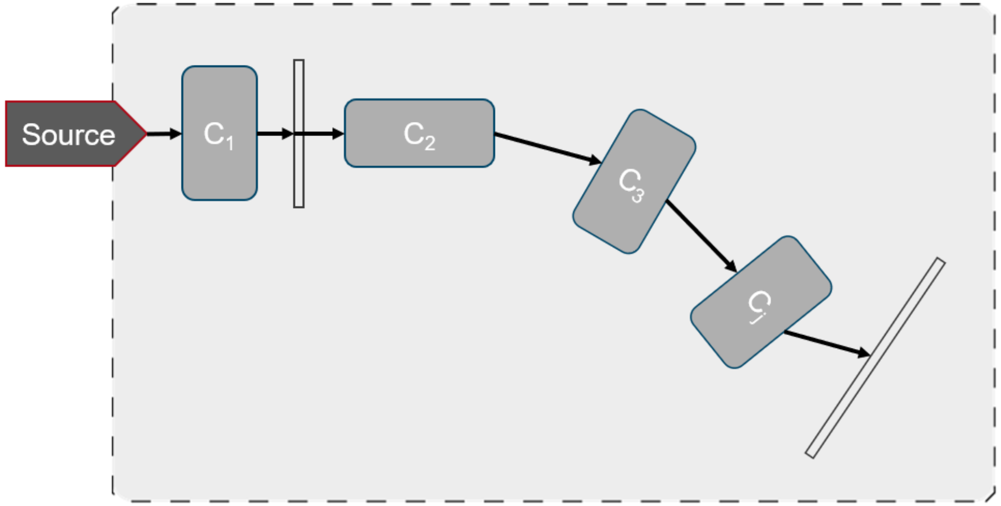


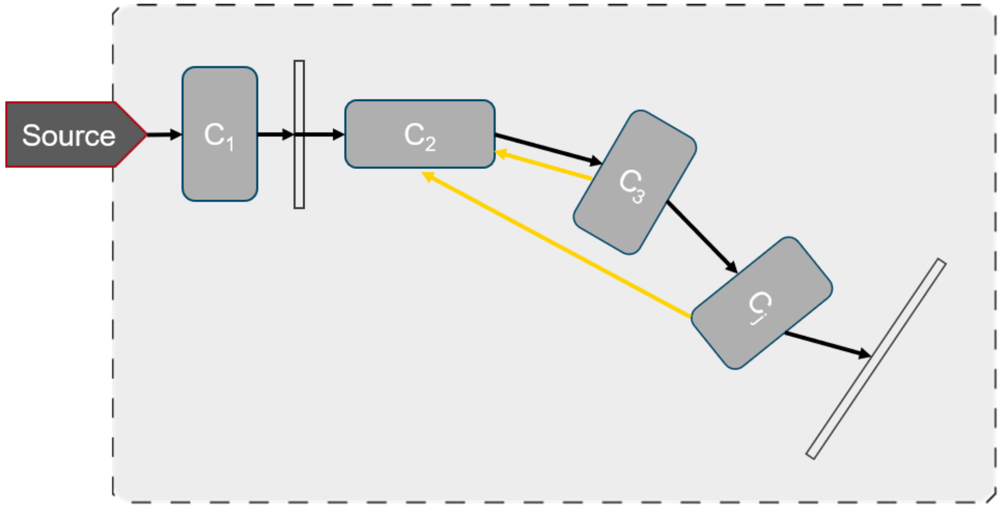
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

Conclusion of Question 1

What is sequential and non-sequential tracing?



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



- Light propagation does not follow any sequence.
- Light propagates through / reflects several times from one component.

Note: *Linkages are still used, but only for the purpose of referencing (position/orientation).*

Different Needs for Non-Sequentiality

A) for evaluation of undesired (detrimental) reflections

- ghost image effects
- stray light orders in waveguides
- ... (any back reflections between different surfaces in a system)

B) for simulation of intended (necessary) reflections

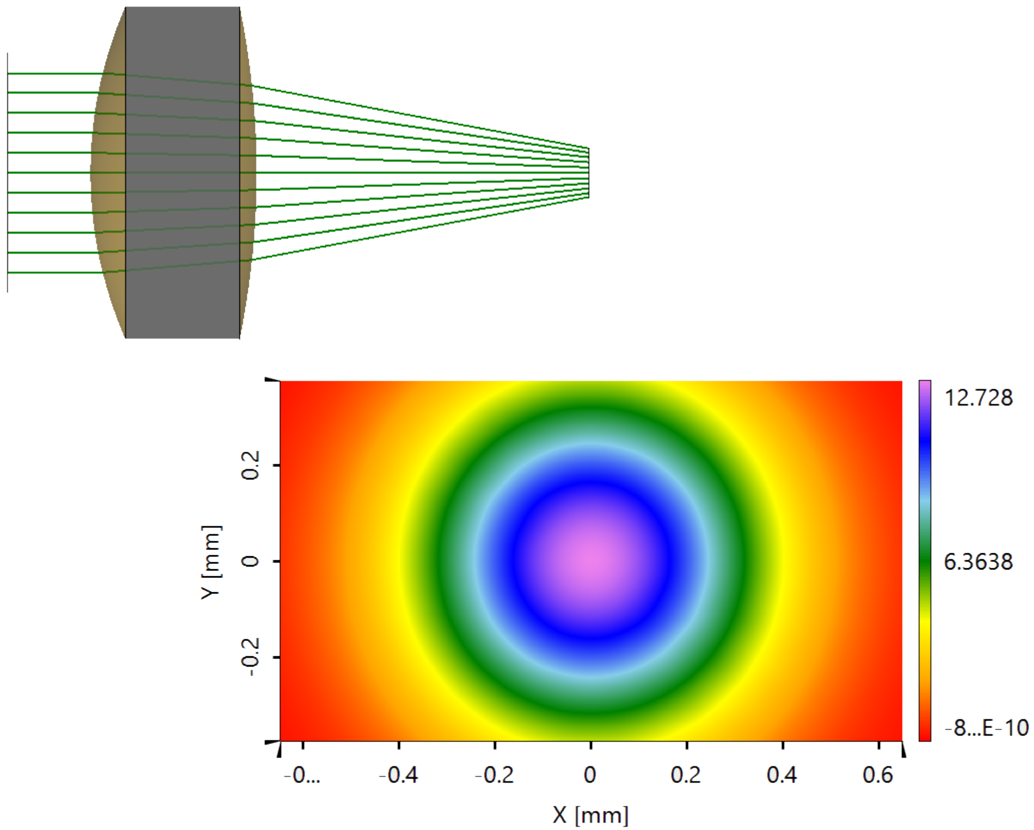
- systems with splitted light paths (e.g. any interferometer setup)
- systems with folded light paths (e.g. diverse telescope setups)
- etalons
- ... (whatever system makes use of multiple or reflected light paths)

A) Unwanted Multiple Reflections / Light Paths

Setup with & without Non-Sequential Extension (NSE)

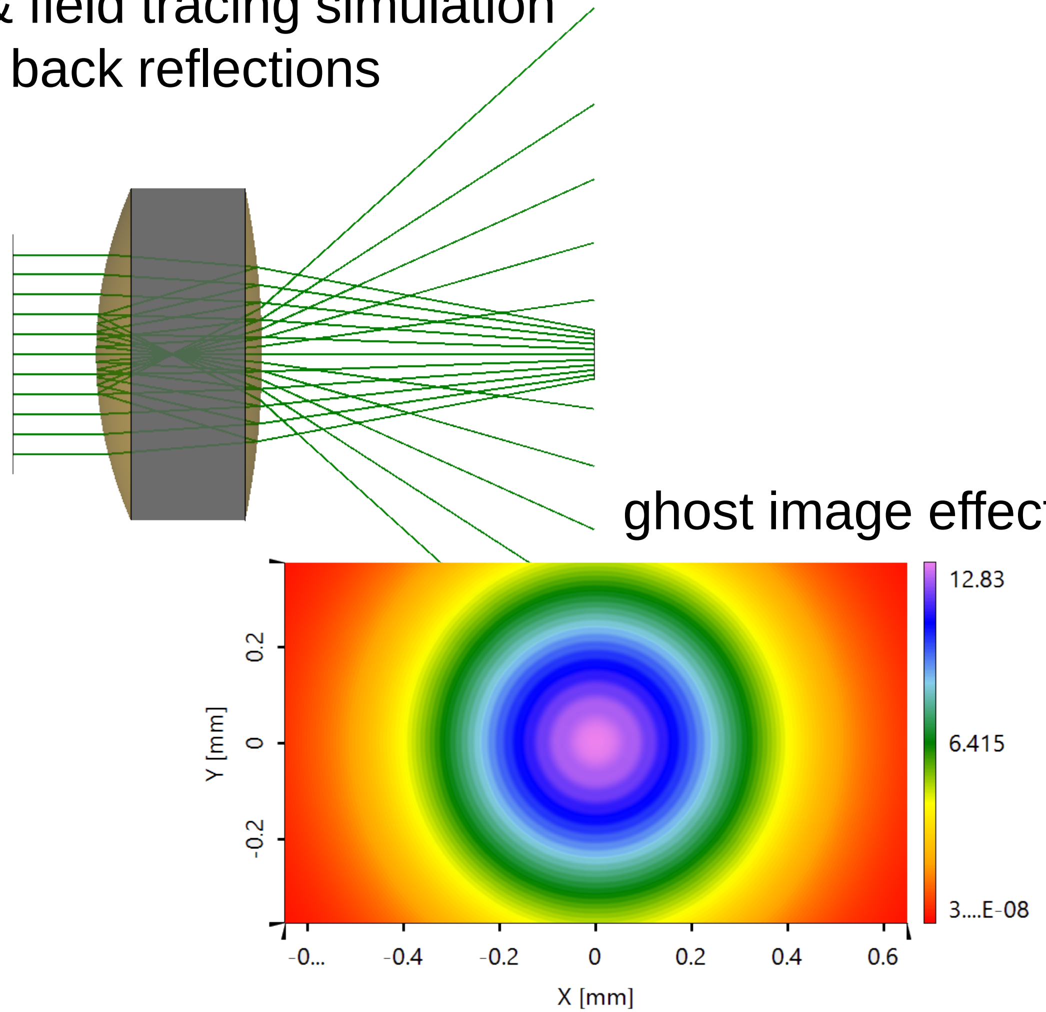
Back Reflection in Bi-Convex Lens

ray & field tracing simulation
without back reflections



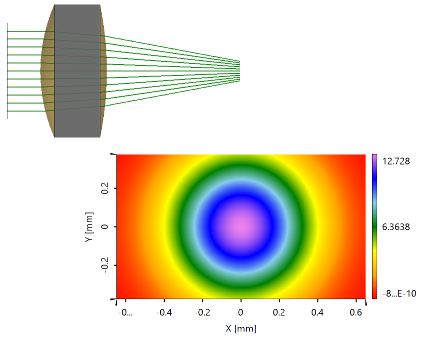
ray & field tracing simulation
with back reflections

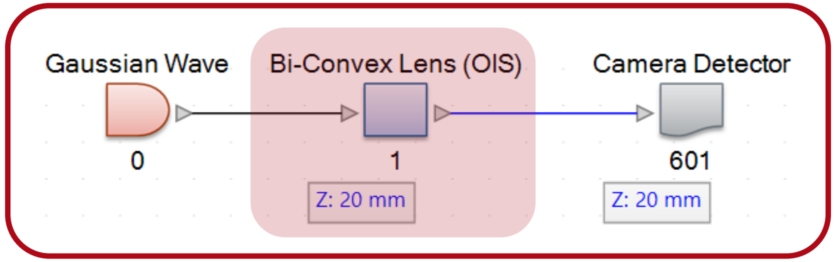
ghost image effect



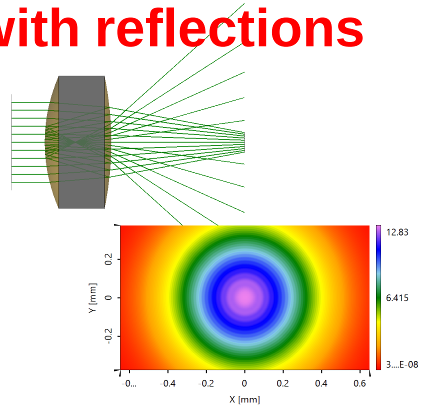
Setup in VirtualLab without Non-Sequential Extension (NSE)

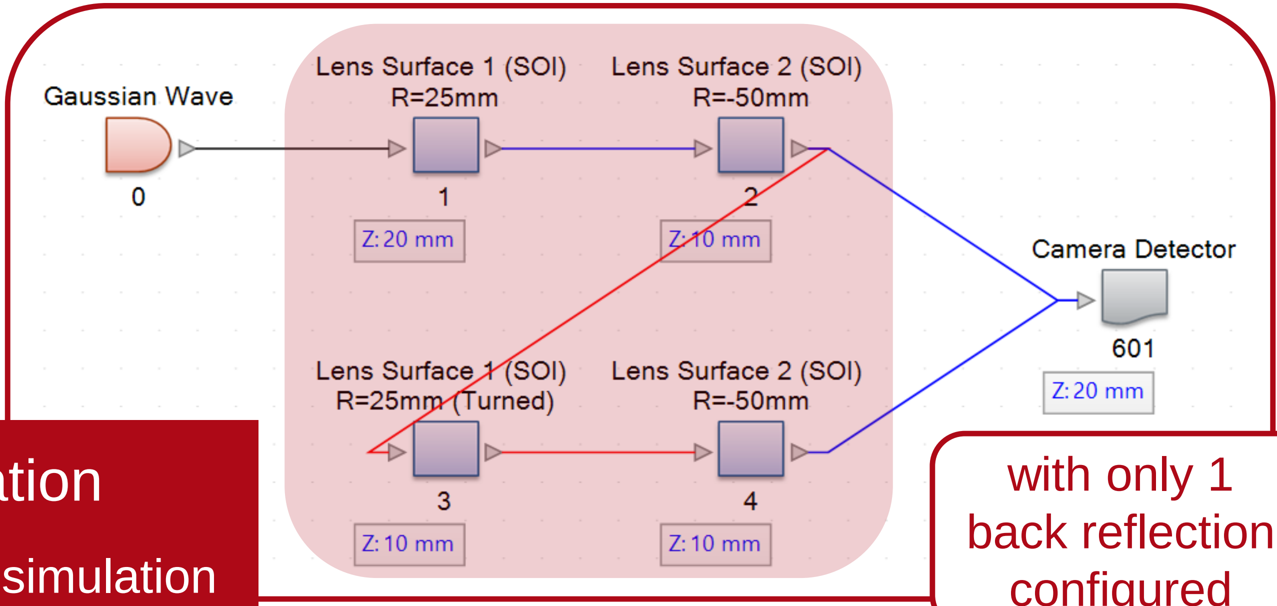
without reflections





with reflections





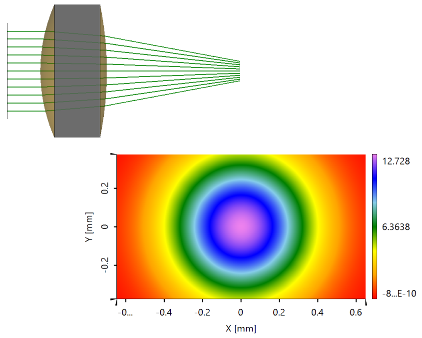
with only 1 back reflection configured

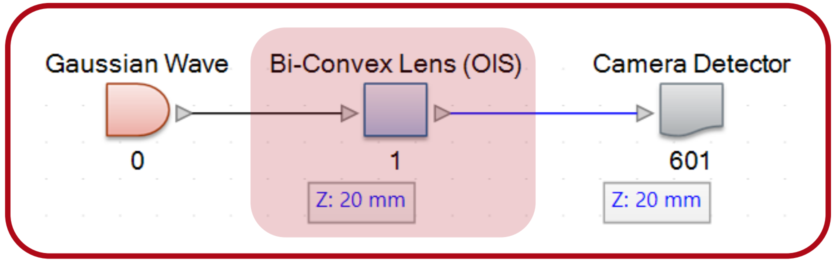
sequential setup ⇏ sequential simulation

complex setup WAS necessary for non-sequential simulation

Setup in VirtualLab with Non-Sequential Extension (NSE)

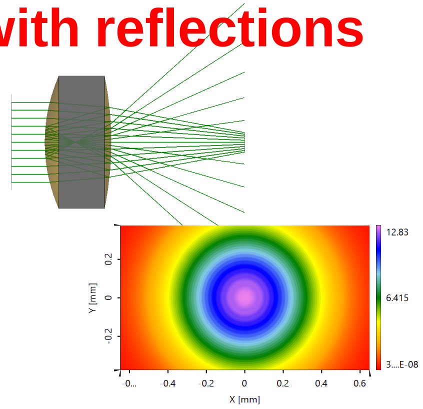
without reflections

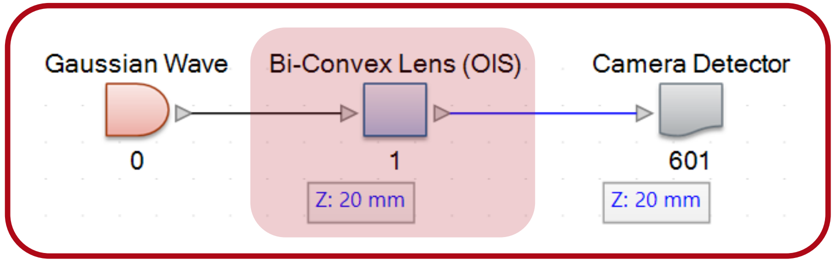




Flag: Non-Sequential Tracing = False

with reflections





Flag: Non-Sequential Tracing = True

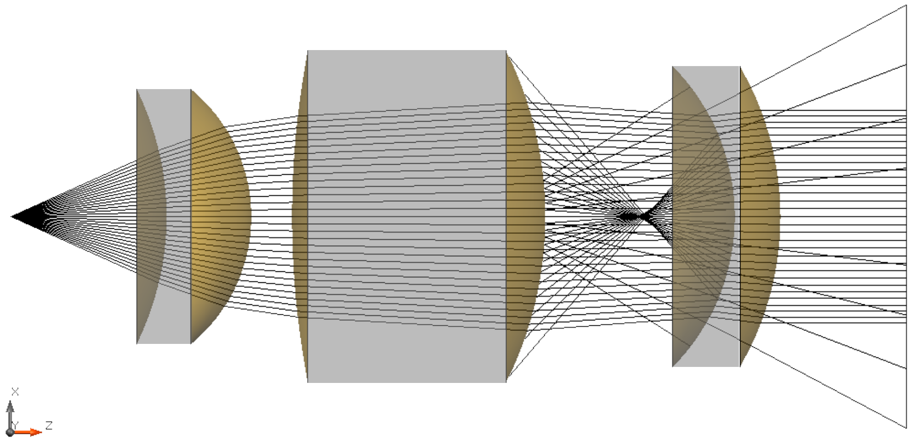
difference for setup = 1 Double CLICK !

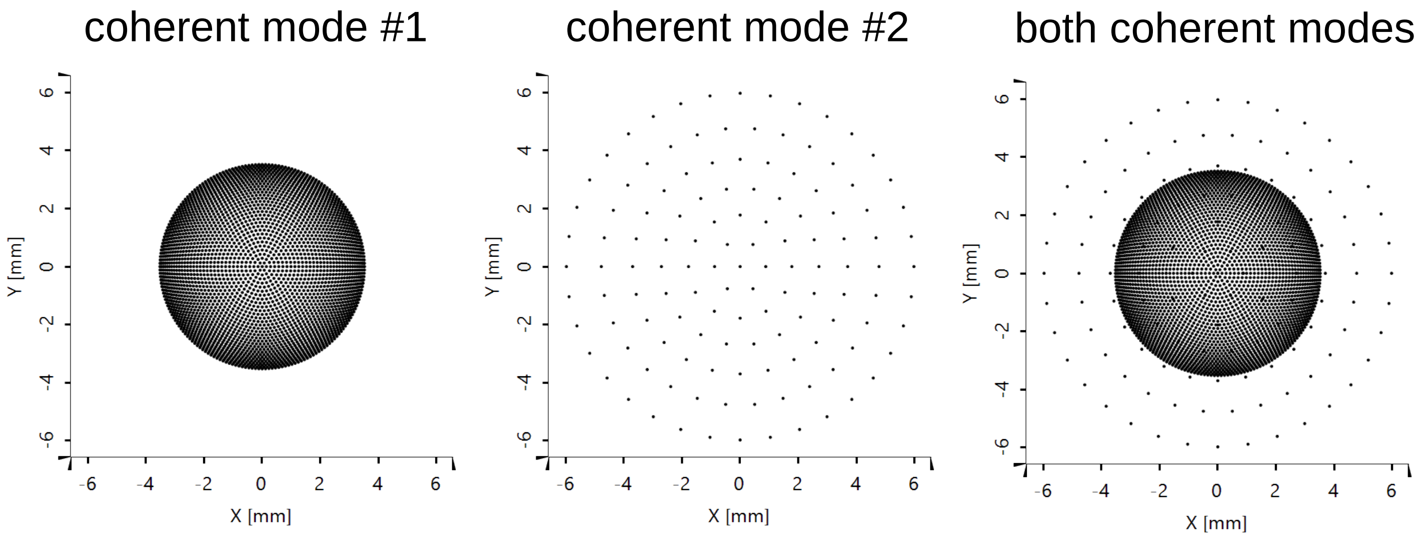
i.e. easy switching between sequential & non-sequential simulations

Energy Consideration

- collimation objective lens example
- near-eye display (NED) waveguide example

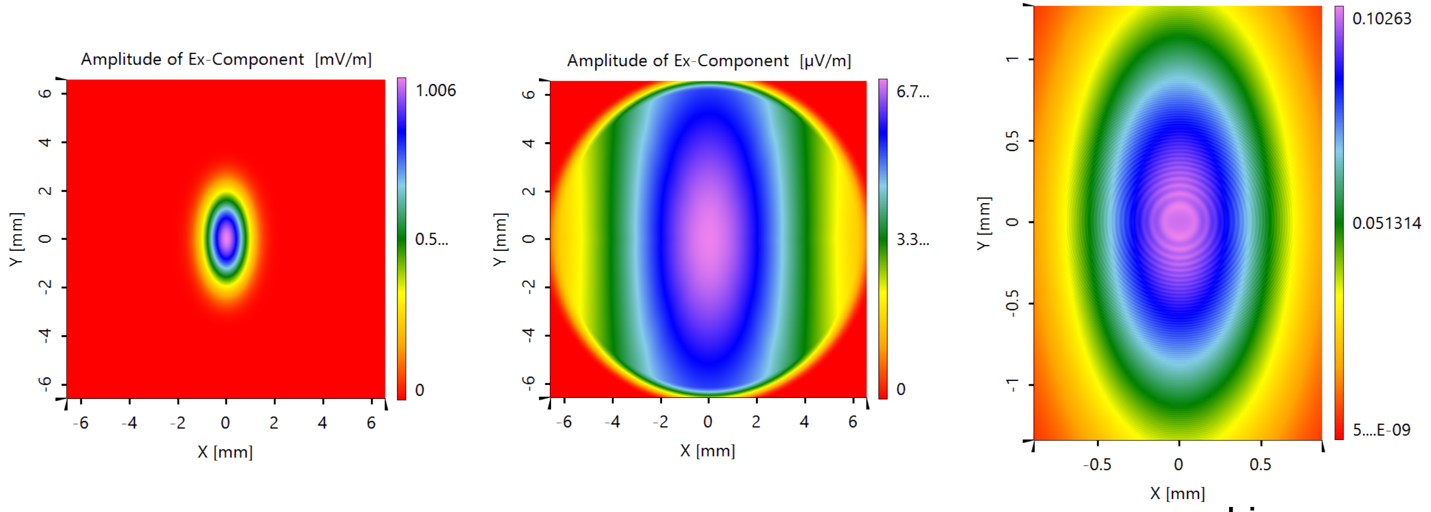
Accurate Representation of Resulting Light





- Non-sequential simulations require the accurate consideration of energy conservation.

- It is of paramount importance to know how much energy the different deflected light portions carry.

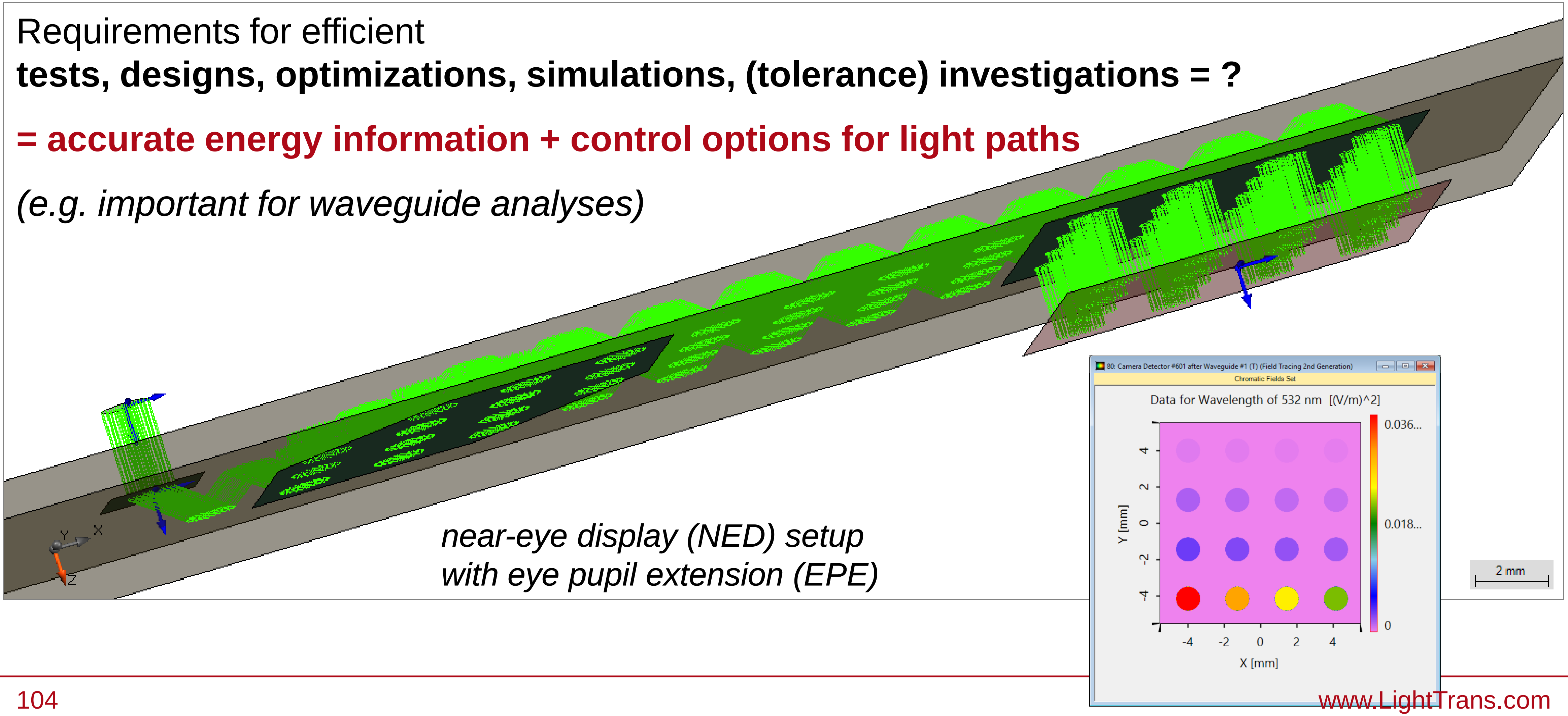


Knowing Which Light Paths Are of Significance

Requirements for efficient
tests, designs, optimizations, simulations, (tolerance) investigations = ?

= accurate energy information + control options for light paths

(e.g. important for waveguide analyses)



near-eye display (NED) setup
with eye pupil extension (EPE)

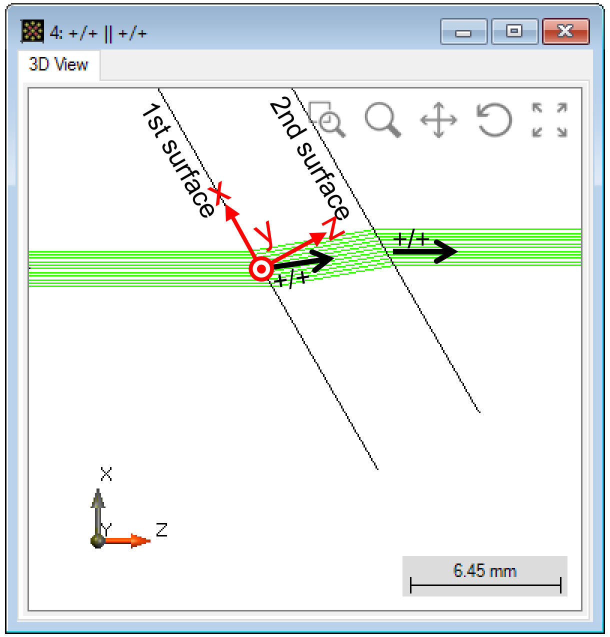
2. Question:
How to Enable & Control
Sequential and Non-Sequential Tracing?

→ Non-Sequential Tracing flag

→ Channel Concept

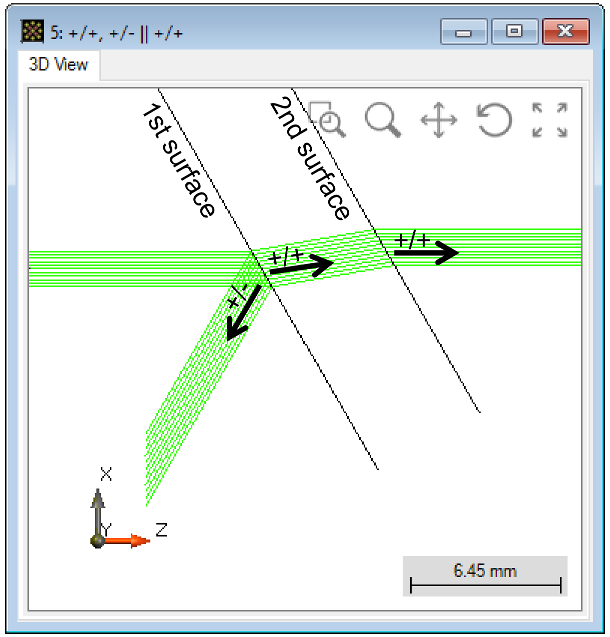
Surface Channels

- Setting A



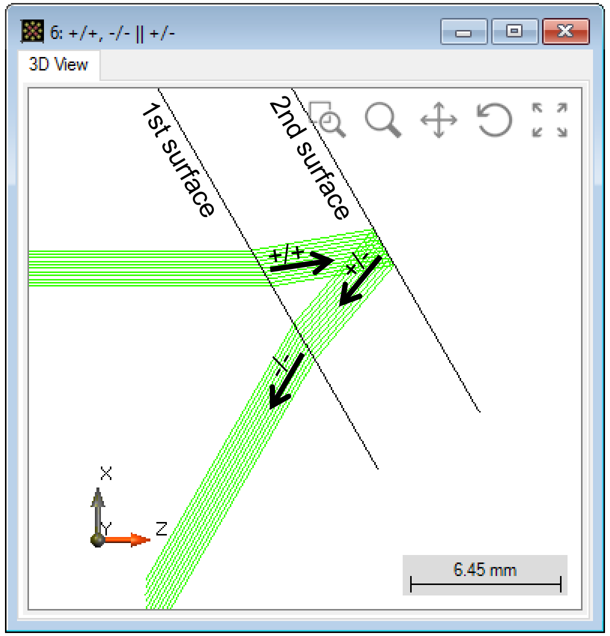
Surface	+/+	+/-	-/-	-/+
1st	✓			
2nd	✓			

- Setting B



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

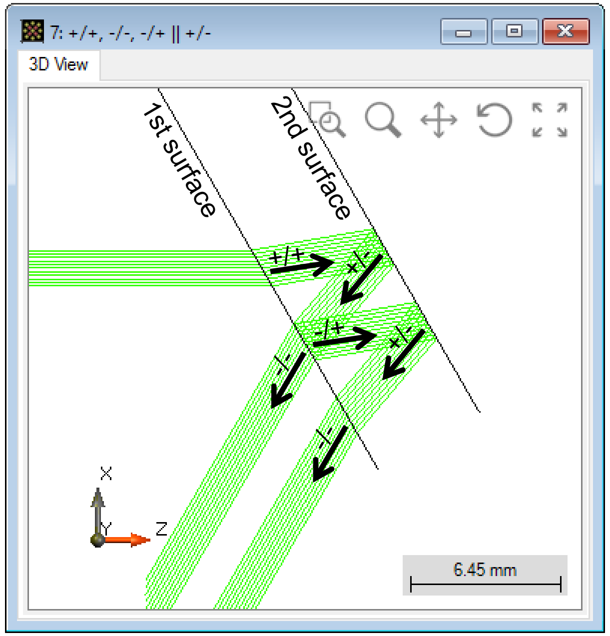
- Setting C



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

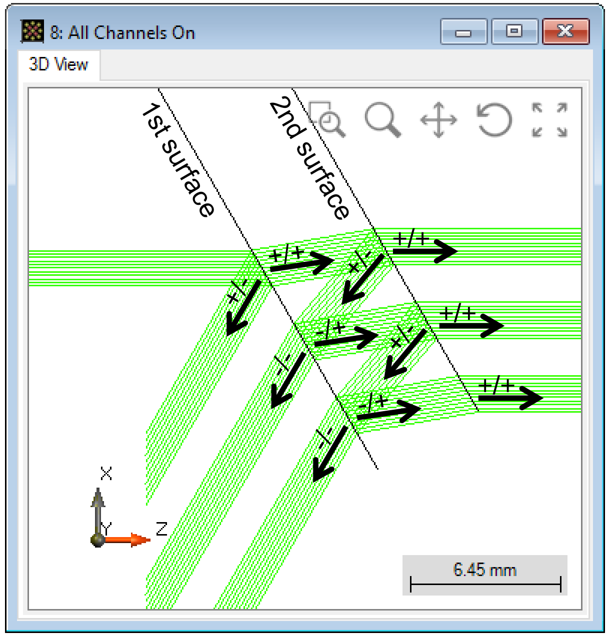
Surface Channels

- Setting D



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

- Setting E

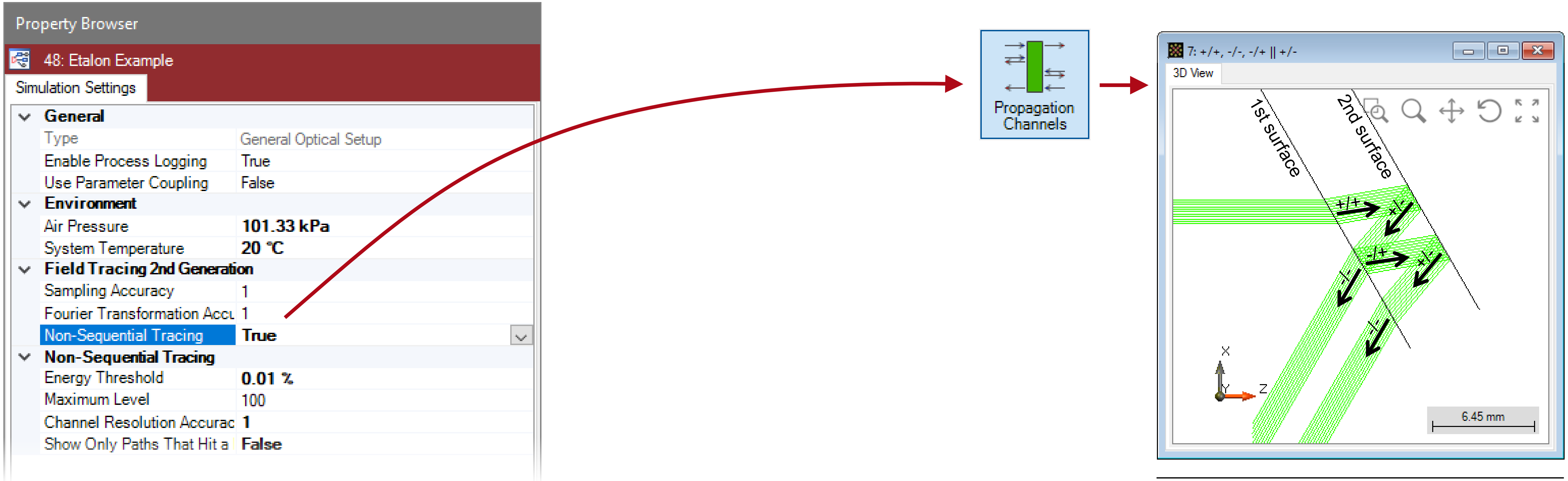


Surface	+/+	+/-	-/-	-/+
1st	✓	✓	✓	✓
2nd	✓	✓	✓	✓

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

Conclusion of Question 2

How to enable & control sequential and non-sequential tracing?



- Set the flag for *Non-Sequential Tracing = True.*
- For each surface 4 channels can be chosen to be regarded (+/+, +/-, -/-, -/+).

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

B) Intended Multiple Reflections / Light Paths

Etalon, Interferometer, Telescope

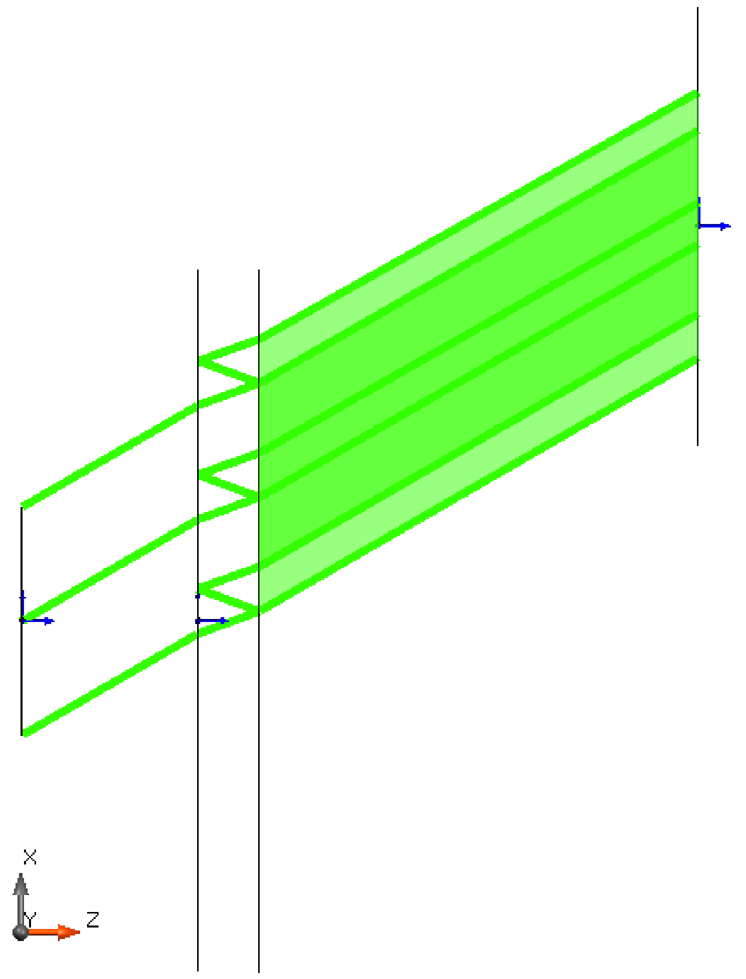
Etalon Example

with regard of polarization of incident light

Optical Etalon

- Configuration of input field
  - plane wave
  - polarization
    - *a)* E_x-polarized
    - *b)* E_y-polarized

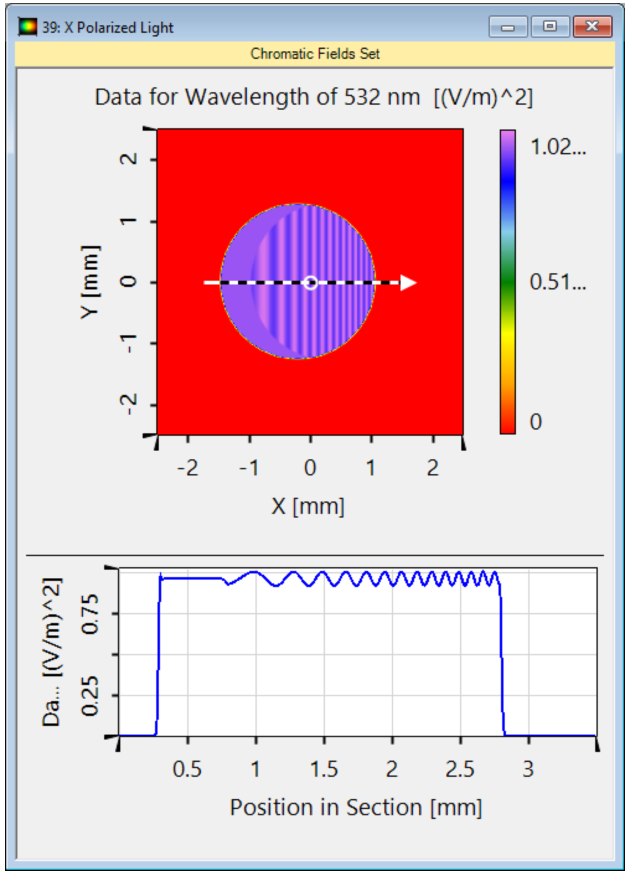
- Configuration of etalon
  - cylindrical-planar
  - center thickness 700 µm
  - cylindrical surface radius 1 m



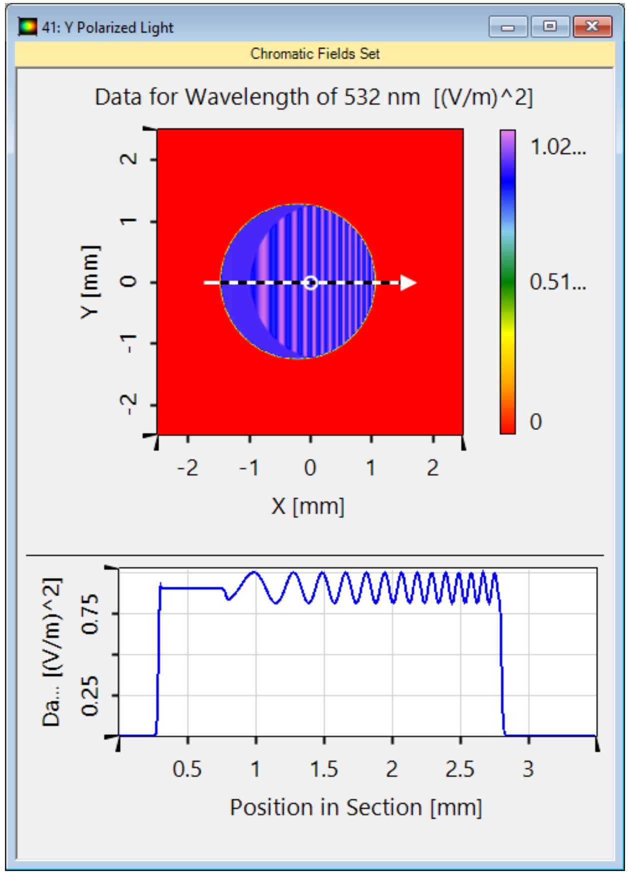
Optical Etalon with Field Tracing Results

- Configuration of input field
  - plane wave
  - polarization
    - *a)* E_x-polarized
    - *b)* E_y-polarized
- Configuration of etalon
  - cylindrical-planar
  - center thickness 700 µm
  - cylindrical surface radius 1 m

There is no 3rd light mode, because the next back reflected light portion carries no significant efficiency any more!



a) x polarized light

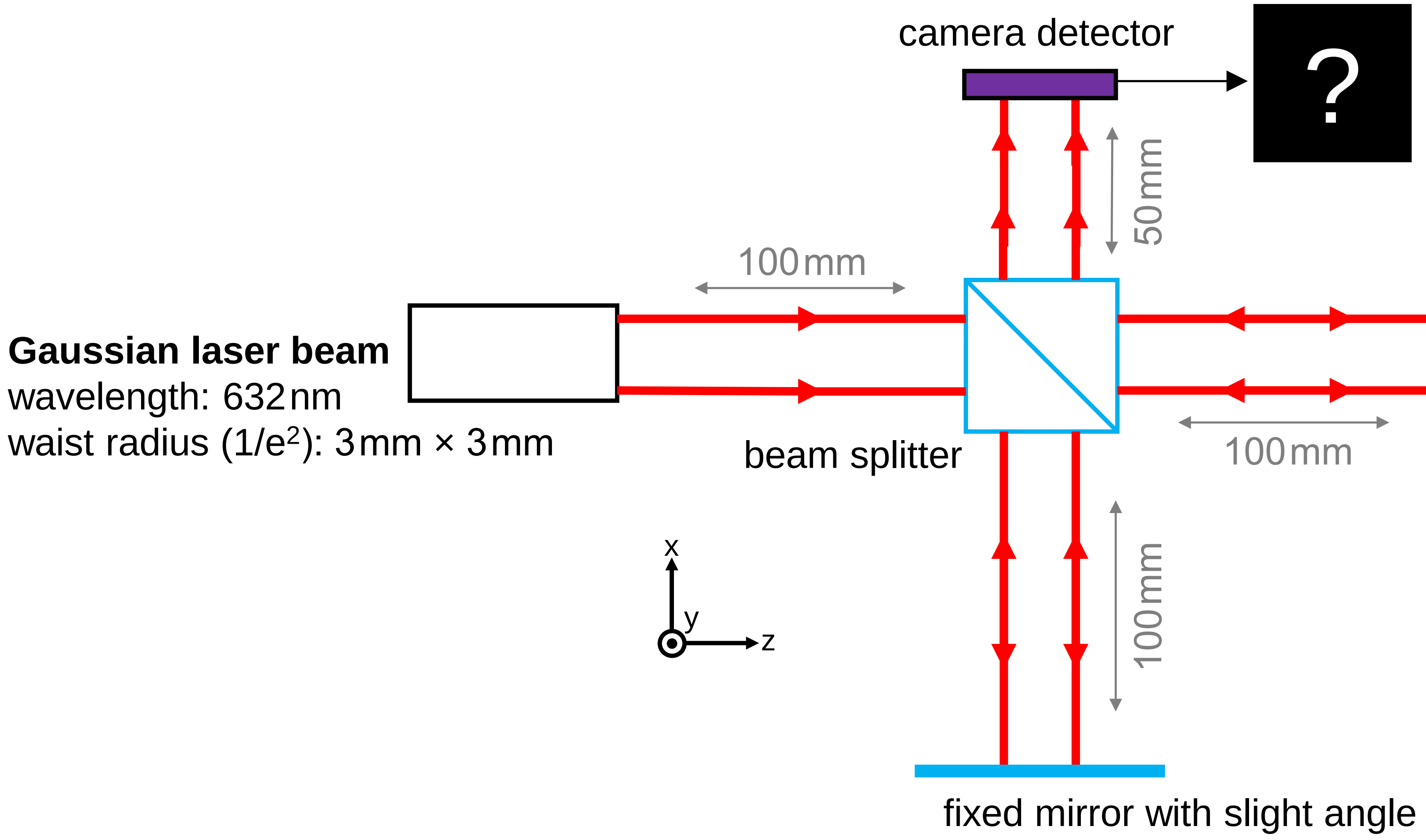


b) y polarized light

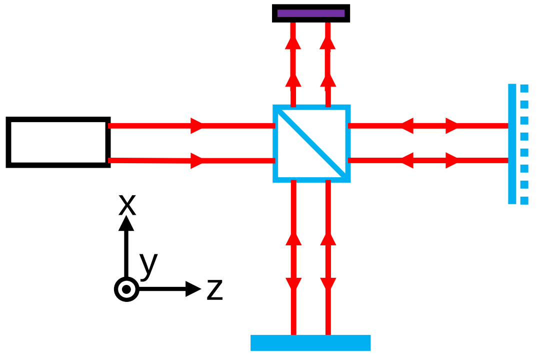
Interferometer Example

Michelson type

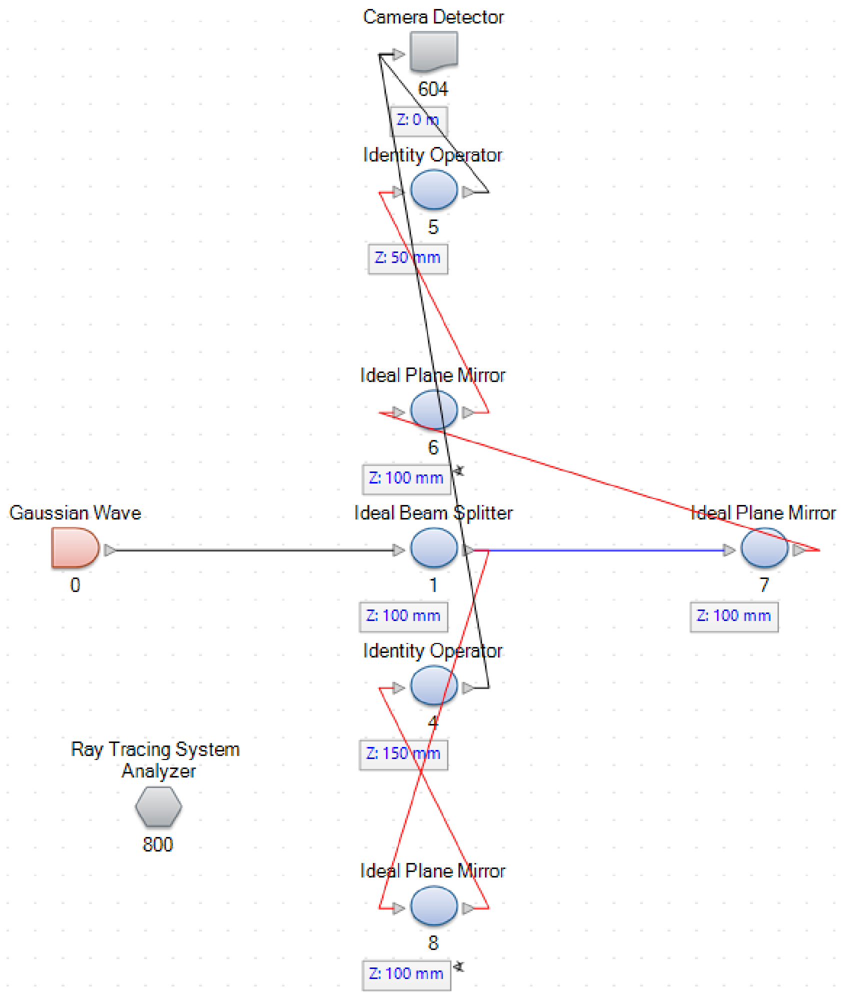
Michelson Interferometer Specification



Michelson Interferometer Setup

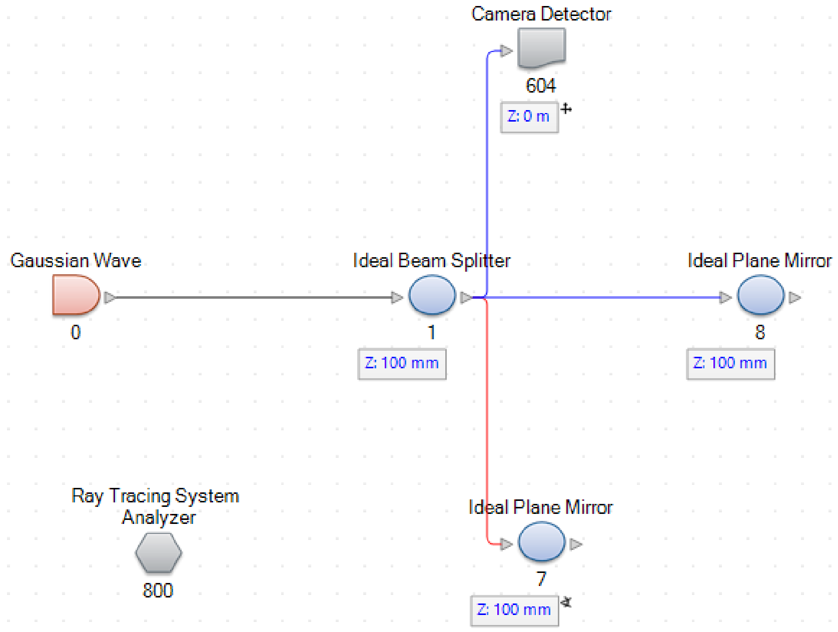


setup without NSE

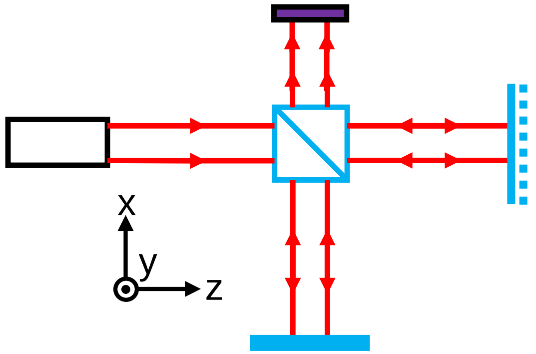


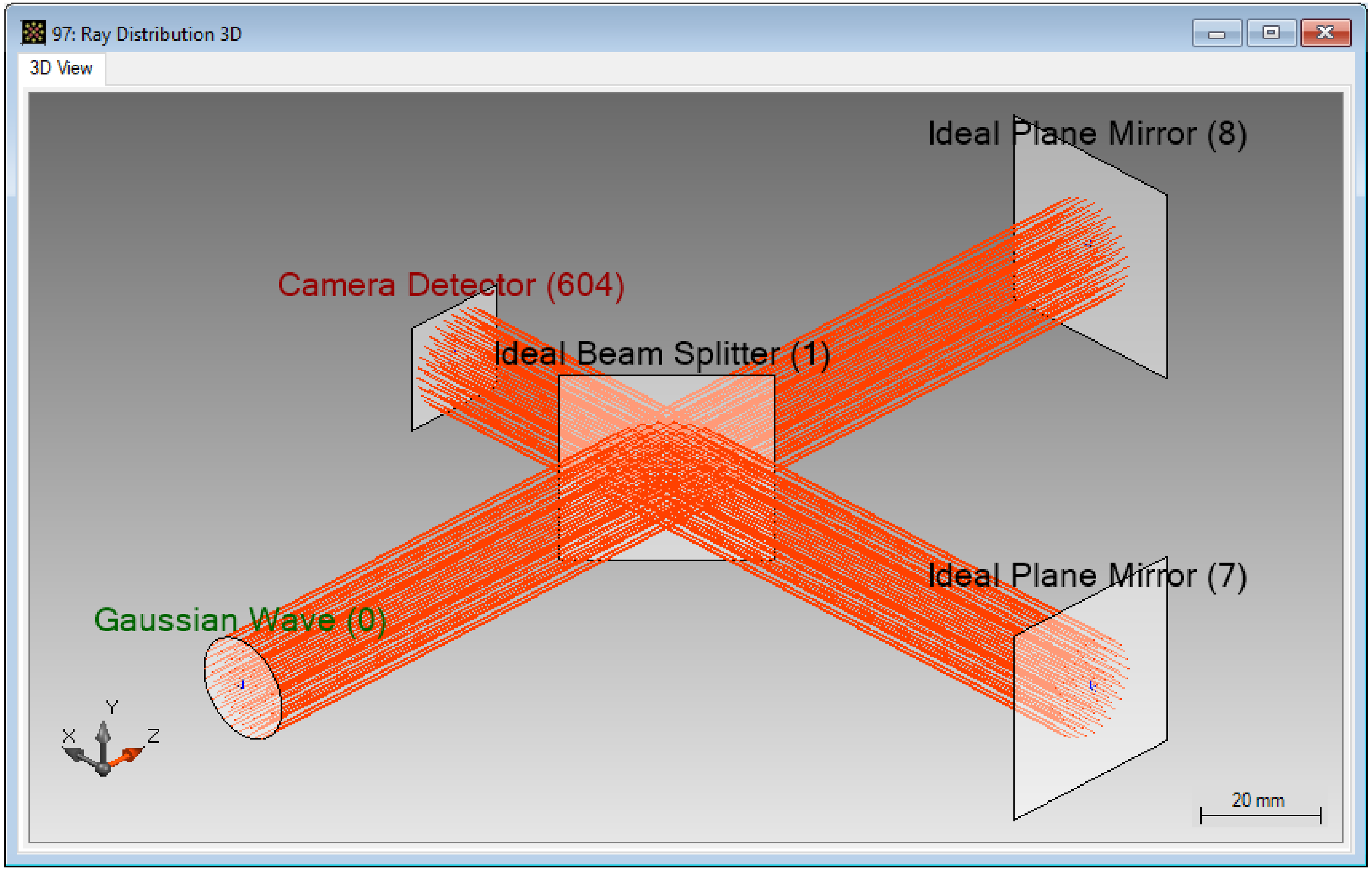
setup with NSE (*)

(*) if system is based on non-sequential effect, and system is build with NSE, simulation does not make sense with deactivated NSE.

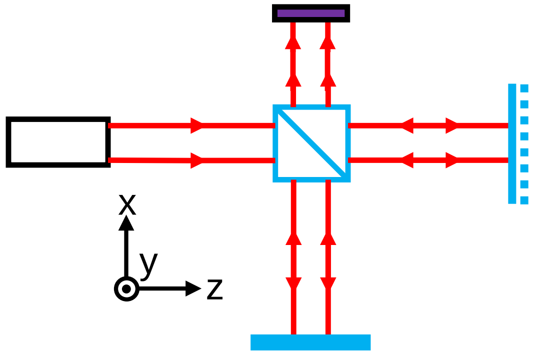


Michelson Interferometer Simulation → Result (3D Ray Tracing)



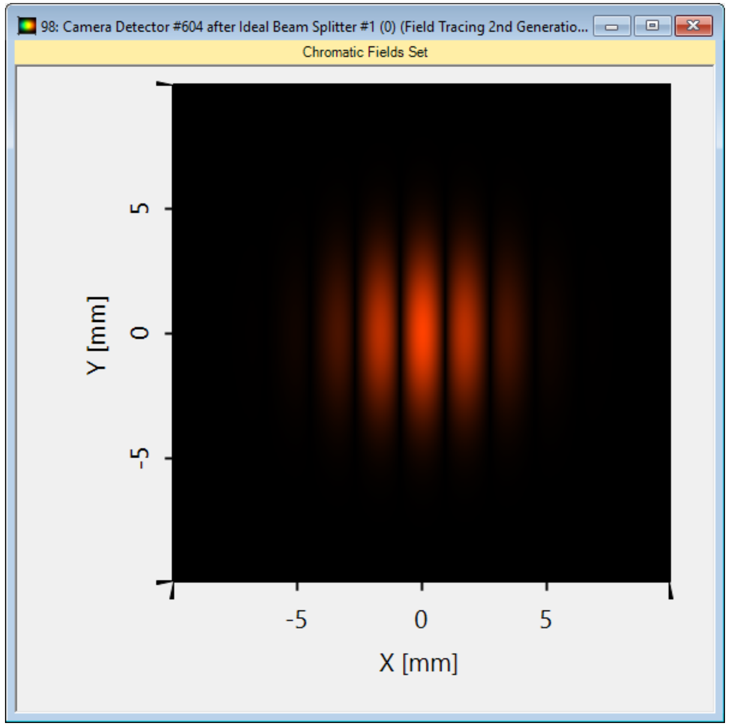


Michelson Interferometer Simulation → Results (Field Tracing) 1

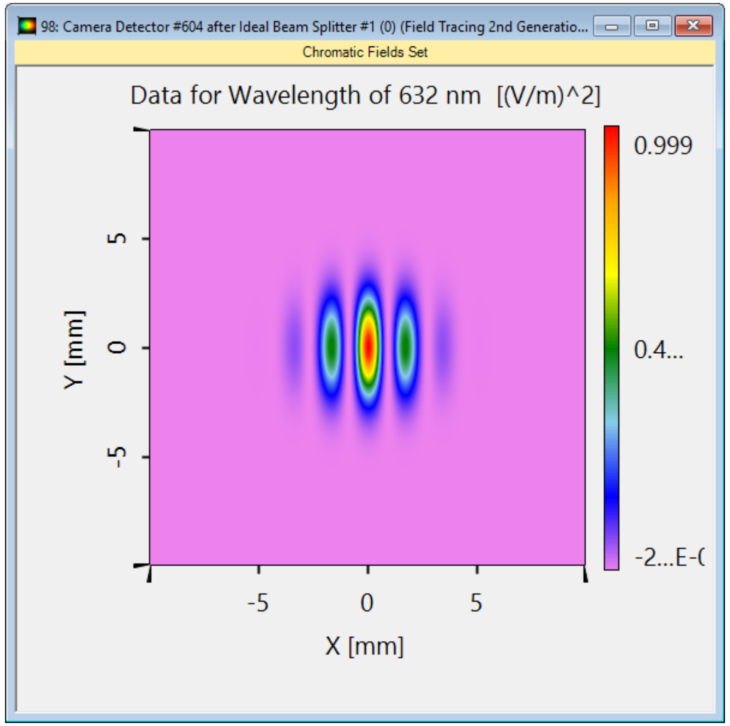


simulation time without NSE: ~3s

simulation time with NSE: ~ 2s

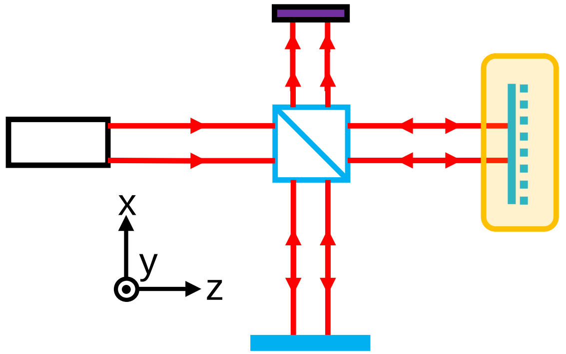


real color



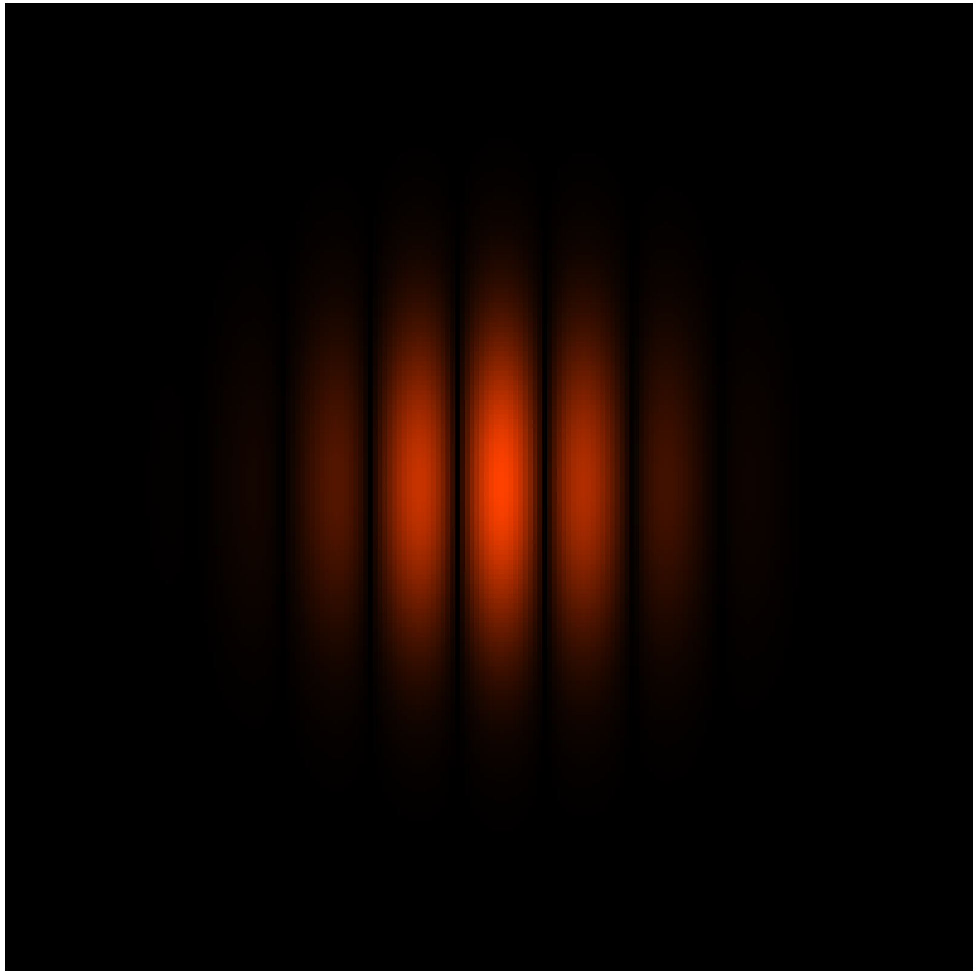
inverse rainbow colors

Michelson Interferometer Simulation → Results (Field Tracing) 2

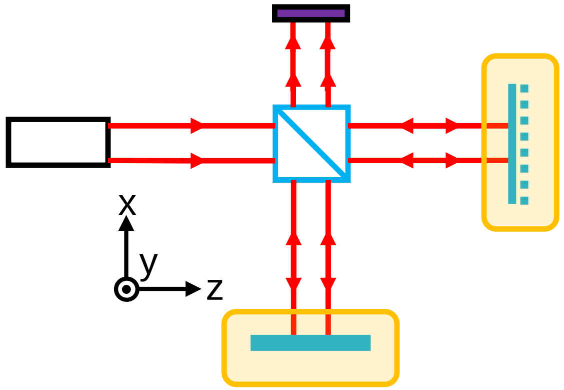


simulation with

- varying distances of movable mirror (from $-600\,\mu\mathrm{m}$ to $+600\,\mu\mathrm{m}$)

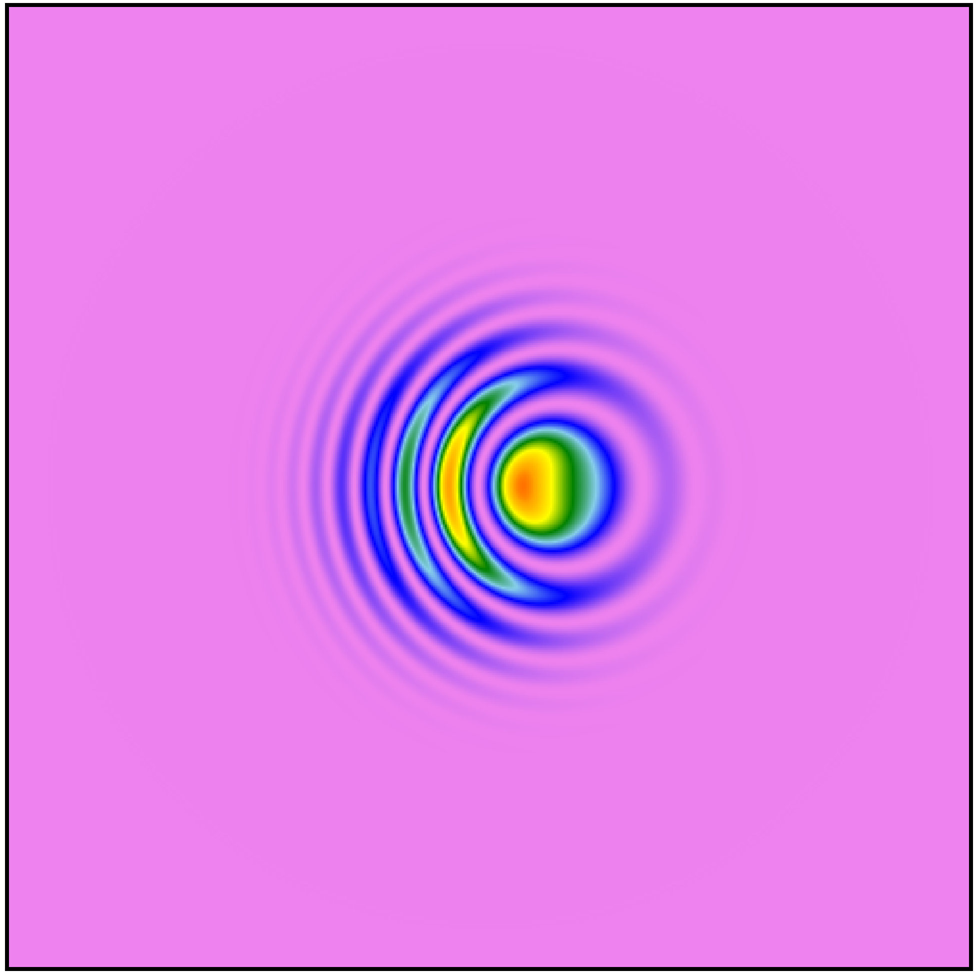


Michelson Interferometer Simulation → Results (Field Tracing) 3



simulation with

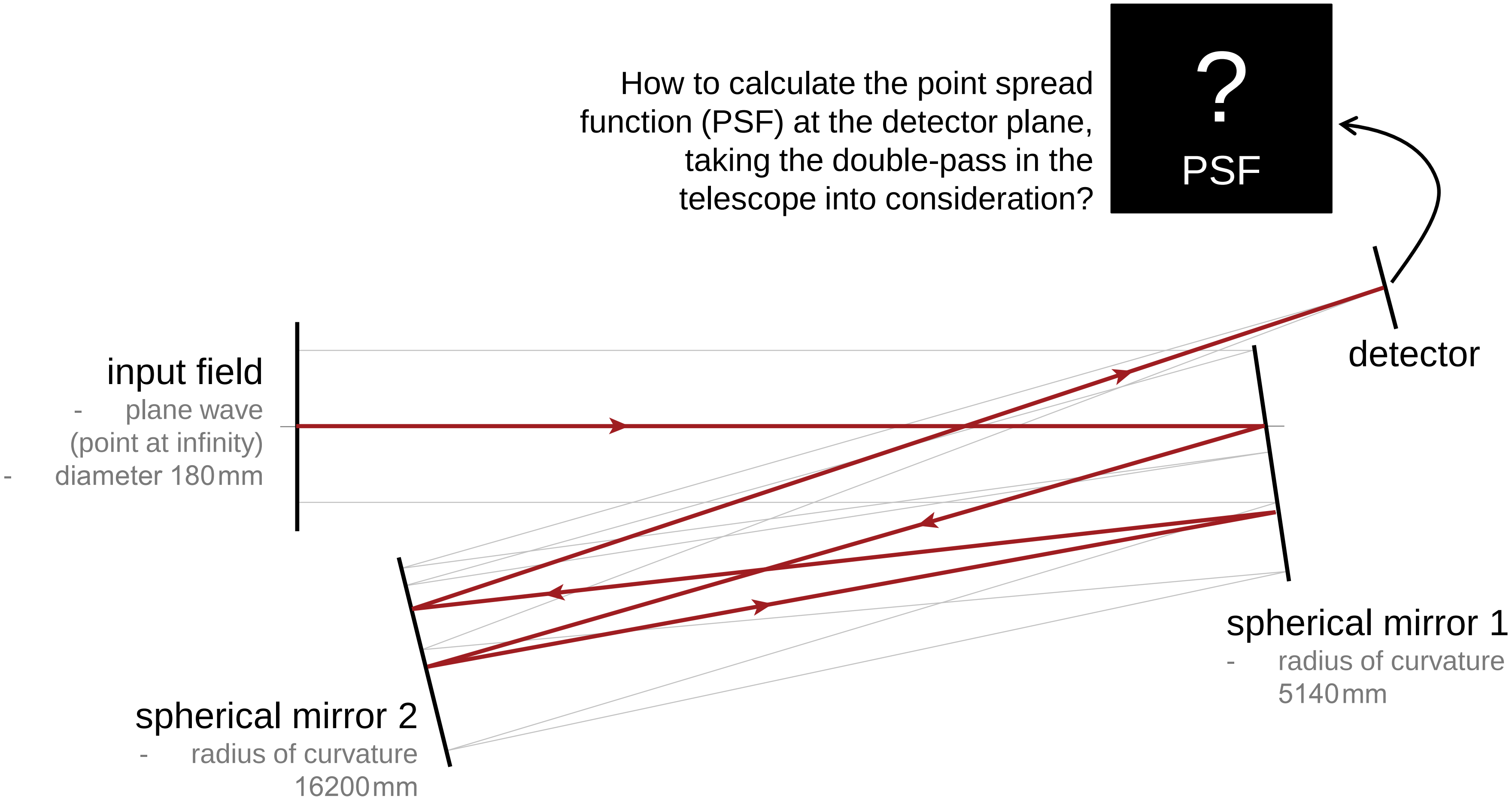
- varying distances of movable mirror (from $-600\,\mu m$ to $+600\,\mu m$)
- and fixed mirror with slight curvature (10 m radius)



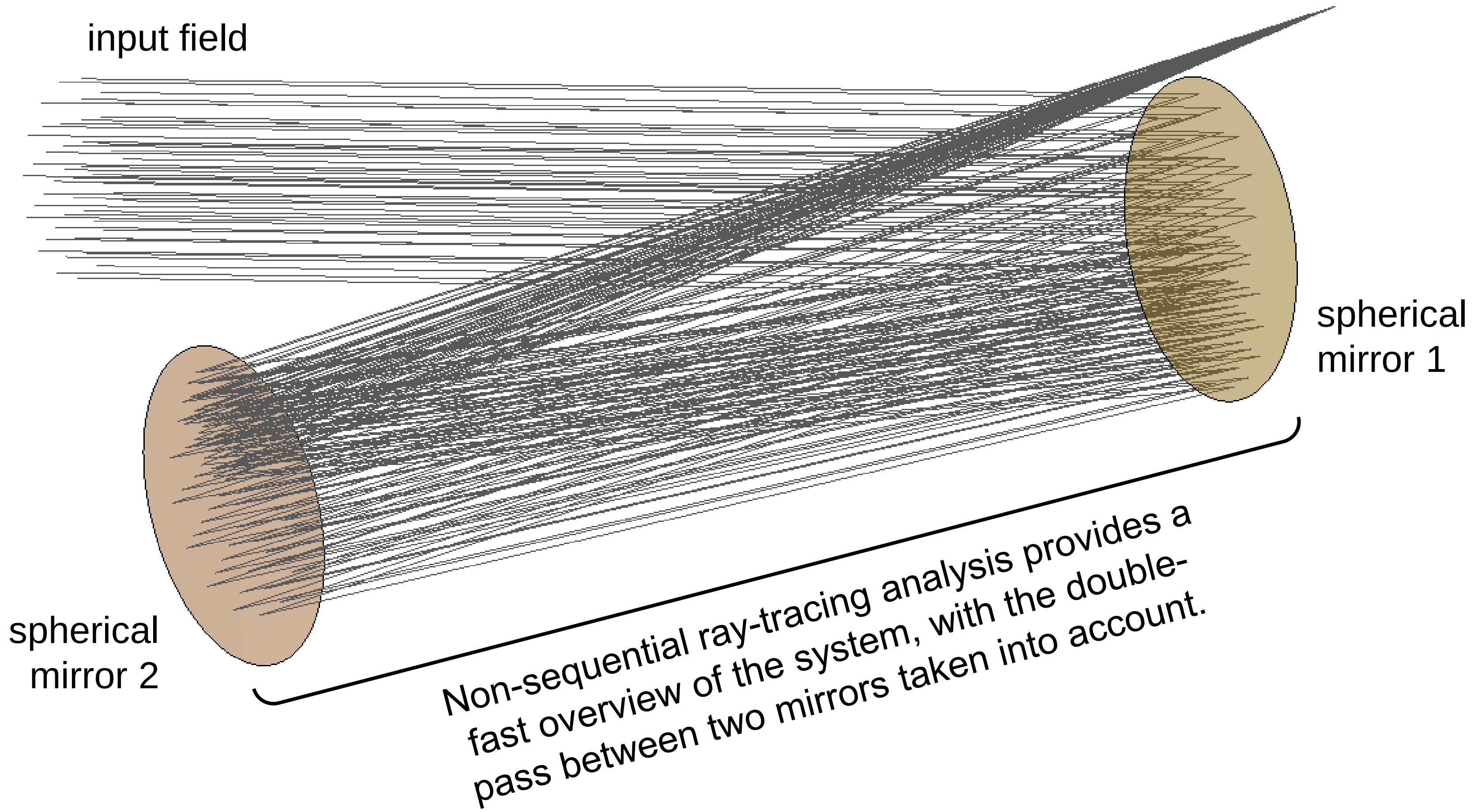
Telescope Example

Herrig Schiefspiegler type

Modeling Task

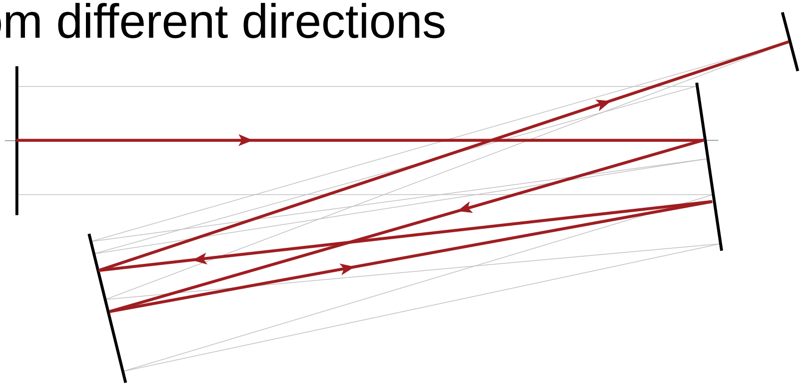


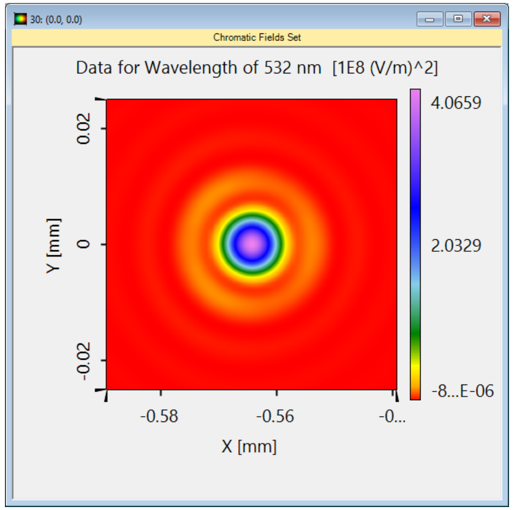
Ray Tracing System Analyzer Result



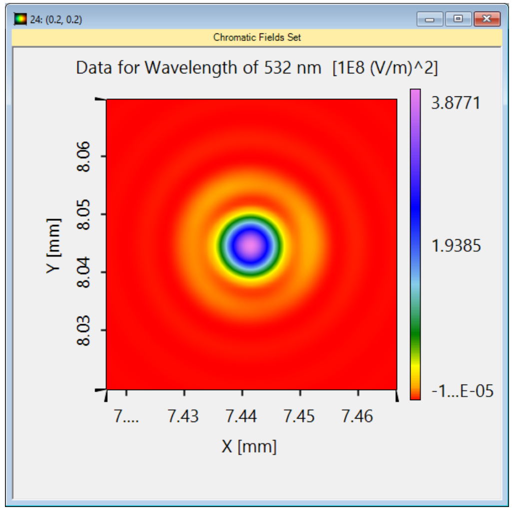
Field Tracing Results (PSFs) with Different Incident Angles

input field
from different directions



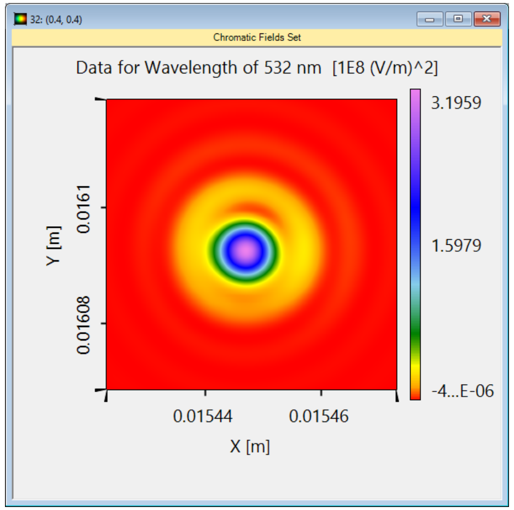


(0°, 0°)

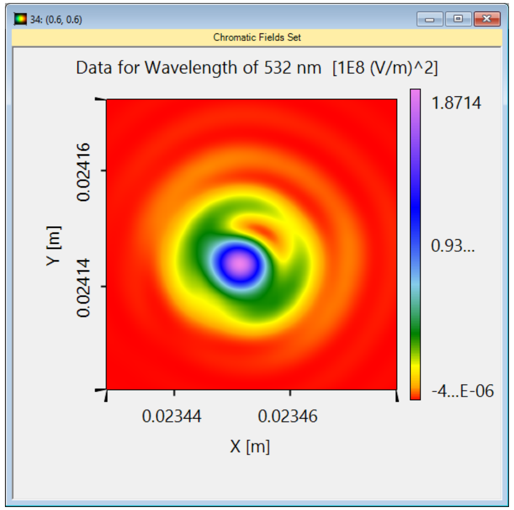


(0.2°, 0.2°)

Non-sequential field tracing
for the PSF calculation,
including double-pass between two mirrors,
takes less than 10 seconds



(0.4°, 0.4°)



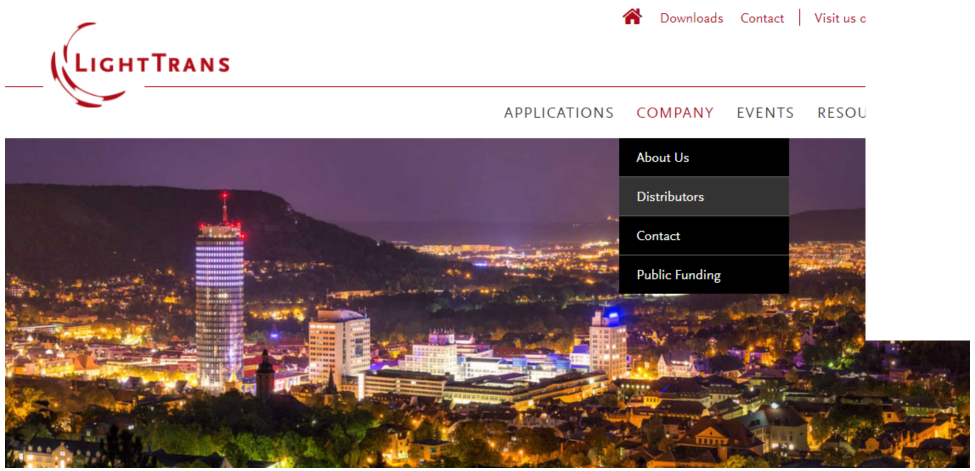
(0.6°, 0.6°)

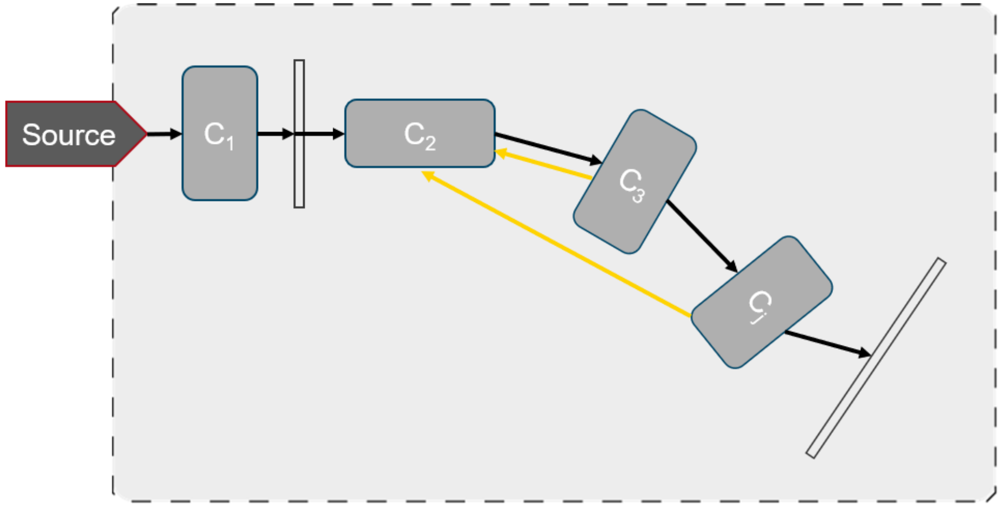
Conclusion

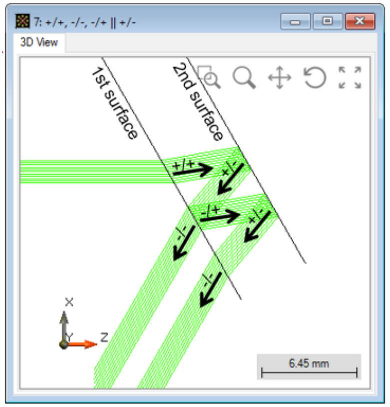
- VirtualLab Fusion offers both, sequential and non-sequential ray & field tracing!
  - with total control of investigations of relevant light paths (energy consideration)

- Modeling of a lot of applications take advantages of non-sequential tracing.

- Further information
  → www.lighttrans.com







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

What Does Fast Physical Optics Mean?

Fast Physical Optics by Field Tracing

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

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

2. **Interconnection:** The solutions per region are connected (through non-sequential field tracing) to solve Maxwell's equations in the entire system.
   → no loss of field information / accuracy

3. **Choice of Domain:** Field operations should be ~linear in the number of field samples N.
   → reduction of numerical effort / much faster computation

4. **Special Fourier Transforms:** The number of field parameters N should be minimized.
   → further reduction of numerical effort → making physical optics calculation really fast!

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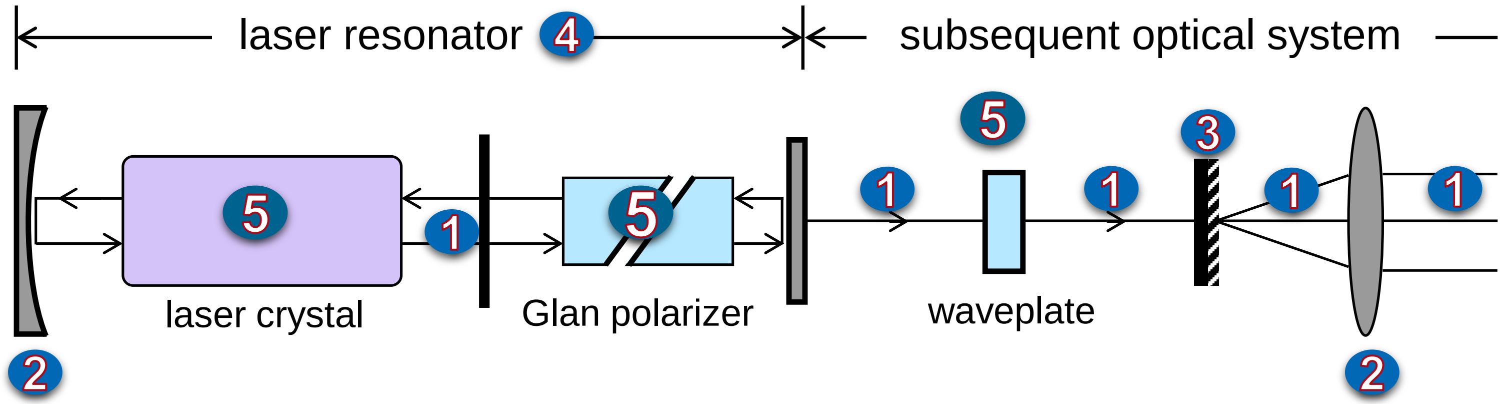
Concept: Different Propagation Techniques (Maxwell Solvers)

- Field tracing concept



1 Free space: Diffraction integral

2 Lens & mirror: Geometrical optics

3 Grating: Fourier Modal Method (FMM)

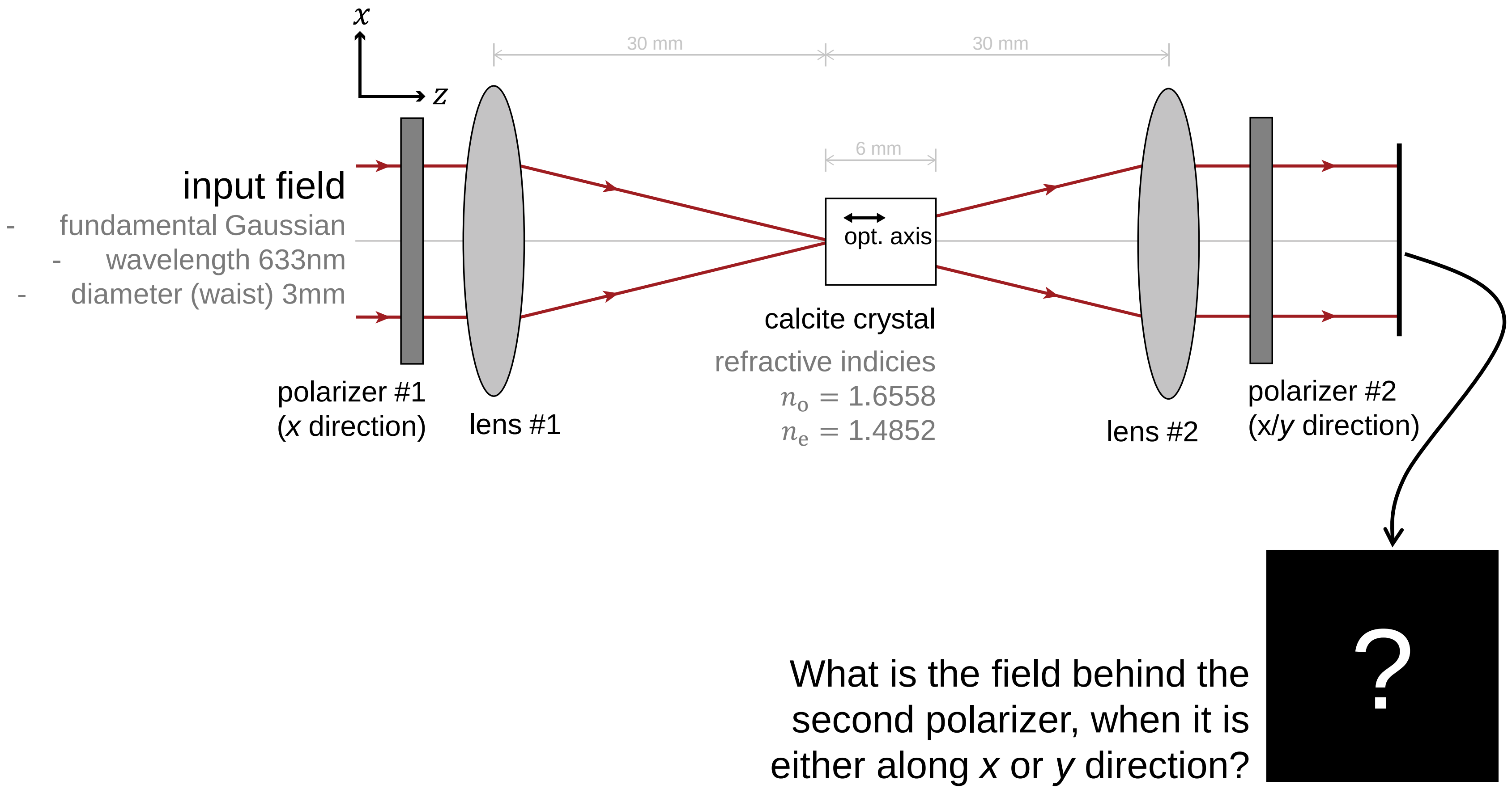
4 Resonator: Fully vectorial Fox and Li algorithm

5 Crystals: fully vectorial field propagation, and include any types of anisotropies

Demonstrational Example:
Dynamics in Linear Polarization Conversion in Uniaxial Crystals

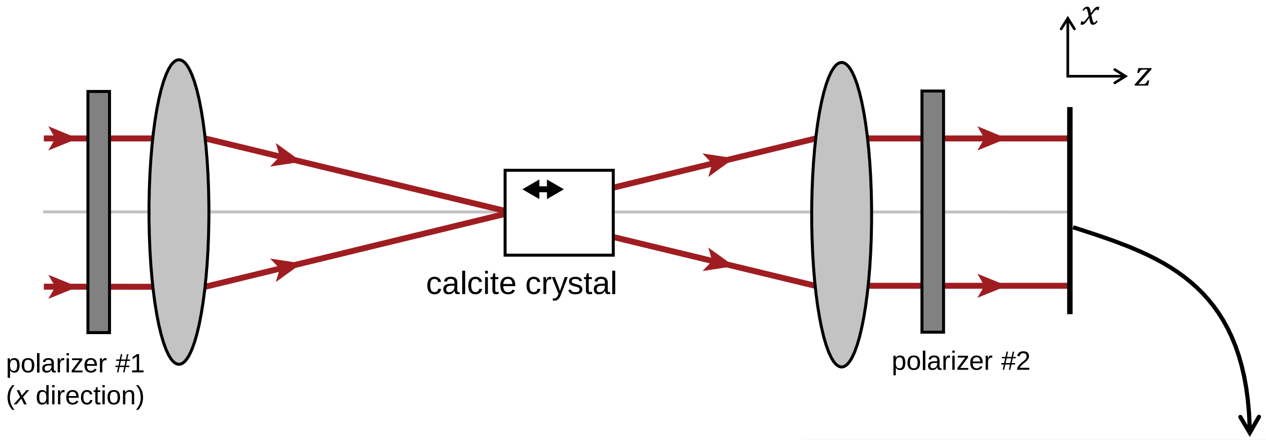
Comparing Experimental with Our Simulation Results

Modeling Task

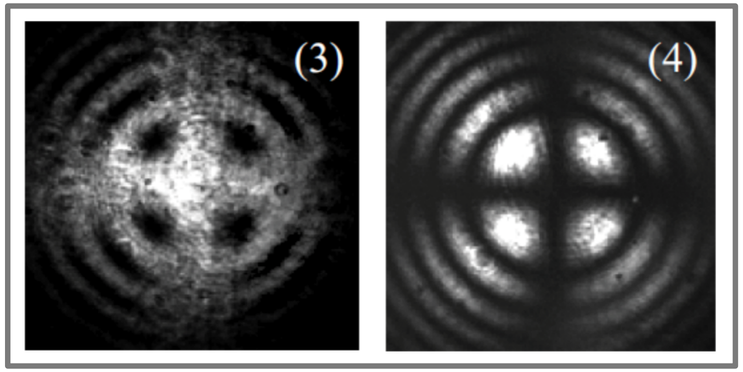


What is the field behind the second polarizer, when it is either along *x* or *y* direction?

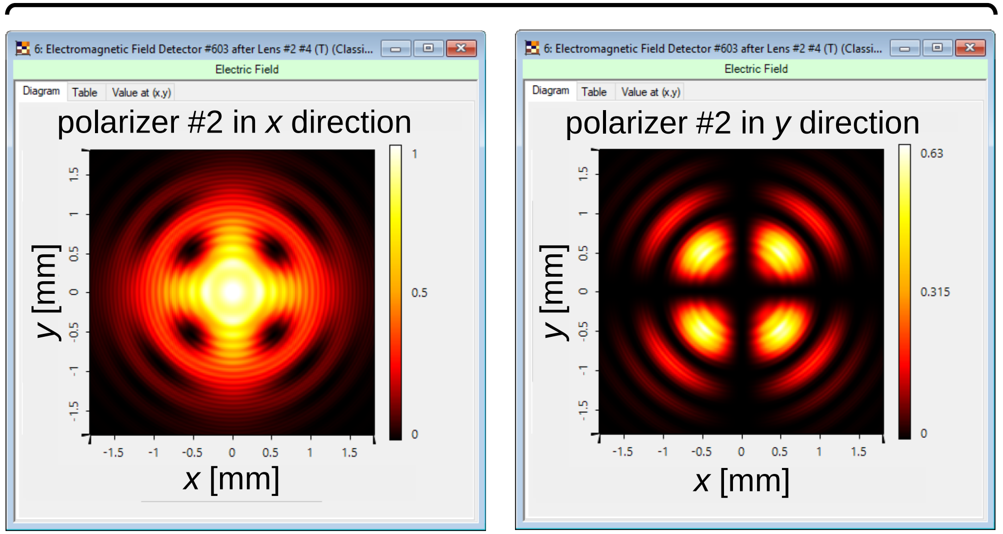
Results



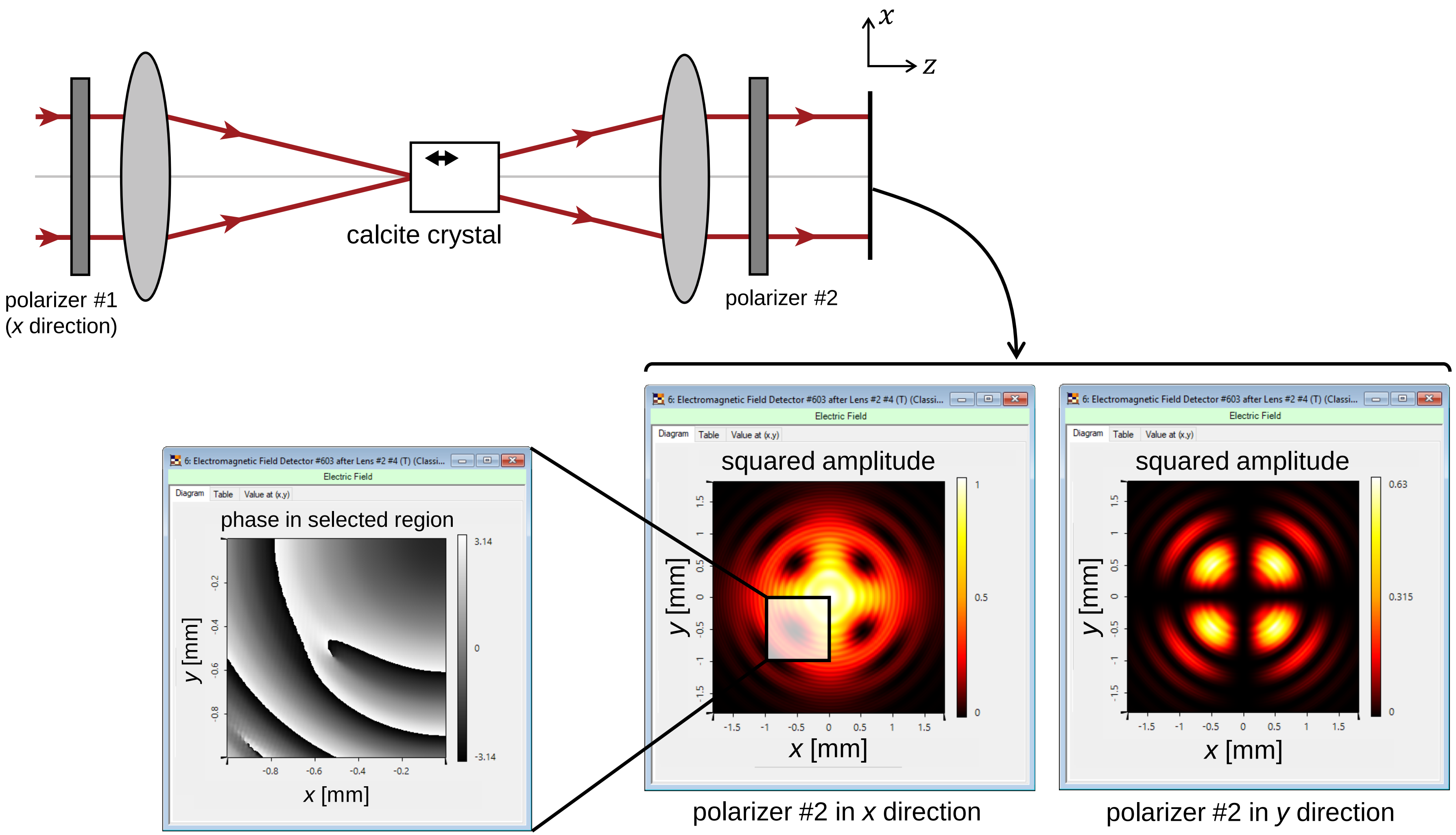
Physical-optics simulation of complete system includes birefringence and interference effects.



Experimental measurements from Y. Izdebskaya *et al.*, Opt. Express **17**, 18196-18208 (2009)



Results



x
z
calcite crystal
polarizer #1
(x direction)
polarizer #2
phase in selected region
squared amplitude
squared amplitude
y [mm]
x [mm]
polarizer #2 in x direction
polarizer #2 in y direction

Fast Physical Optics by Field Tracing

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

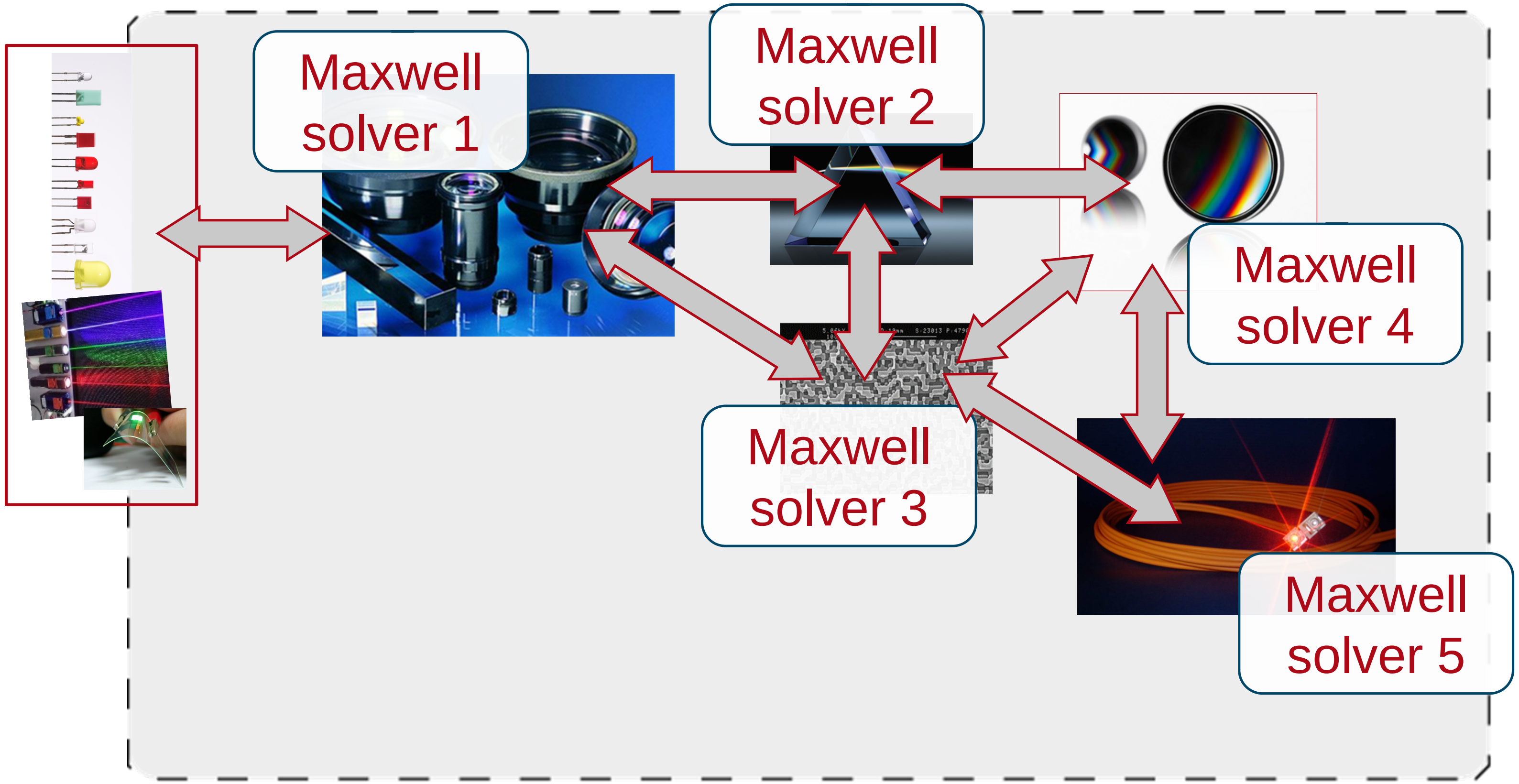
1. **Tearing:** The optical system is decomposed into various regions in which different types of specialized Maxwell solvers are applied.
   → guarantees physical optics

2. **Interconnection:** The solutions per region are connected (through non-sequential field tracing) to solve Maxwell's equations in the entire system.
   → no loss of field information / accuracy

3. **Choice of Domain:** Field operations should be ~linear in the number of field samples N.
   → reduction of numerical effort effort / much faster computation

4. **Special Fourier Transforms:** The number of field parameters N should be minimized.
   → further reduction of numerical effort → making physical optics calculation really fast!

Interconnection of Regional Maxwell Solvers



VirtualLab uses equidistant and non-equidistant sampling
as well as gridded and non gridded data representations.
→ suitable data transfer and clever interpolation techniques are required

Fast Physical Optics by Field Tracing: with Non-Sequentiality

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

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

2. **Interconnection:** The solutions per region are connected (through non-sequential field tracing) to solve Maxwell's equations in the entire system.
→ no loss of field information / accuracy

3. **Cho** … mples N.
→ re …

4. **Spe** … mized.
→ fu … y fast!

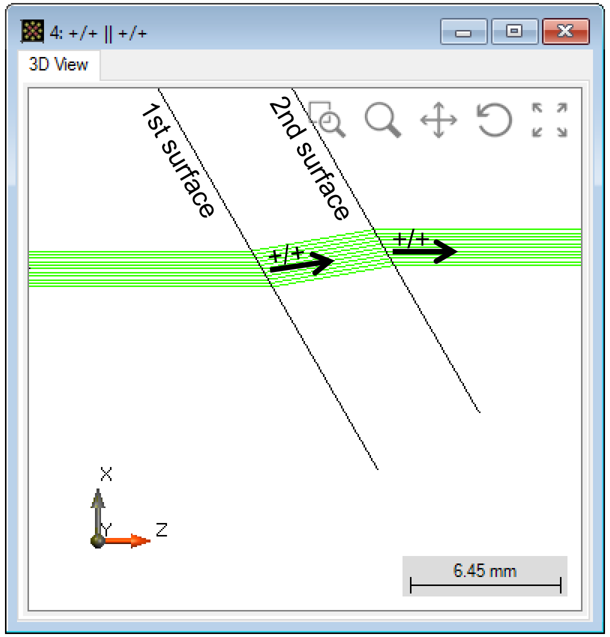
Non-Sequential Optical Field Tracing

Michael Kuhn, Frank Wyrowski, and Christian Hellmann

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

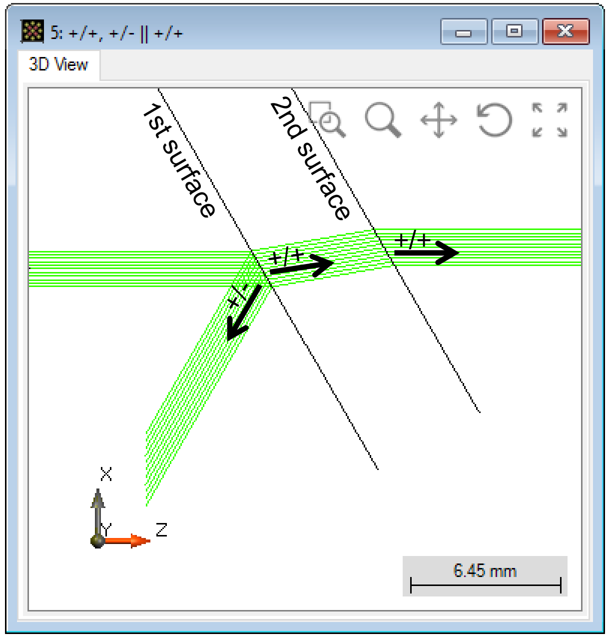
Surface Channels

- Setting A



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

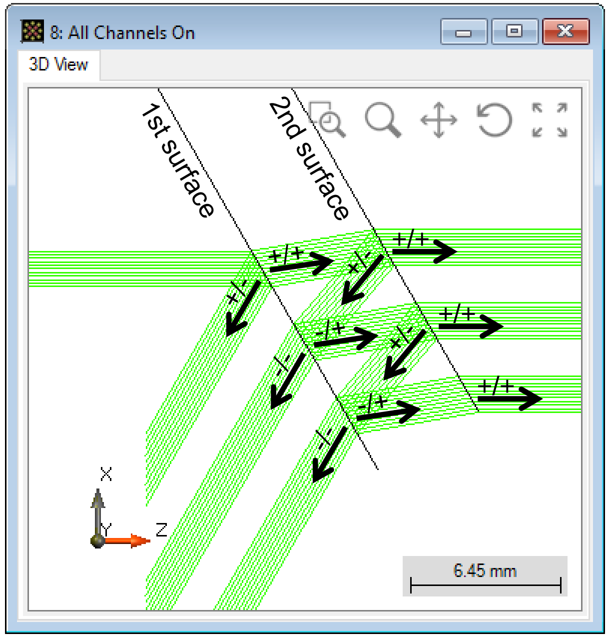
- Setting B



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

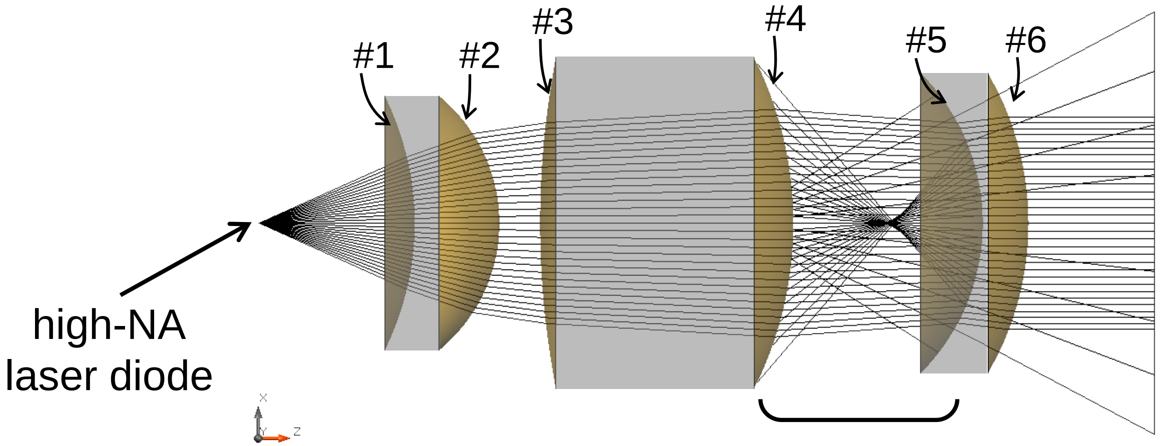
Surface Channels

- Setting E



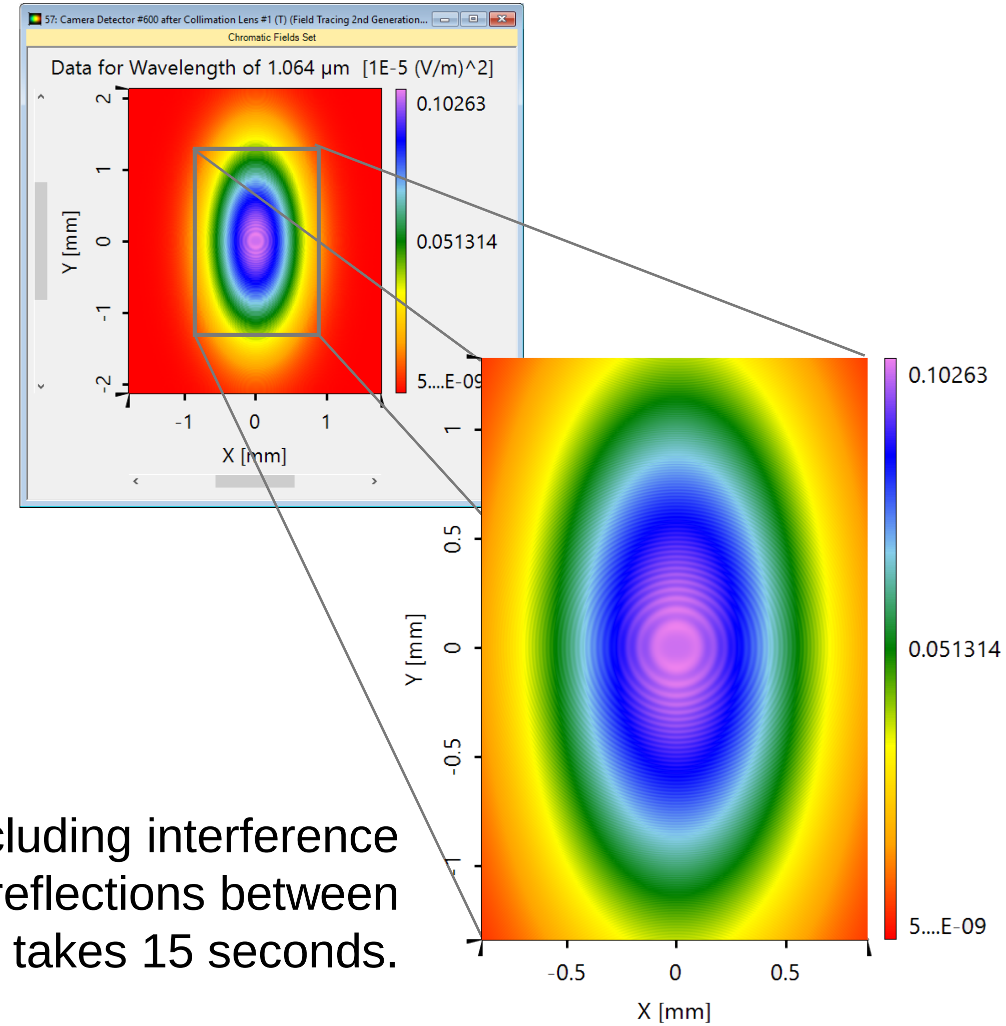
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

Collimation System: Non-Sequential Simulation



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

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



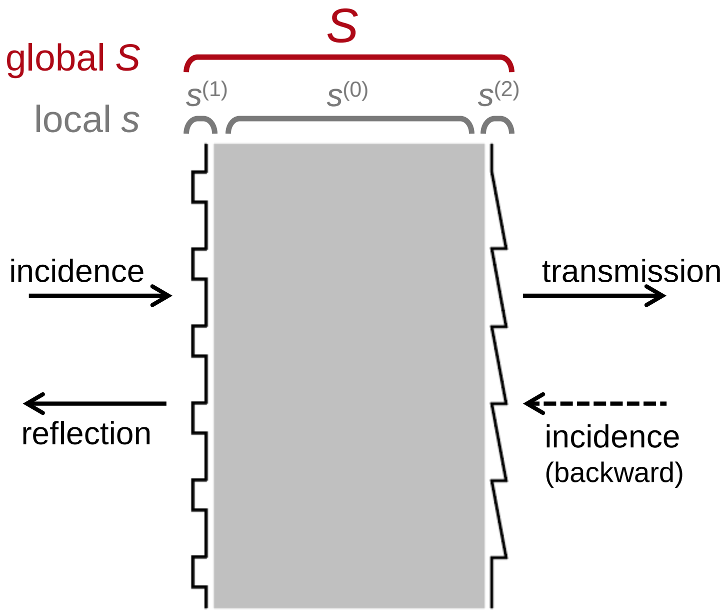
Simulation including interference caused by multiple reflections between uncoated surfaces takes 15 seconds.

Non-Sequential Field Tracing

Coupled Surfaces Analysis by Using Non-sequential Field Tracing

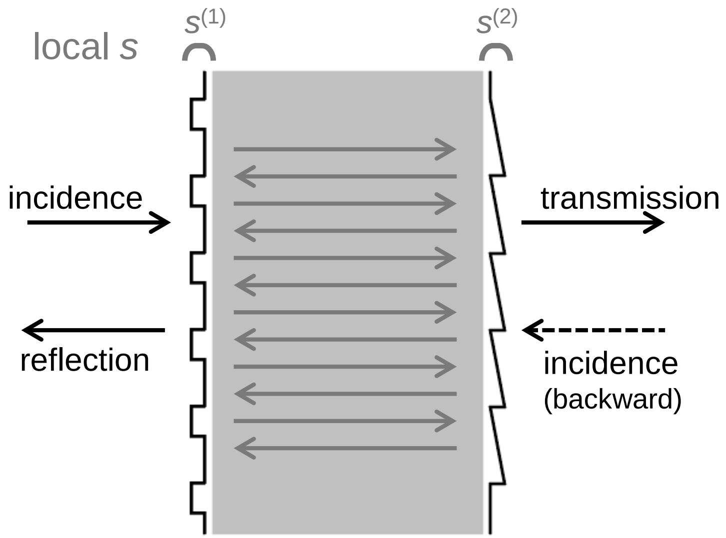
Theory Background

- Global S matrix



  - Recursion with respect to number of regions / layers

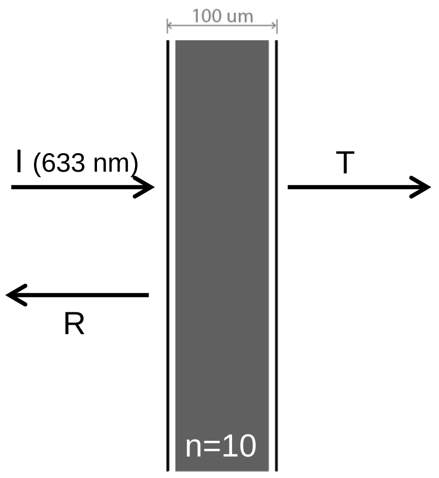
- Non-sequential field tracing



  - Recursion with respect to number of light paths

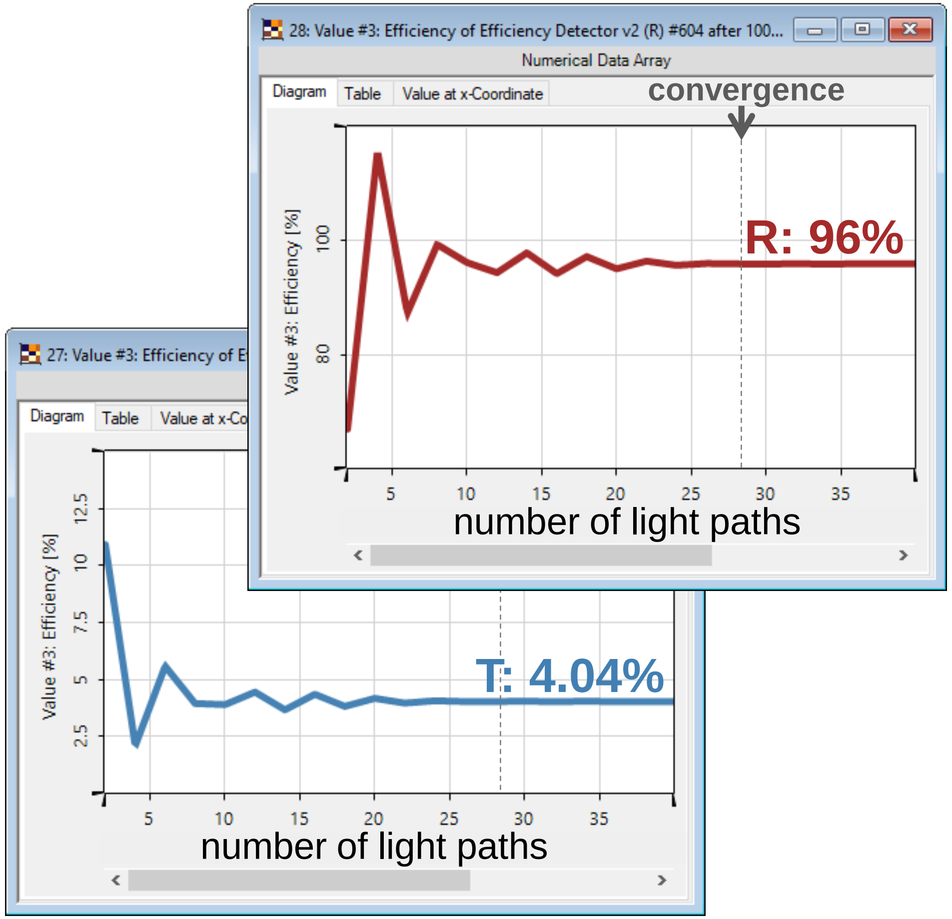
Planar Surface + Planar Surface

- Structure
- Non-sequential field tracing



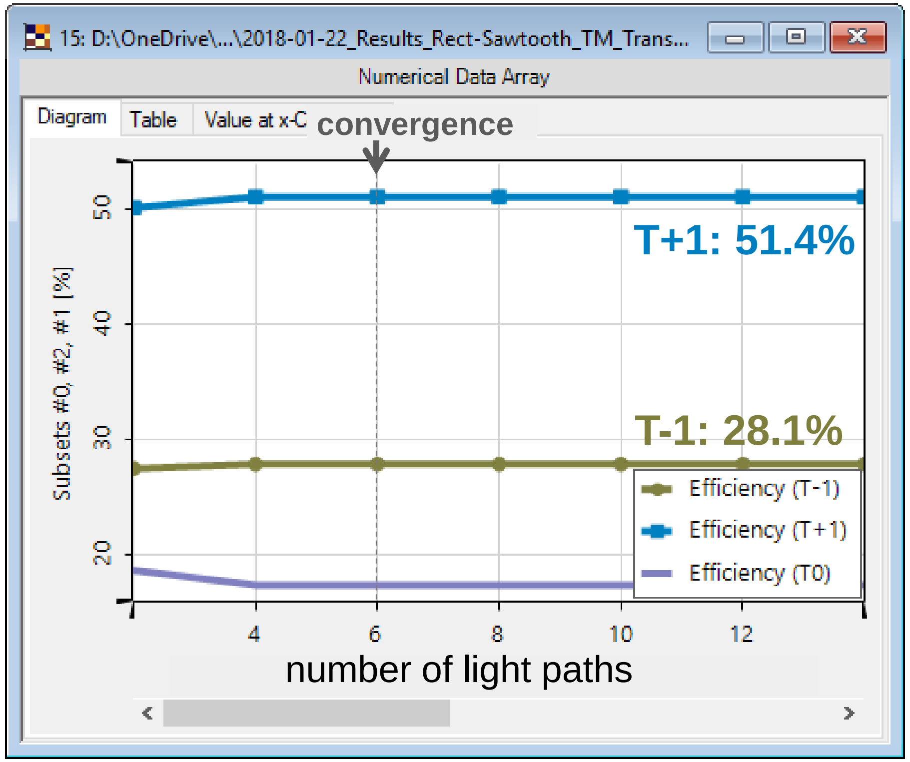
Global S matrix

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

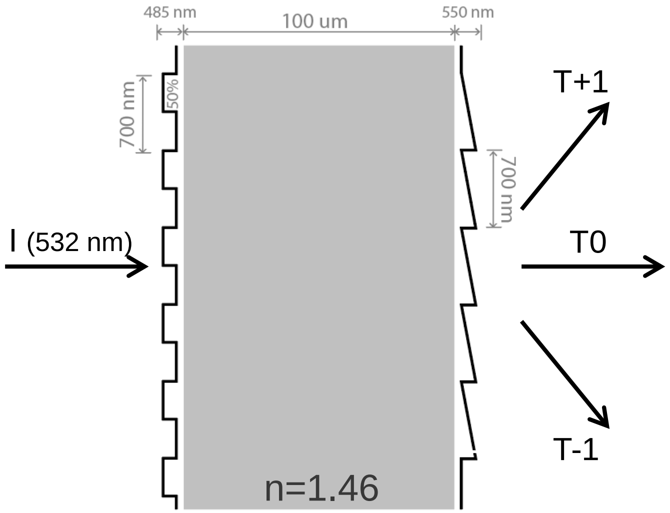


Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating

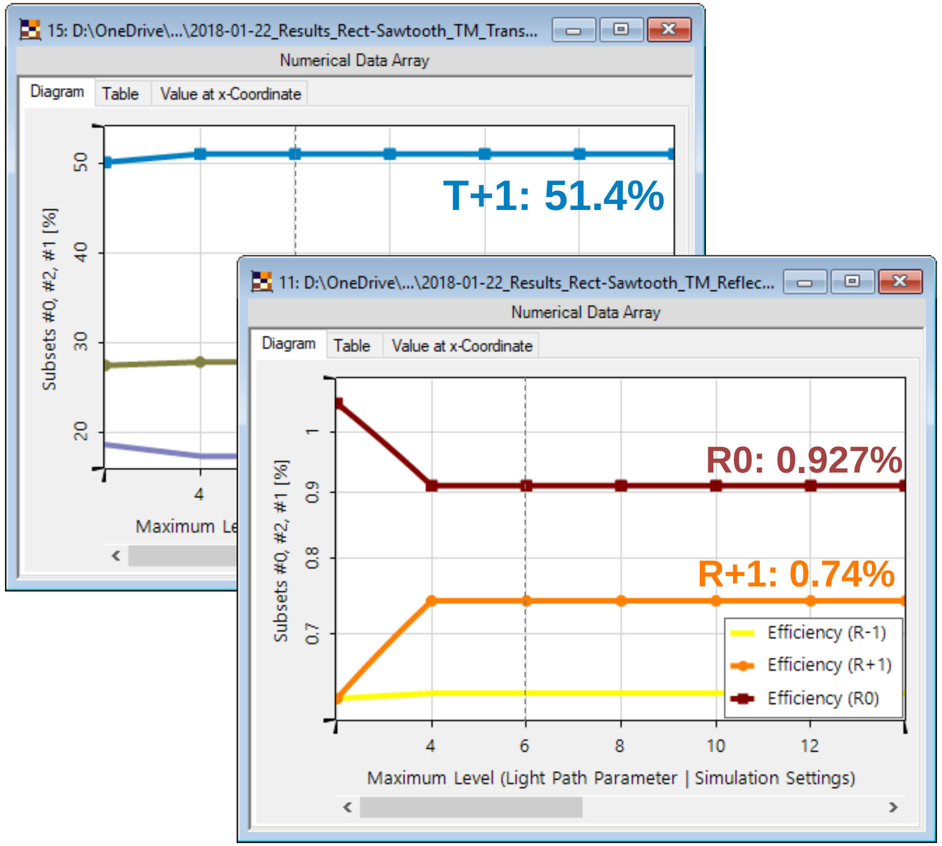


Global S matrix (TM)

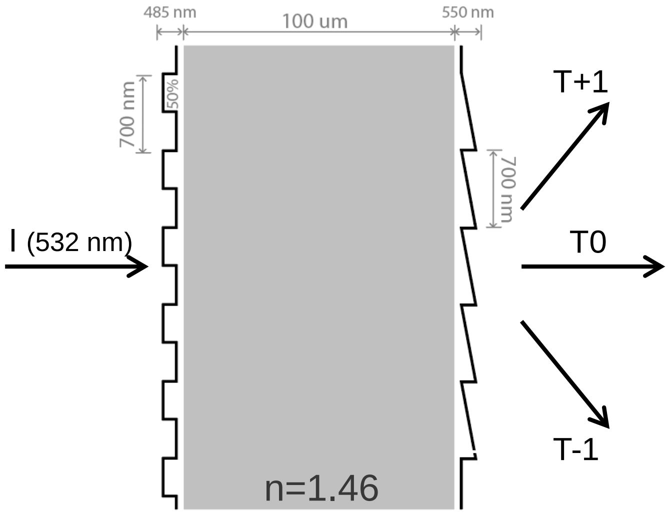
T	Eff.	R	Eff.
-1	28.1%	-1	0.65%
0	18.2%	0	0.923%
+1	51.4%	+1	0.74%

Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing



- ... with sawtooth coating



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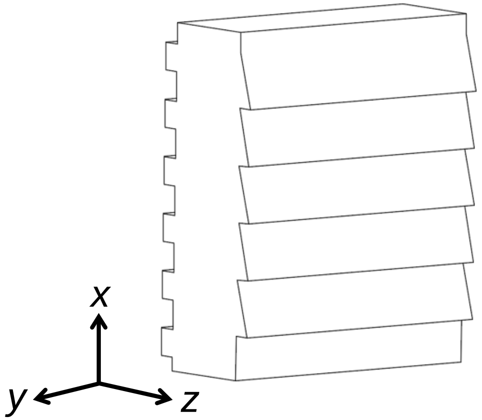
0	18.2%	**0**	**0.923%**
+1	51.4%	**+1**	**0.74%**

Computational Effort

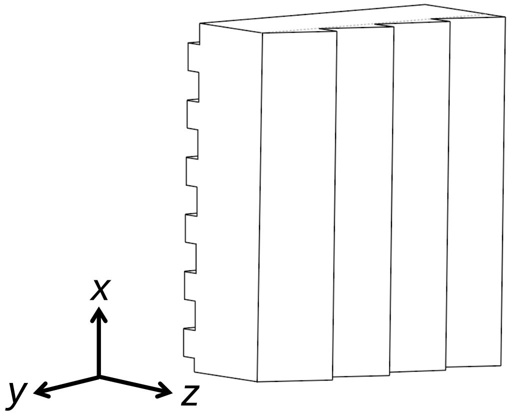
- Parallel gratings



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

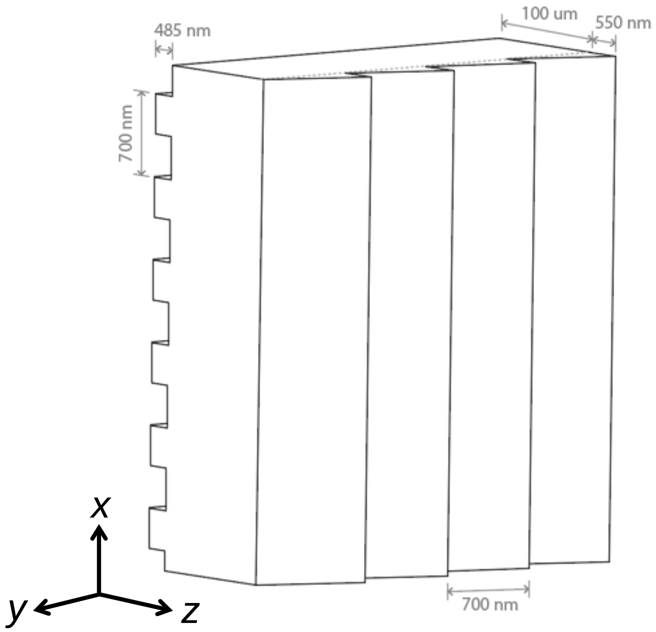


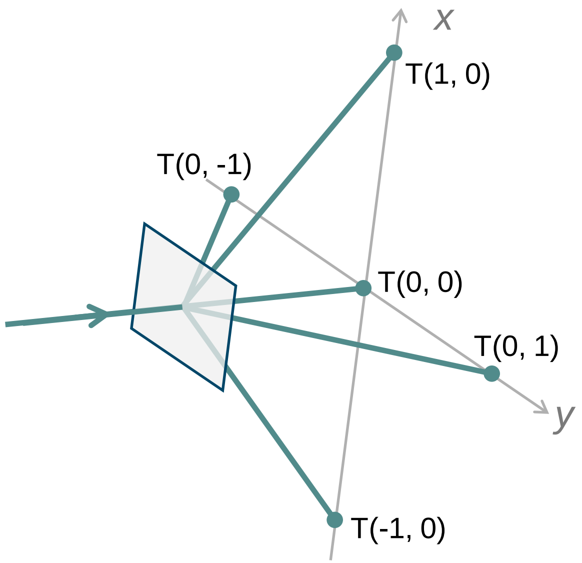
Global S matrix	Non-sequential field tracing
$\sim(M_x \times M_y)^3$ (scaling with number of layers)	$\sim(M_x^3 + M_y^3)$ (scaling with number of light paths)

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)



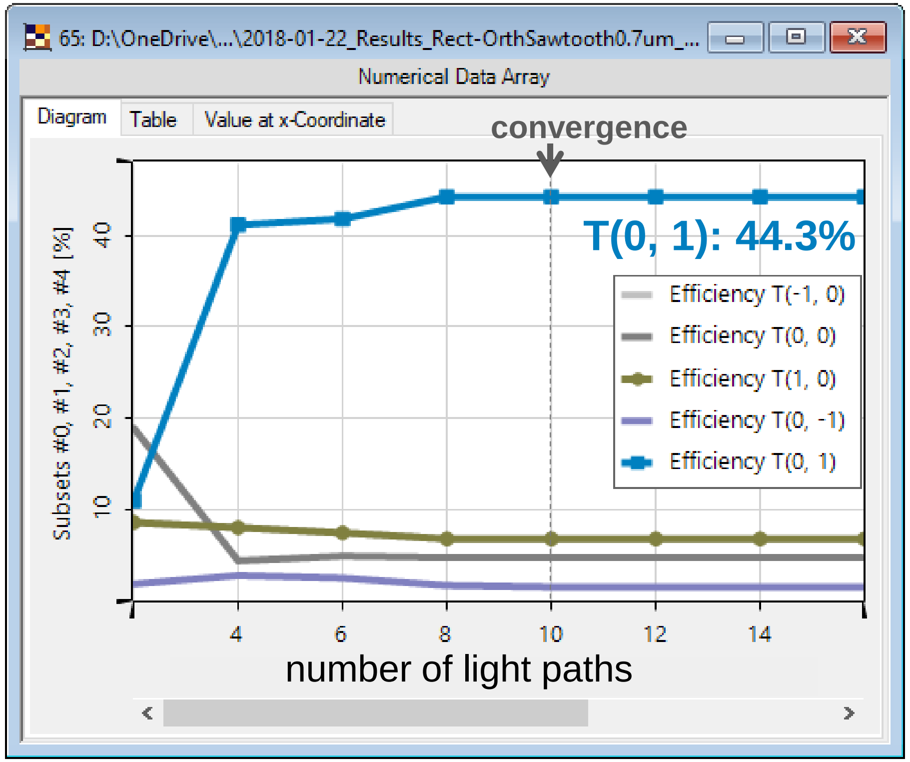


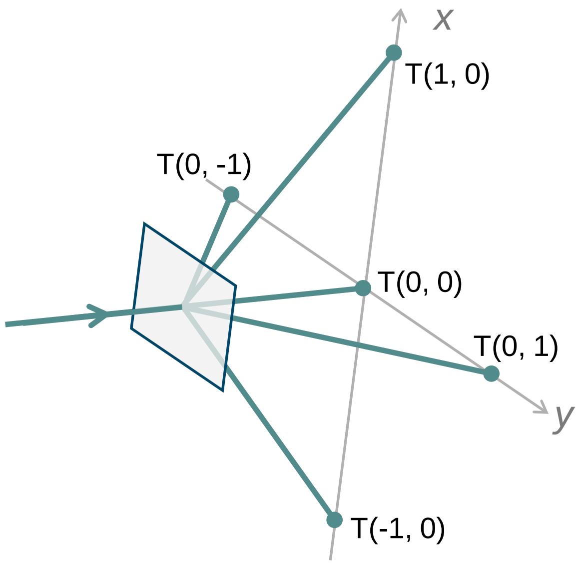
Global S matrix (TM)

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)



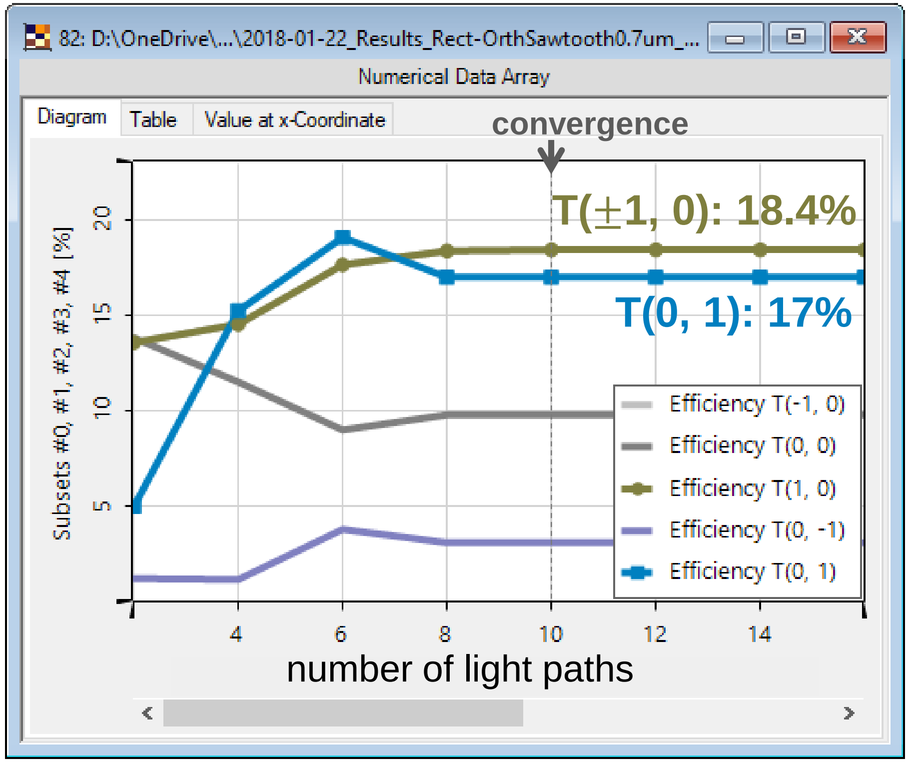


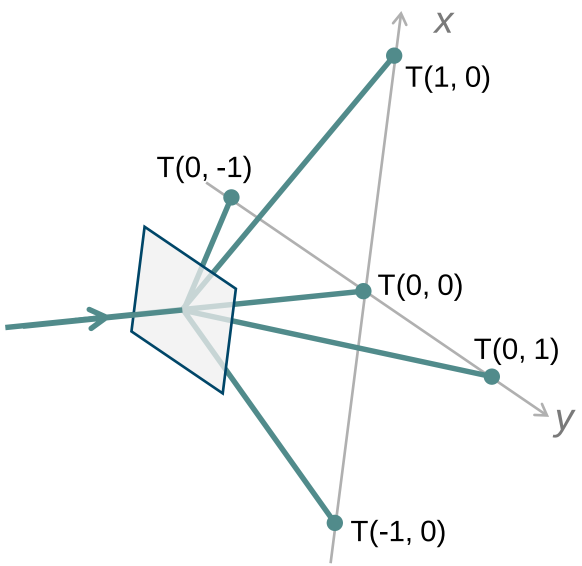
Global S matrix (TM)

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)



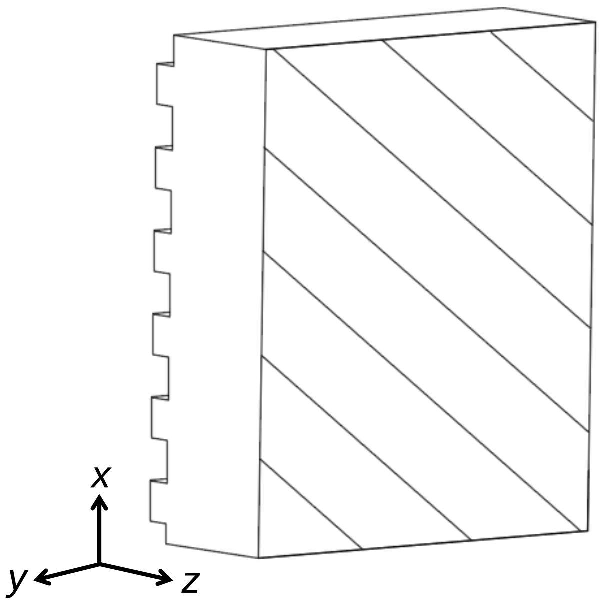


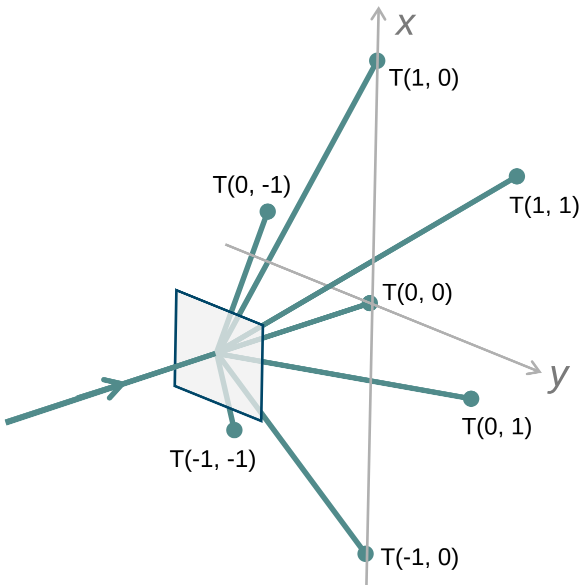
Global S matrix (TE)

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)

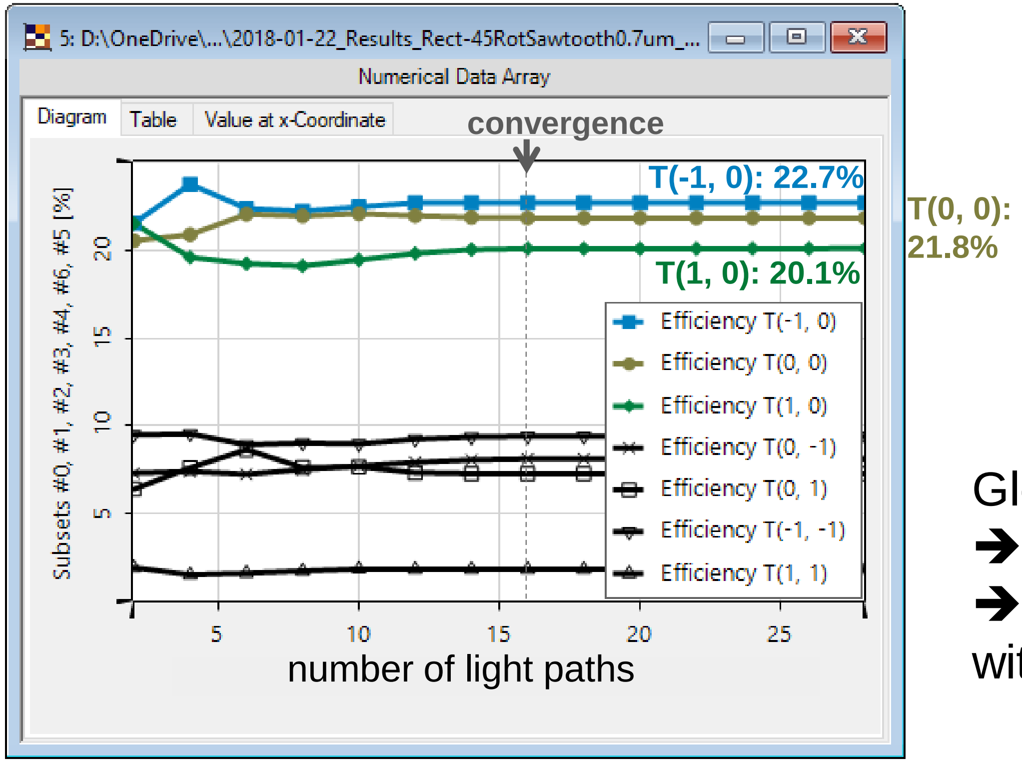


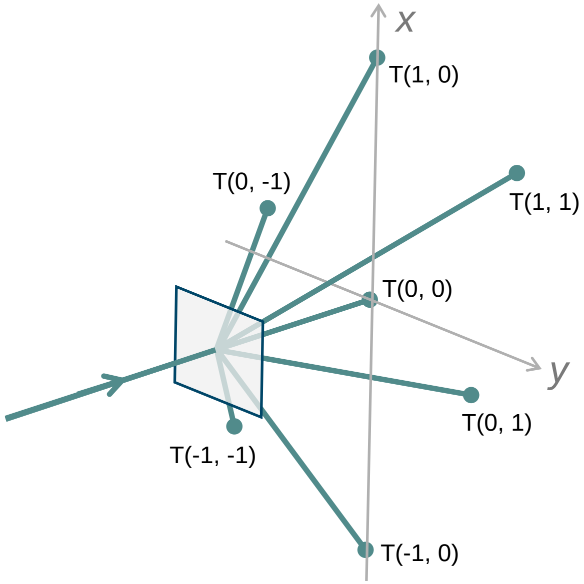


Global S matrix (TM)
➔ No common period!
➔ Huge computational effort even with approximated common period

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

Fast Physical Optics by Field Tracing

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

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

2. **Interconnection:** The solutions per region are connected (through non-sequential field tracing) to solve Maxwell's equations in the entire system.
   → no loss of field information / accuracy

3. **Choice of Domain:** Field operations should be ~linear in the number of field samples N.
   → reduction of numerical effort effort / much faster computation

4. **Special Fourier Transforms:** The number of field parameters N should be minimized.
   → further reduction of numerical effort → making physical optics calculation really fast!

Rigorous Propagation in Homogeneous Media

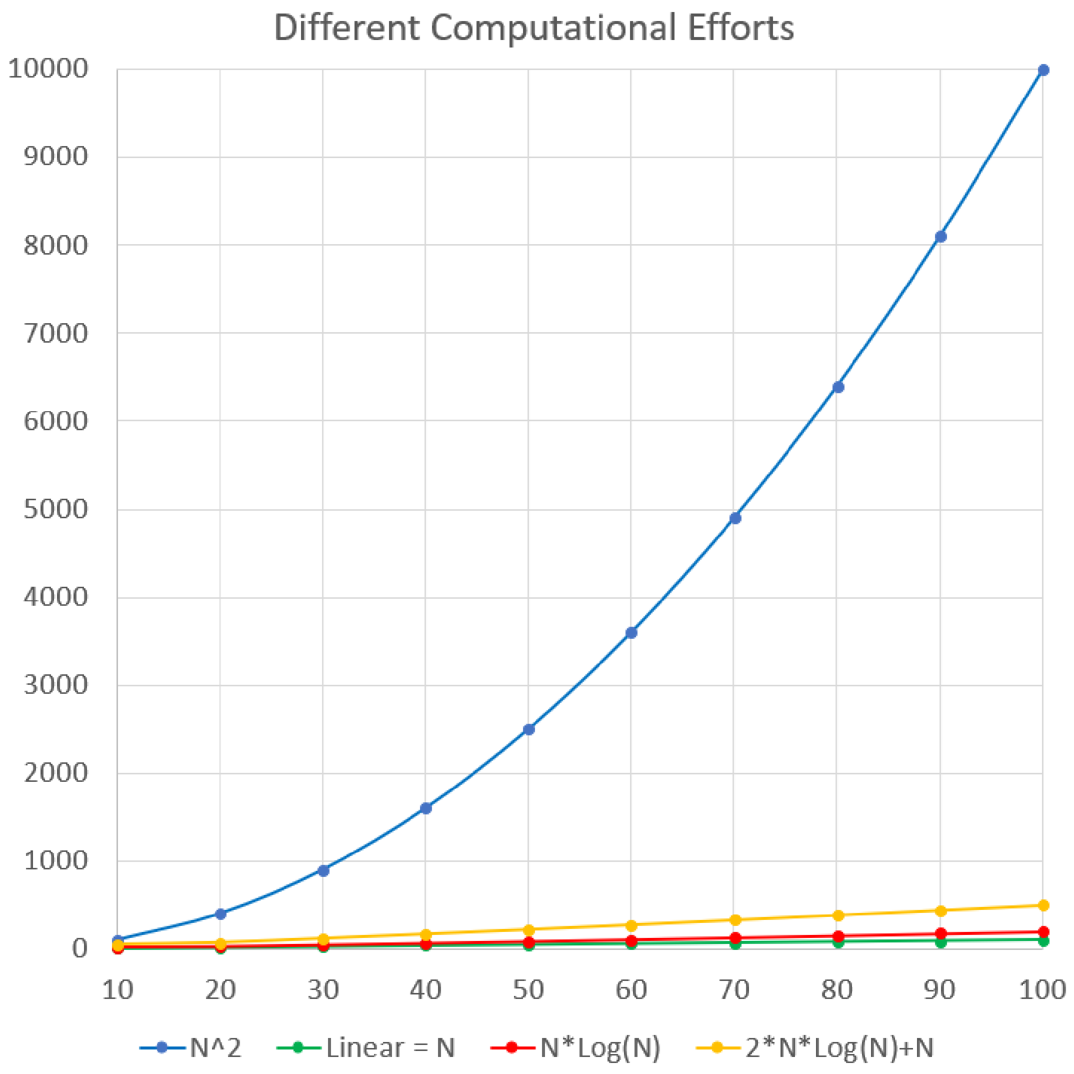
- The rigorous propagation in the x-domain (Rayleigh-Sommerfeld integral) has the complexity (i.e. numerical effort) of N^2 with N ... the sampling number.

N^2 operation

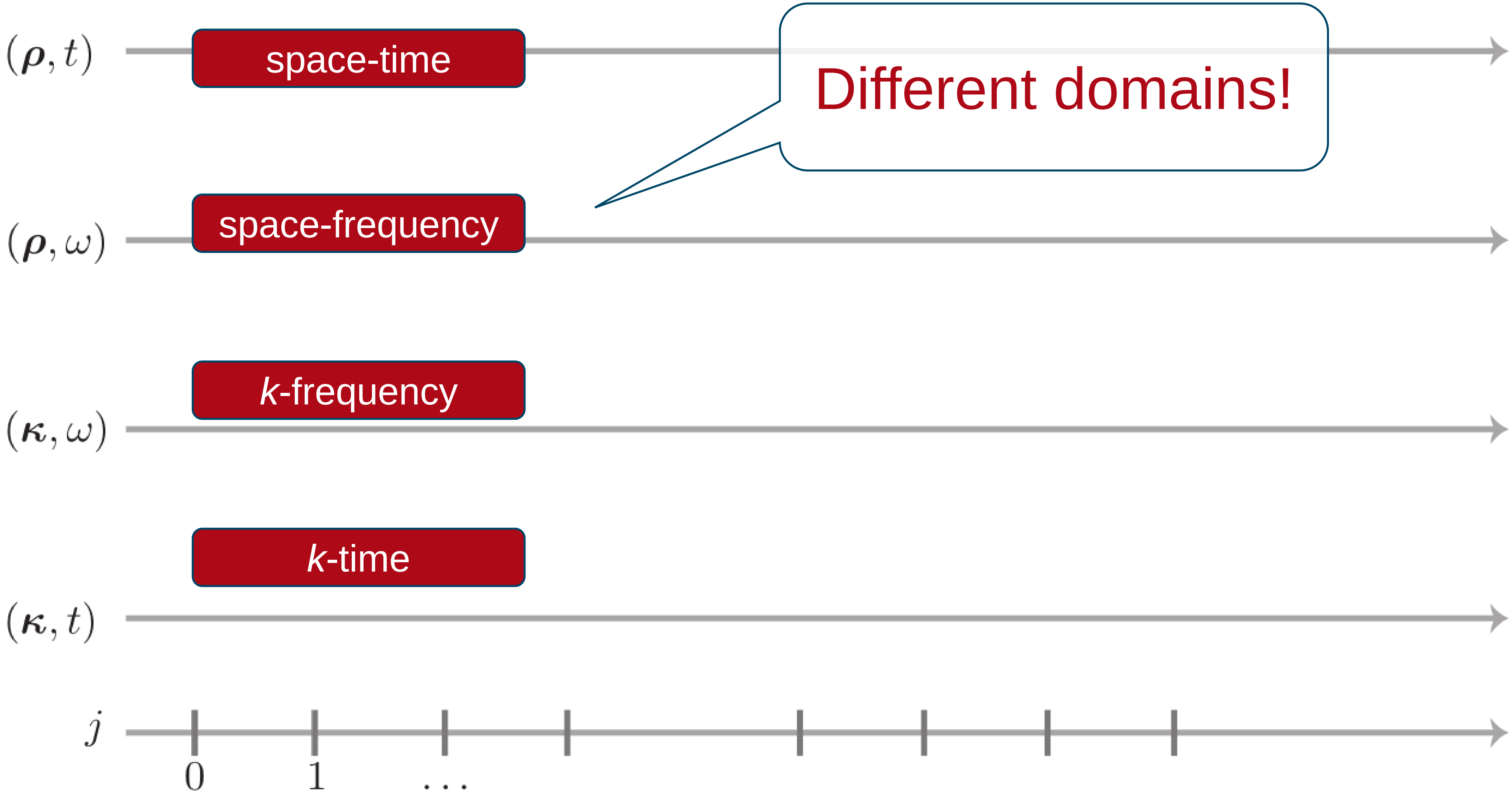
- In the k-domain the propagation reduces to a simple product → linear in N.
- But two Fast Fourier Transforms are required (FFT & FFT^{-1}), which each requires a sampling effort of N log(N).

$2 \cdot N \log(N) + N$ operation

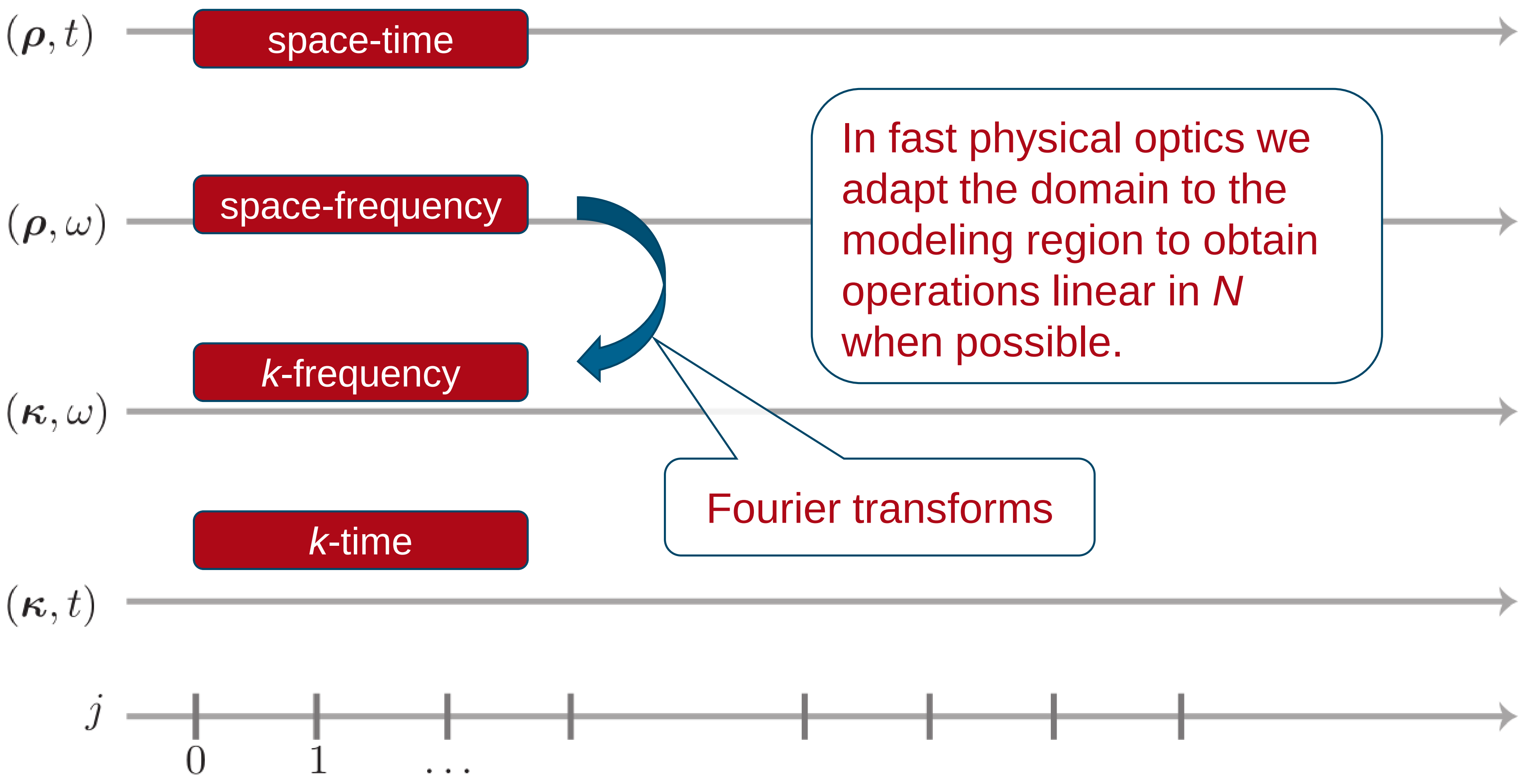
can be extended to propagation between tilted planes



Field Tracing in Different Domains



Field Tracing in Different Domains



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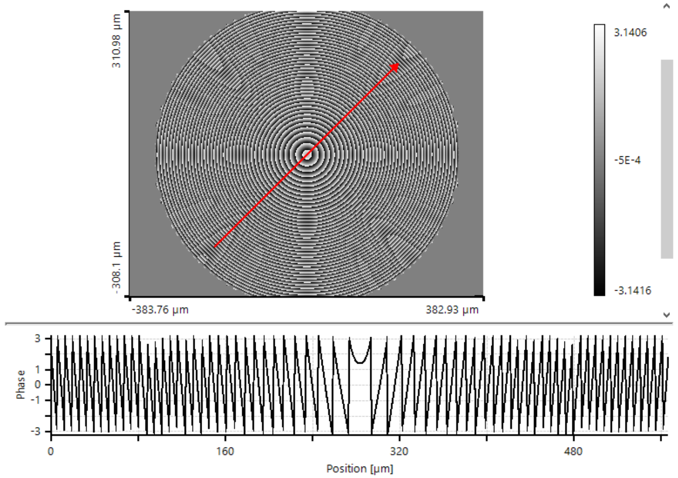
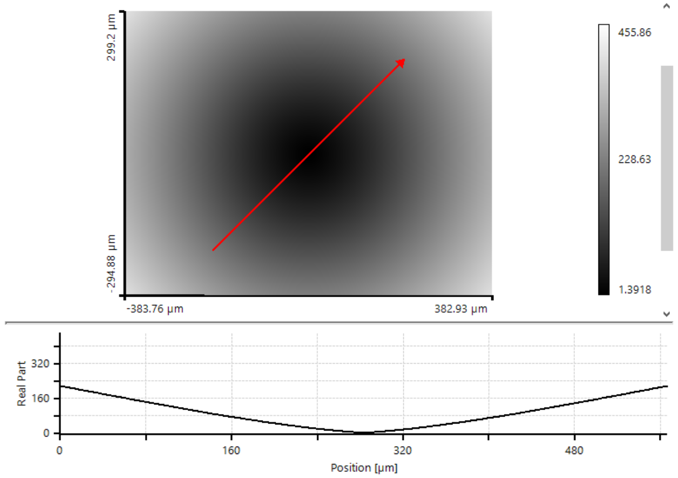
What does it mean for the Fourier transform?

Explanation for Numerical Effort

- In physical optics' algorithms a complex field representation is advantegeous (e.g. for the Fourier transform calculations). Then field components are represented by their amplitude and phase values (A and φ) in the form $V = A \cdot e^{i\varphi}$. Thus phase modulations are handled in a **2π modulo mode**.
→ To fulfill the Nyquist-Shannon sampling theorem each phase deviation of 2π radians requires at least 2-3 data points in 1D regard.
- Below the **2π modulo vs the unwraped phase representation** is shown. The unwraped version requires view data points for sufficient sampling together with a suitable interpolation.





Representation of Fields by Separately Handled Phase Factors

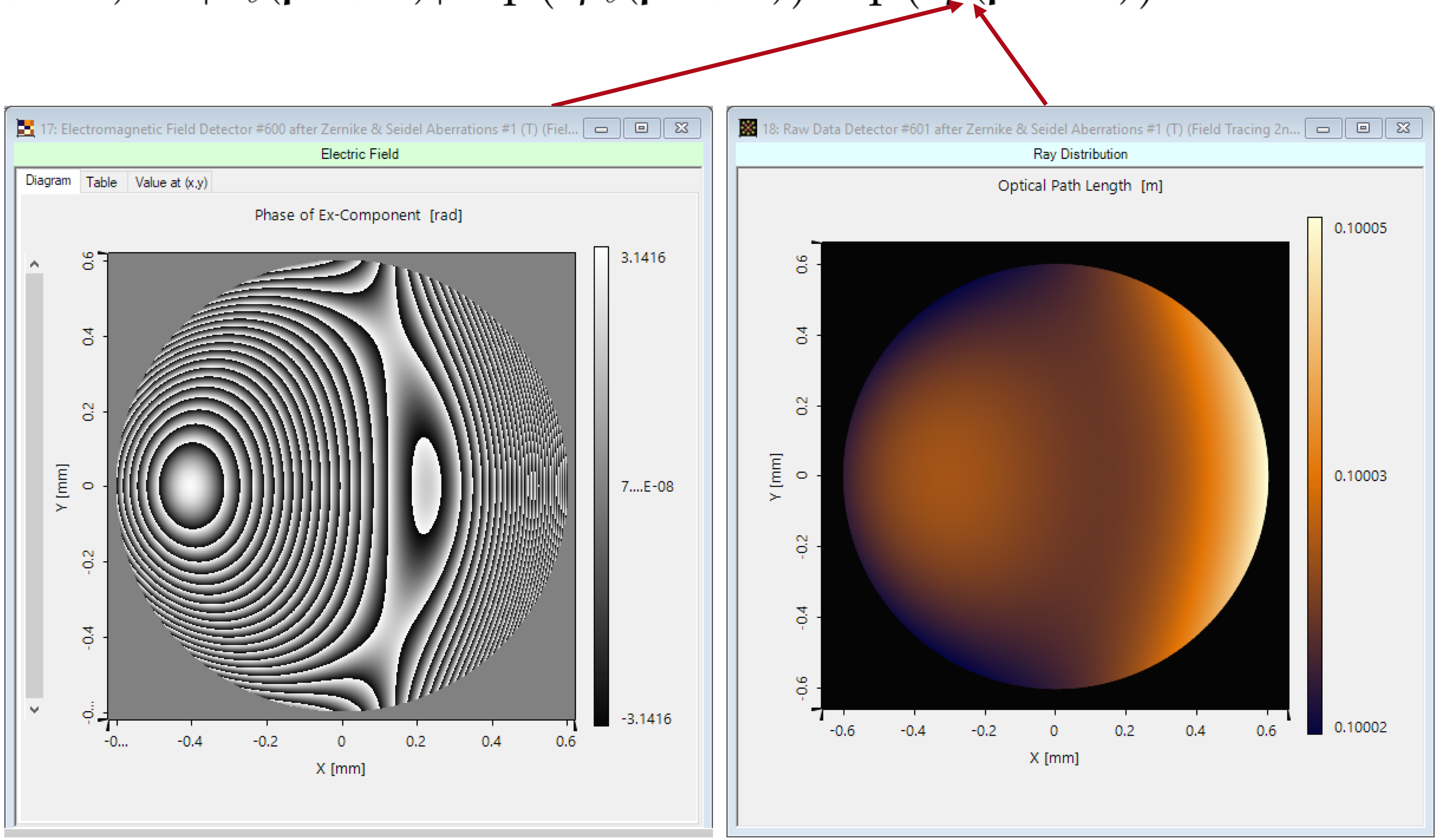
$$V_\ell(\boldsymbol{\rho}, z, \omega) = |V_\ell(\boldsymbol{\rho}, z, \omega)| \exp\big(\mathrm{i}\varphi_\ell(\boldsymbol{\rho}, z, \omega)\big) \exp\big(\mathrm{i}\psi(\boldsymbol{\rho}, z, \omega)\big)$$

arbitrary amplitude and diffractive phase factor

geometric/wavefront phase factor

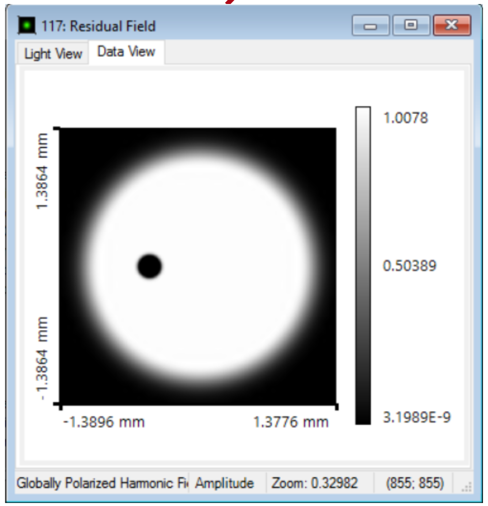
Example: Phase Aberrations Are Handled in Geometric Factor

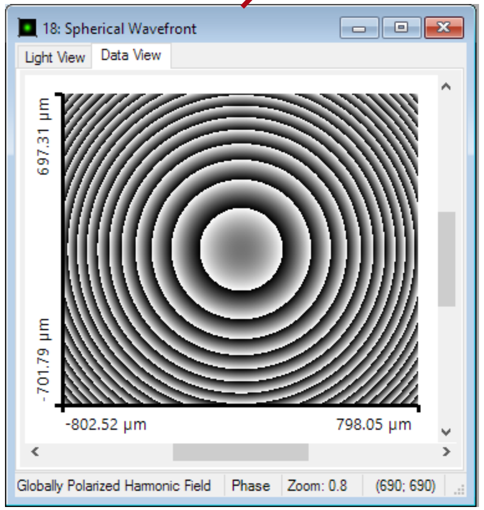
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)|\exp\big(\mathrm{i}\varphi_\ell(\boldsymbol{\rho},z,\omega)\big)\exp\big(\mathrm{i}\psi(\boldsymbol{\rho},z,\omega)\big)$$



Example: Spherical Field with Stop

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



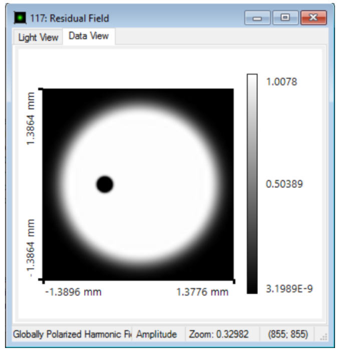


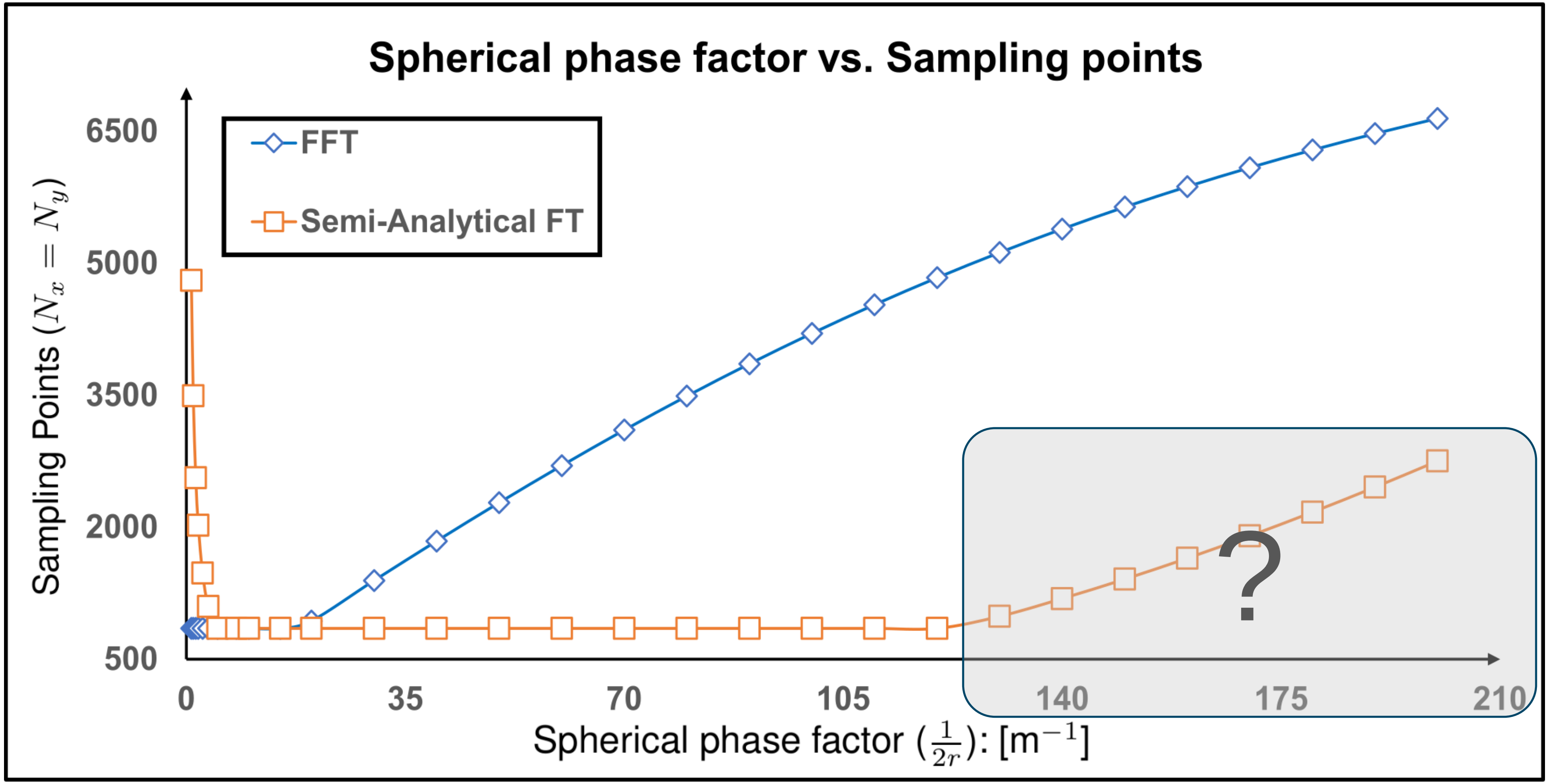
storing spherical phase data in complex representation requires fine sampling

→ finding efficient ways to handle/store wavefront phase factors

- by analytical spherical phase factor (classic field tracing option; not always possible)
- by extracting a quadratic phase factor (semi analytical approach)
- by mapping concept (geometrical approach)

Needed Sampling of Spherical Field with Stop





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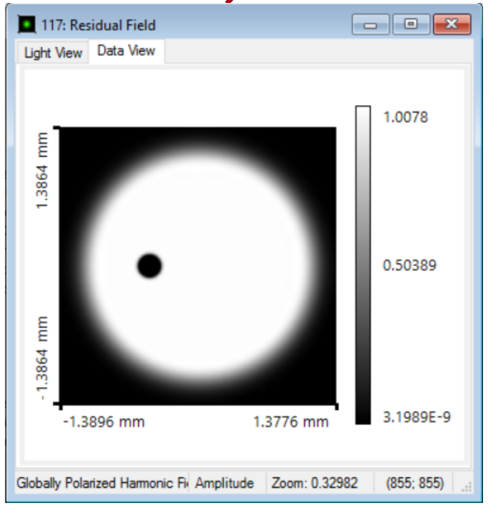
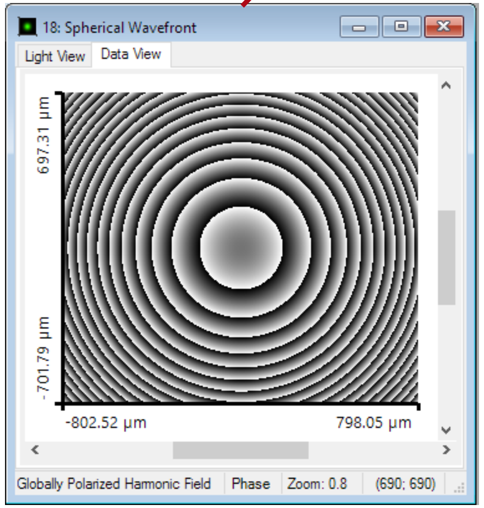
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)| \exp\left(i\varphi_\ell(\boldsymbol{\rho},z,\omega)\right) \exp\left(i\psi(\boldsymbol{\rho},z,\omega)\right)$$





→ **finding efficient ways to hanlde/store wavefront phase factors**

- by analytical spherical phase factor (classic field tracing option; not always possible)
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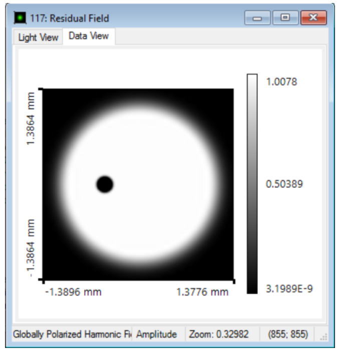
Results of Fourier Transform



initial field with spherical phase → FT

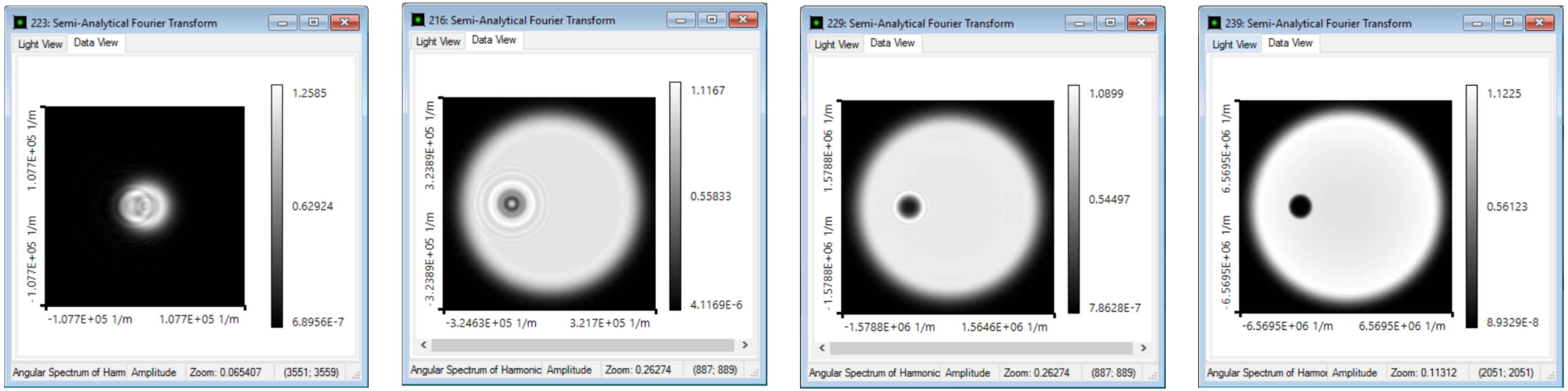
$$V_\ell(\boldsymbol{\rho},z,\omega) = |V_\ell(\boldsymbol{\rho},z,\omega)|\exp\left(i\varphi_\ell(\boldsymbol{\rho},z,\omega)\right)\exp\left(i\psi(\boldsymbol{\rho},z,\omega)\right)$$

spherical wavefront

spherical wavefront with decreasing radius of curvature; increasing NA

weak wavefront factor → strong wavefront factor

Fourier transform results



Types of Fourier Transforms for Field without Diffractive Factor

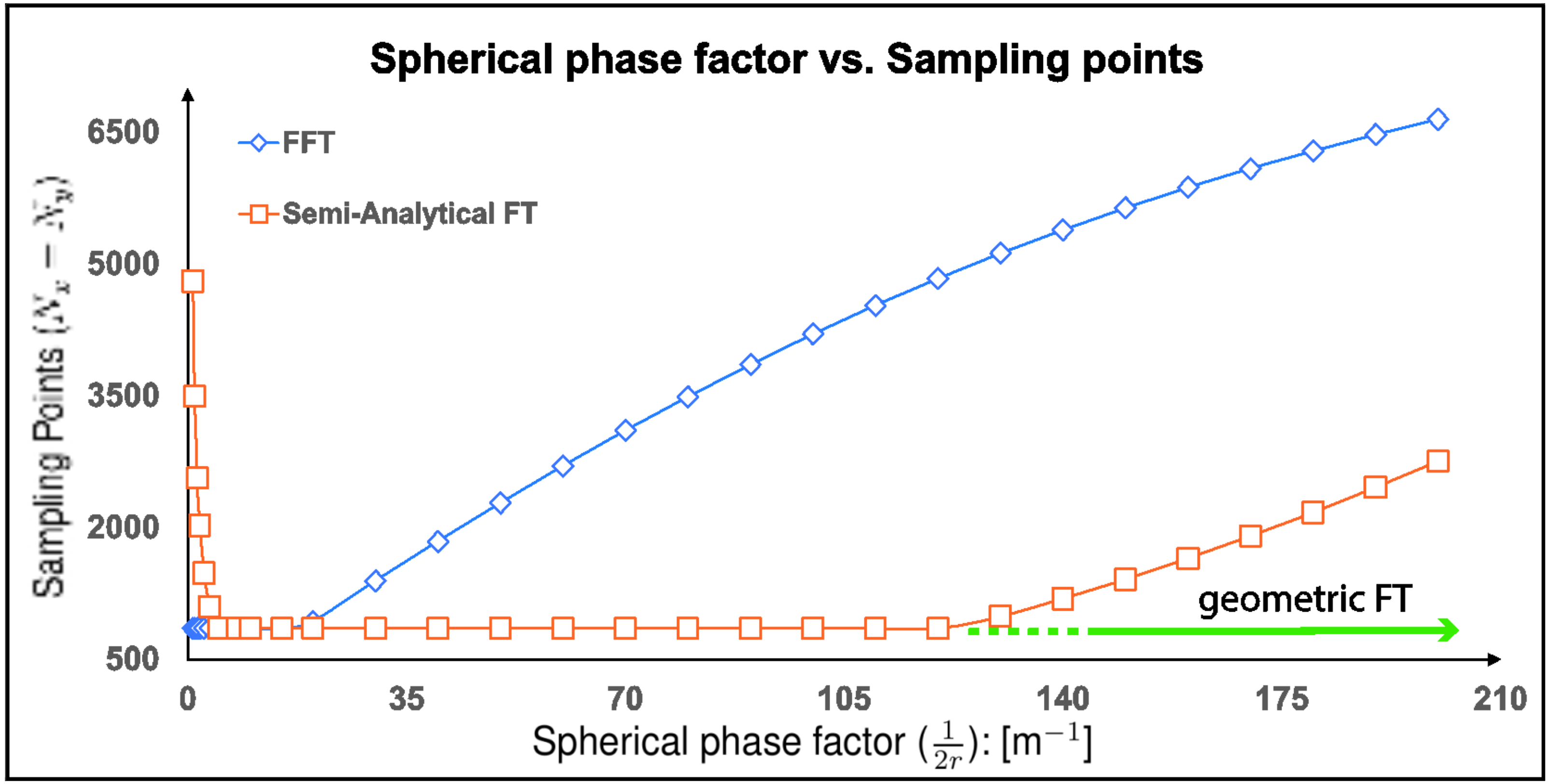
Regular FFT: Requires sampling of full phase information according to Nyquist- Shannon theorem (number of sampling points $N^{\mathrm{Nyq}}(\psi)$).
→ suited for weak wavefront phase factors only.

Semi-Analytical FFT: Can analytically handle a wavefront phase represented by $\psi^{\mathrm{q}}(x, y) = A + \boldsymbol{B} \cdot (x; y) + C \cdot x \cdot y + \boldsymbol{D} \cdot (x^2; y^2)$, thus up to a quadratic phase factor. Only the remaining/residual phase differences need to be sampled (number of sampling points $N^{\mathrm{Nyq}}(\psi^{\mathrm{res}})$).
→ suited for weak to moderate wavefront phase factors.

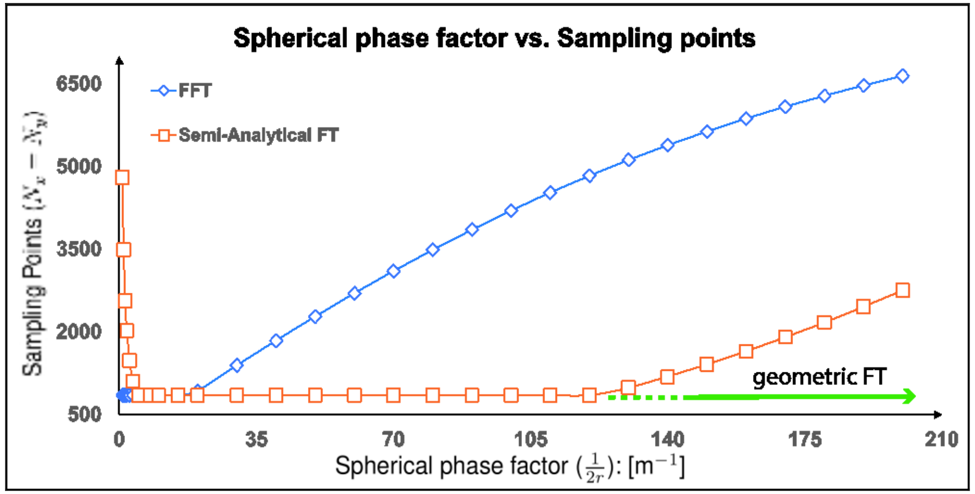
Geometric FT: wavefront can be sampled in its unwrapped real (non-complex) data representation $N(\psi)$.
→ suited for fields with strong wavefront phase factors.

➡ Minimization of *N* enables fast physical optics!

Triad of Fourier Transform Techniques



Triad of Fourier Transform Techniques



- Techniques have been implemented in 2nd generation field tracing engine in VirtualLab Fusion.
- Algorithm is based on a hybrid sampling: combination of equidistant sampling, non-equidistant sampling, analytical expressions.
- Automatic selection of techniques per operation.

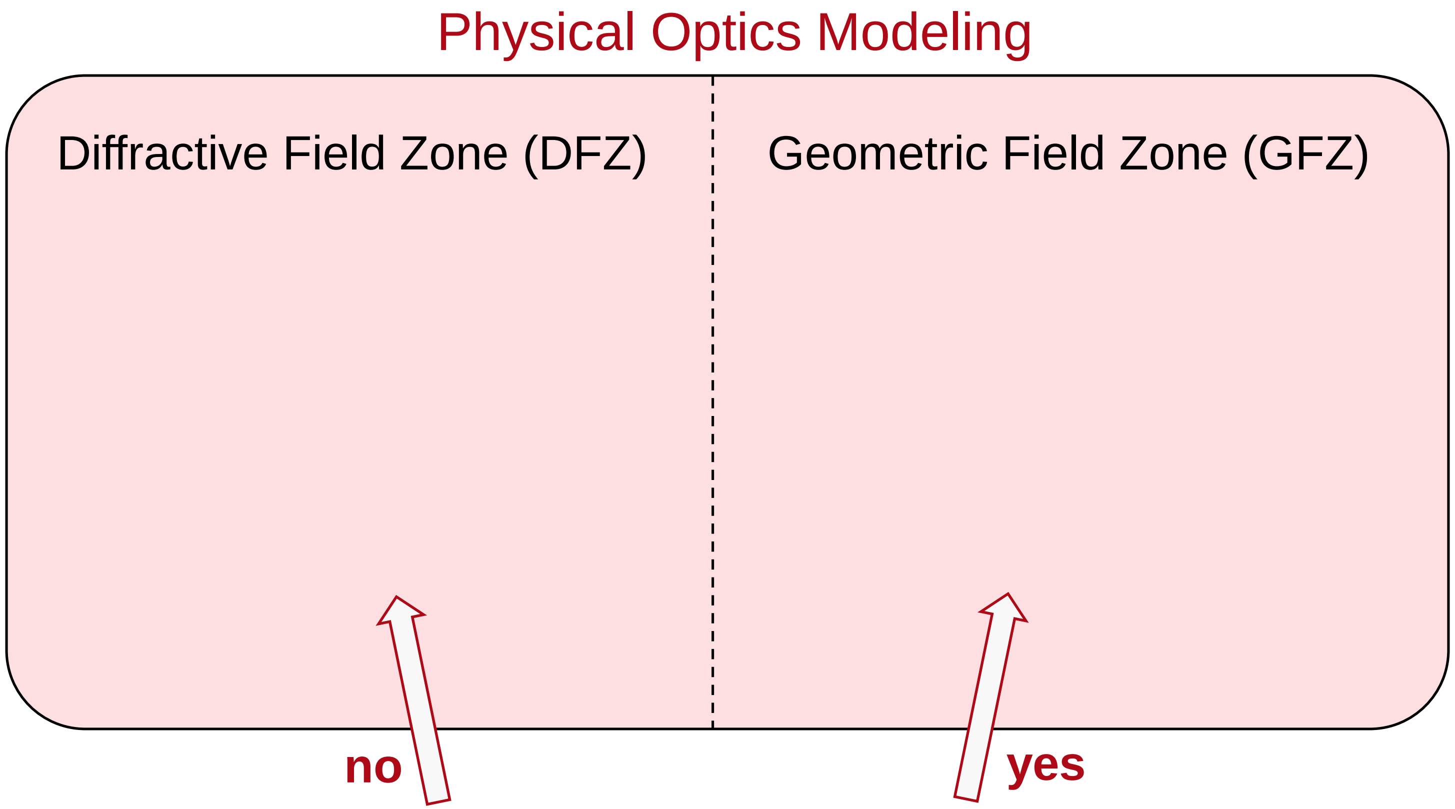
Fast Physical Optics Modeling Zones

Physical Optics Modeling

Diffractive Field Zone (DFZ)

Geometric Field Zone (GFZ)

Fast Physical Optics Modeling Zones



Is the geometric Fourier transform
accurate enough for application?

Fast Physical Optics Modeling Zones

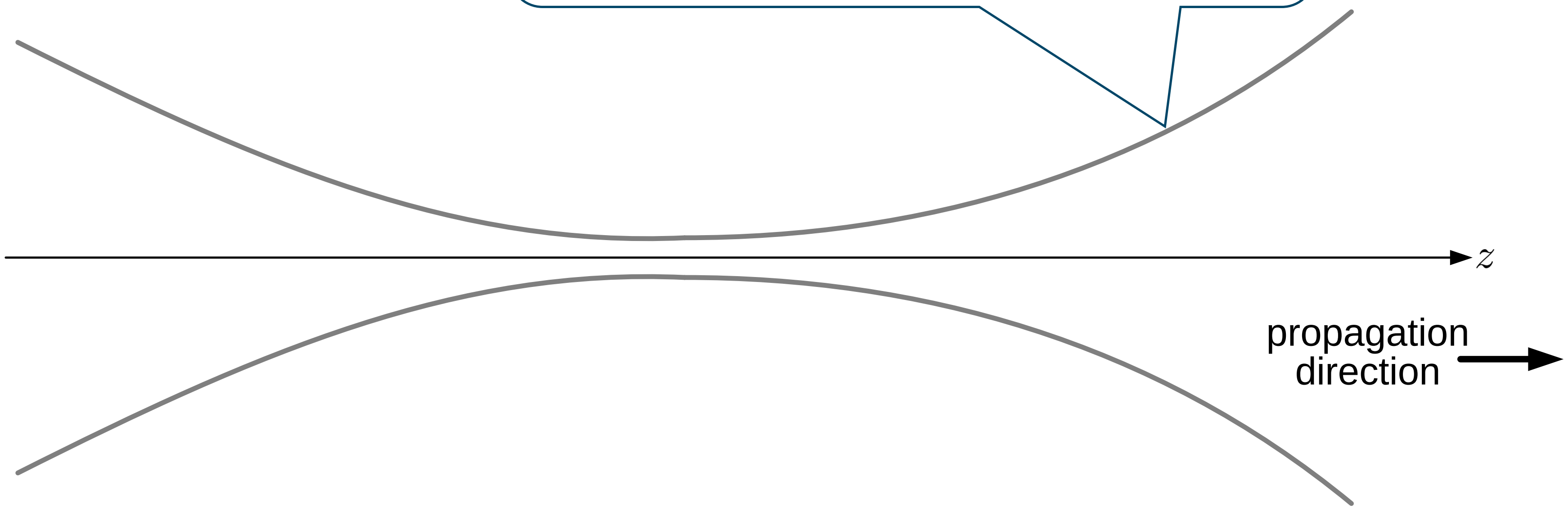
Physical Optics Modeling

Diffractive Field Zone (DFZ)	Geometric Field Zone (GFZ)
modeling governed by $N^{\mathrm{Nyq}}(\psi^{\mathrm{res}})$	modeling governed by $N(\psi)$
Semi-analytical FFT	Geometric FT

$$N(\psi) \ll N^{\mathrm{Nyq}}(\psi^{\mathrm{res}}) \ll N^{\mathrm{Nyq}}(\psi)$$

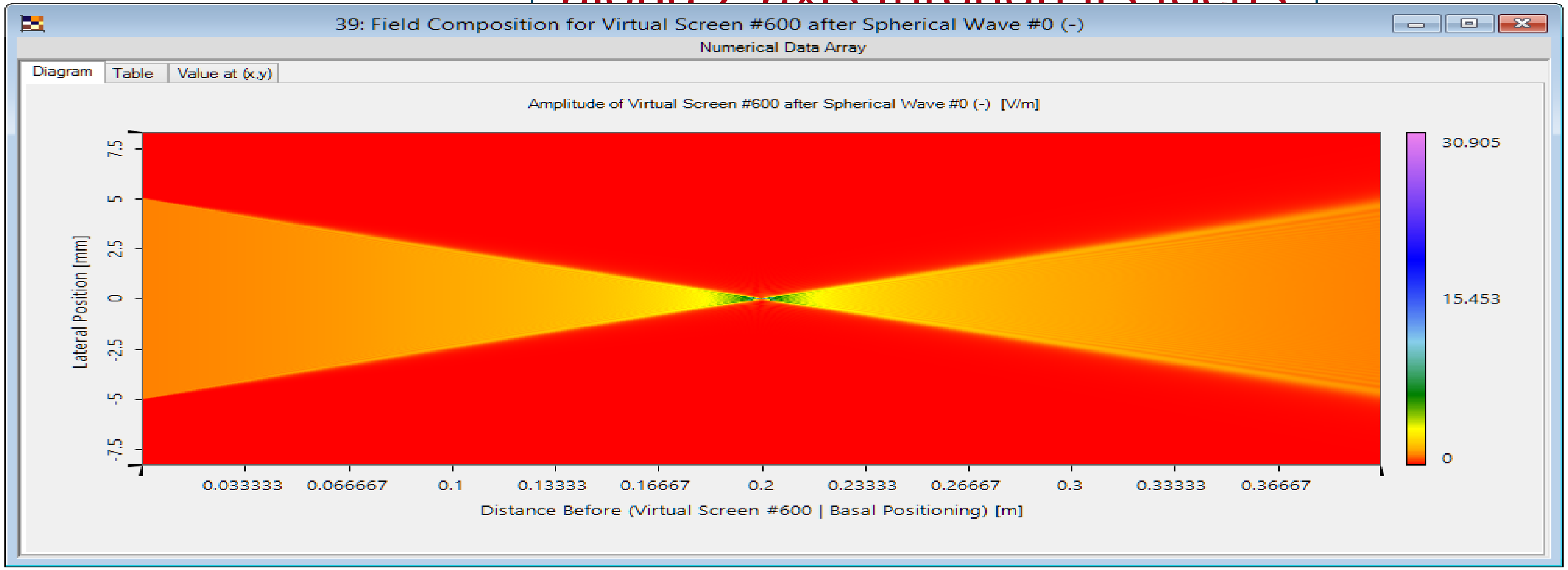
Field Zones in Fast Physical Optics

Envelope of propagating field along z-axis through its focus

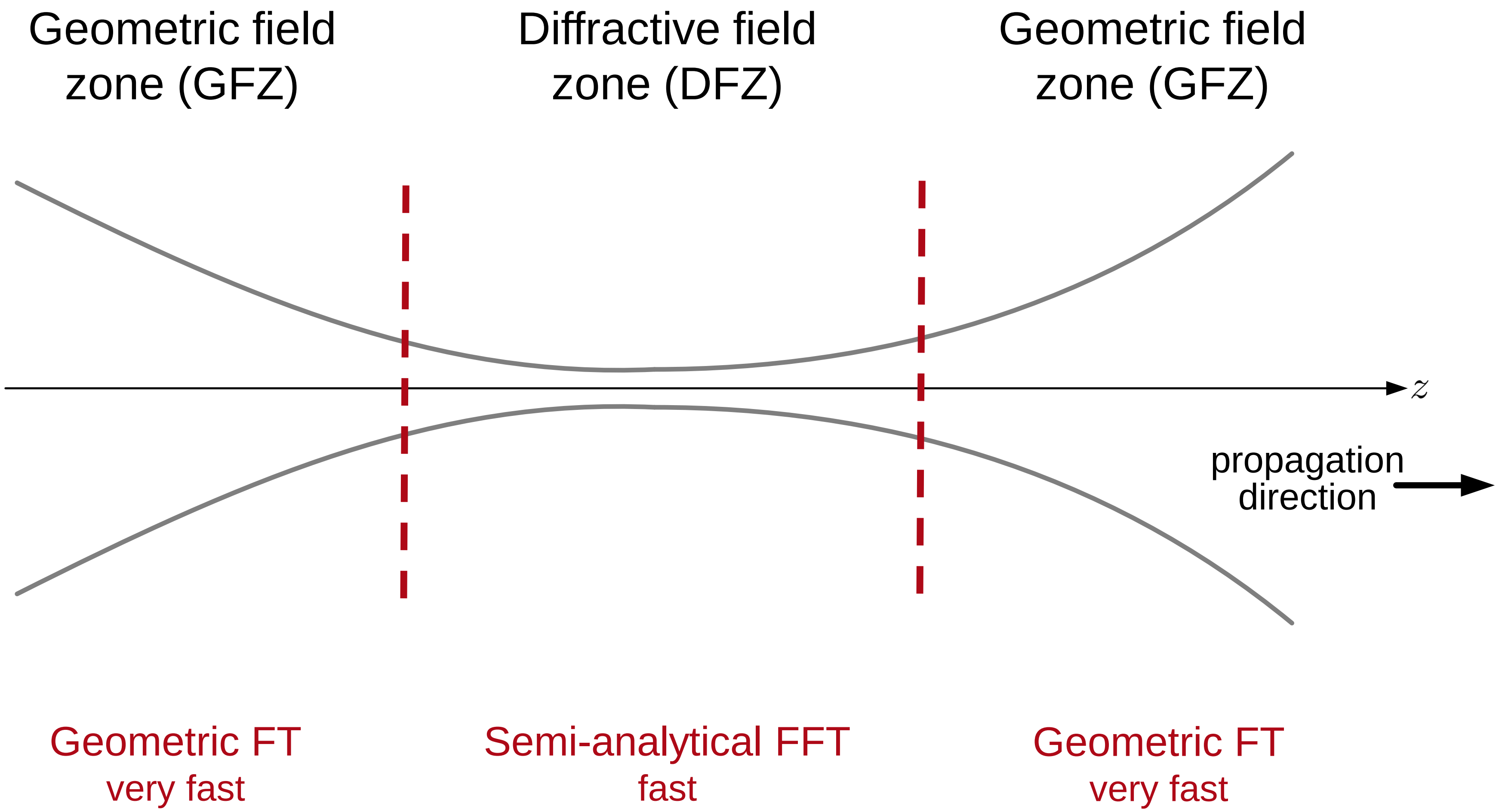


Field Zones in Fast Physical Optics

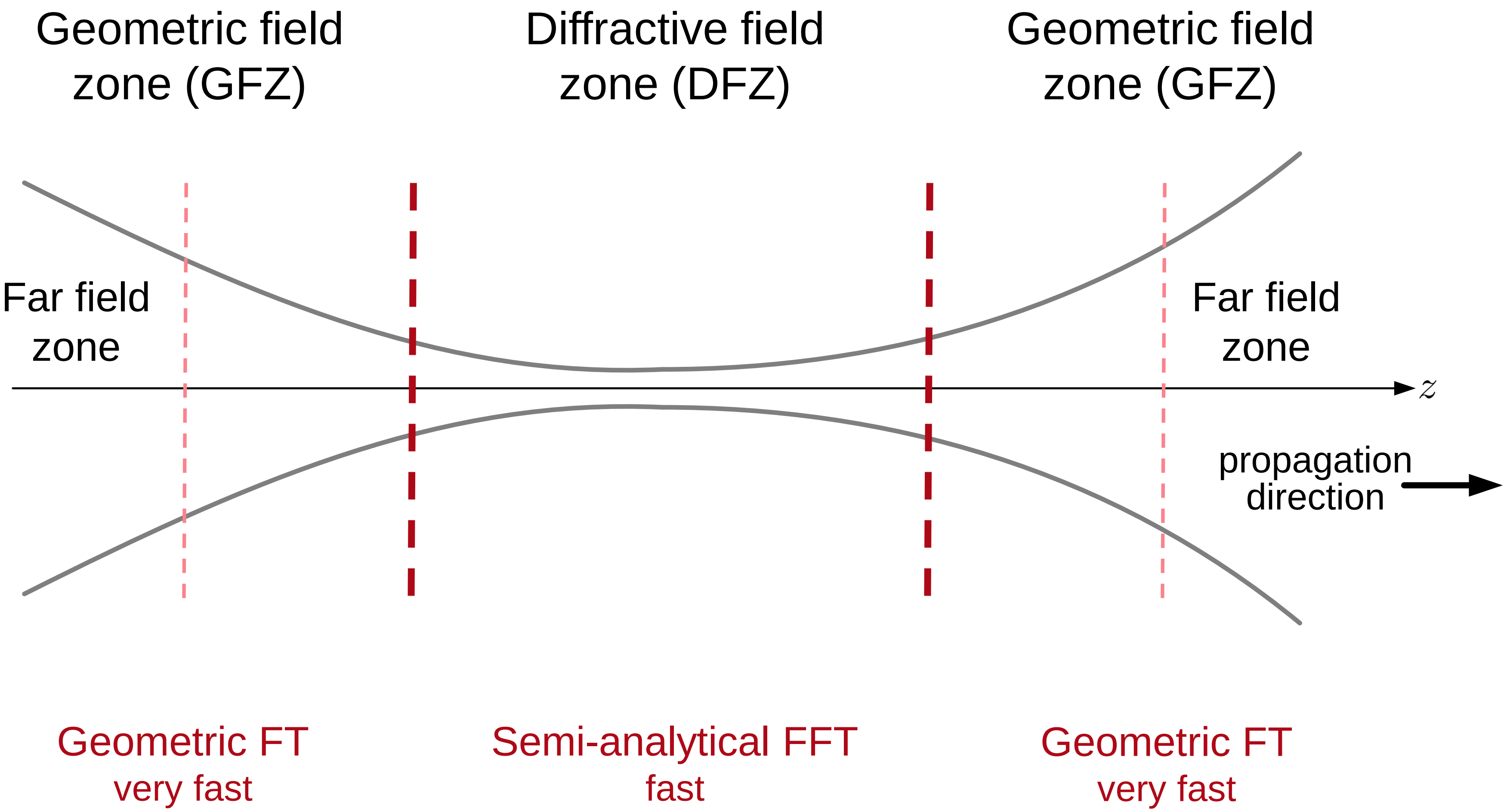
Envelope of propagating field along z-axis through its focus



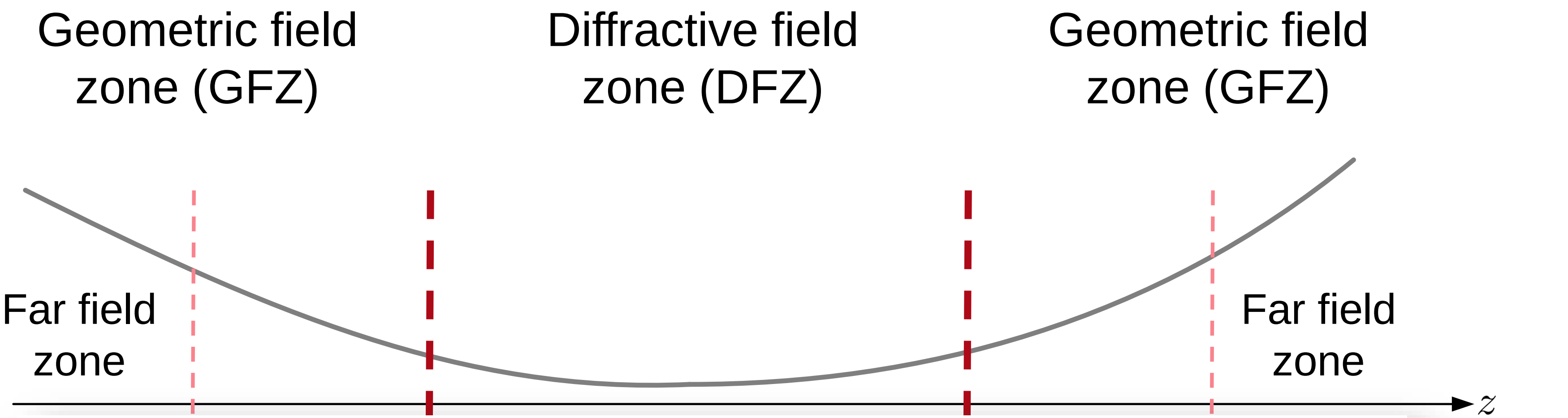
Field Zones in Fast Physical Optics



Field Zones in Fast Physical Optics



Field Zones in Fast Physical Optics



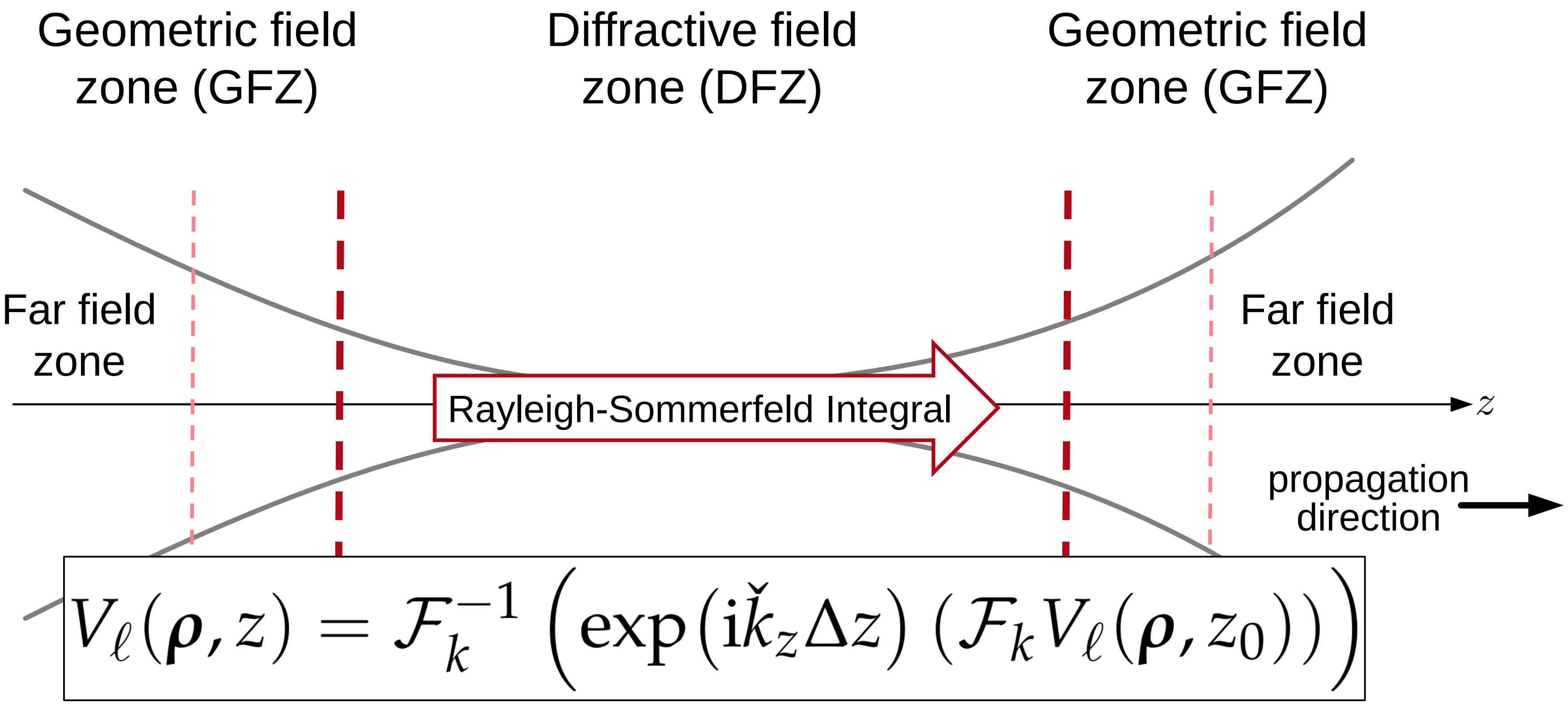
Zone	Geometric FT	Phase ψ
diffractive zone	No	—
geometric zone	Yes	general
far zone	Yes	spherical

Geometric FT
very fast

Semi-analytical FFT
fast

Geometric FT
very fast

Example: Free-Space Propagation



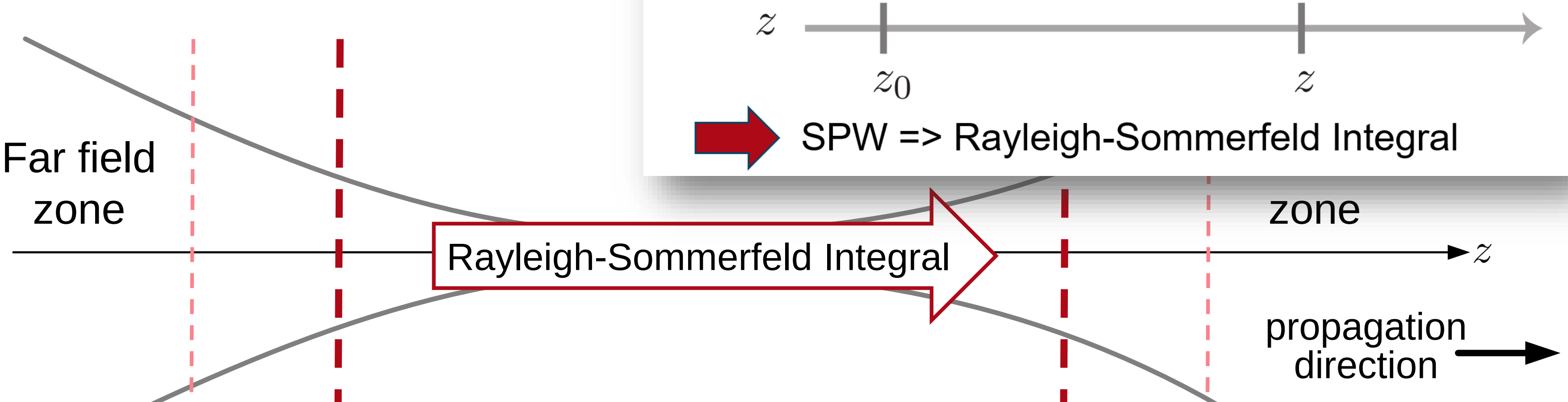
$$V_\ell(\boldsymbol{\rho}, z) = \mathcal{F}_k^{-1}\left(\exp(\mathrm{i}\check{k}_z \Delta z)\, (\mathcal{F}_k V_\ell(\boldsymbol{\rho}, z_0))\right)$$

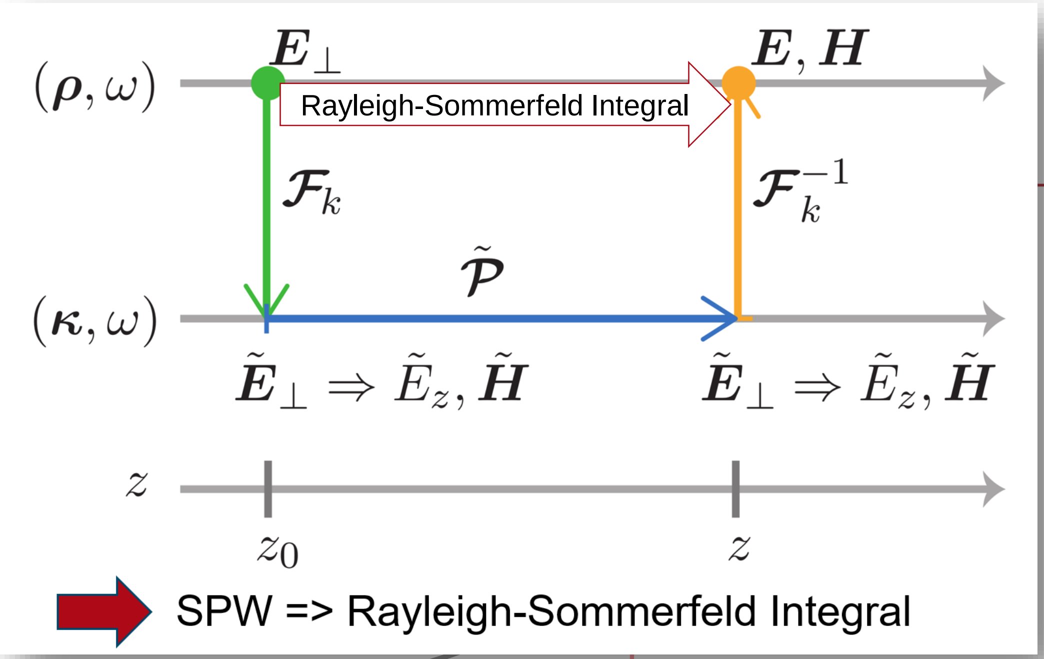
Geometric FT
very fast

Semi-analytical FFT
fast

Geometric FT
very fast

Example: Free-Space Propag





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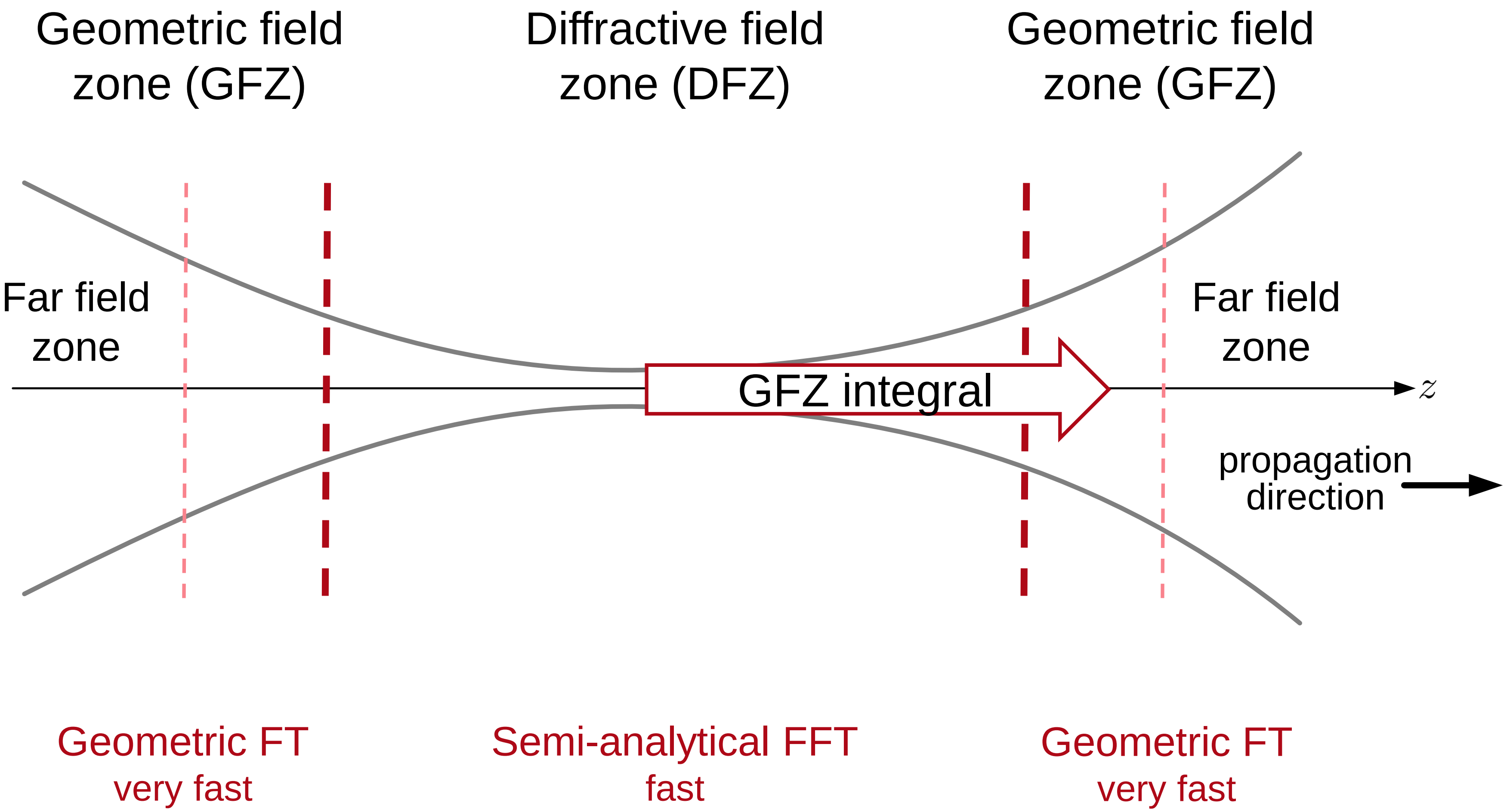
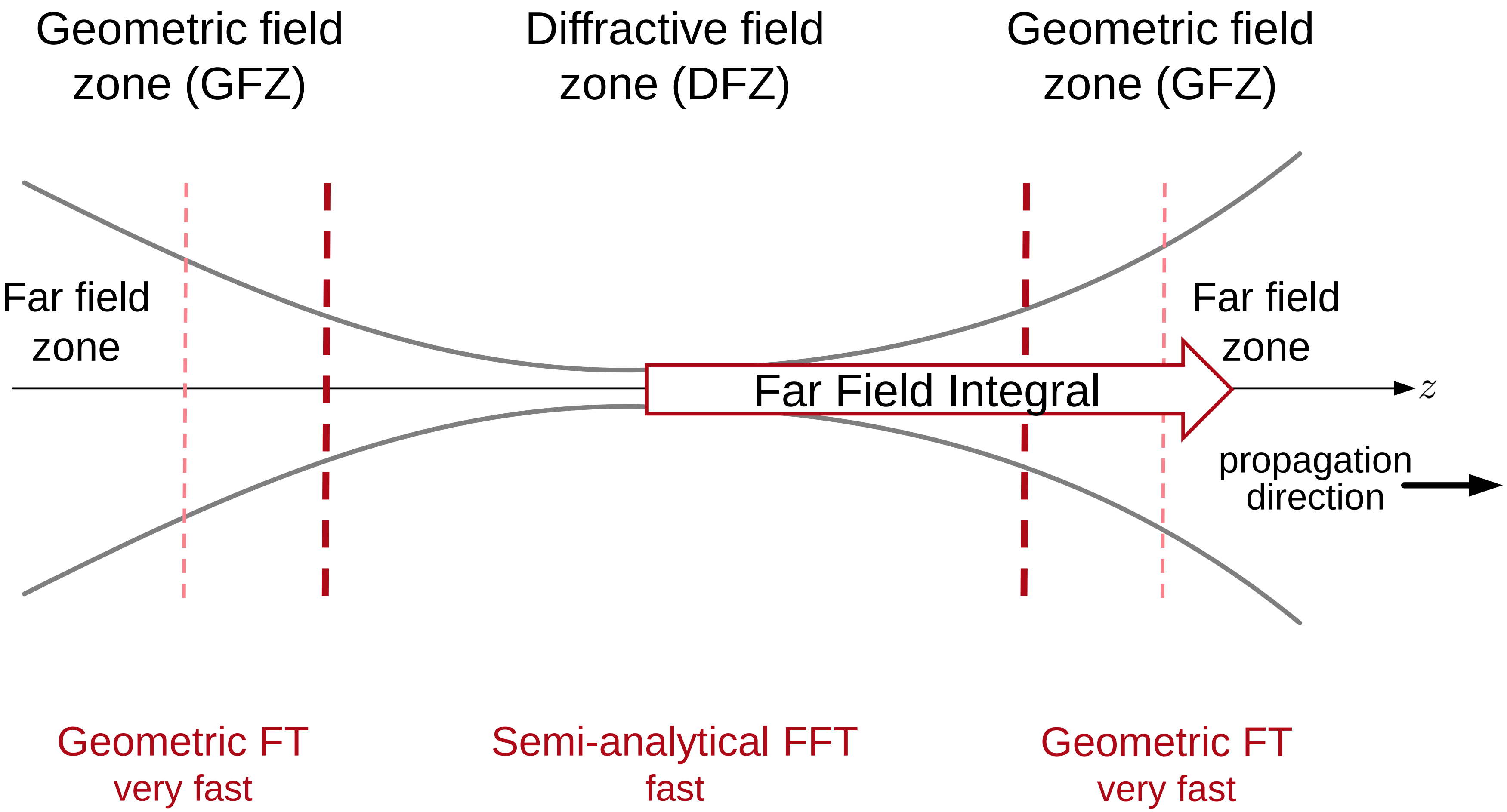
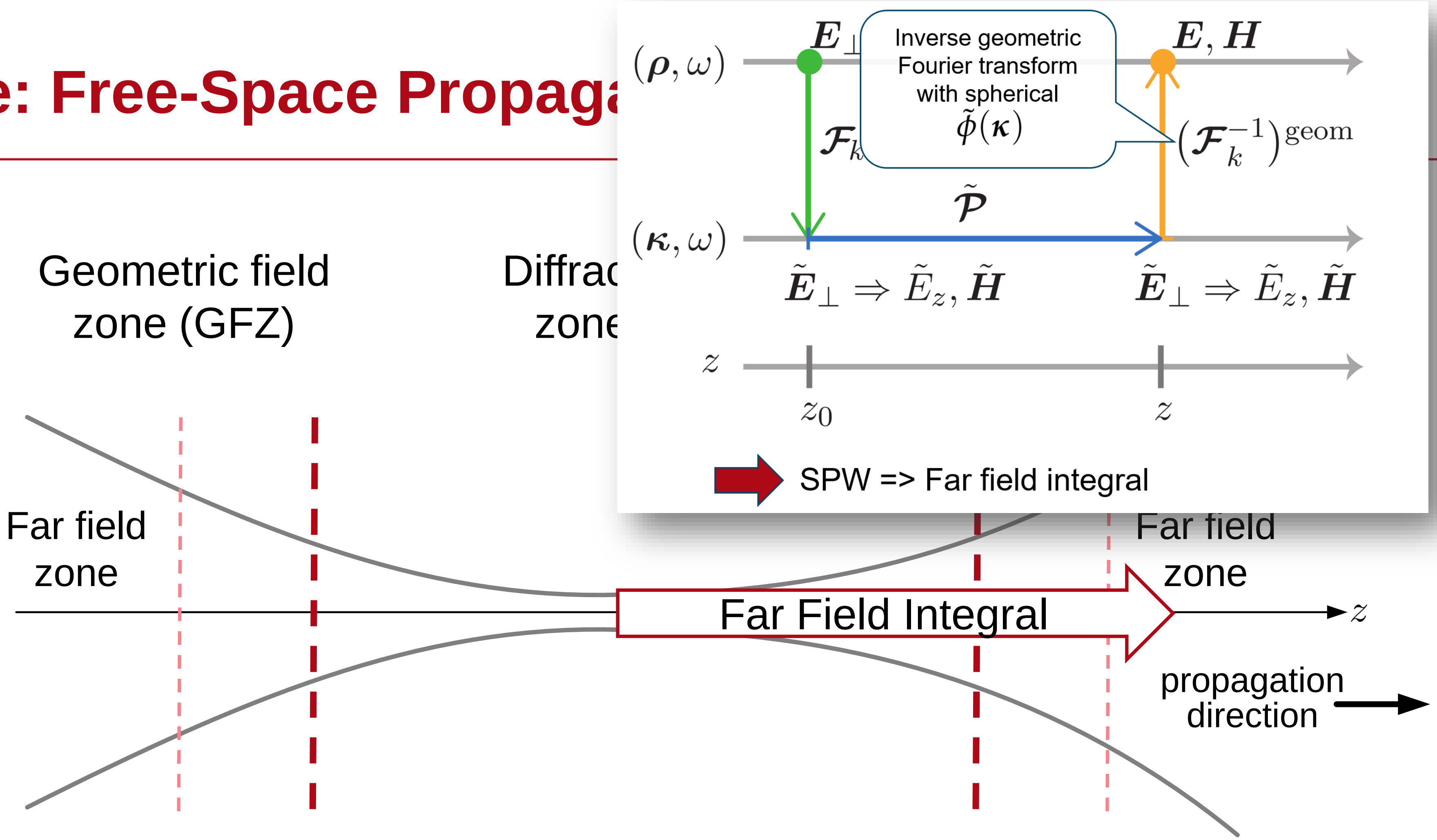


Example: Free-Space Propagation



Example: Free-Space Propaga

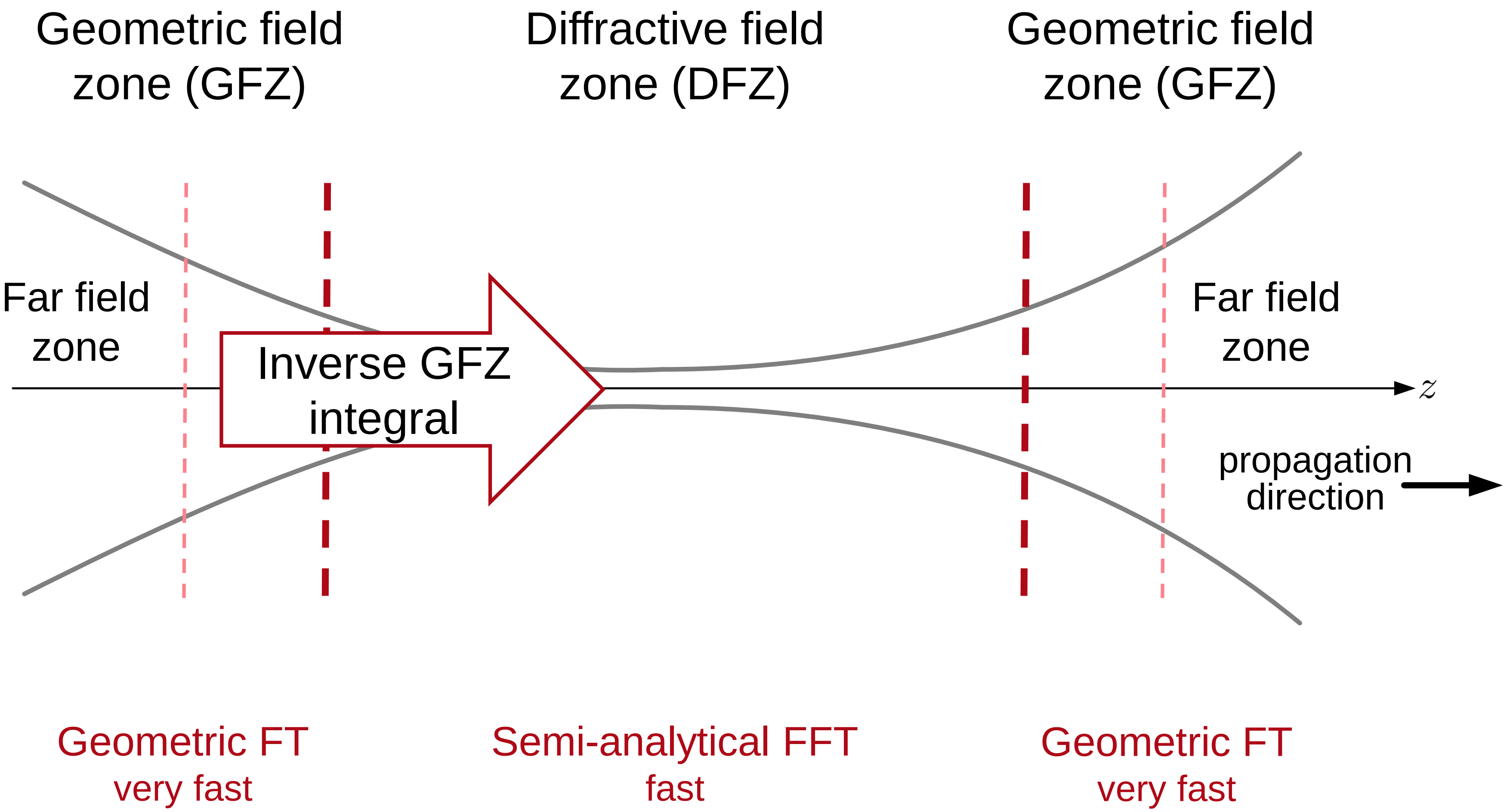


Geometric FT
very fast

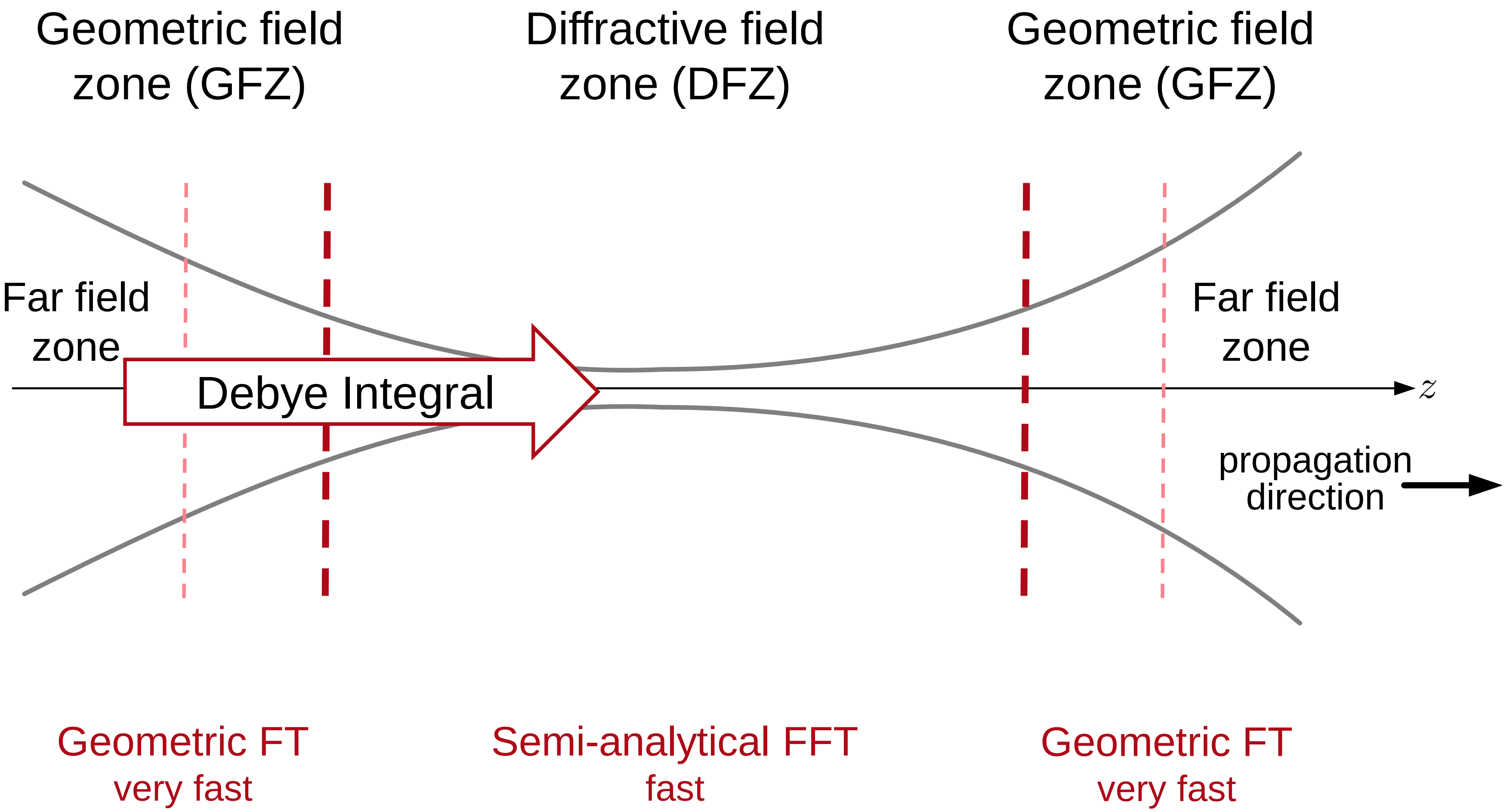
Semi-analytical FFT
fast

Geometric FT
very fast

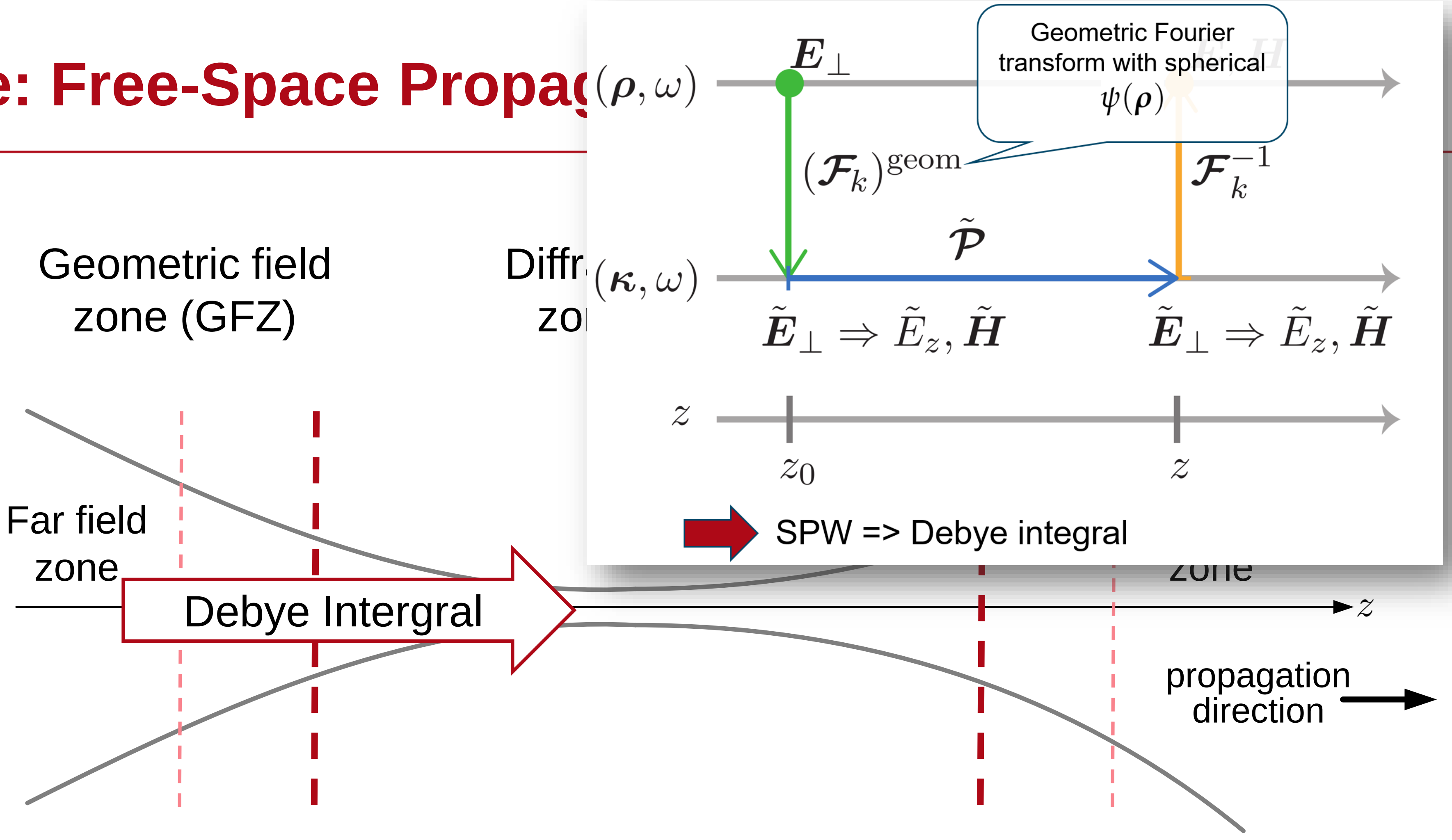
Example: Free-Space Propagation



Example: Free-Space Propagation



Example: Free-Space Propag



Geometric FT
very fast

Semi-analytical FFT
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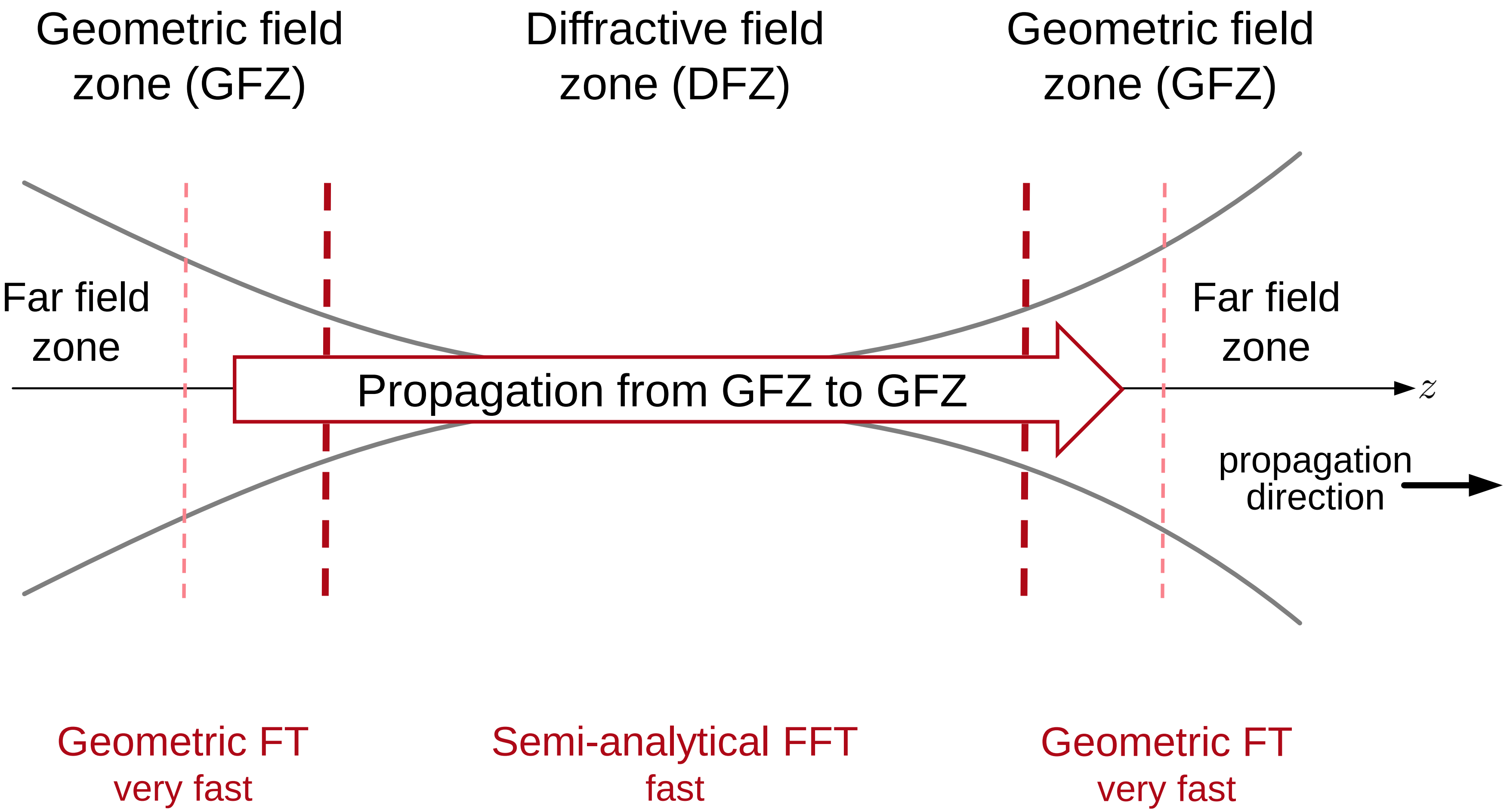
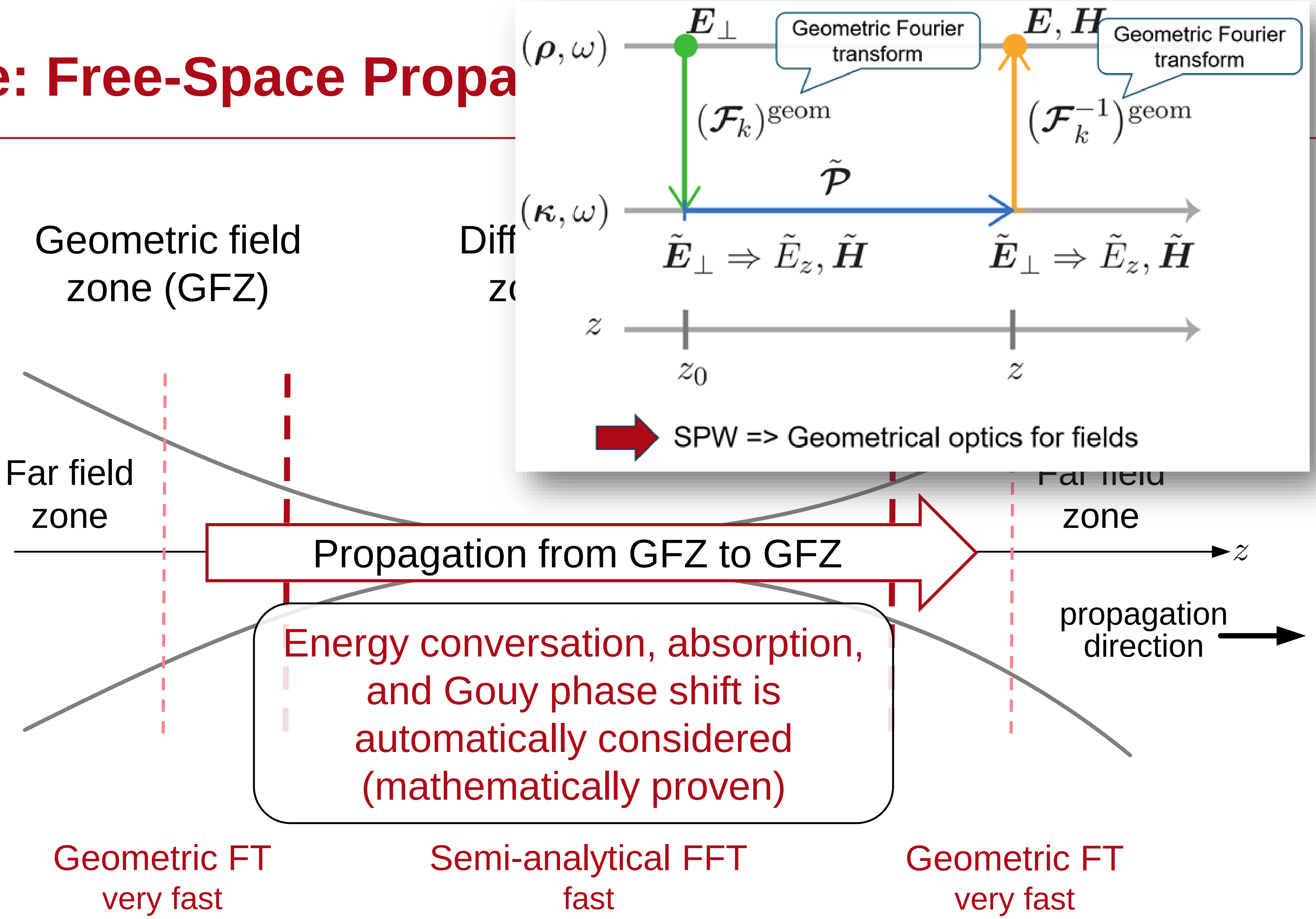
very fast

Example: Free-Space Propagation



Example: Free-Space Propa



What's Coming Next #3 ...

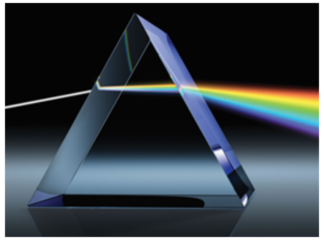
- propagation techniques with examples
- sources (demonstrational examples)
- detectors (some impressions)

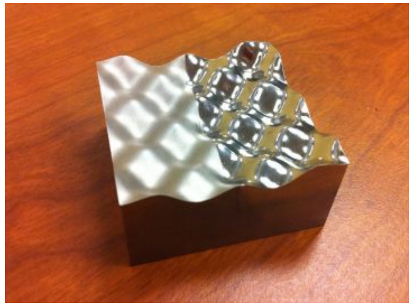
Information about Propagation Techniques

Different Specialized Solvers of Maxwell's Equations

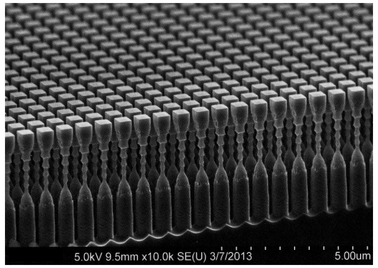
Optical Components

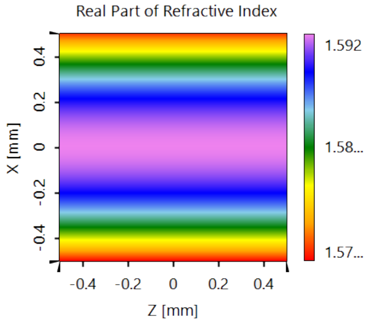
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

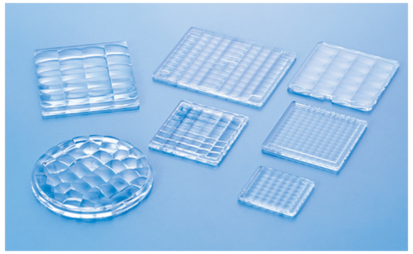




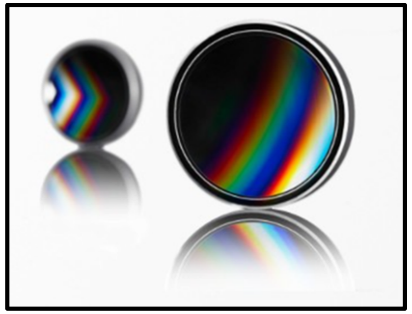
[1] IMS-Mechatronics Lab





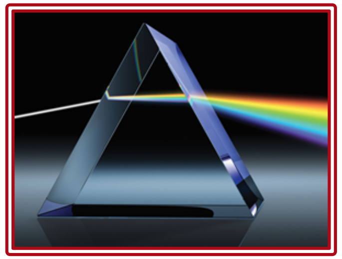


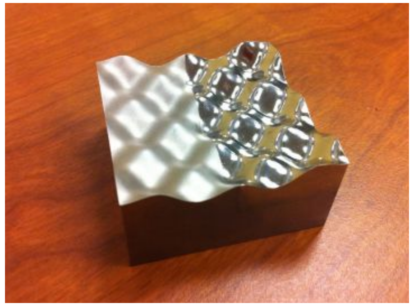
[2] ISUZU GLASS



Optical Components

- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media





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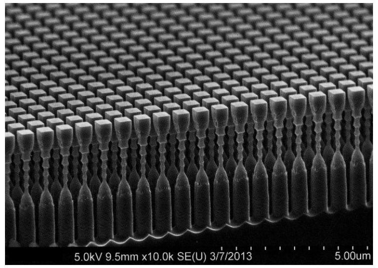

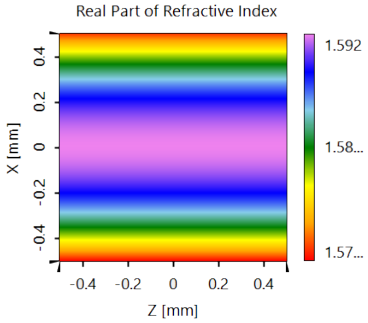

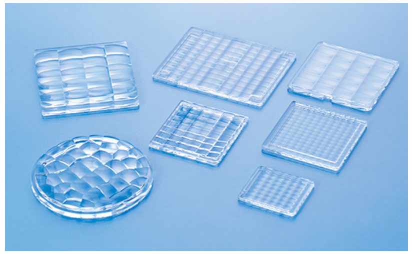

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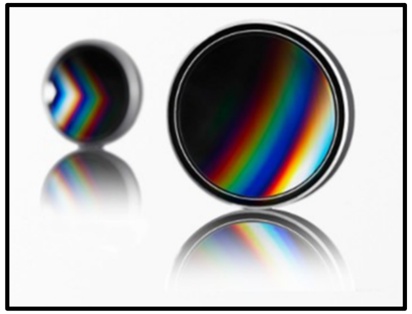
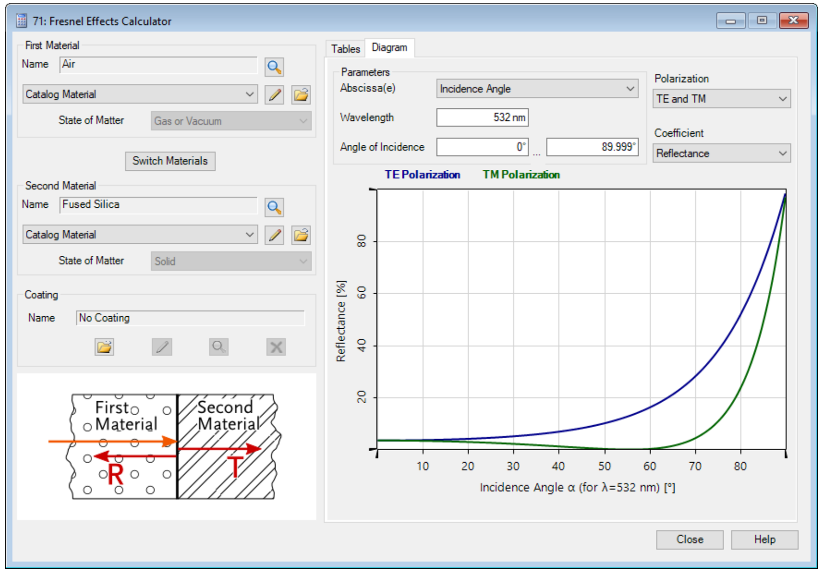
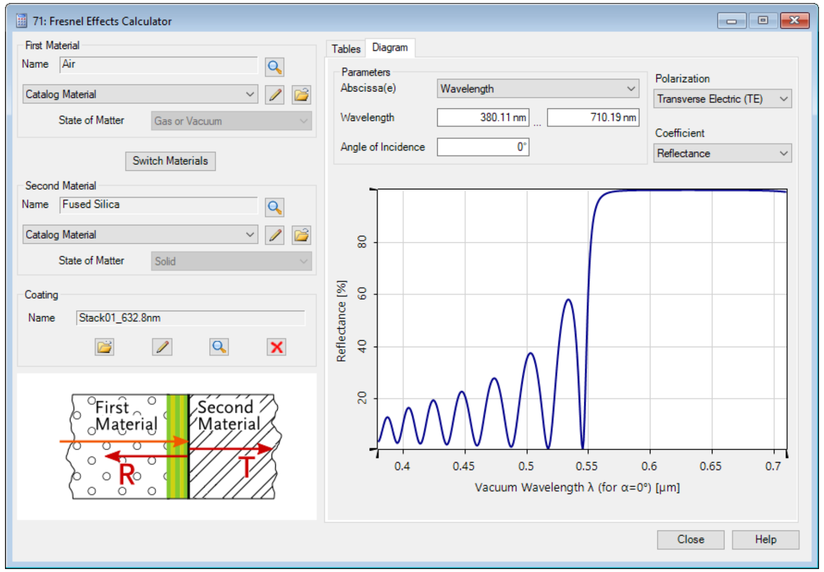


Fresnel Effects

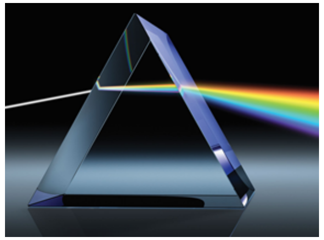
- Fresnel effects calculator with different diagram, and possibilities to include coatings

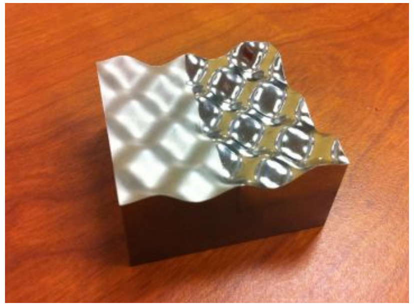




Optical Components

- elements with planar interfaces
- **lenses**
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media





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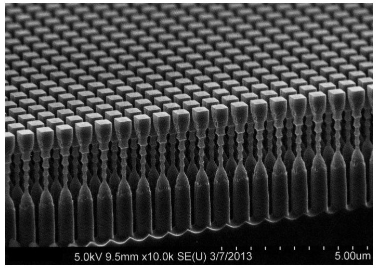

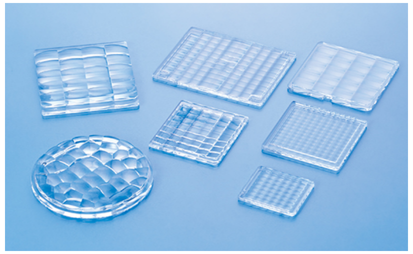

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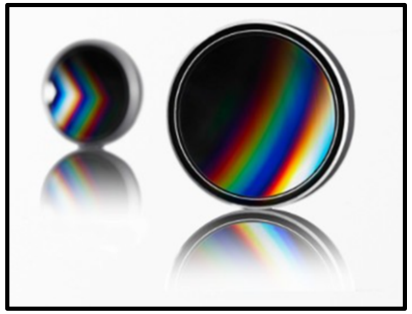
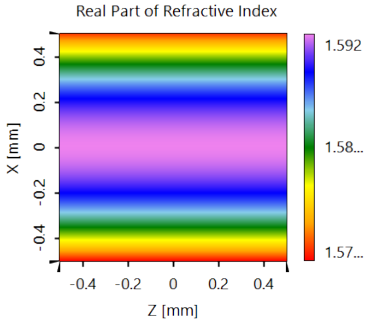




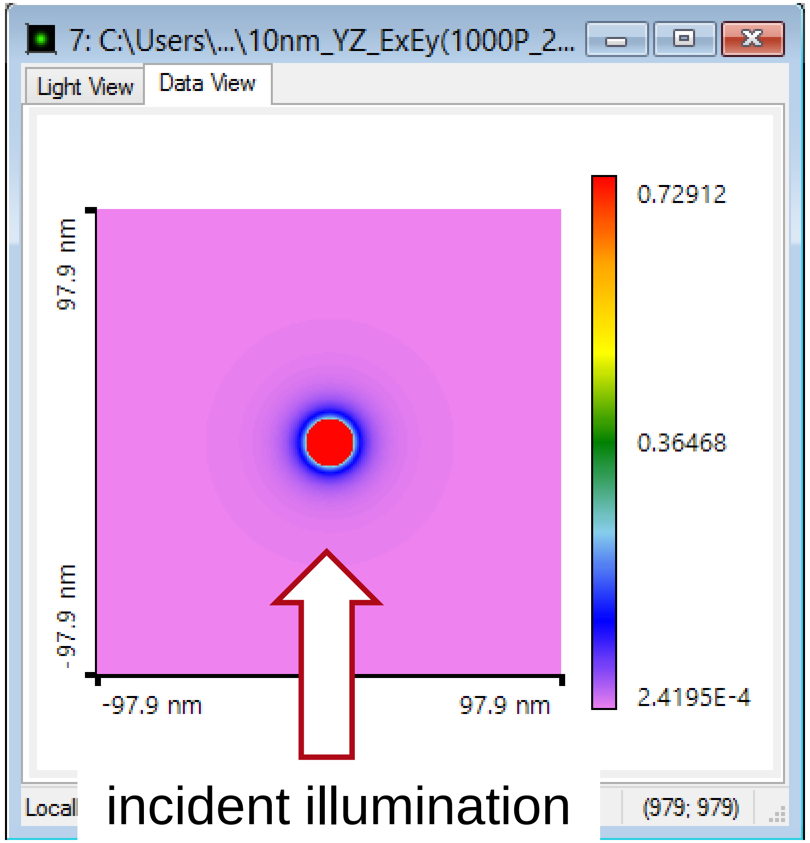
Extreme Case of a Lens

Investigation of a Ball Lens of Different Size

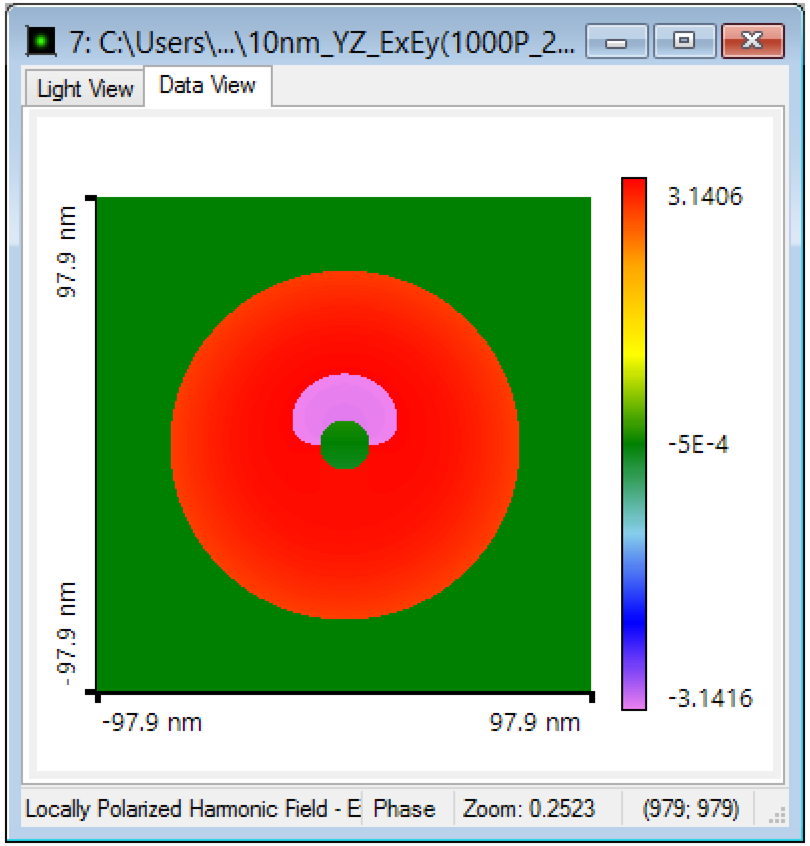
→ Mie Scattering

Radius = 10nm

Ex-amplitude

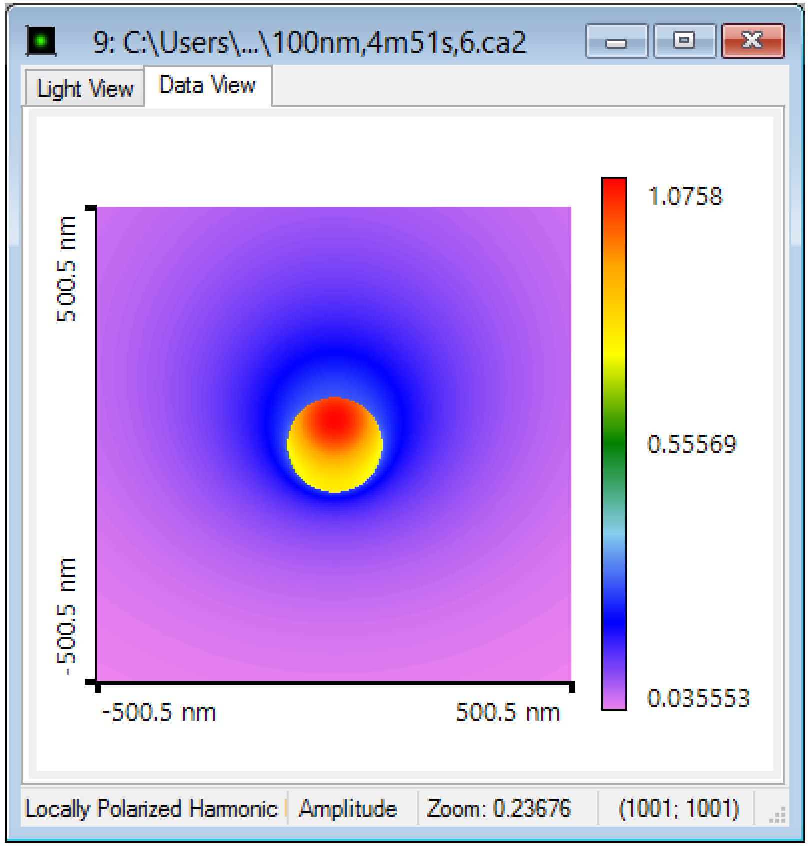


Ex-phase

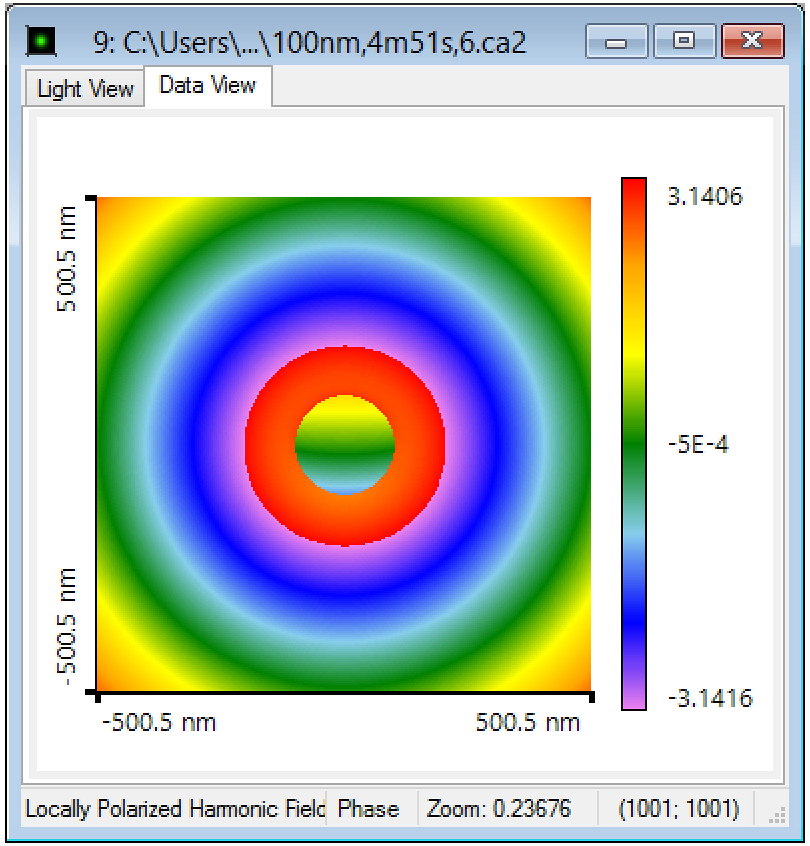


Radius = 100nm

Ex-amplitude

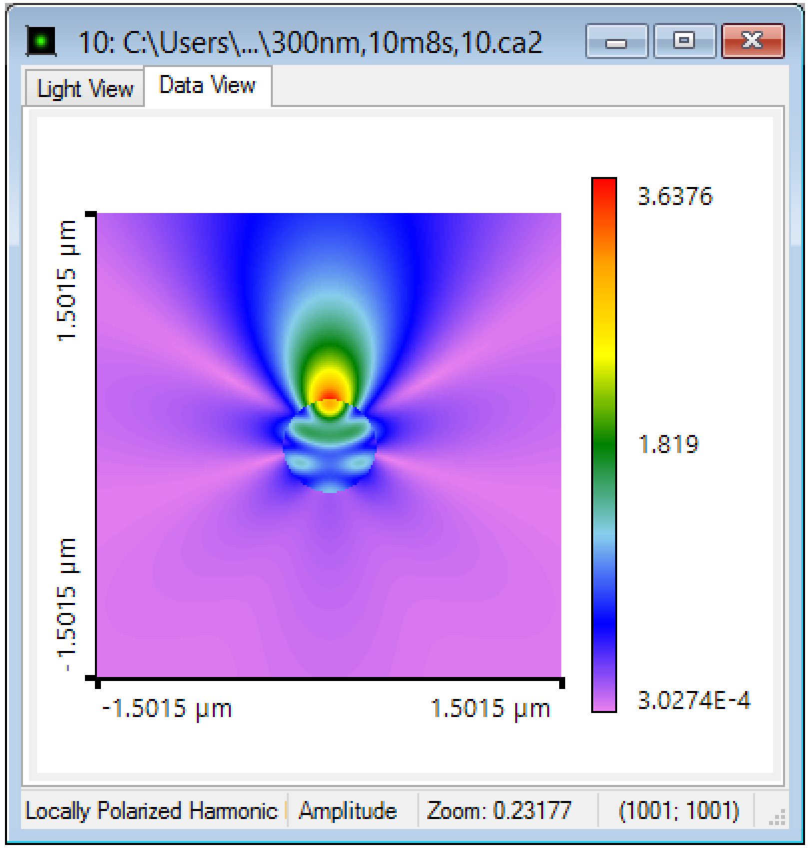


Ex-phase

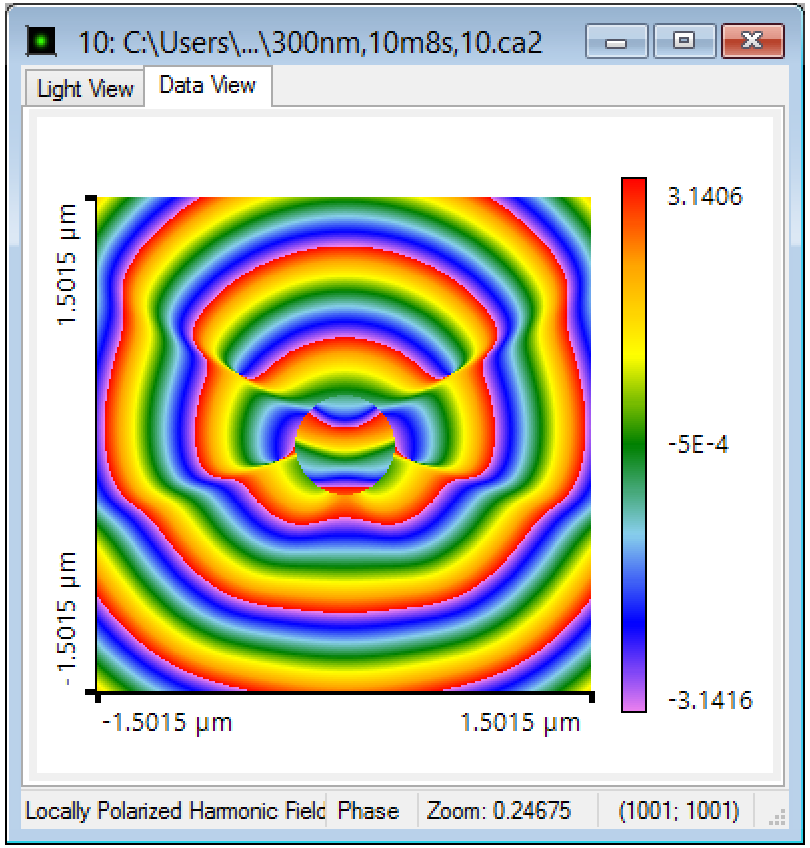


Radius = 300nm

Ex-amplitude

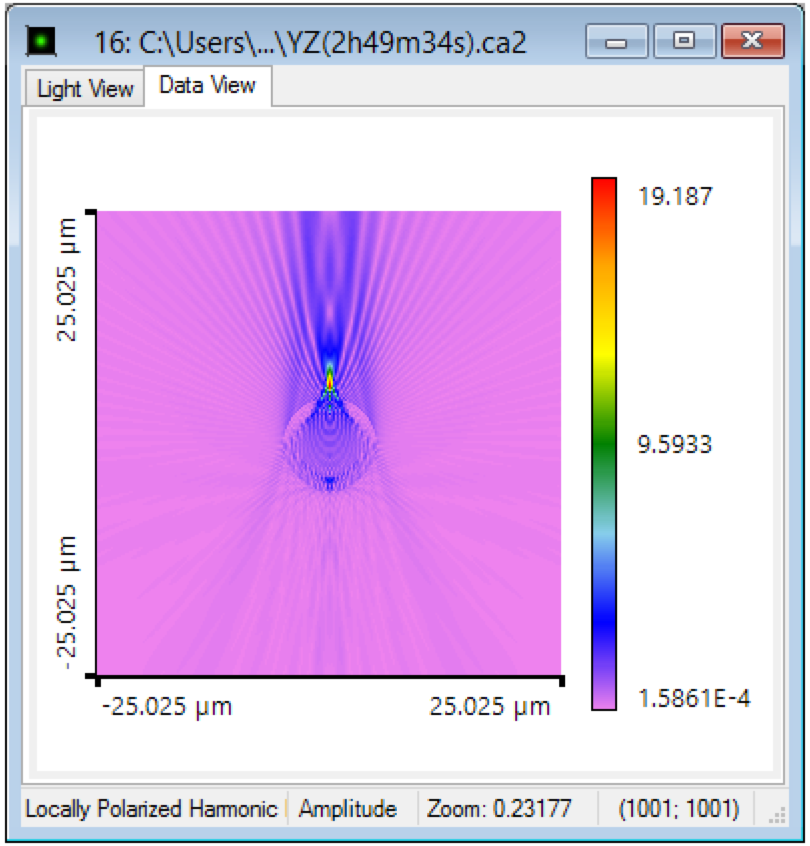


Ex-phase

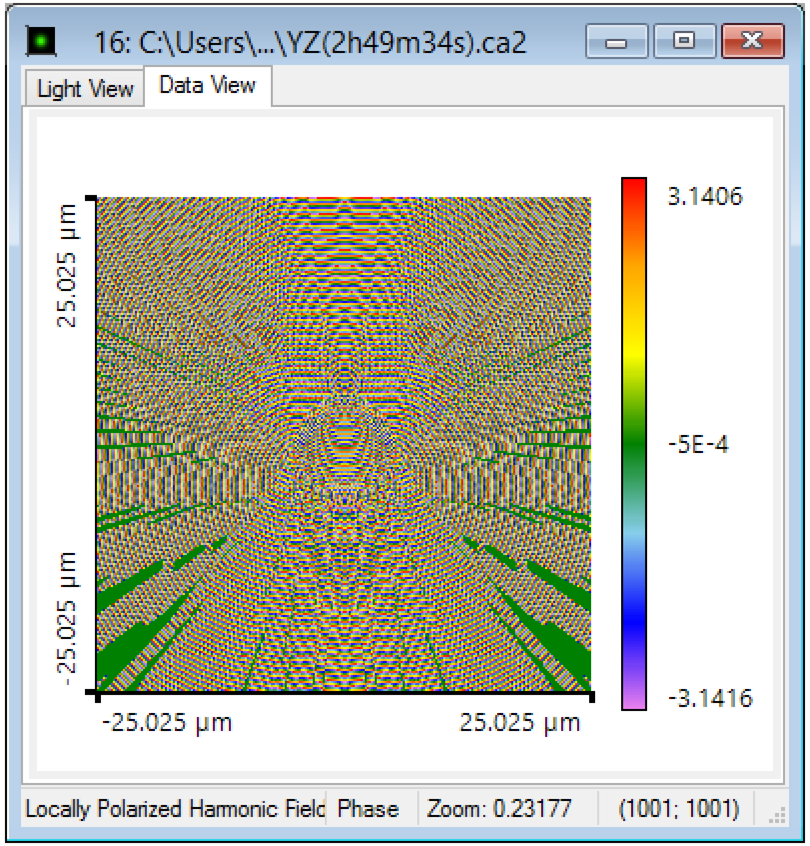


Radius = 5μm

Ex-amplitude

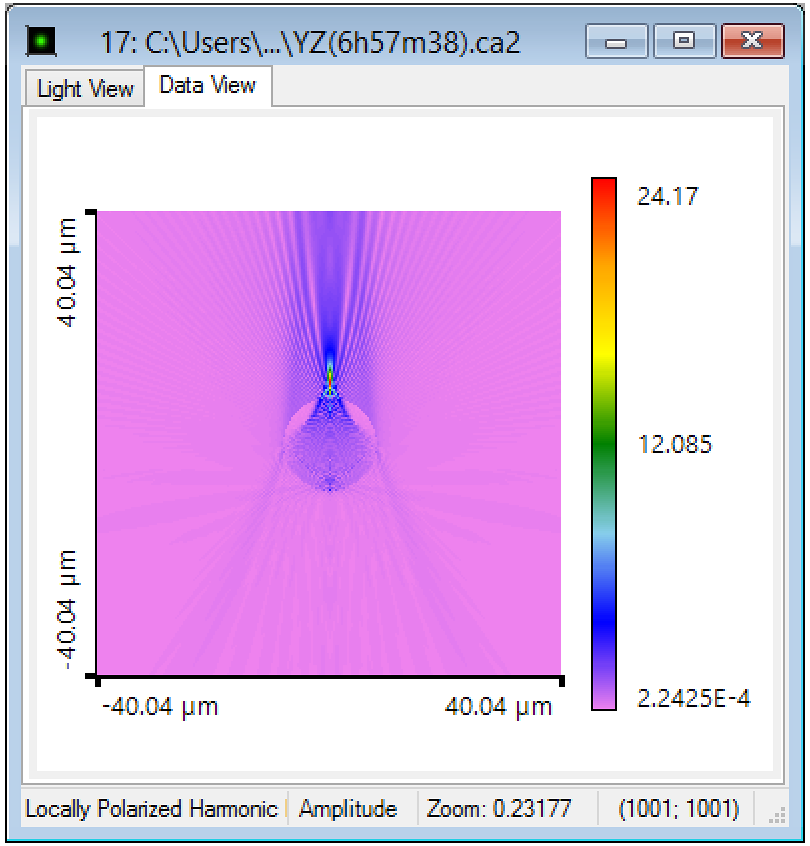


Ex-phase

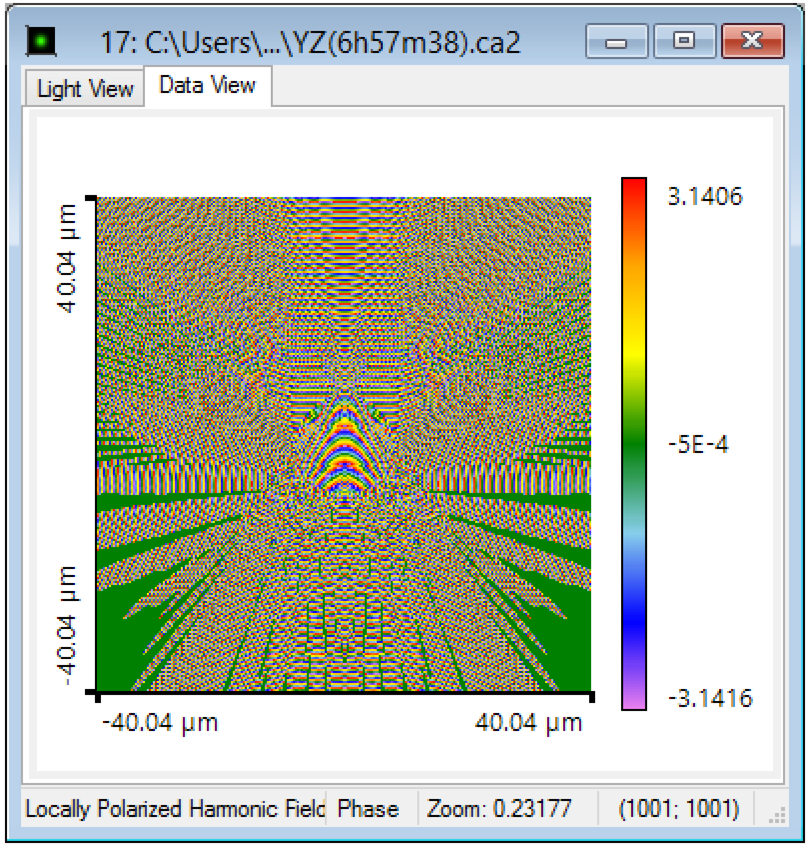


Radius = 8μm

Ex-amplitude

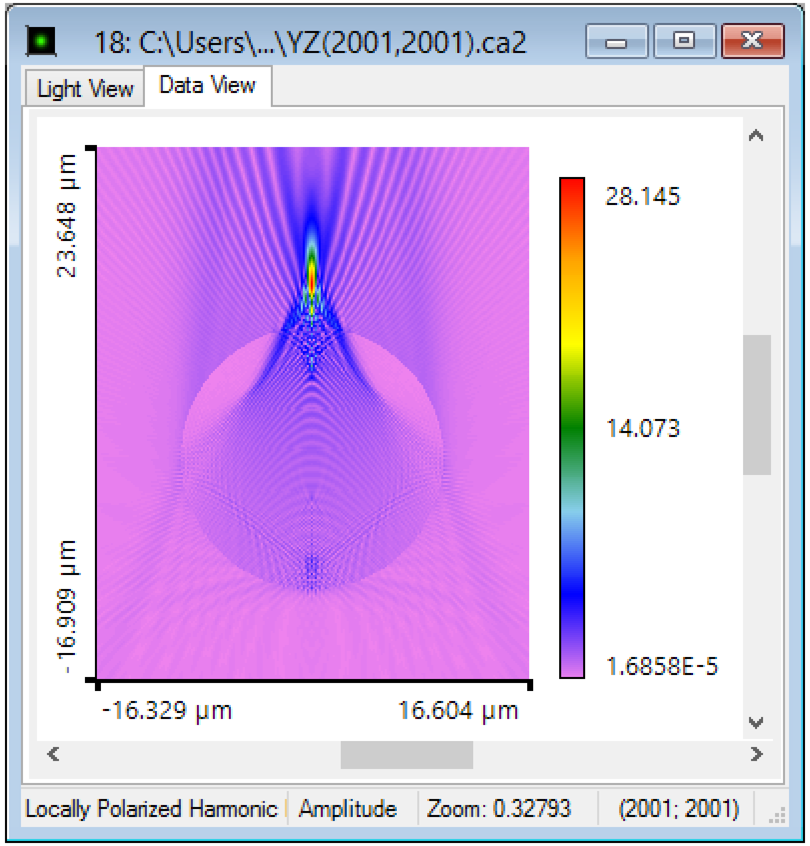


Ex-phase

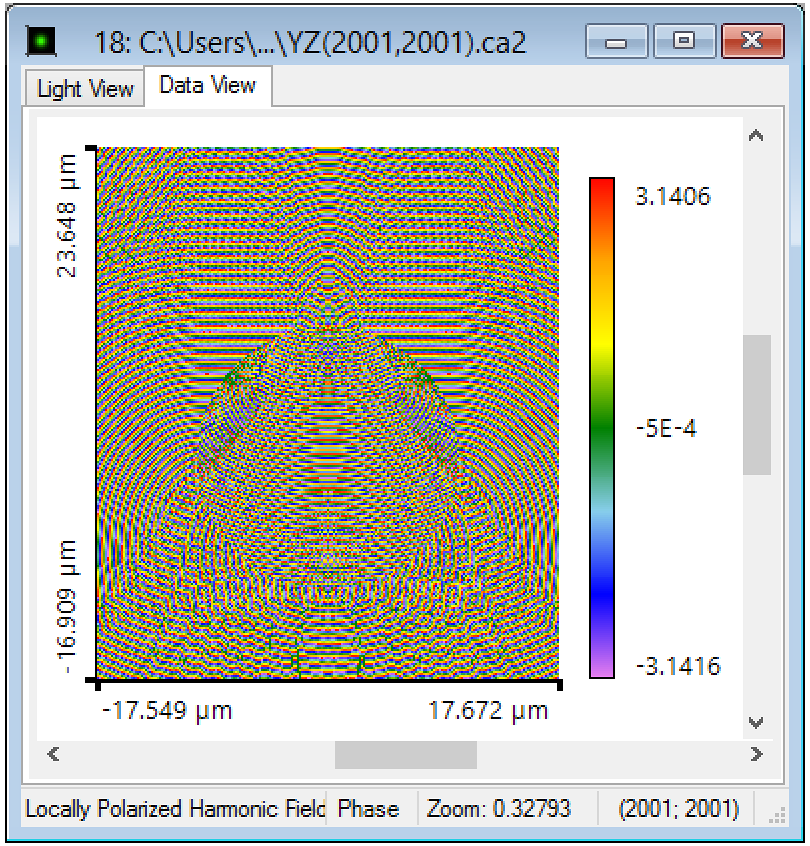


Radius = 10μm

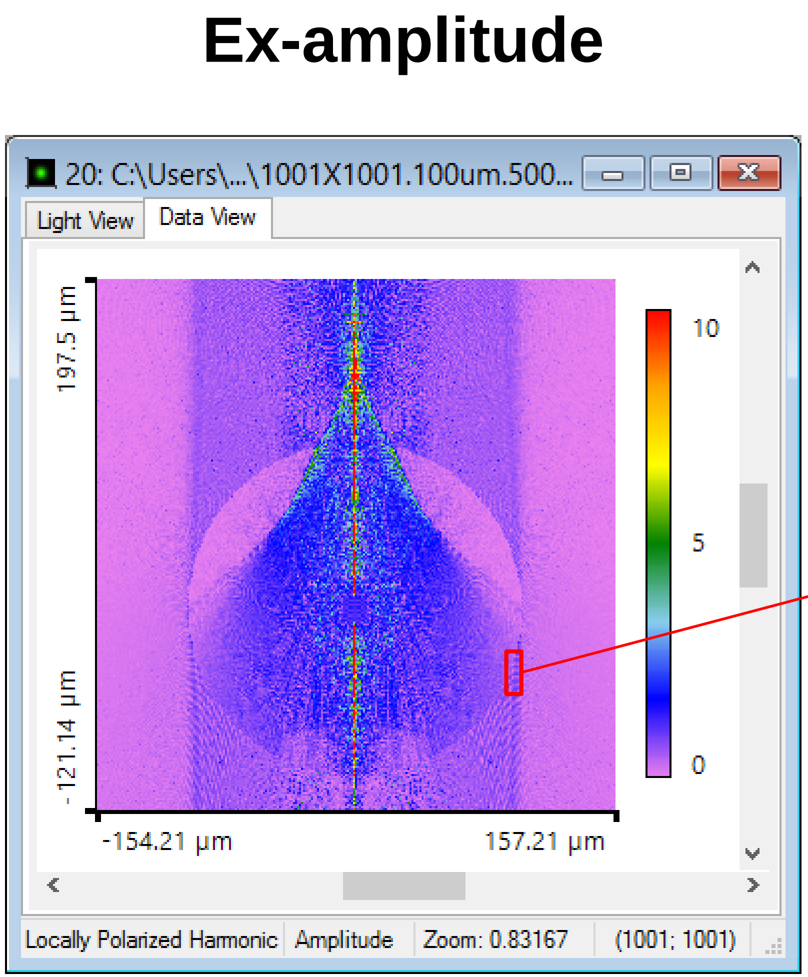
Ex-amplitude

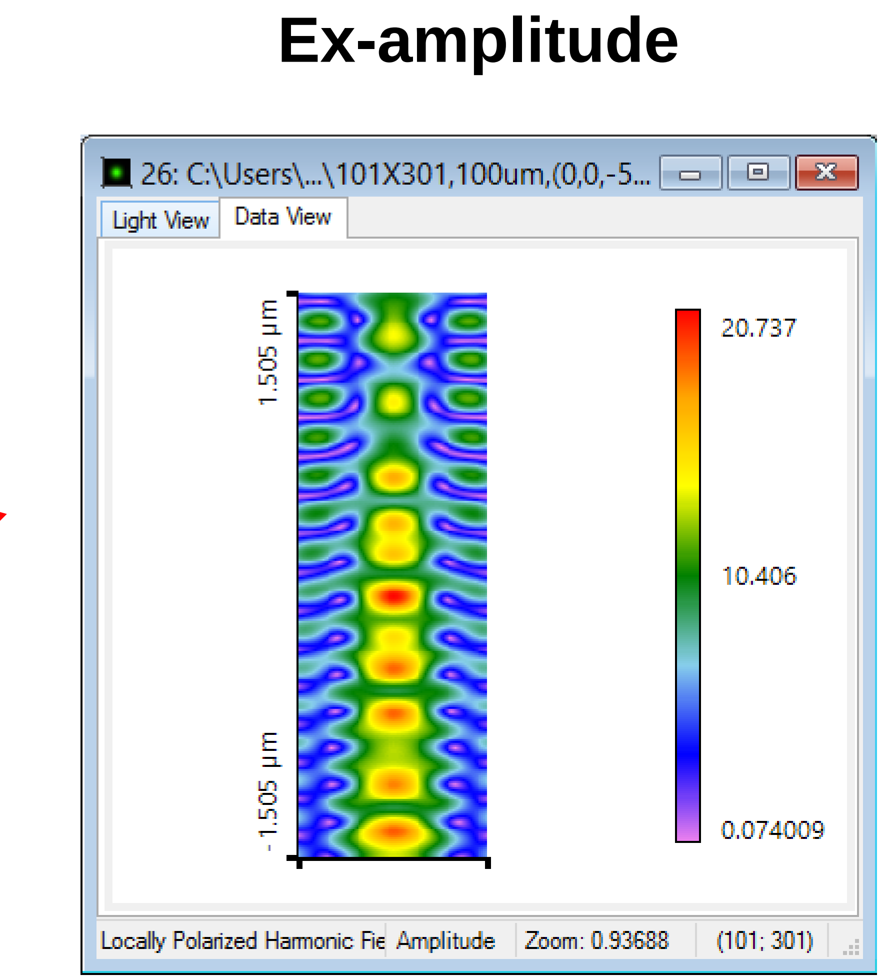


Ex-phase



Radius = 100μm





Examplary Evaluations: Computational Time

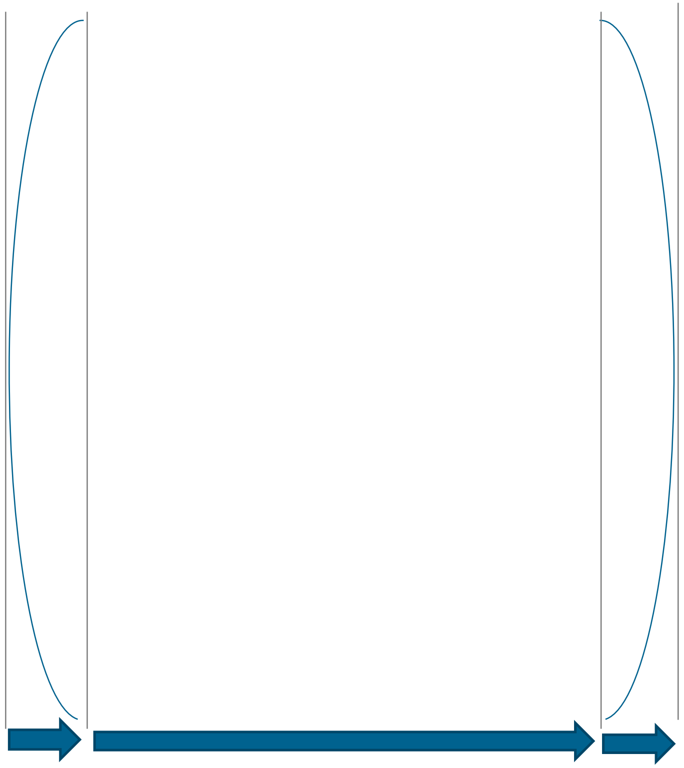
Sampling Points (SP) X × Y	Considered Number of Orders (Nt)(*)	Time
2000 × 2000	2200	?
1000 × 1000	1150	4d10h
2000 × 2000	150	1d 14h 40m
1000 × 1000	125	7h12m
1000 × 1000	80	2h 50m
1000 × 1000	30	21m
1000 × 1000	10	8m11s

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

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

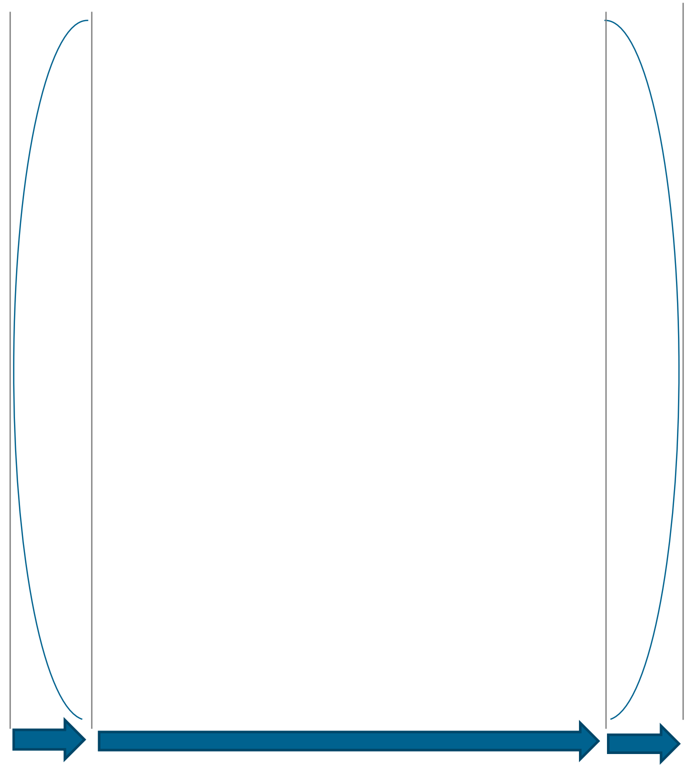
Further Tearing

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

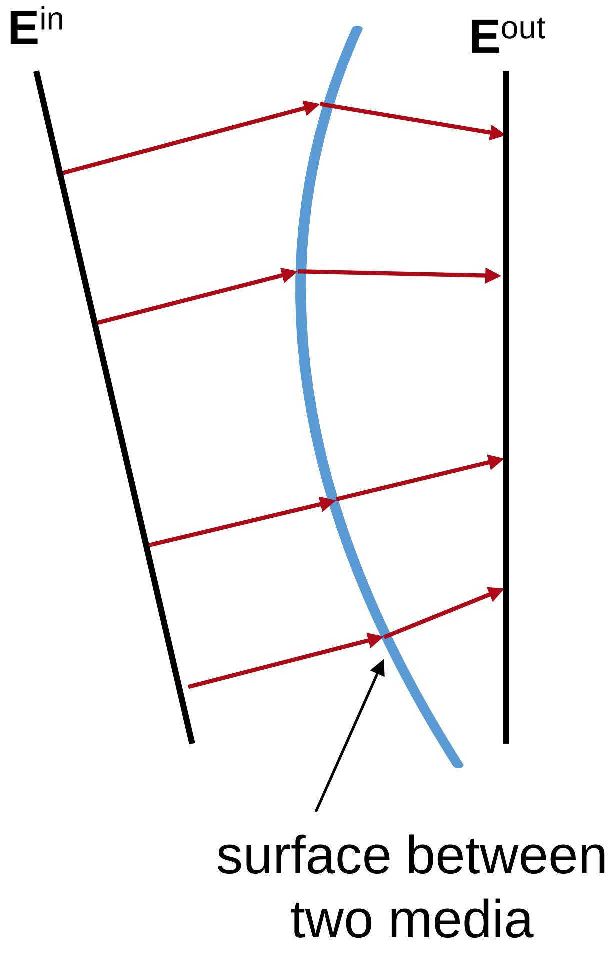


Further Tearing

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



Local Plane Interface Approximation (LPIA)

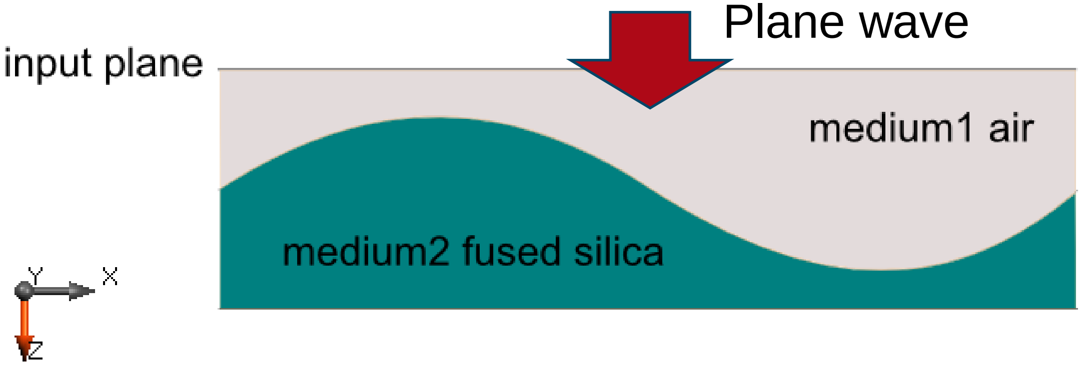


- For each k-value the so-called bidirectional (B) operator(*) in space domain is the response of the surface on a plane wave.
- Response is obtained by local satisfaction of boundary condition.

(*) generalization of the bidirectional scattering distribution function (BSDF)

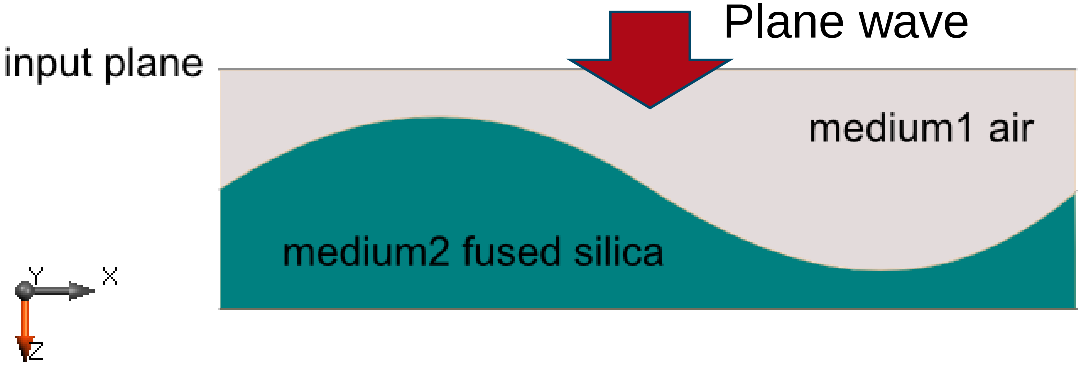
LPIA: FEM Reference Sinusoidal Grating

Structure: single interface with air and fused silica

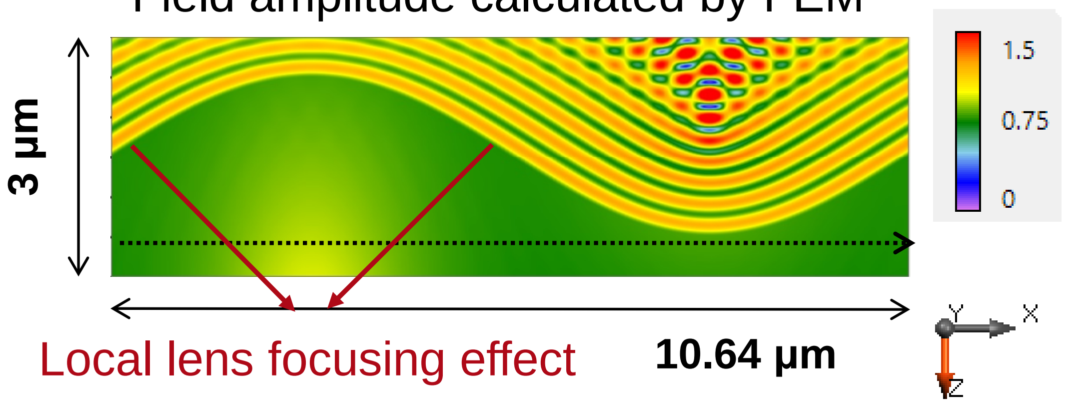


LPIA: FEM Reference Sinusoidal Grating

Structure: single interface with air and fused silica



Field amplitude calculated by FEM

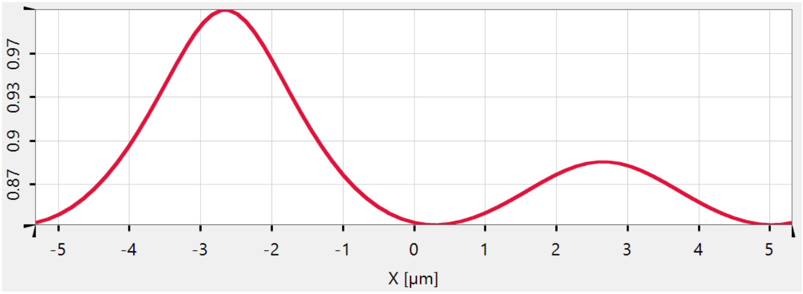


Comparison of Near Field: LPIA vs. FEM

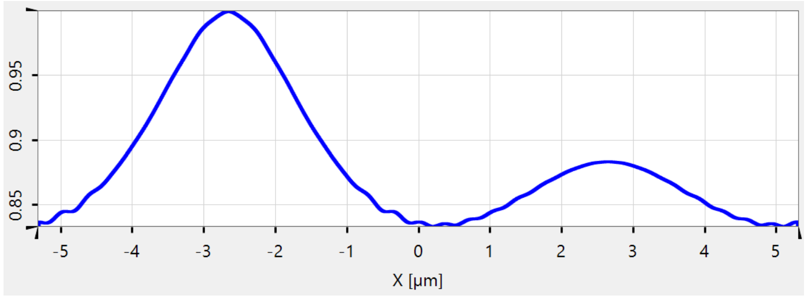
[depth: 2 μm]

- Incident field:
  - TE polarized plane wave;
  - Wavelength: 532 nm;
  - Normal incidence;
- Structure:
  - Sinusoidal grating 2D;
  - Air/Fused silica;
  - Period: 10.64 um= 20λ;
- Output:
  - Amplitude of the electric field behind the grating(LPIA);
  - Amplitude of the electric field behind the grating(FEM);

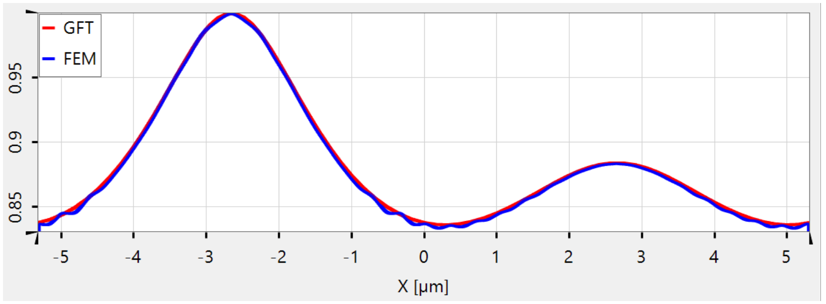
LPIA: Normalized Amplitude



FEM: Normalized Amplitude

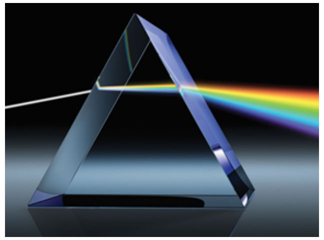


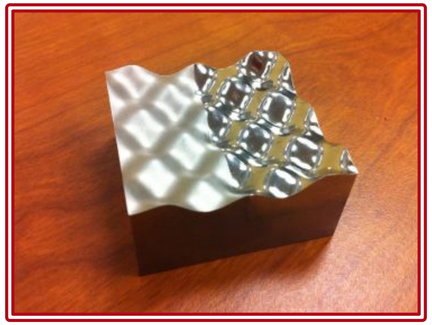
LPIA vs. FEM: Normalized Amplitude



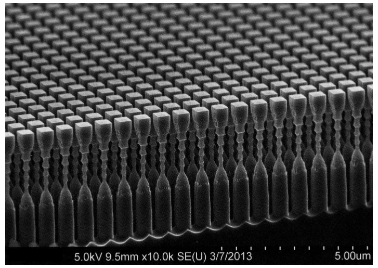
Optical Components

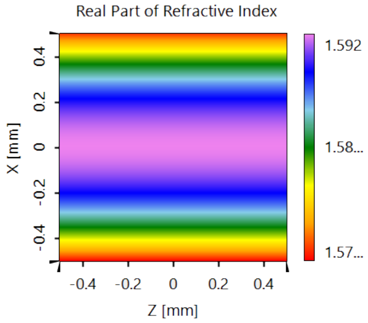
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

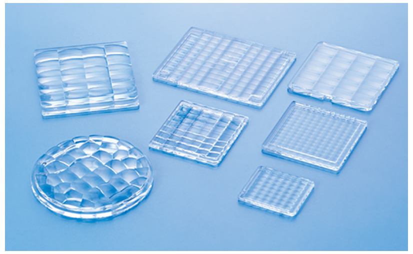




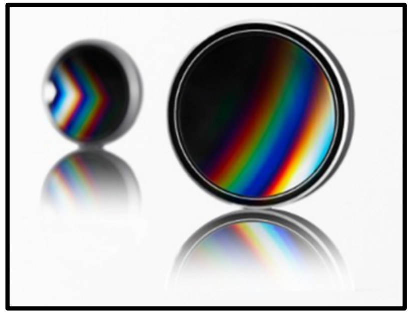
[1] IMS-Mechatronics Lab



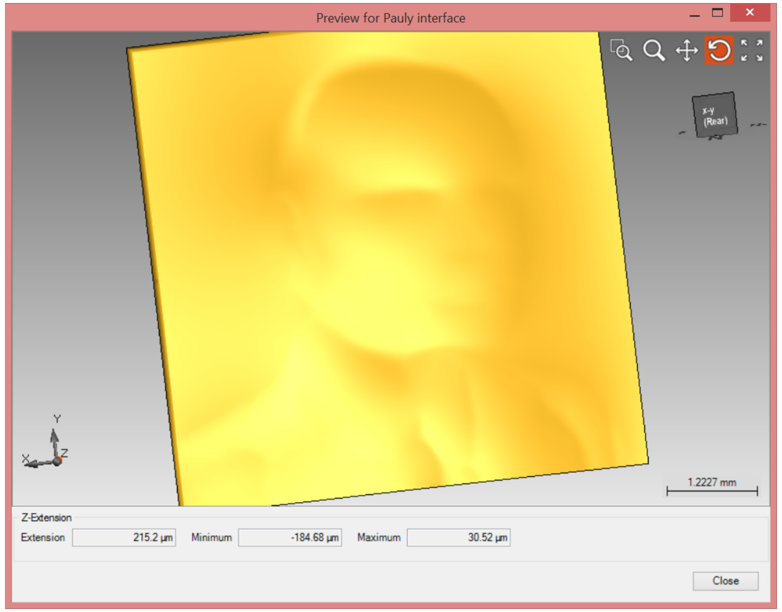




[2] ISUZU GLASS



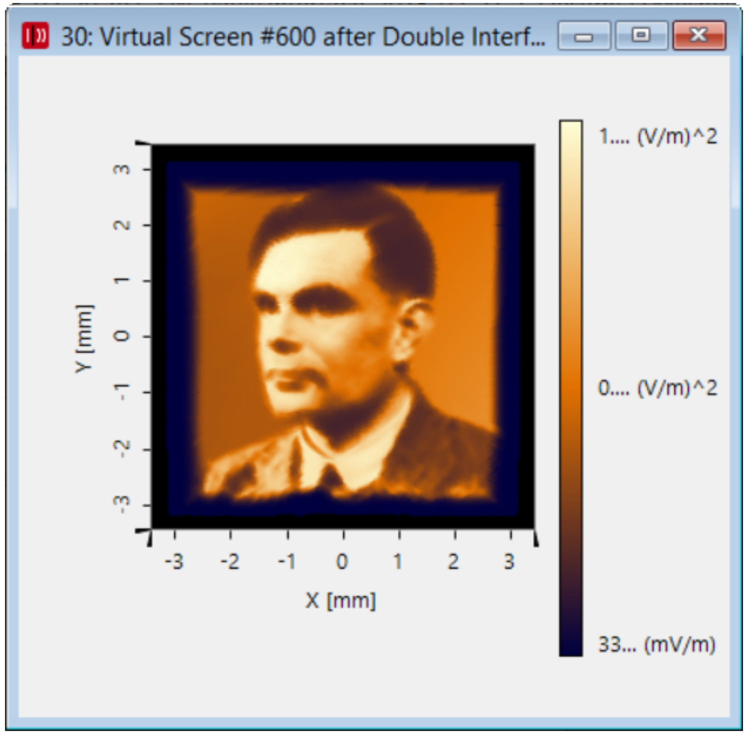
Freeform 1: Simulation through Freeform Interface



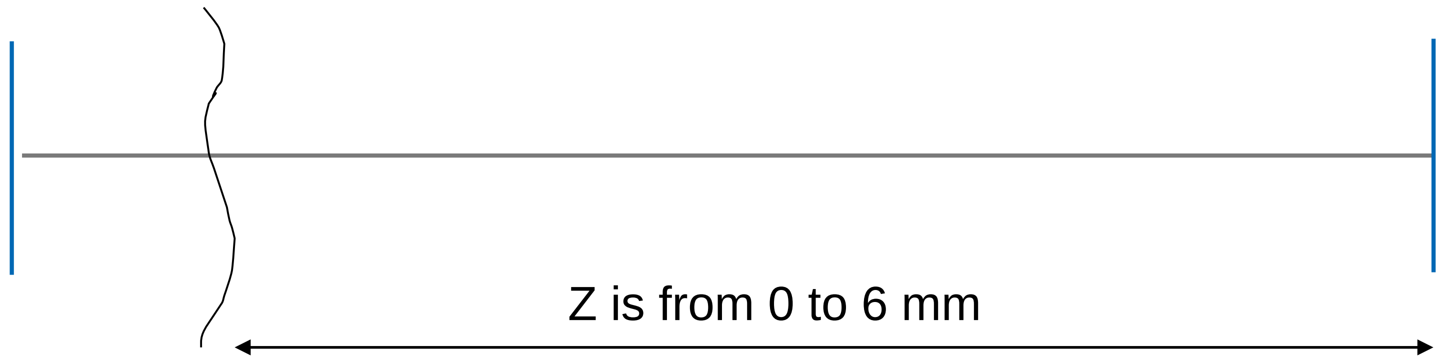
Yuliy Schwartzburg, Romain Testuz, Andrea Tagliasacchi, Mark Pauly

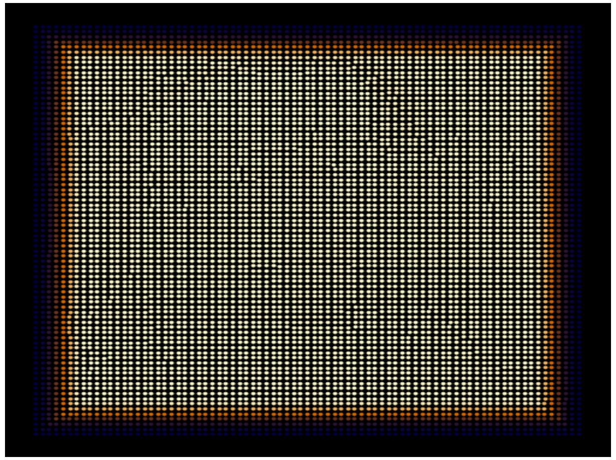
École Polytechnique Fédérale de Lausanne, Computer Graphics and Geometry Laboratory

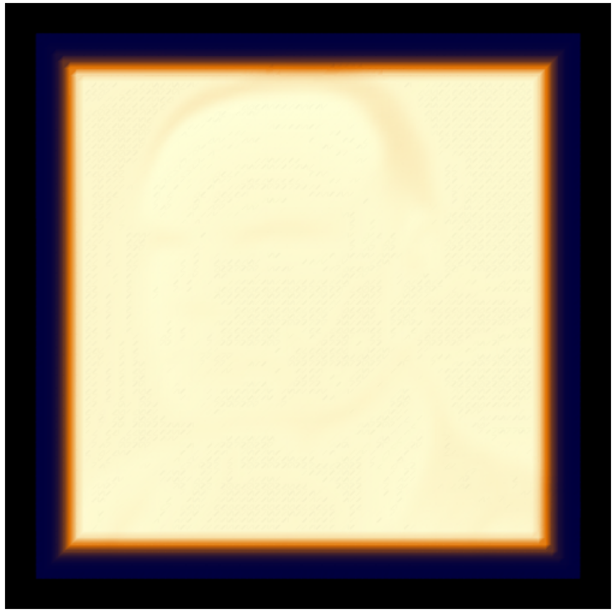
High-contrast Computational Caustic Design



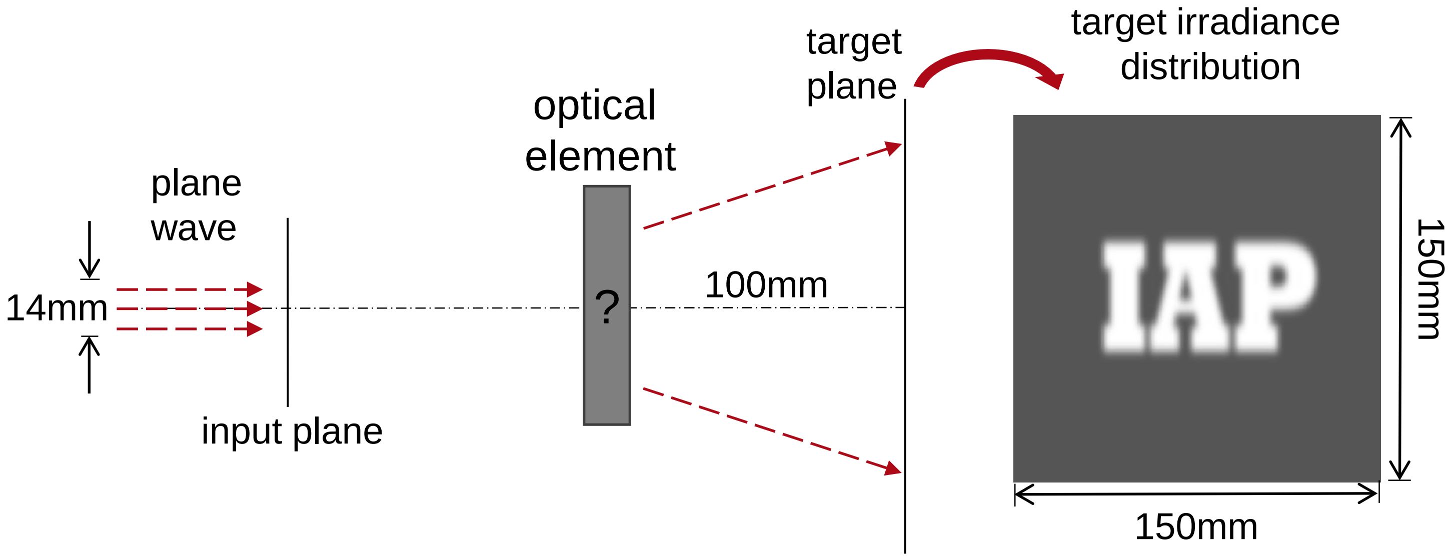
Freeform 1: Developing Result behind Freeform Interface



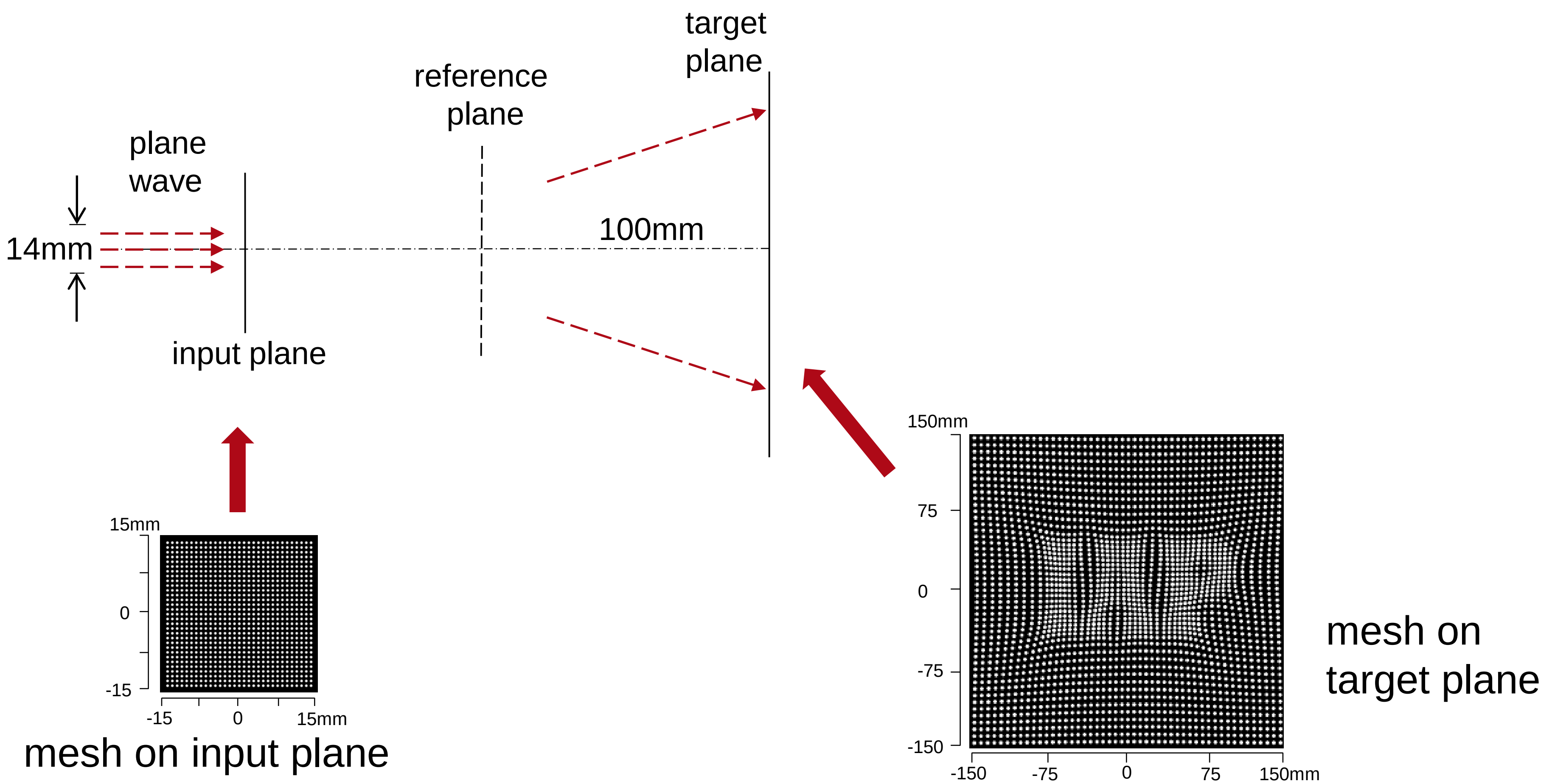




Freeform 2: Research Design Topic: Plane Wave → „IAP“

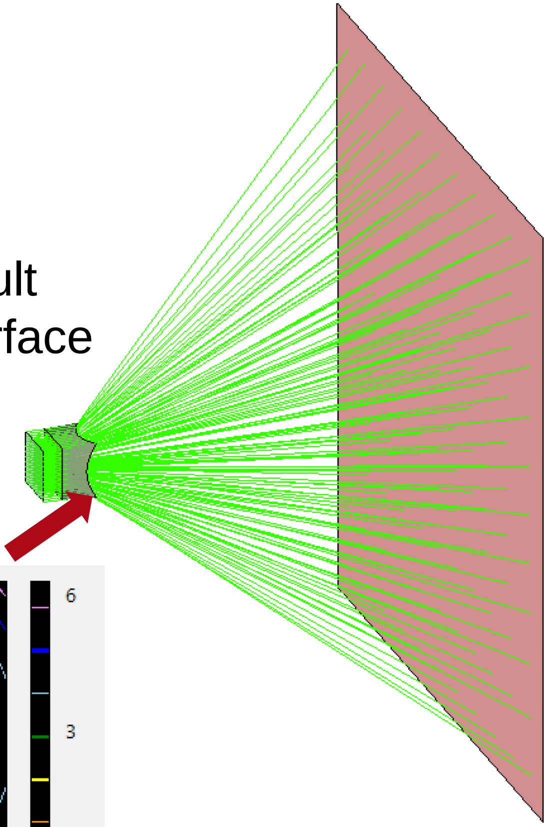


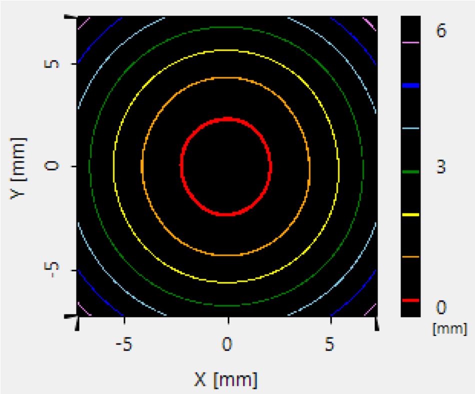
Freeform 2: Mesh Design



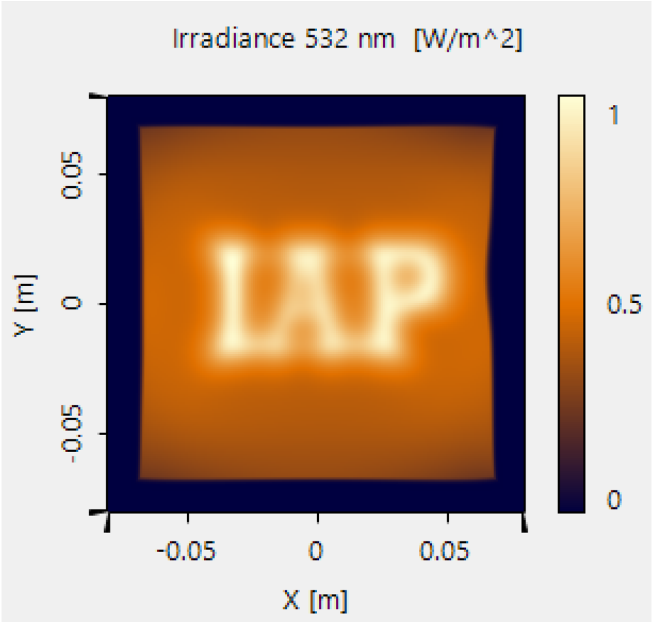
Freeform 2: Current Simulation Results from Freeform Design

ray tracing result
with design surface





Height Profile
(2D Contour line)

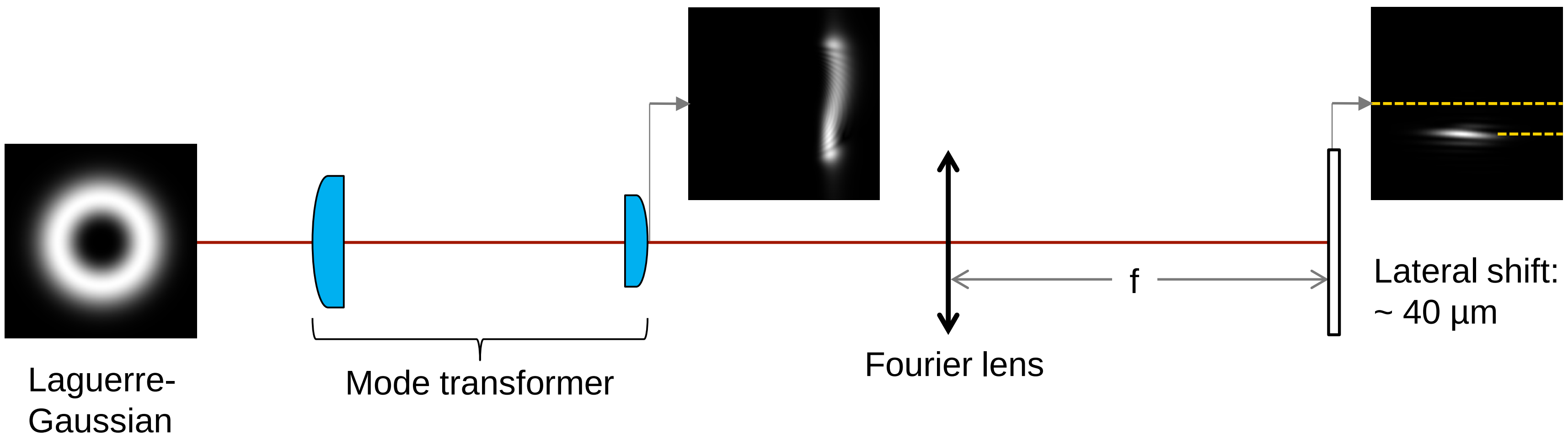


irradiance at target plane
(normalized)

Freeform Example 3:
Measurement of Orbital Angular Momentum (OAM)

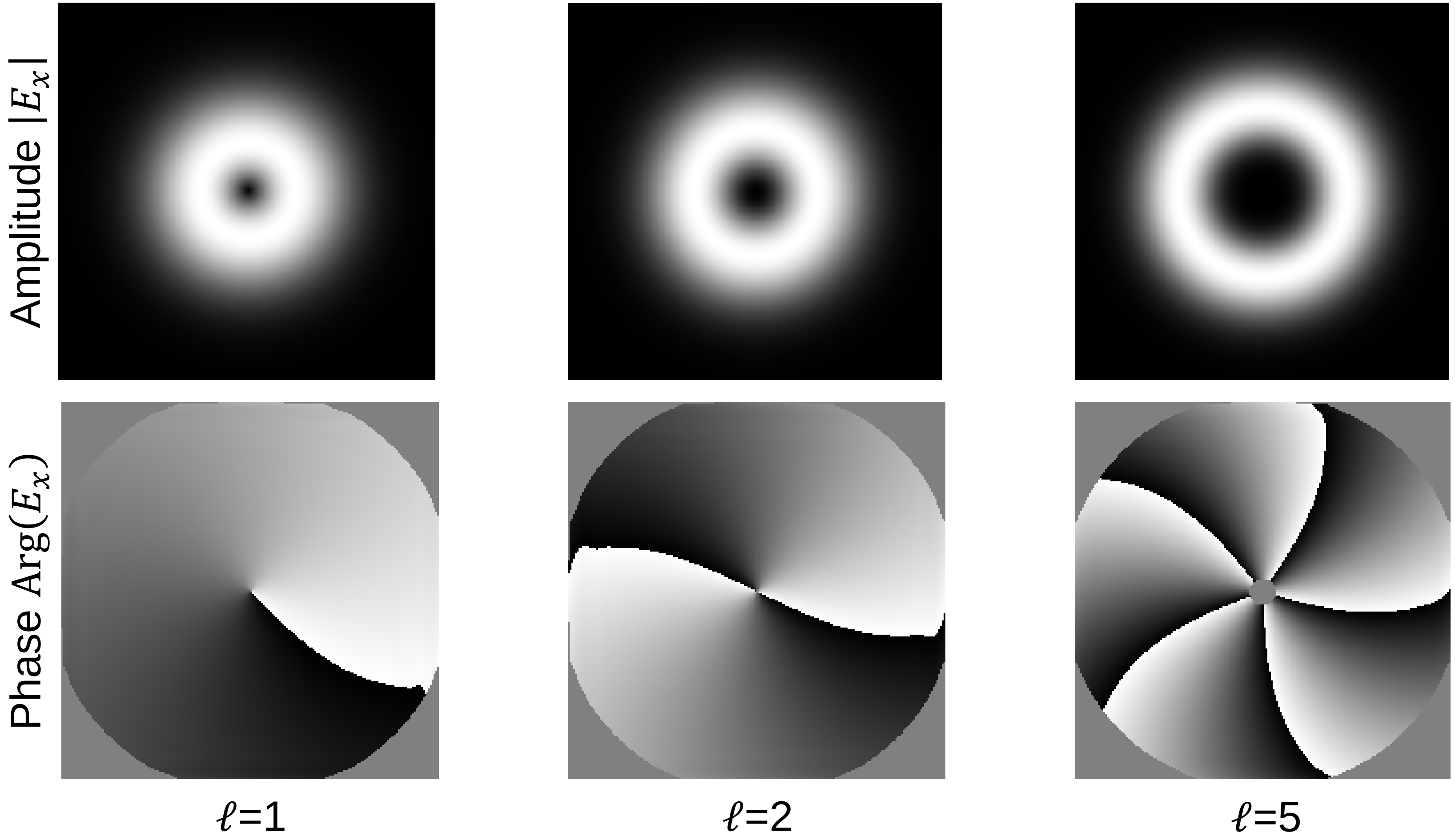
Martin P. J. Lavery, *et al*., "Refractive elements for the measurement of the orbital angular momentum of a single photon," Opt. Express 20, 2110-2115 (2012)

Simulation in VirtualLab Fusion



Laguerre-Gaussian

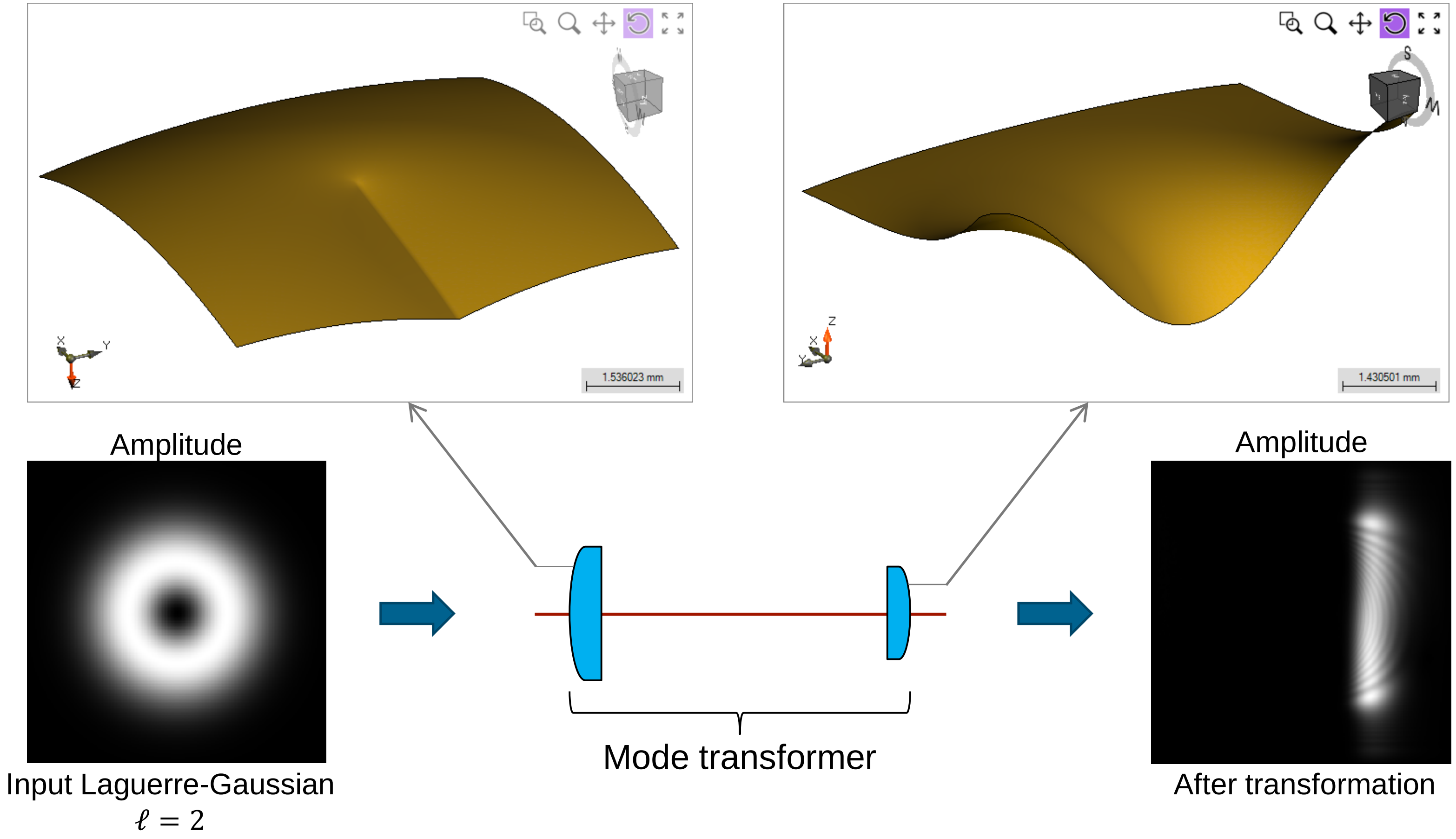
- Light source



Mode Transformer

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

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



Mode Transformer

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

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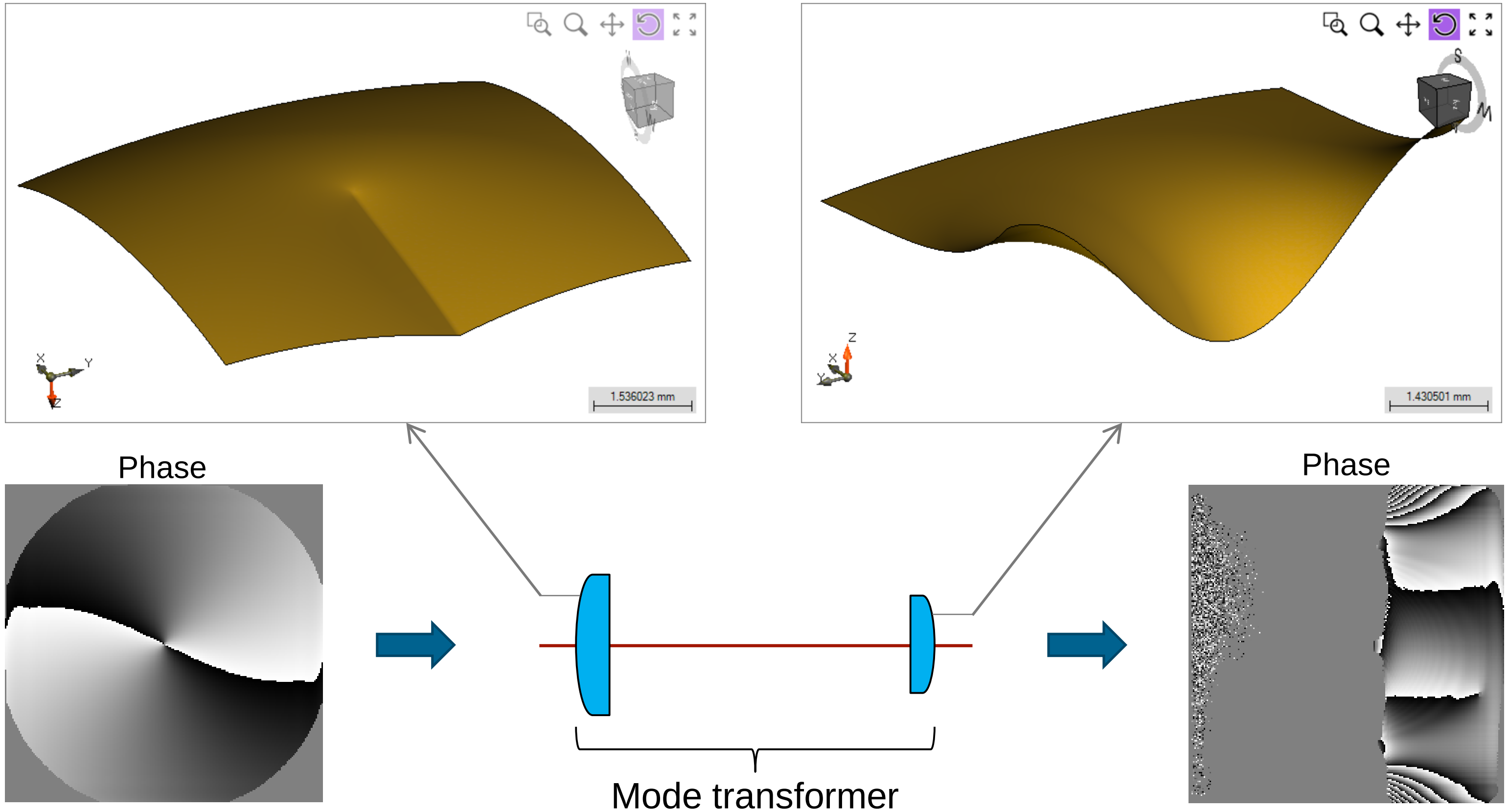
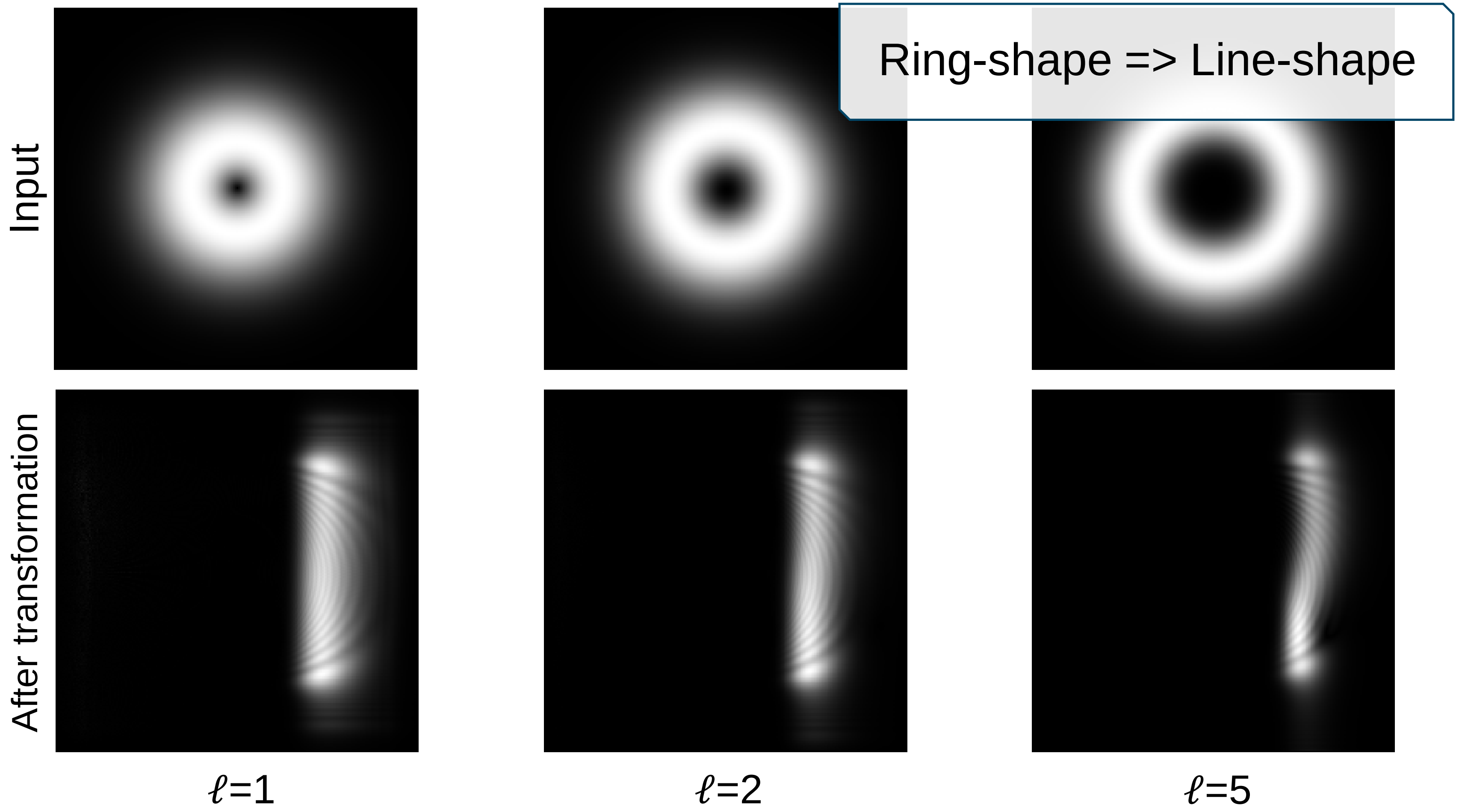


Input Laguerre-Gaussian $\ell = 2$

After transformation

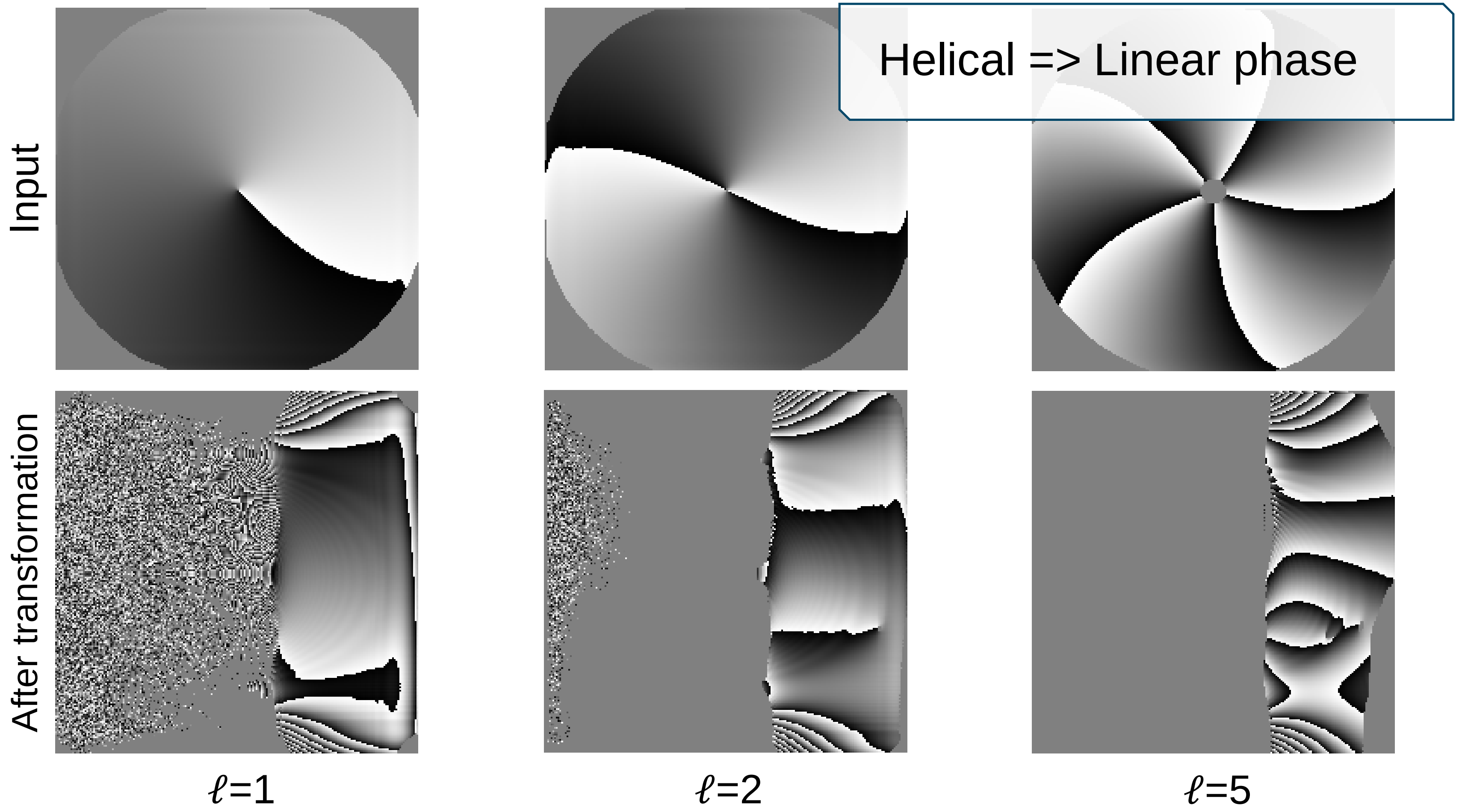
Mode Transformer

- Amplitude distributions before and after transformation



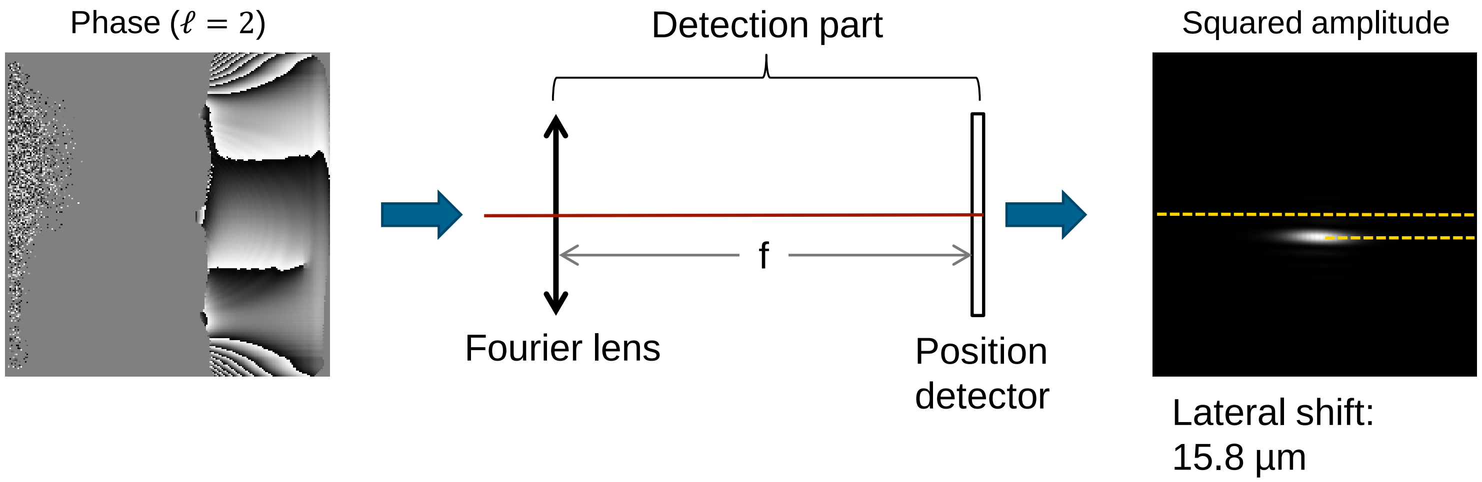
Mode Transformer

- Phase distribution before and after transformation



Detection Part

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



Detection Part

- Shift theorem
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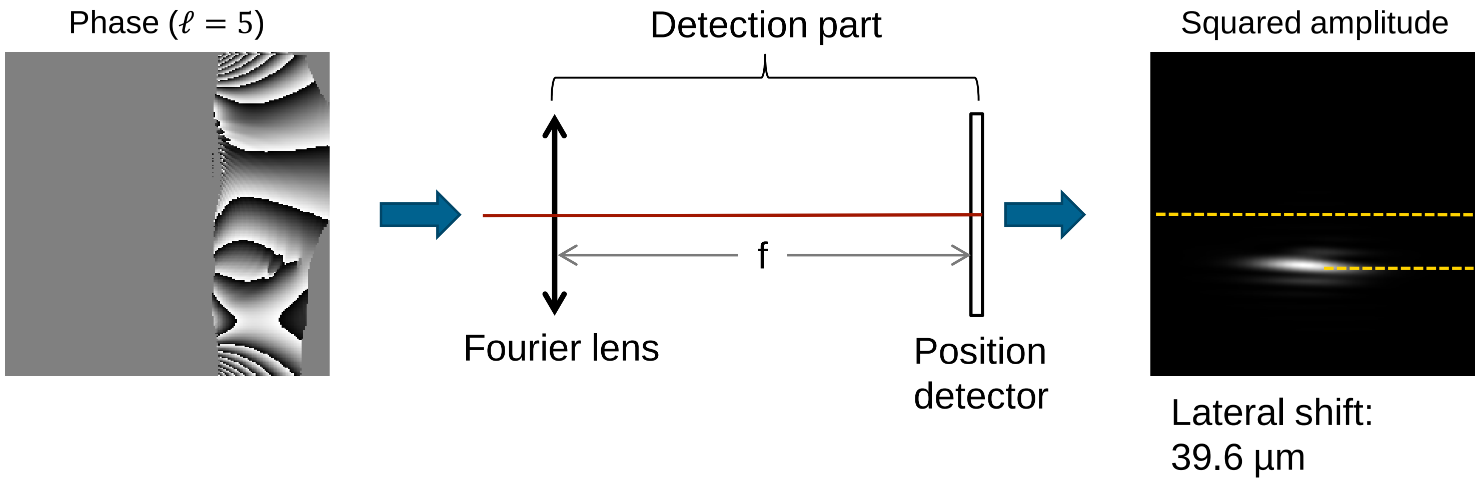
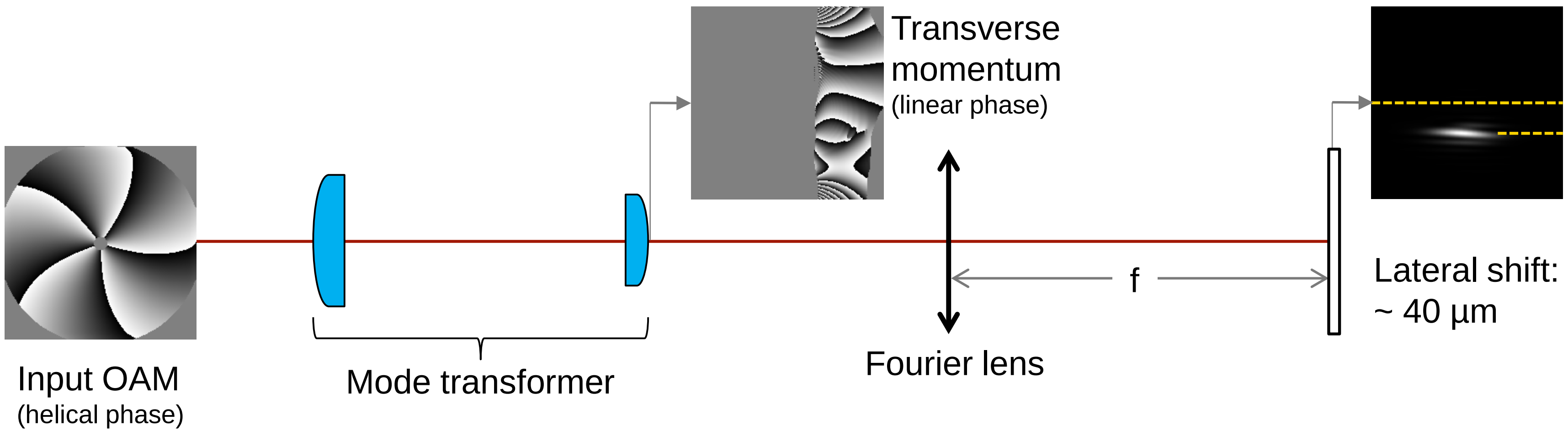


System Functioning



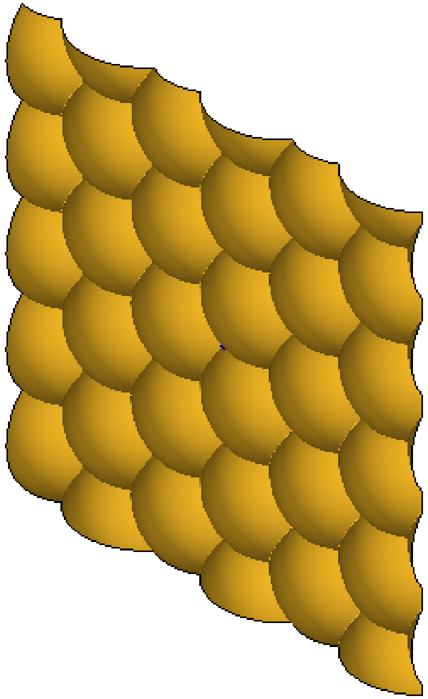
- An input orbital angular momentum (OAM) is firstly transformed to transverse momentum by the mode transformer, which is composed of two freeform refractive optical elements
- The transverse momentum is then transformed into lateral position shift by a Fourier lens
- By precise measurement of the lateral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

Visualization of Surface Profiles in 1D, 2D and 3D

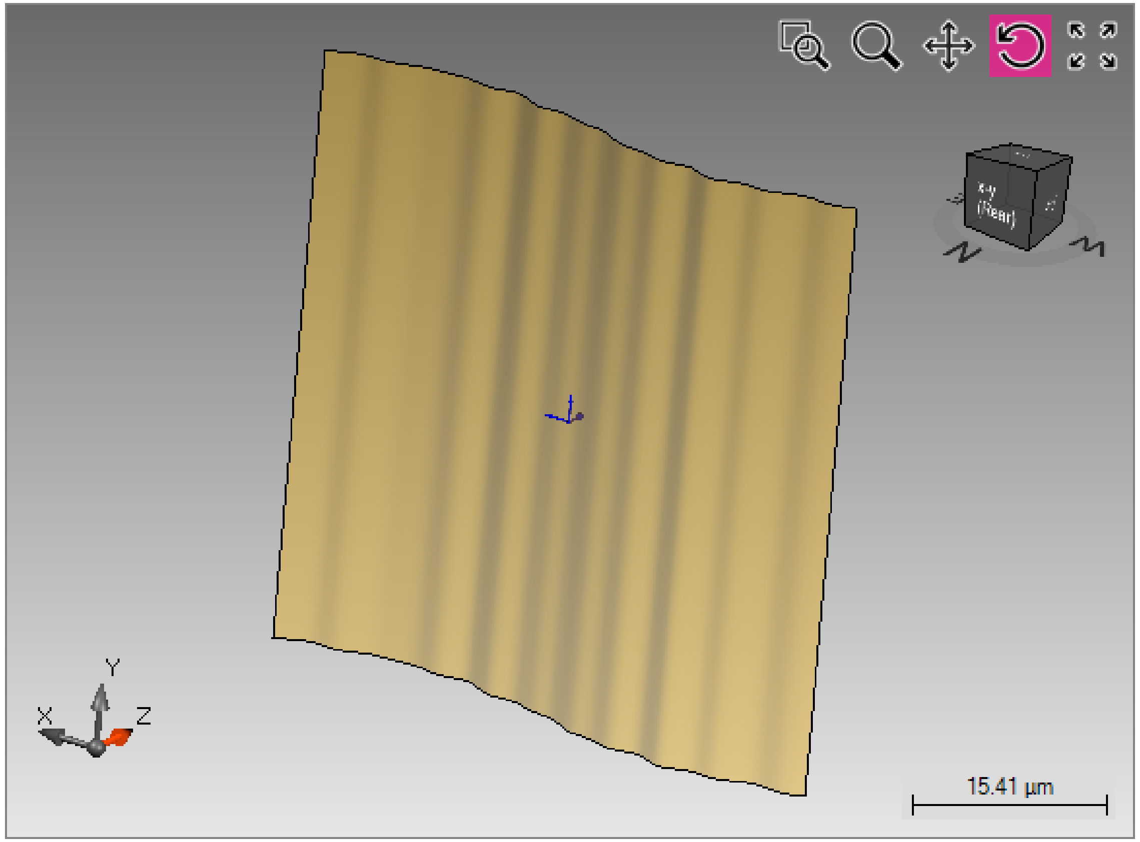
Demo of Customization → here: Conversion Module

Task: Visualization of Surface Profiles

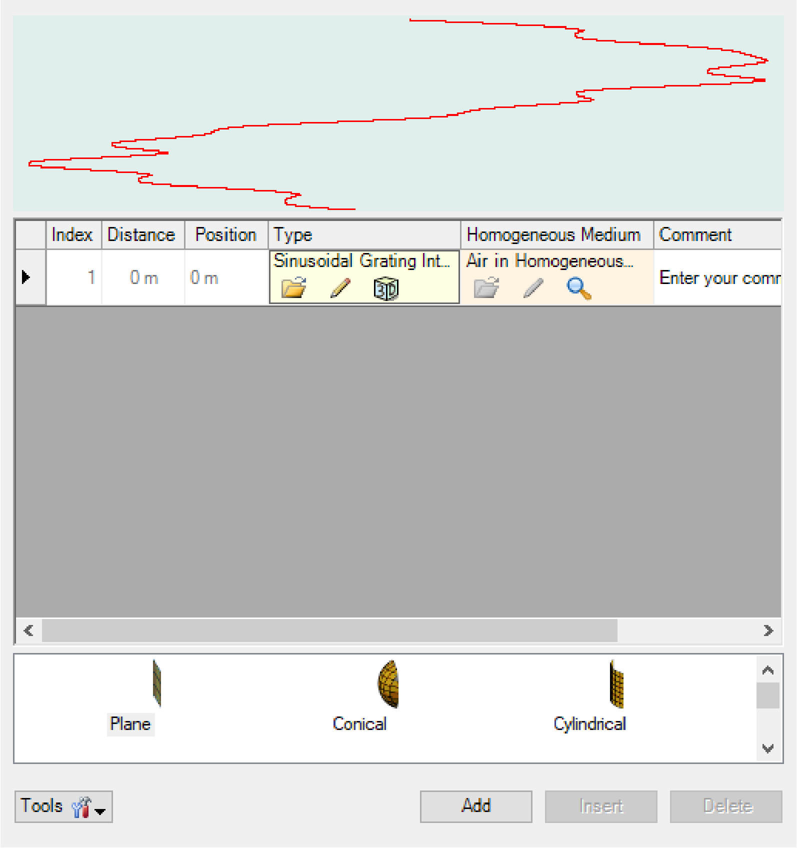
- To define the structure of any optical system it is pretty typical to define components, which are oriented within the system.
- Each component can by typically defined by combining optical surfaces and media.
- The visualization of these building blocks is very important.
- VirtualLab provides several options to visualize surfaces in 1D and 3D.
- In addition a 2D visualization of surfaces is possible.



Standard Surface Visualization



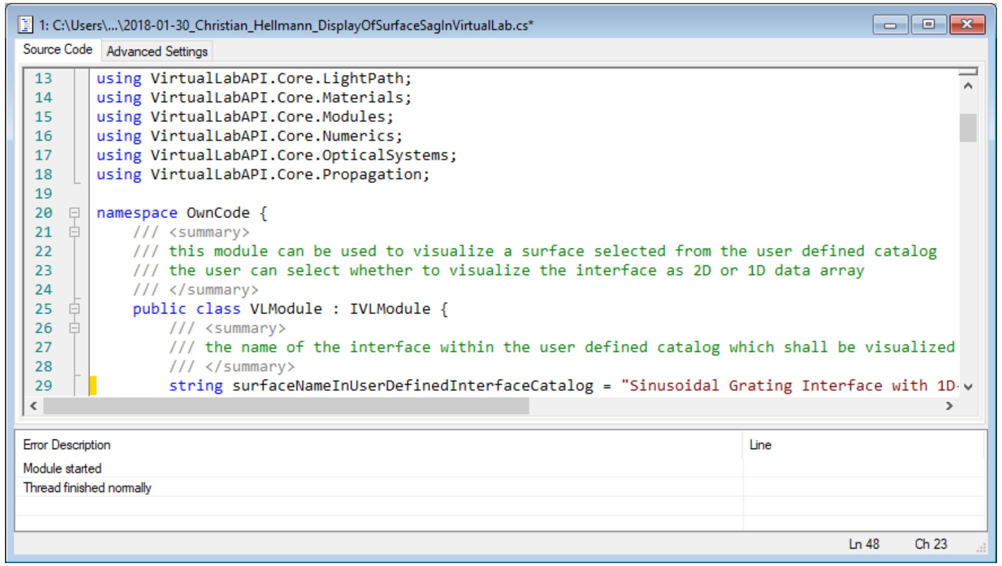
3D view of optical surfaces



Edit dialog of optical interface sequence including 1D profile

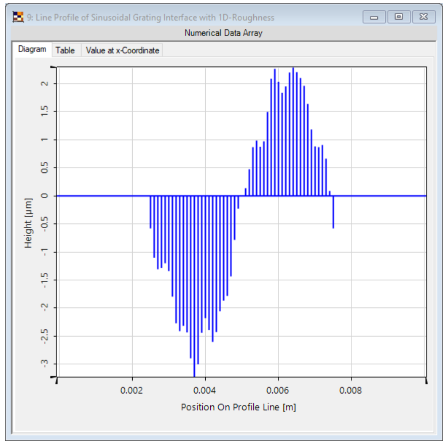
Customized Surface Visualization

2018-01-30_Christian_Hellmann_DisplayOfSurfaceSagInVirtualLab

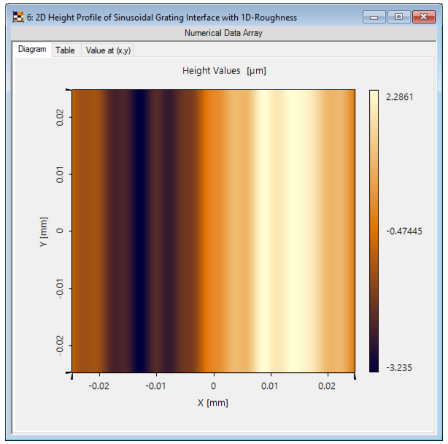


Select name of surface which should be load from user defined catalog.

1D

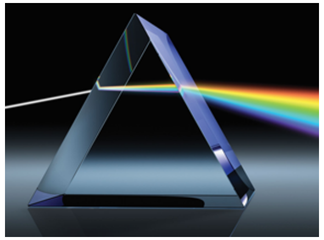


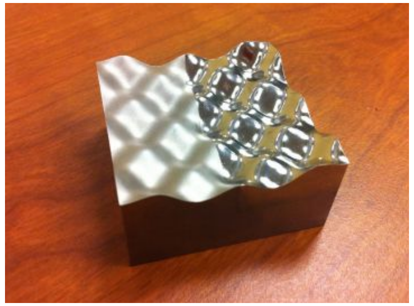
2D



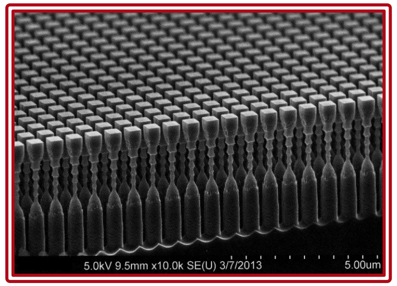
Optical Components

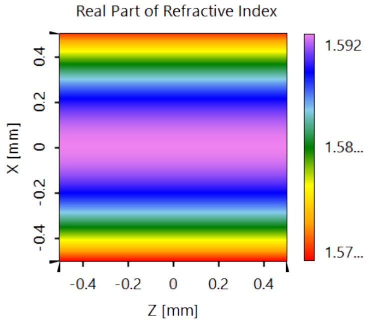
- elements with planar interfaces
- lenses
- freeforms
- **gratings**
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

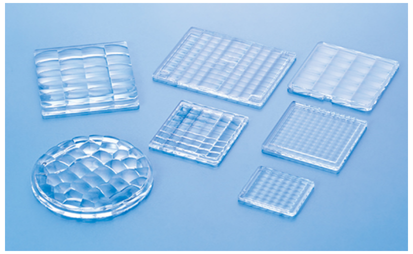




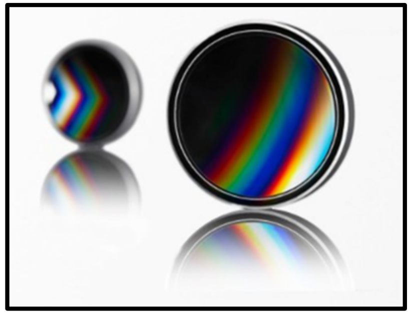
[1] IMS-Mechatronics Lab





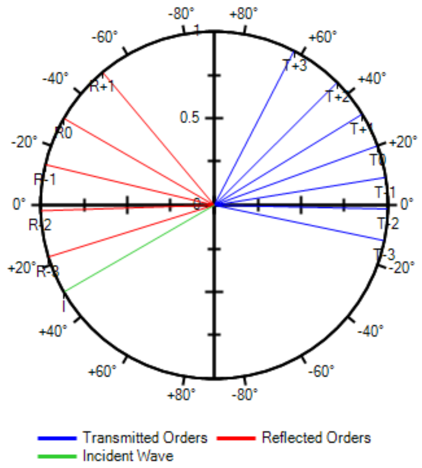


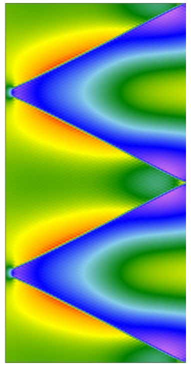
[2] ISUZU GLASS



Modeling Technologies

- Electromagnetic analysis of gratings by
  - Fourier Modal Method (FMM)
  - (also called) Rigorous Coupled Wave Analysis (RCWA)
  - Integral Method
- Approximated analysis by Thin Element Approximation
- Merit functions:
  - Diffraction efficiency
  - Near field
  - Far field
  - Field inside grating
  - Polarization analysis
  - Customized merit functions





- Grating analysis for plane and general incident waves
- Analysis include degree of coherence, color, polarization.

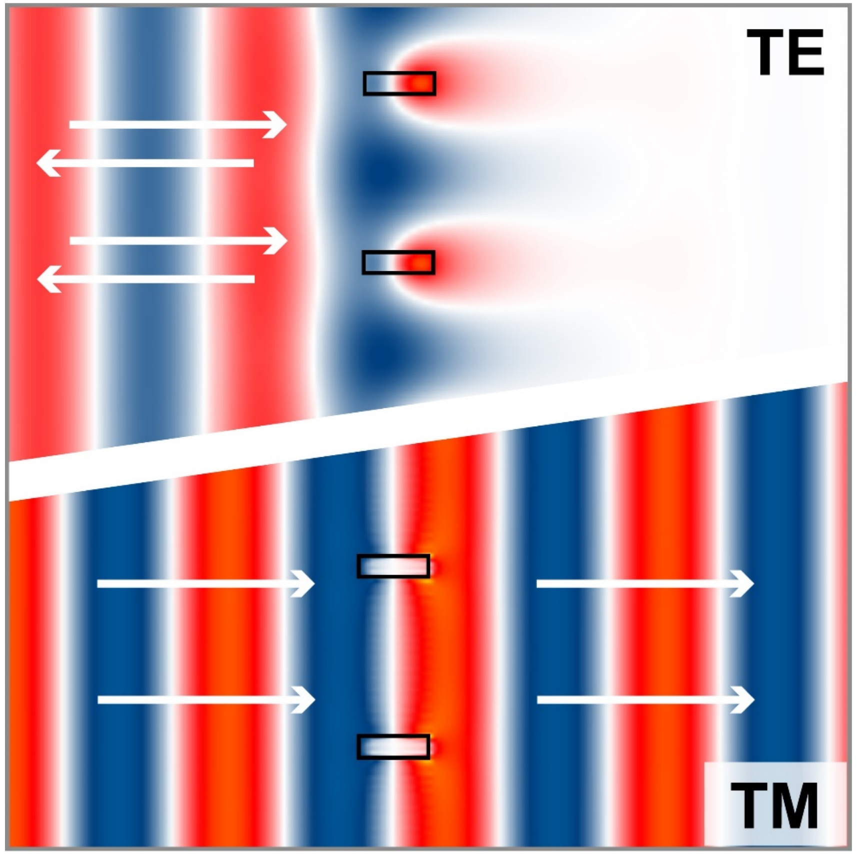
Grating analysis for general incident waves.

- Typically gratings are only a part of an entire optical system
- In addition to the grating there are e.g. illumination and detector optics
- Simulation of multi-scale optical systems including macroscopic optical components and gratings.
- Fourier Modal Method for general incident waves in combination with other field tracing techniques enables the simulation of such multi-scale optical setups.

Ultra-Sparse Dielectric Nano-Wire Grid Polarizers

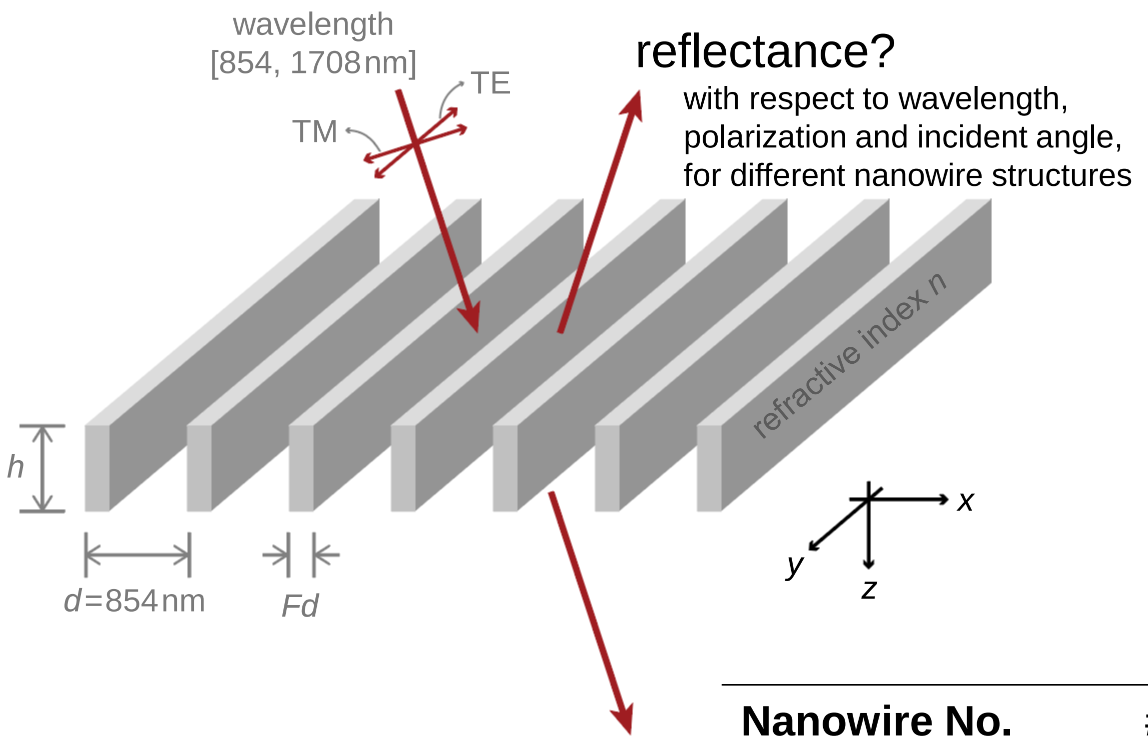
1D photonic crystal

Abstract



Ultra-sparse dielectric nanowire grids show strongly polarization-dependent properties and they can be employed as wideband reflectors [J. W. Yoon *et al*., Opt. Express **23**, 28849-28856 (2015)]. The polarization-, wavelength-, and angle-dependent properties of selected nanowire grids are investigated by using the Fourier modal method (FMM). Visualization of the interaction between electric field and the nanowire grids are presented.

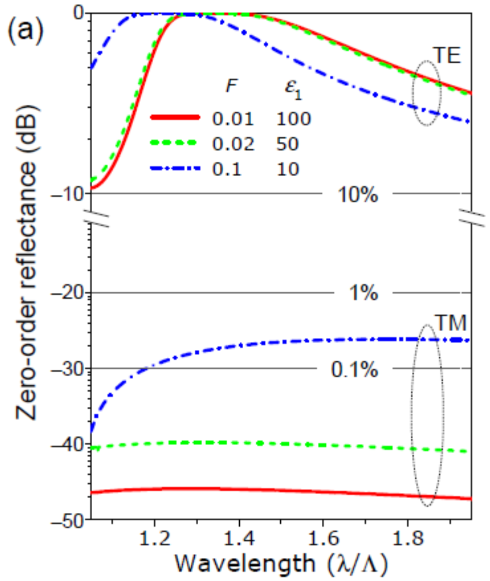
Modeling Task



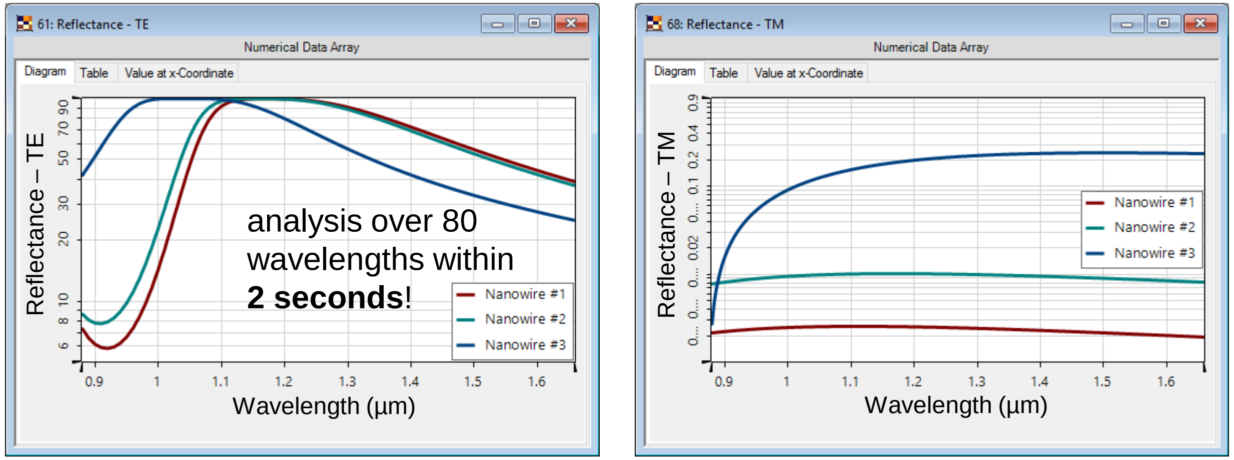
Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Results

- Reflectance vs. wavelength for different structures



reference results from J. W. Yoon *et al.*, Opt. Express **23**, 28849-28856 (2015)

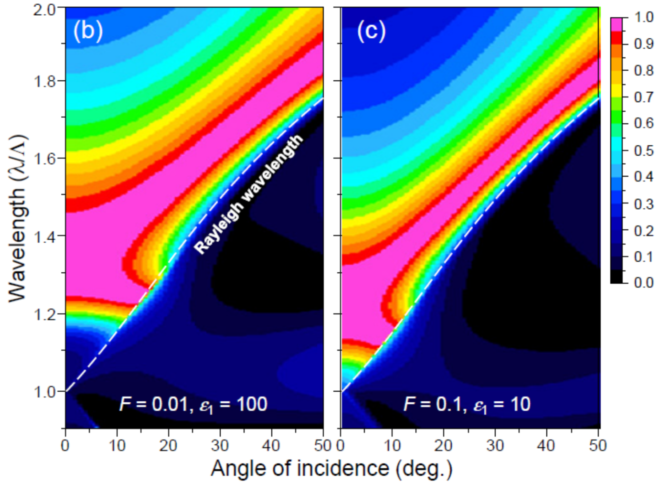


Fourier modal method (FMM) simulation in VirtualLab

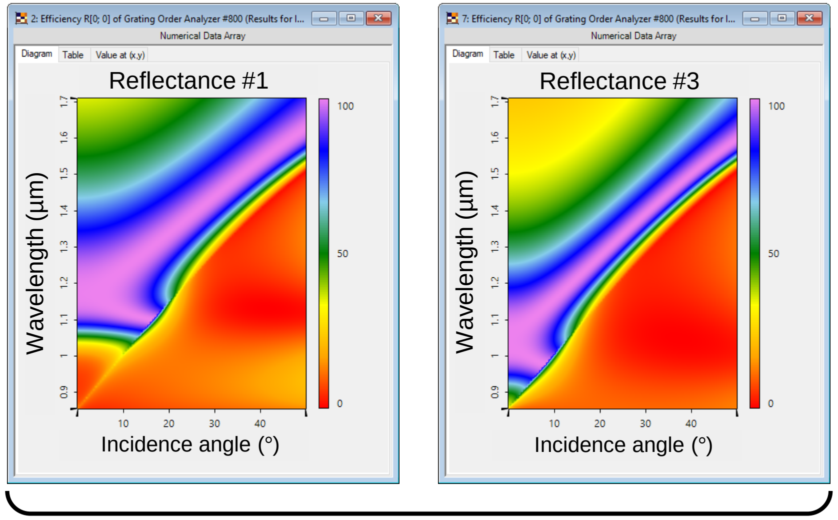
Nanowire No.	**#1**	**#2**	**#3**
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Results

- Reflectance vs. wavelength & incident angle



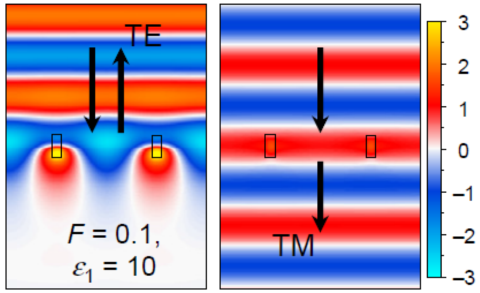
reference results from J. W. Yoon *et al.*, Opt. Express **23**, 28849-28856 (2015)



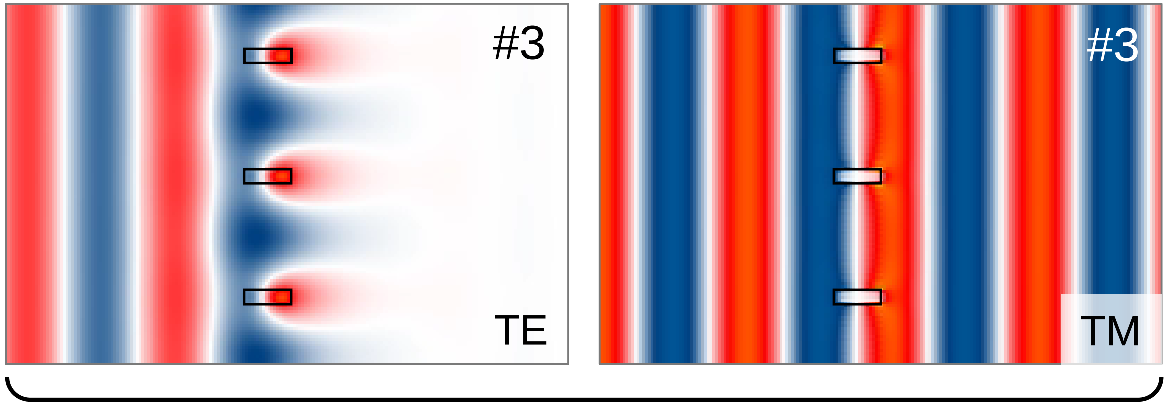
Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

Results

- Visualization of fields inside a nanowire grid



reference results from J. W. Yoon *et al.*, Opt. Express **23**, 28849-28856 (2015)



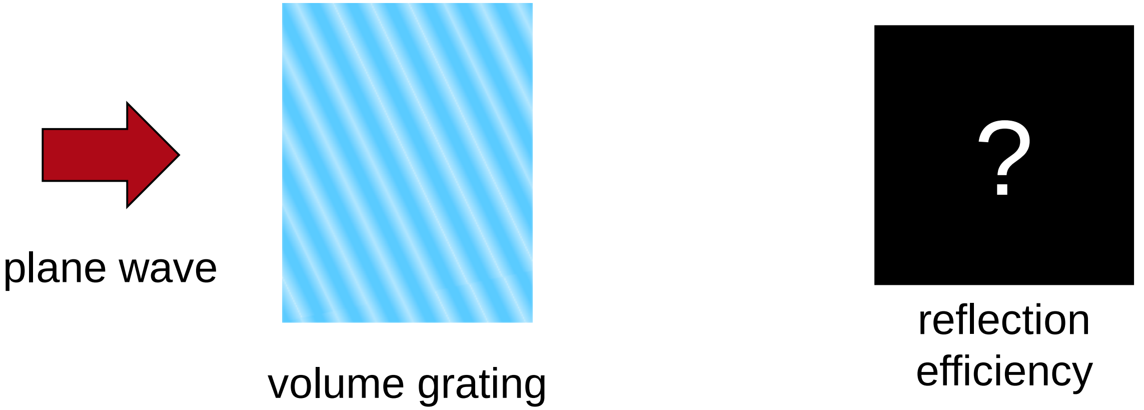
FMM simulation in VirtualLab (animation)

Nanowire No.	#1	#2	#3
refractive index *n*	10	7.07	3.16
height *h*	269 nm	270 nm	292 nm
filling factor *F*	0.01	0.02	0.1

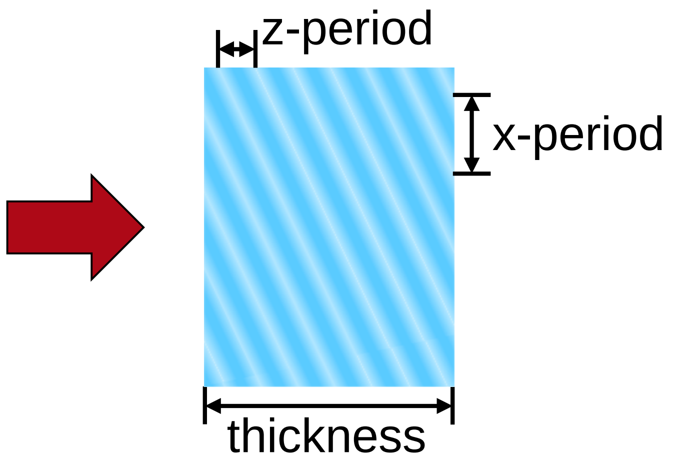
Imaging Systems > Inclusion of Gratings

Rigorous Simulation of Holographic generated Volume Grating

Task/System Illustration

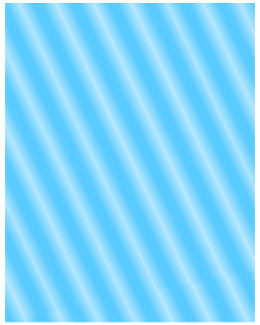


Specification: Volume Grating

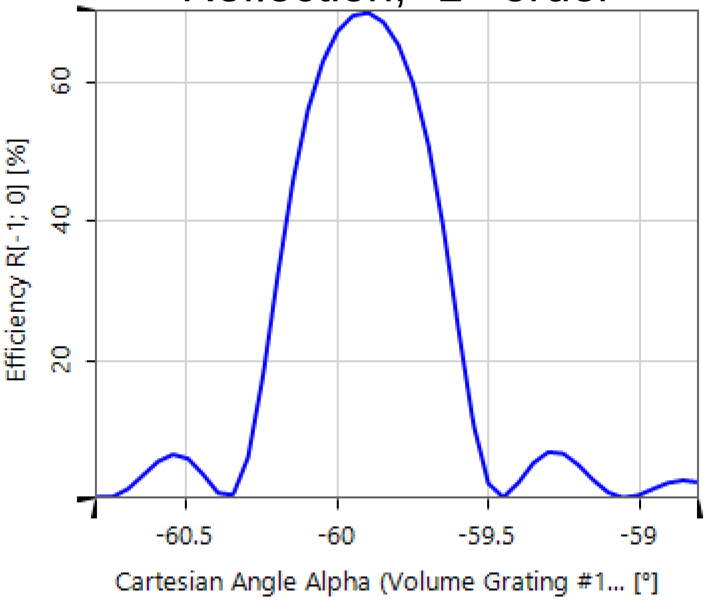


Parameter	Description / Value & Unit
type	holographic generated
index modulation	0.01 (increased due to exposure)
thickness	70 µm
period in x-direction	507.6 nm
period in z-direction	292.5 nm
tilt of modulation	59.9°

Result: Angular Dependency of Reflection

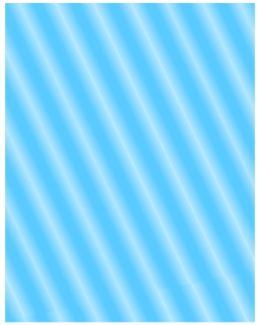


Reflection, -1st order

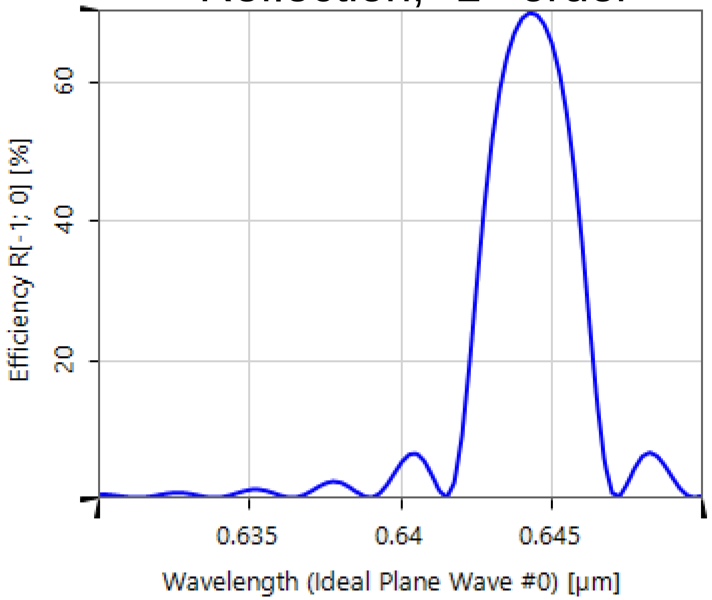


shift of angular dependent reflection due to holographic interference angle of 59.9°

Result: Wavelength Dependency of Reflection



Reflection, -1st order



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

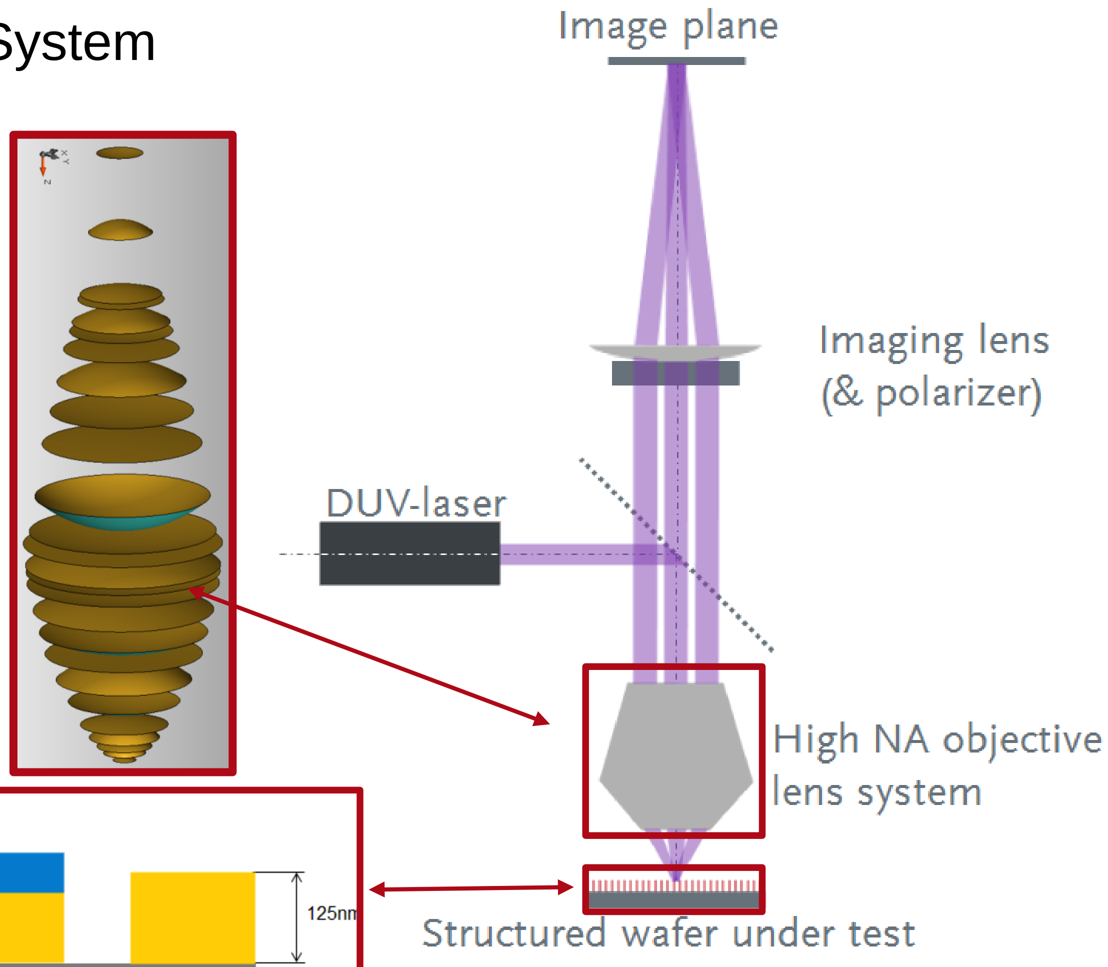
Fields in Focal Regions

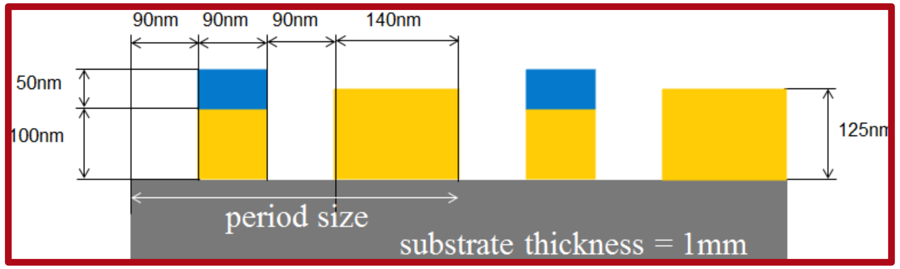
Example Wafer inspection system

Example of Multi-scale Optical System

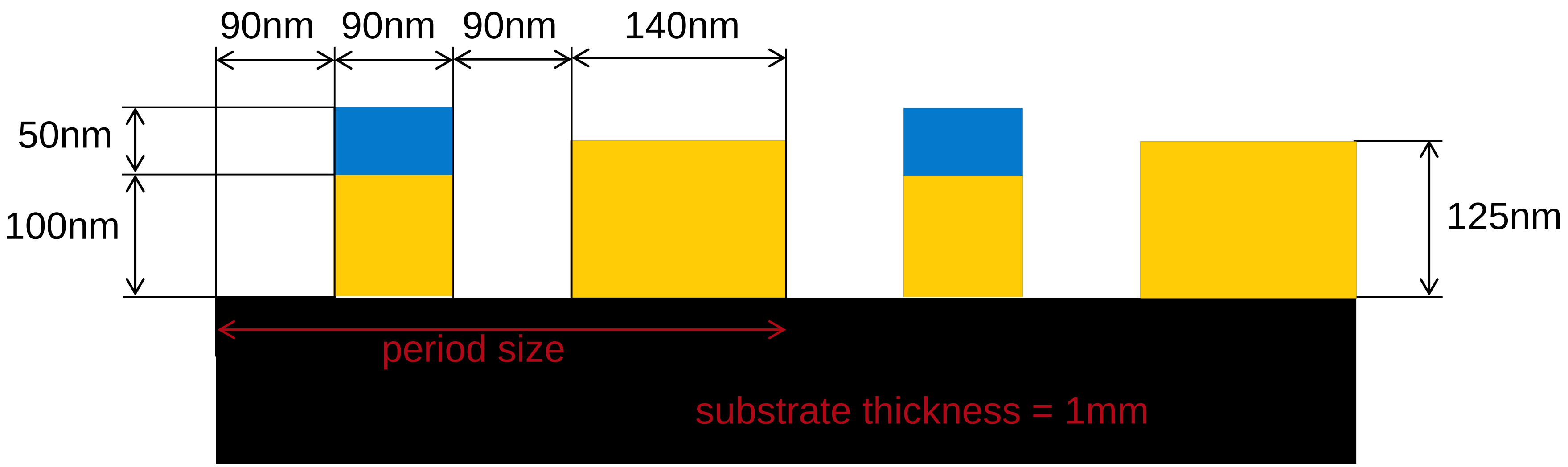
Example: Wafer Inspection System

Complex macroscopic high NA imaging lens system and microscopic grating structure (integrated circuit wafer structure) in one optical setup. Simulation results can be found in Scenario 515



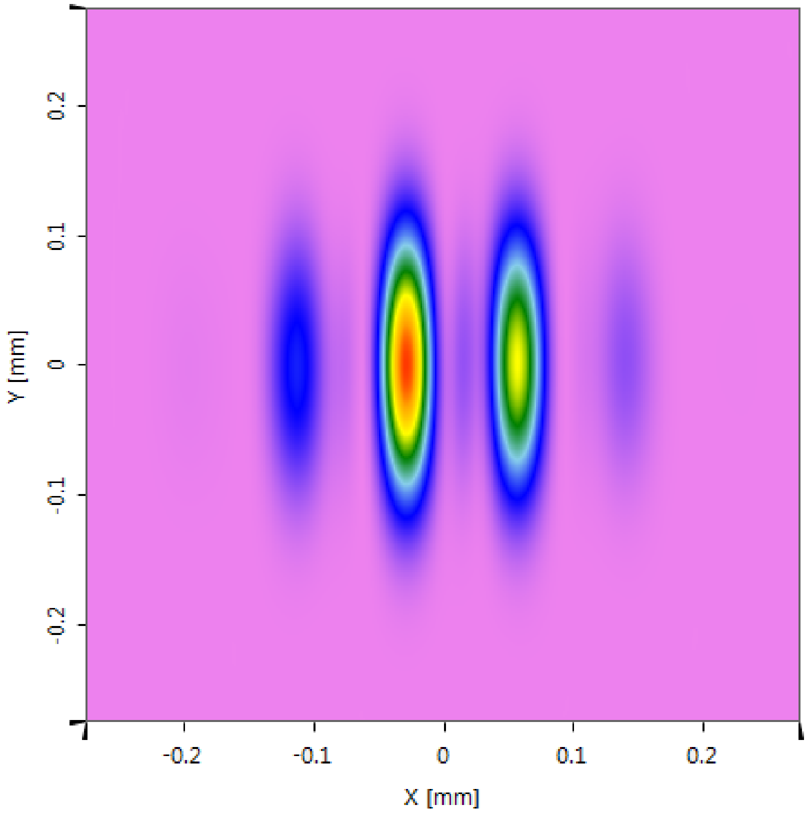


Base Grating Structure

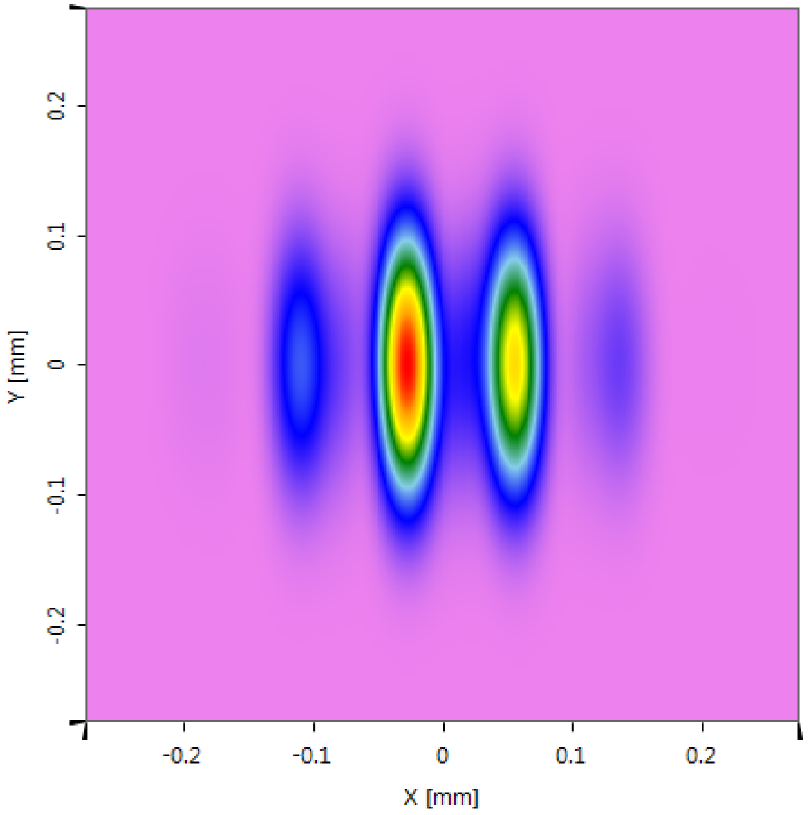


Base Structure Analysis

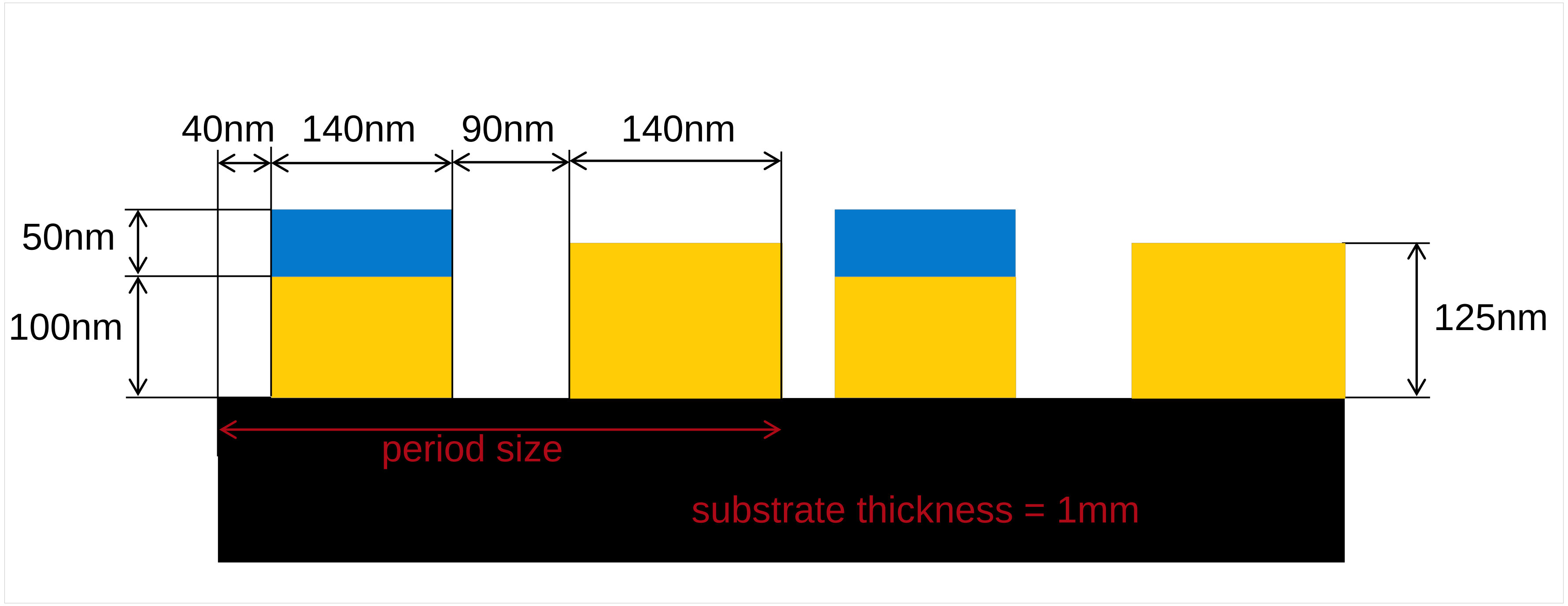
Intensity Image of Grating after Polarizer in X-Direction



Intensity Image of Grating after Polarizer in Y-Direction

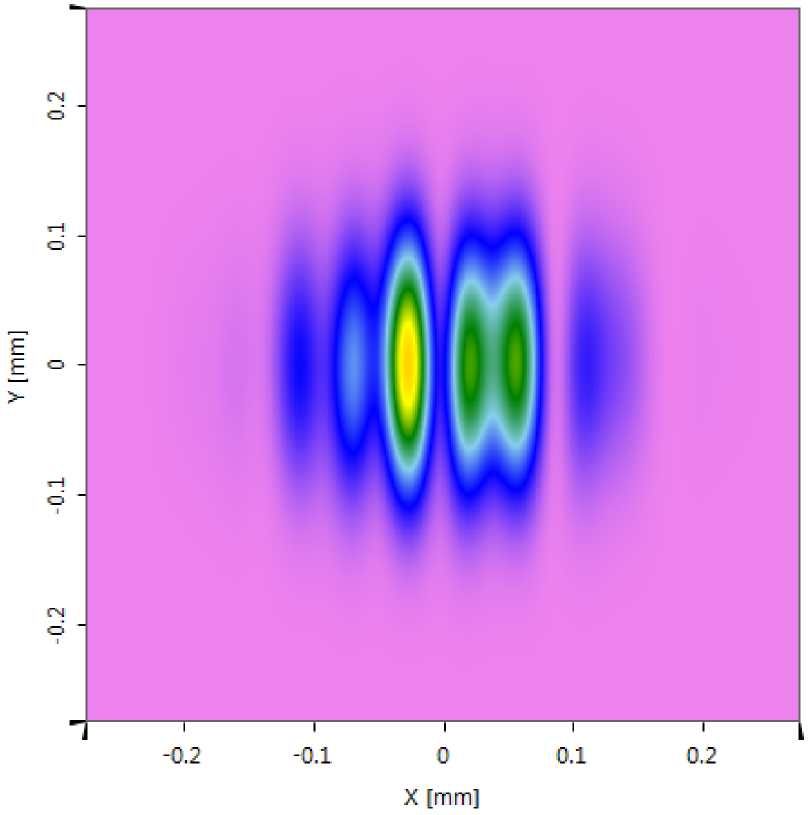


Modified Grating Structure

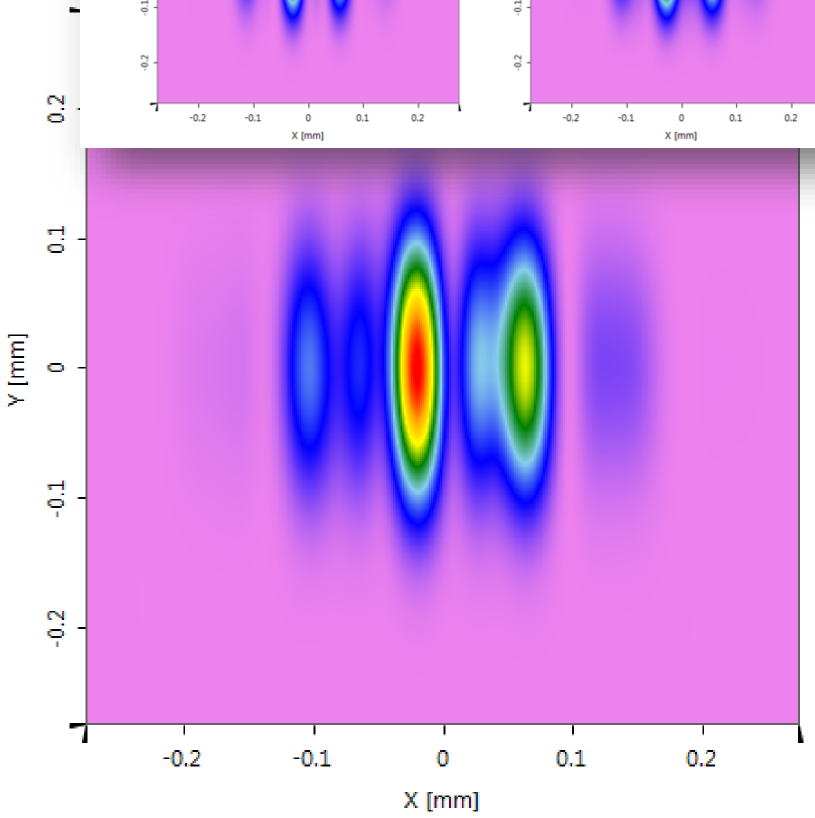


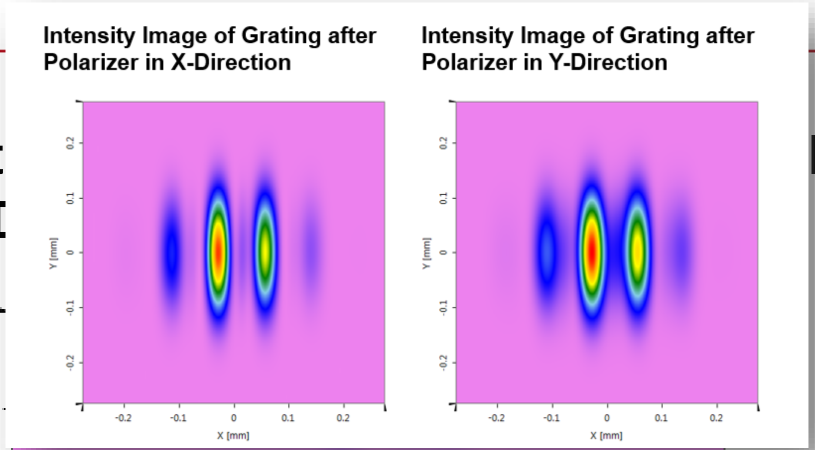
Modified Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction



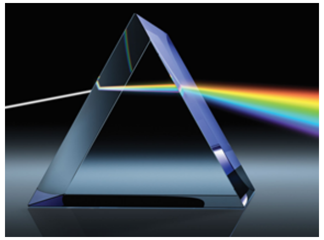
Int larizer in Y-D

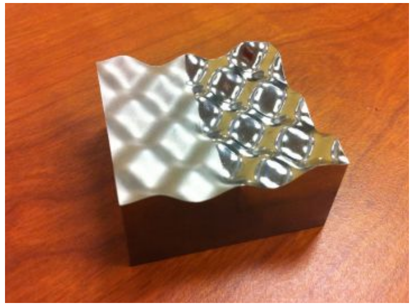




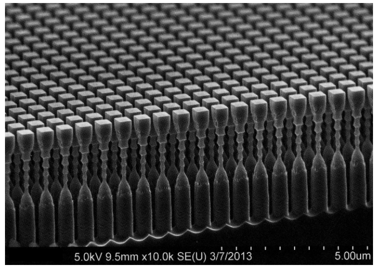
Optical Components

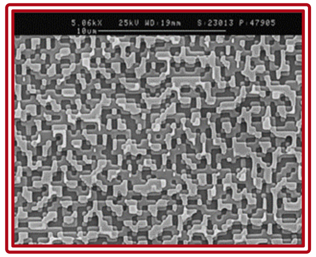
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

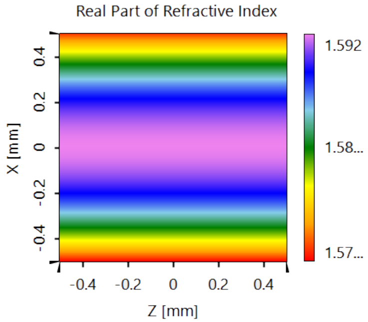


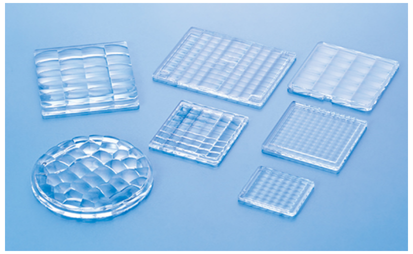


[1] IMS-Mechatronics Lab

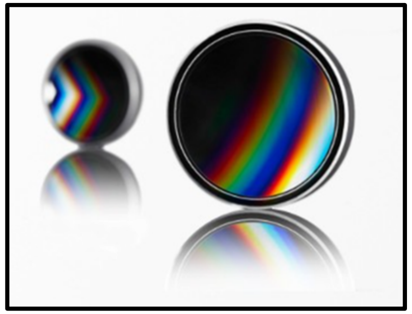








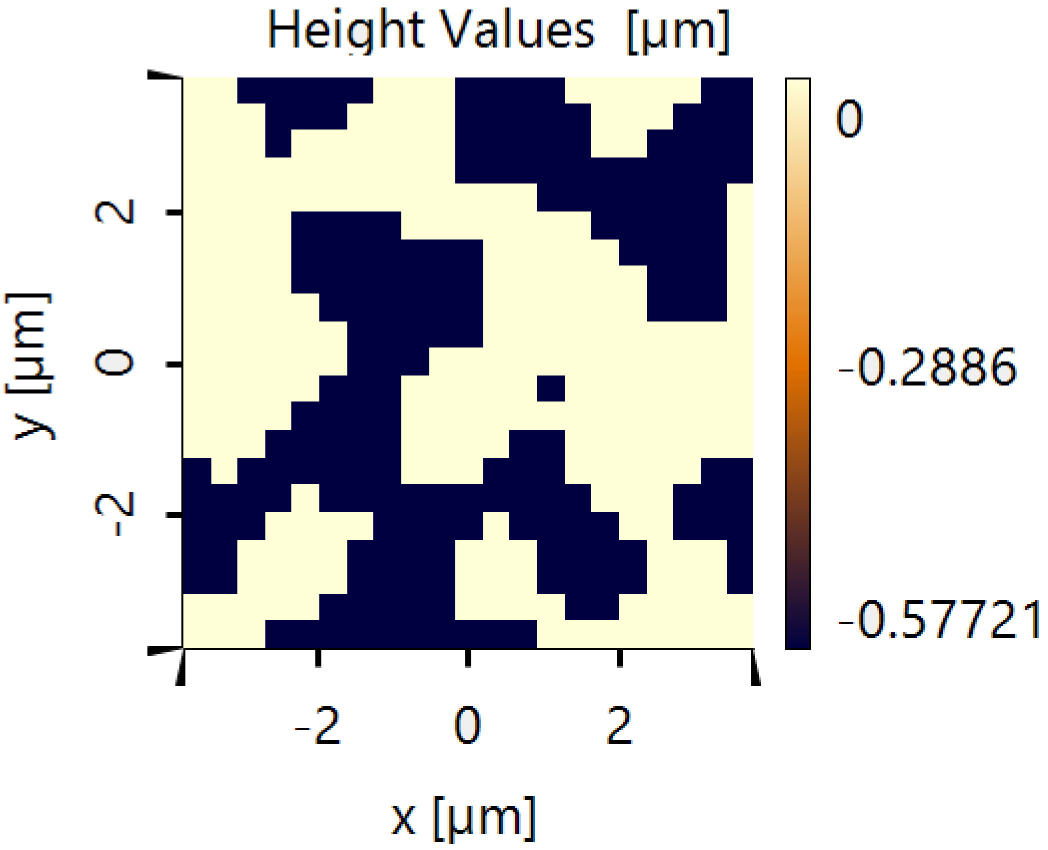
[2] ISUZU GLASS



Nutshell (Hartwig Crailsheim v0.2)

Analysis of Sub-Wavelength Beam Splitter Structure with Approximated, Rigorous and Semi-Rigorous Method

Light, Structure & Analysis Methods



wavelength: 532 nm

Diffractive 1 : 7 × 7 Splitter

period: 7.56 μm

smallest feature size: 360 nm

on-axis order separation: ~4°

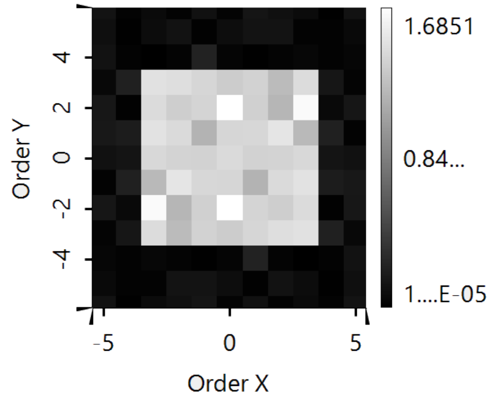
Analysis Methods

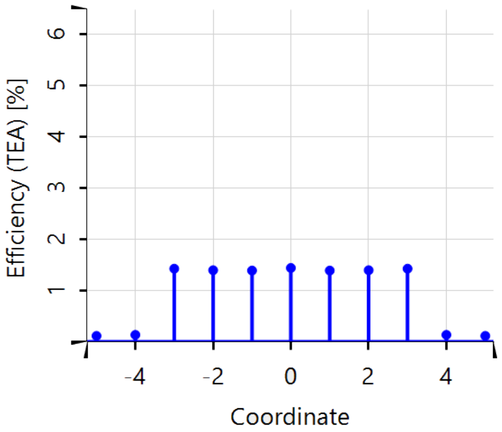
- Thin Element Approximation (**TEA**)
- Rigorous Fourier Modal Method (**FMM**)
- Semi Rigorous **Split Step** Method (with Periodic Boundary Conditions?)

Analysis Results

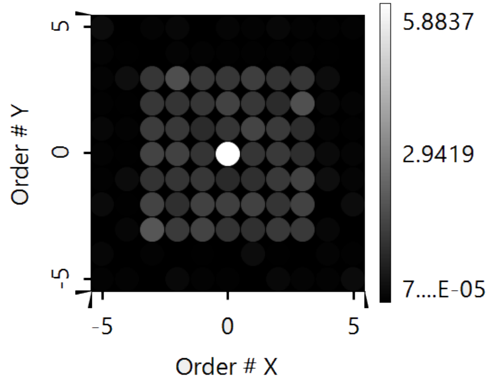
TEA	FMM	Split Step

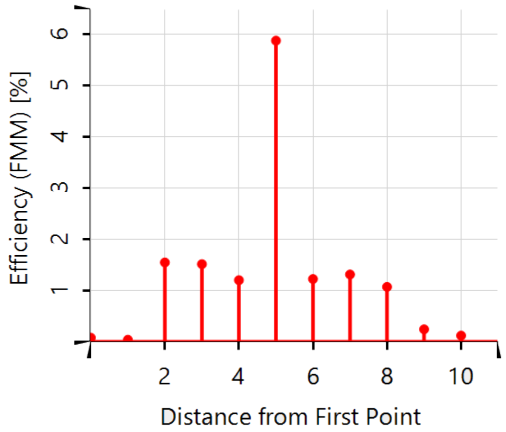
TEA



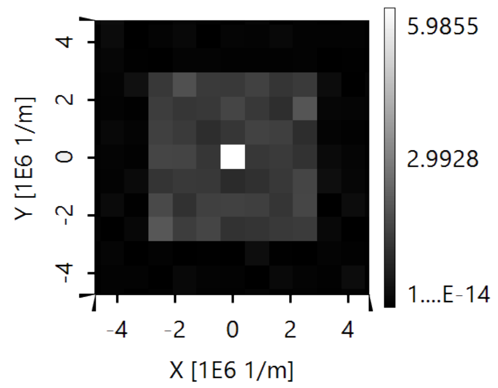


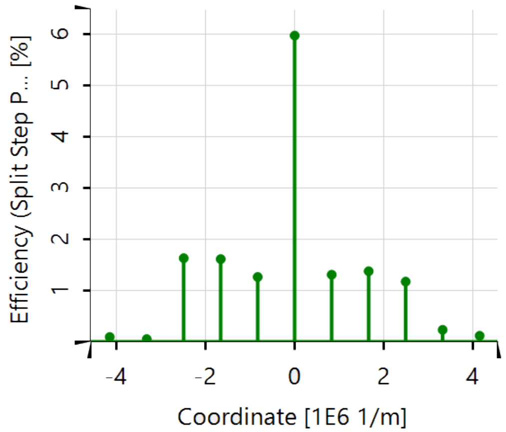
FMM





Split Step





Computation Time of Efficiencies	instantaneous	~6min	~15s

Result Compilation

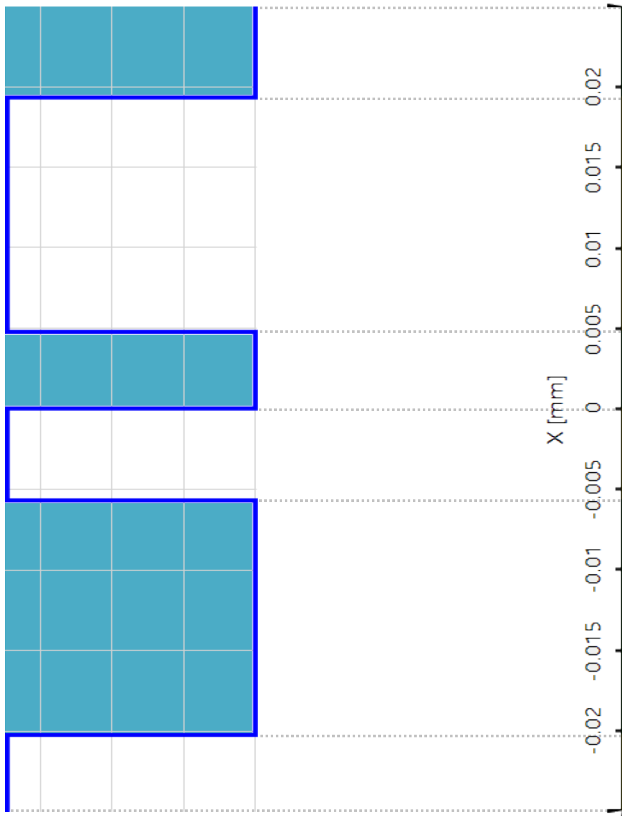
Field Inside

> Split Step & FMM

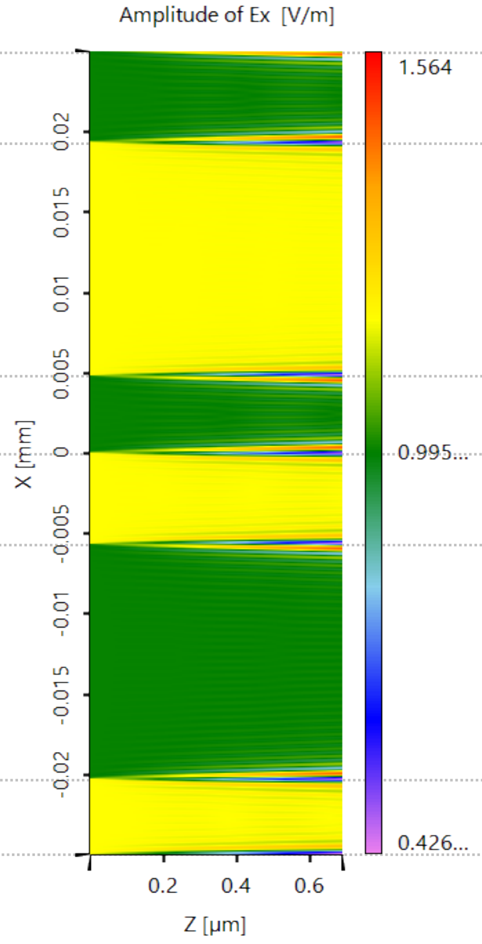
> Amplitudes

Period = 50µm; Smallest Feature = 4.7410µm

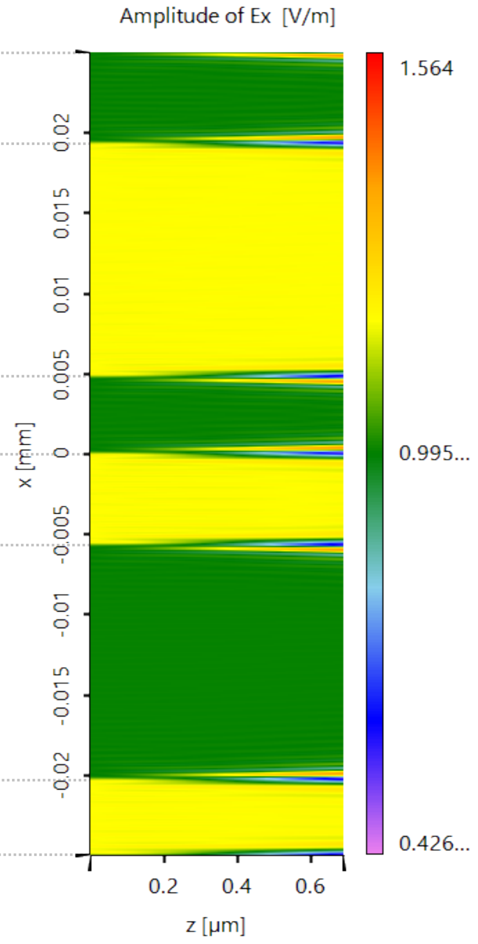
Structure Height Profile



Split Step

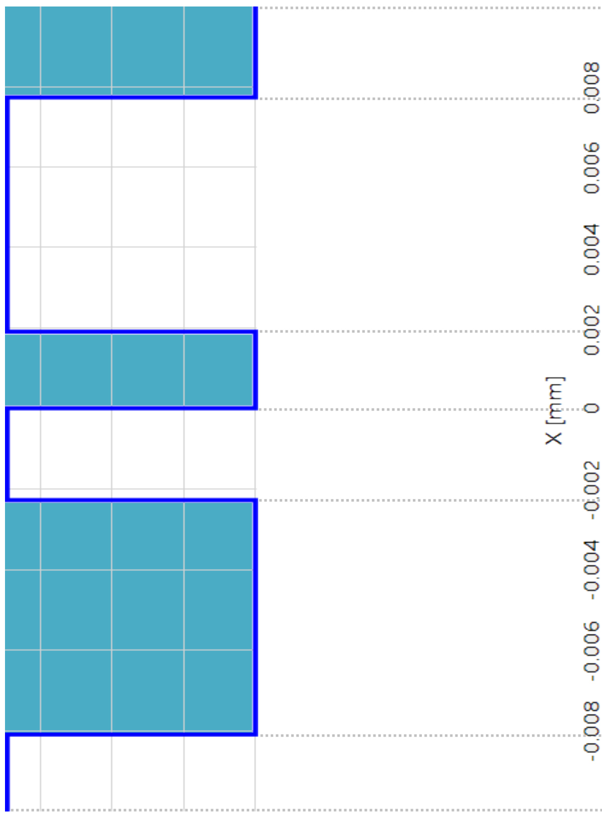


FMM

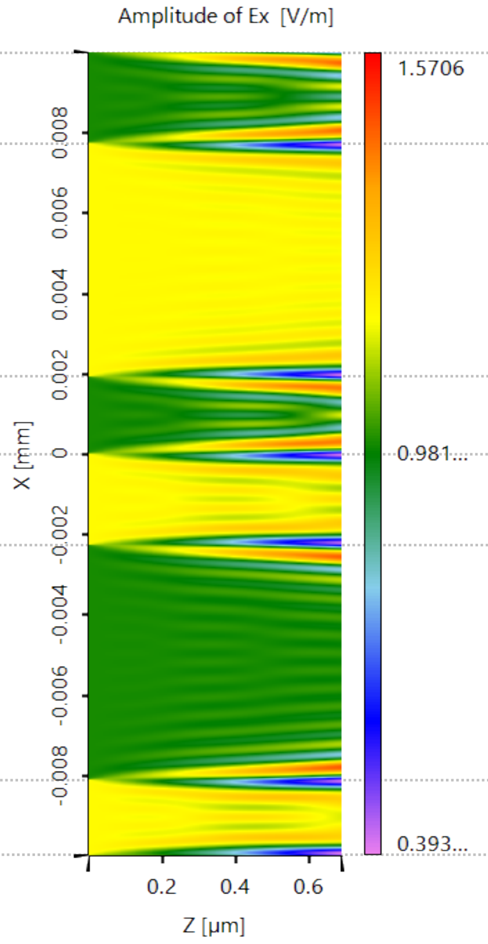


Period = 20µm; Smallest Feature = 1.8964µm

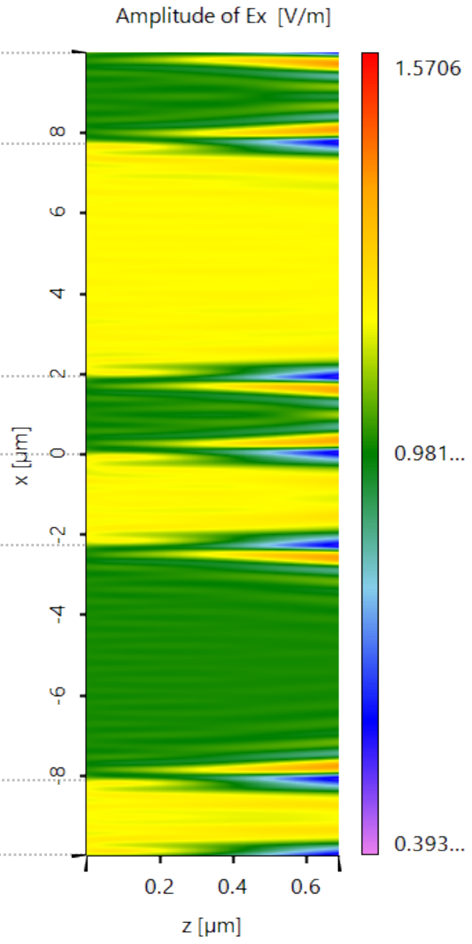
Structure Height Profile



Split Step

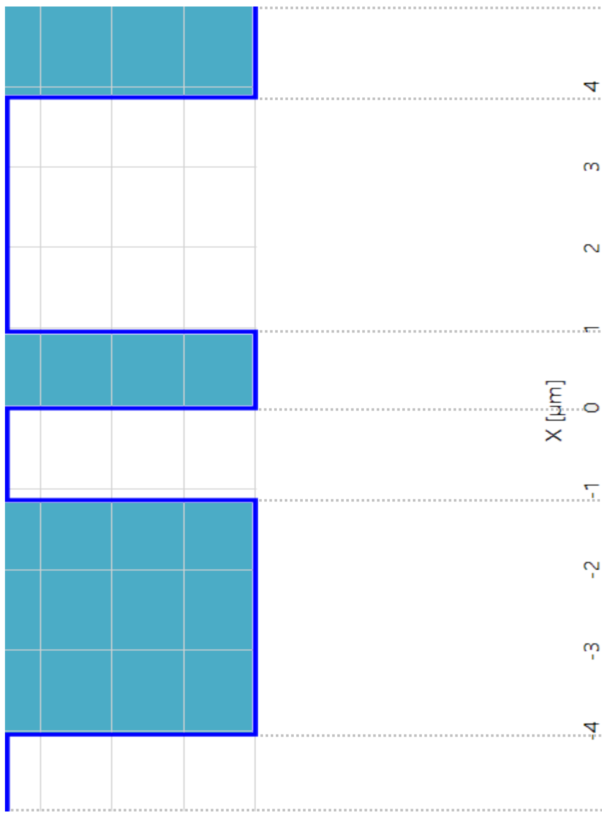


FMM

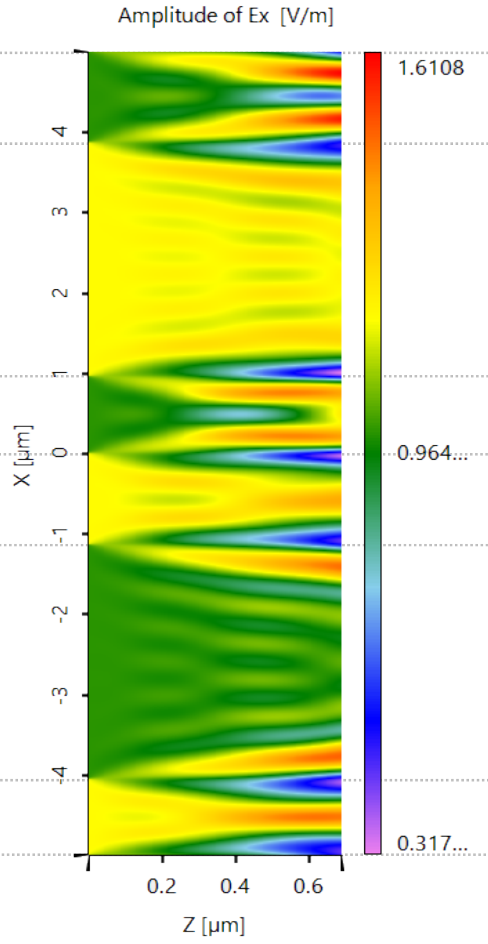


Period = 10µm; Smallest Feature = 0.9482µm

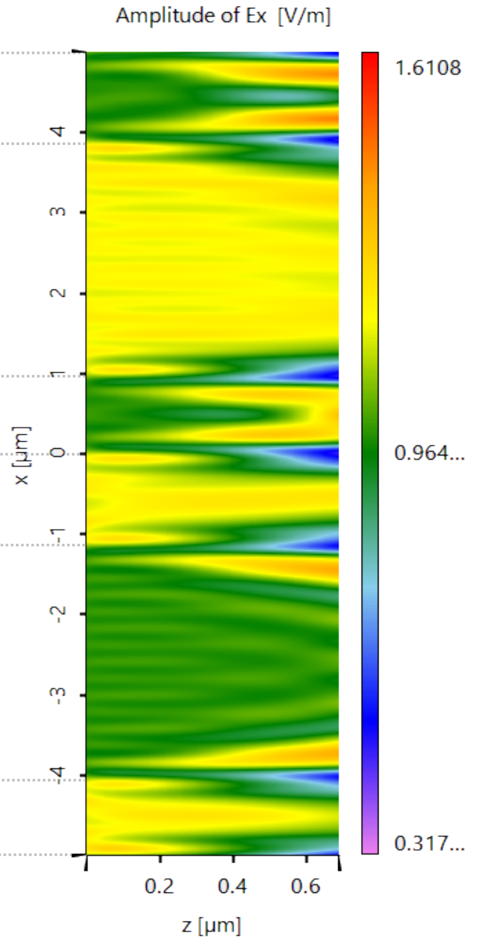
Structure Height Profile



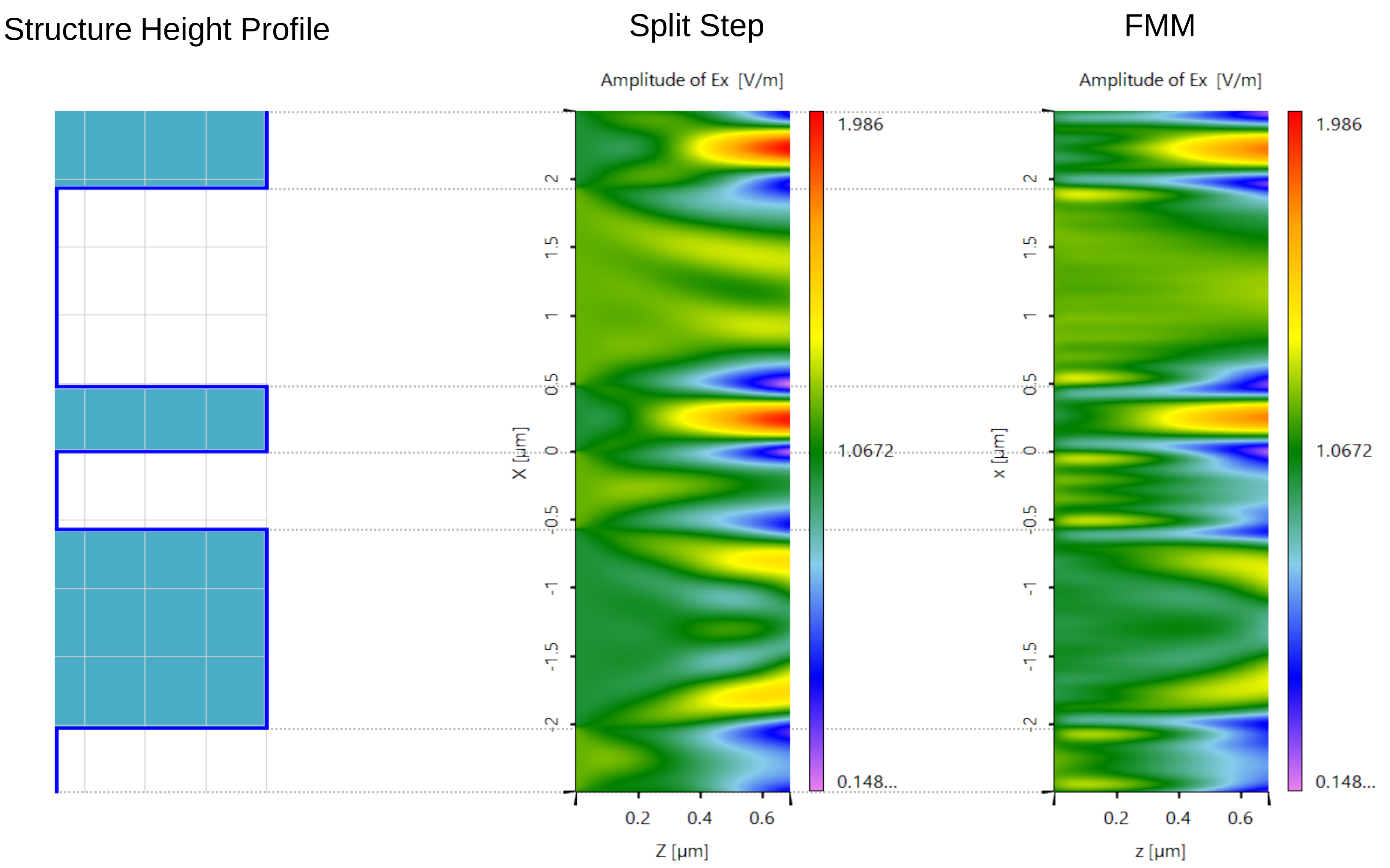
Split Step



FMM



Period = 5µm; Smallest Feature = 0.4741µm



Result Compilation

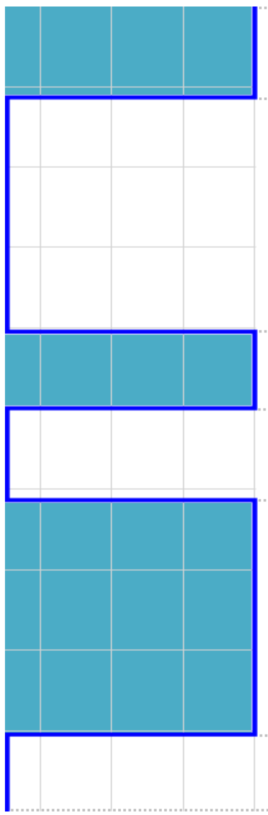
Field Inside

> Split Step & FMM

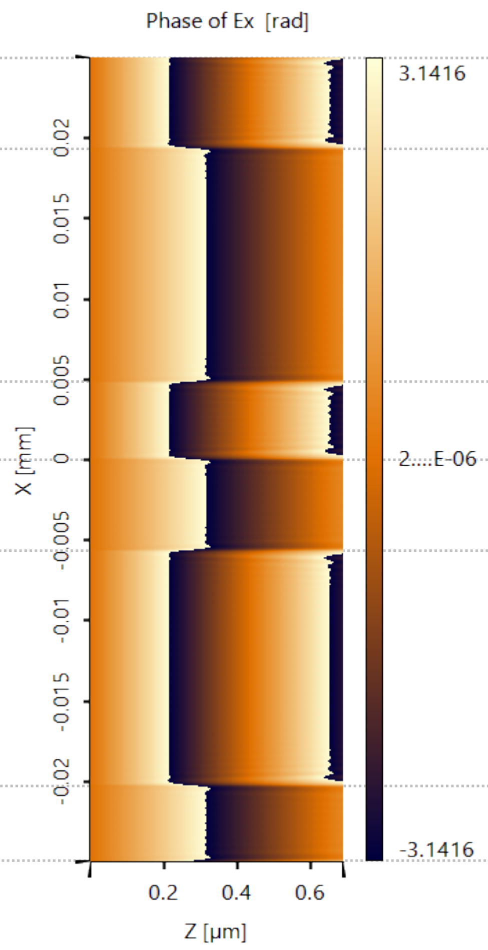
> Phases

Period = 50µm; Smallest Feature = 4.7410µm

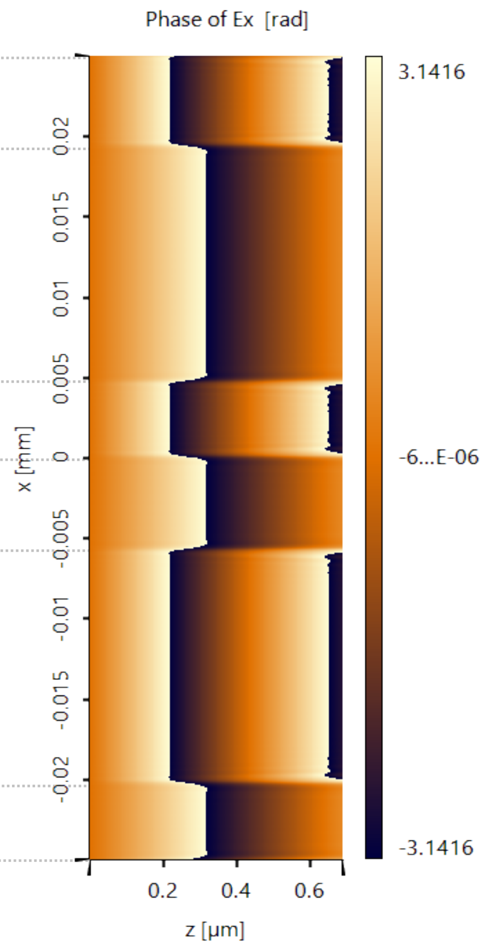
Structure Height Profile



Split Step

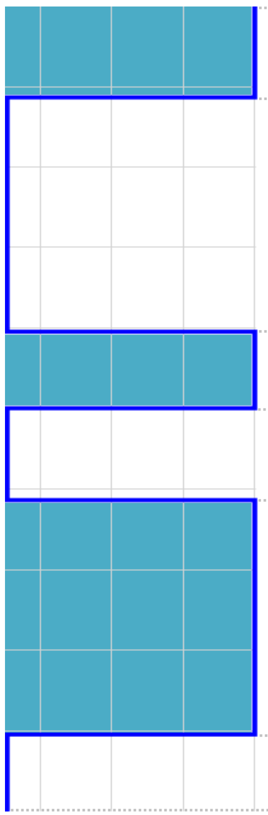


FMM

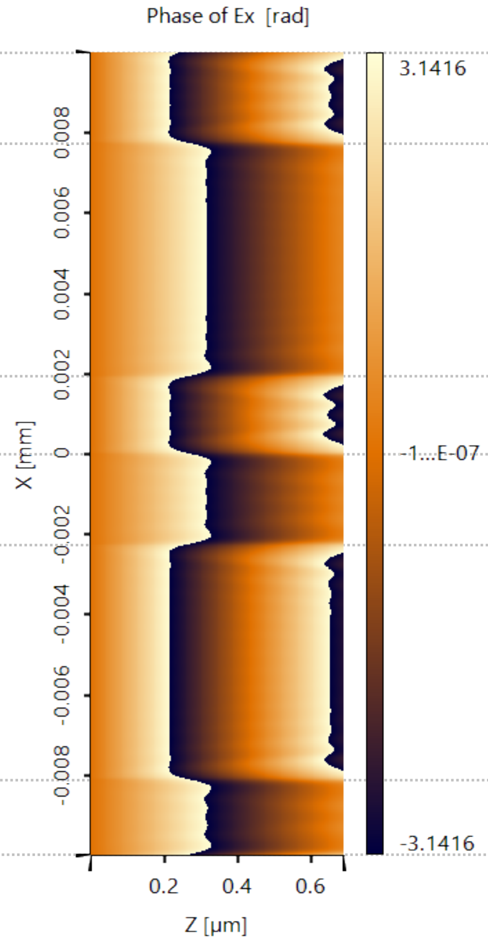


Period = 20µm; Smallest Feature = 1.8964µm

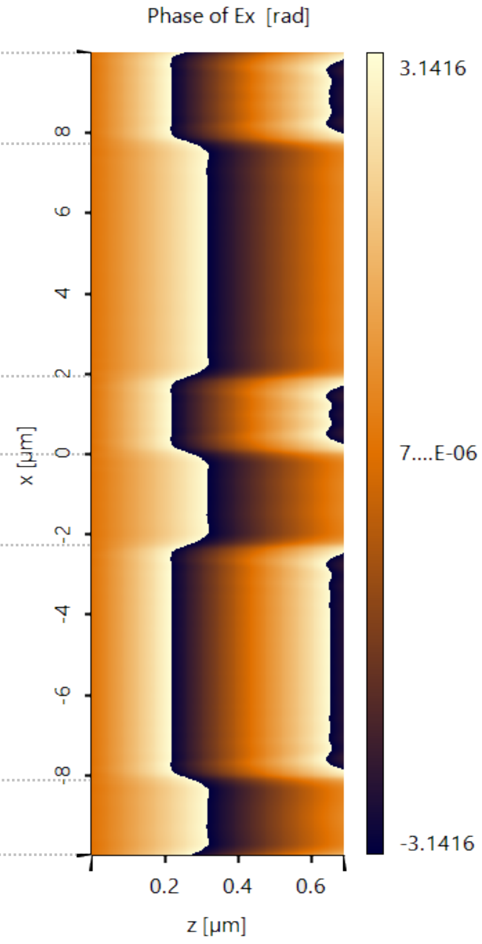
Structure Height Profile



Split Step

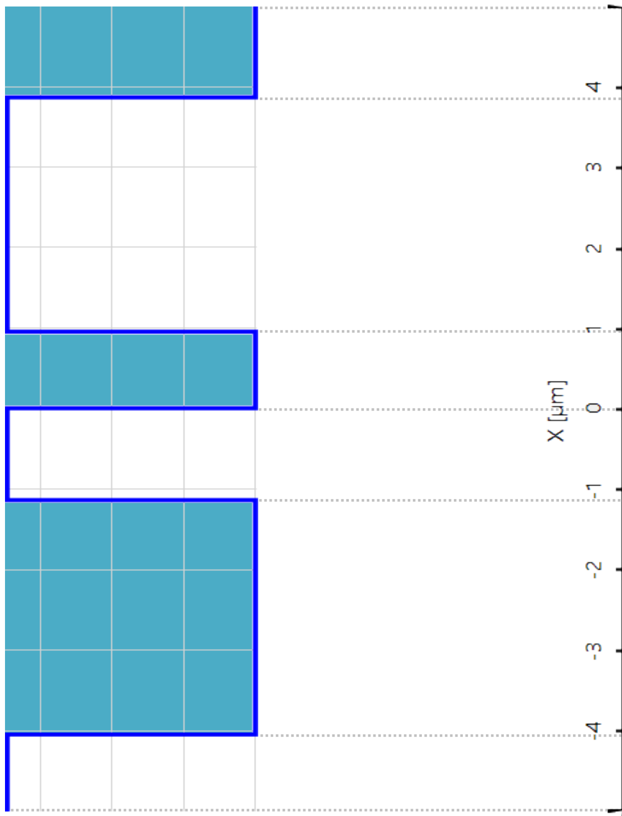


FMM

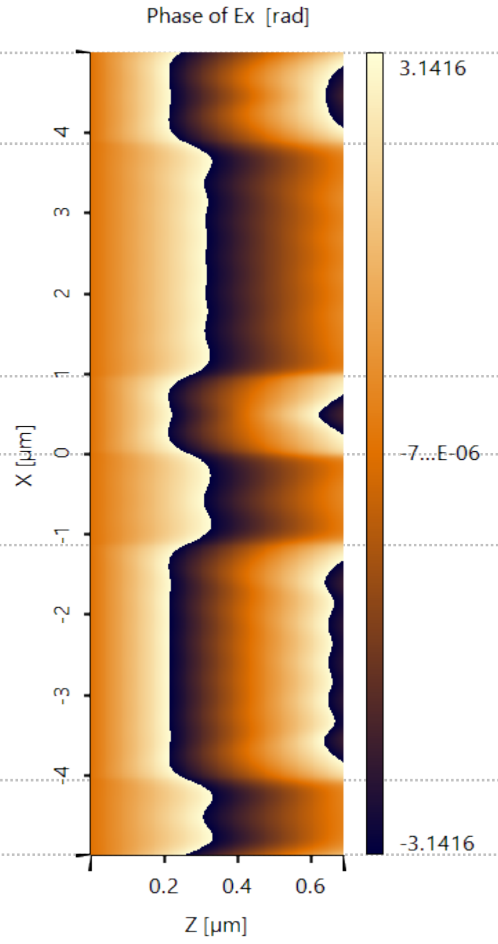


Period = 10µm; Smallest Feature = 0.9482µm

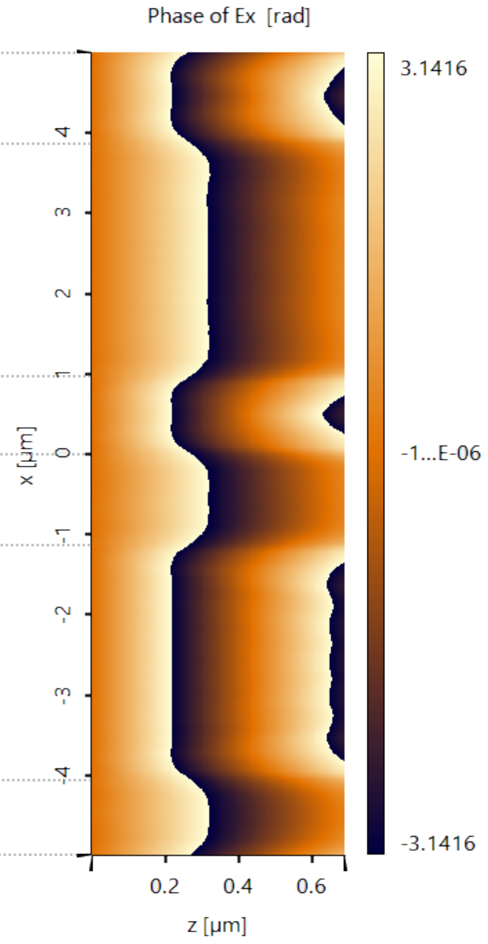
Structure Height Profile



Split Step

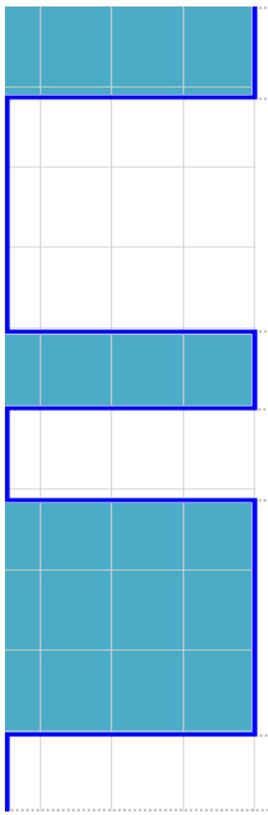


FMM

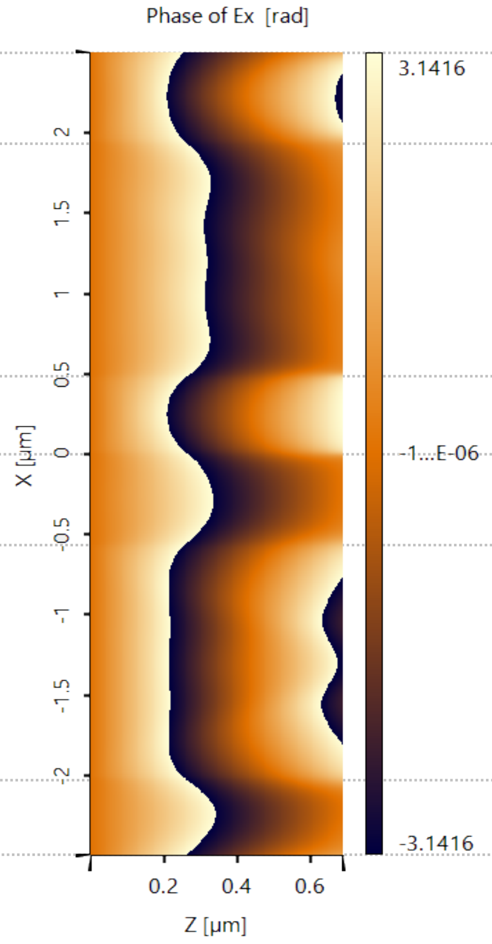


Period = 5µm; Smallest Feature = 0.4741µm

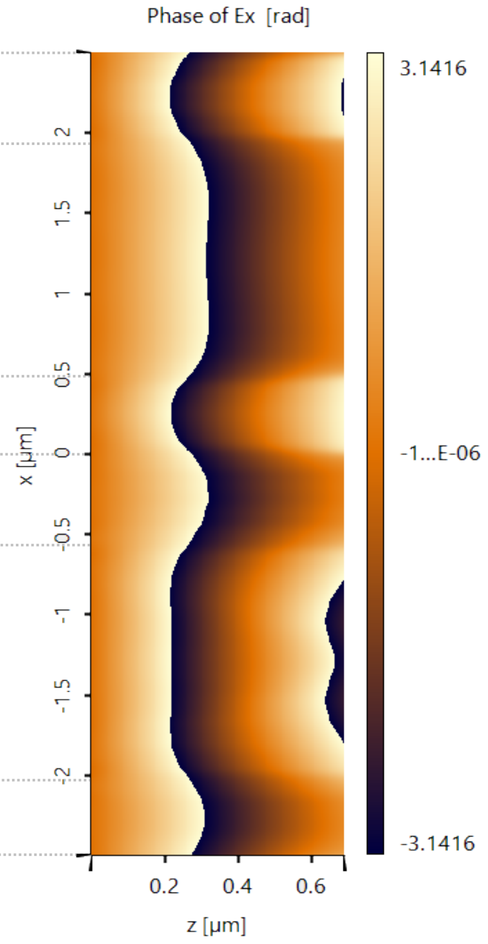
Structure Height Profile



Split Step



FMM



Result Compilation

Field Inside + Efficiencies

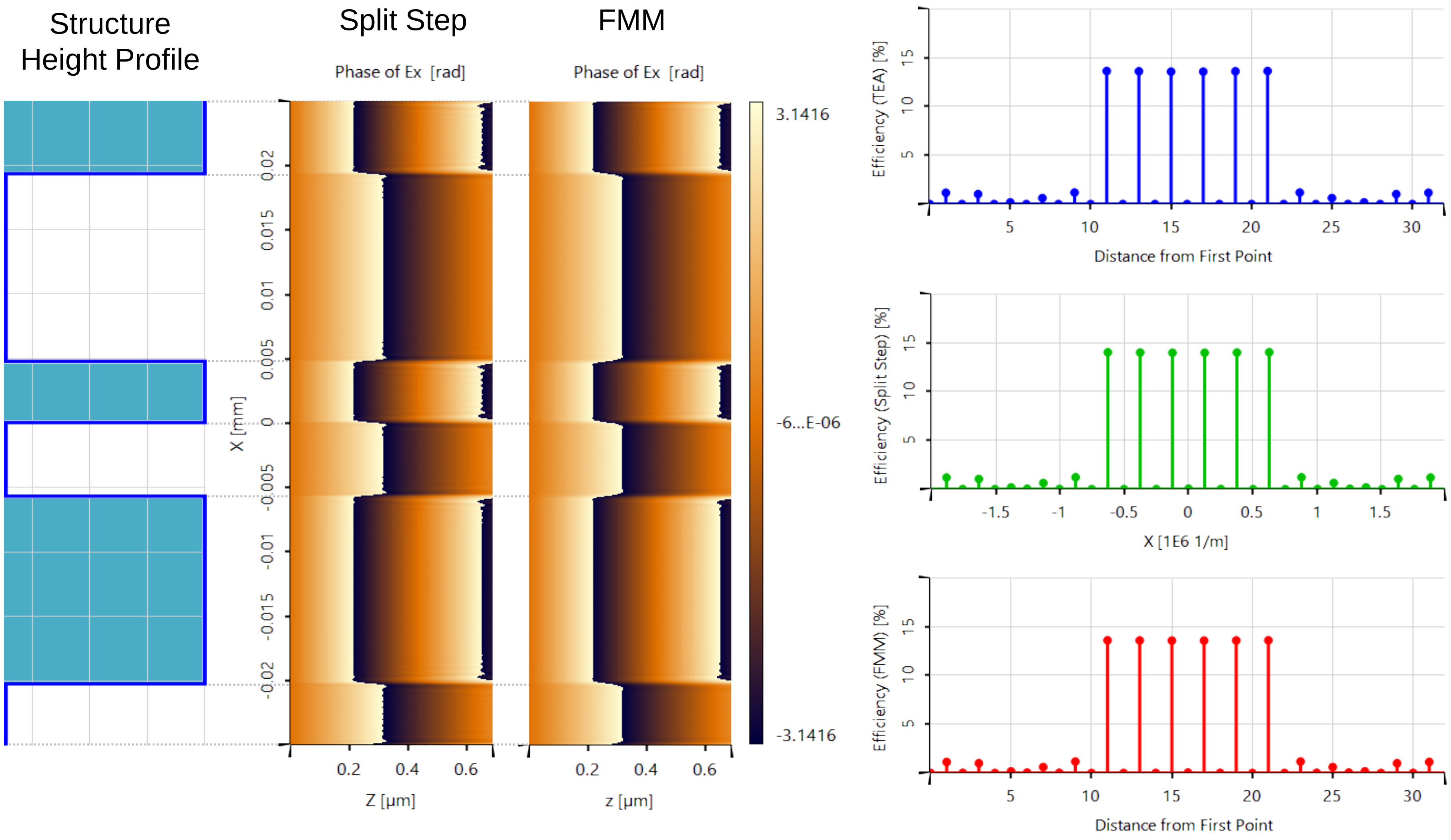
> Split Step & FMM

> Phases

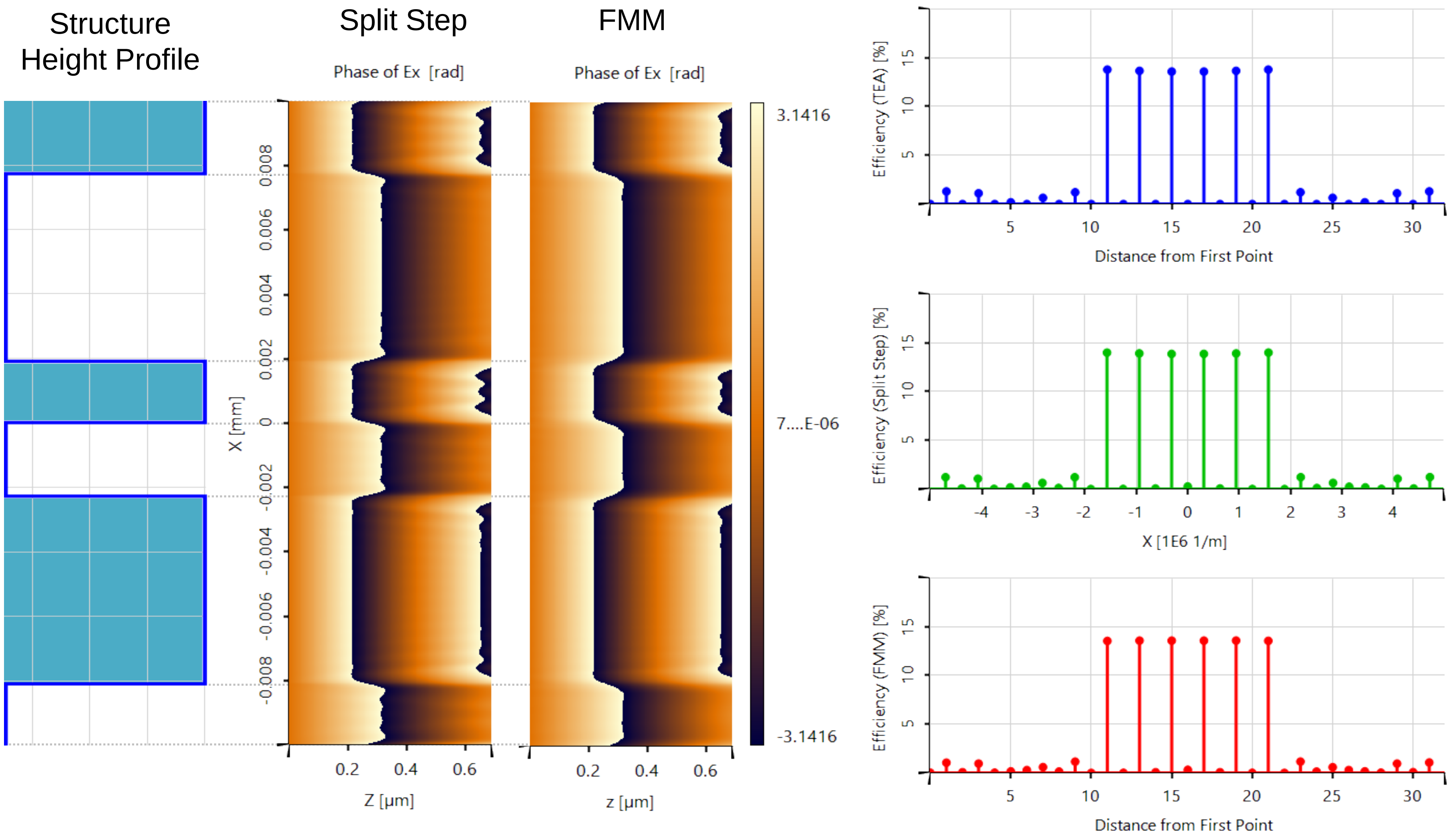
Efficiency Calculation

- For the calculation based on TEA and FMM, the Grating Toolbox was used.
- In case of the Split Step method the Starter Toolbox was used. But this analysis method is still in the investigational phase. E.g. the result evaluation has to be improved.

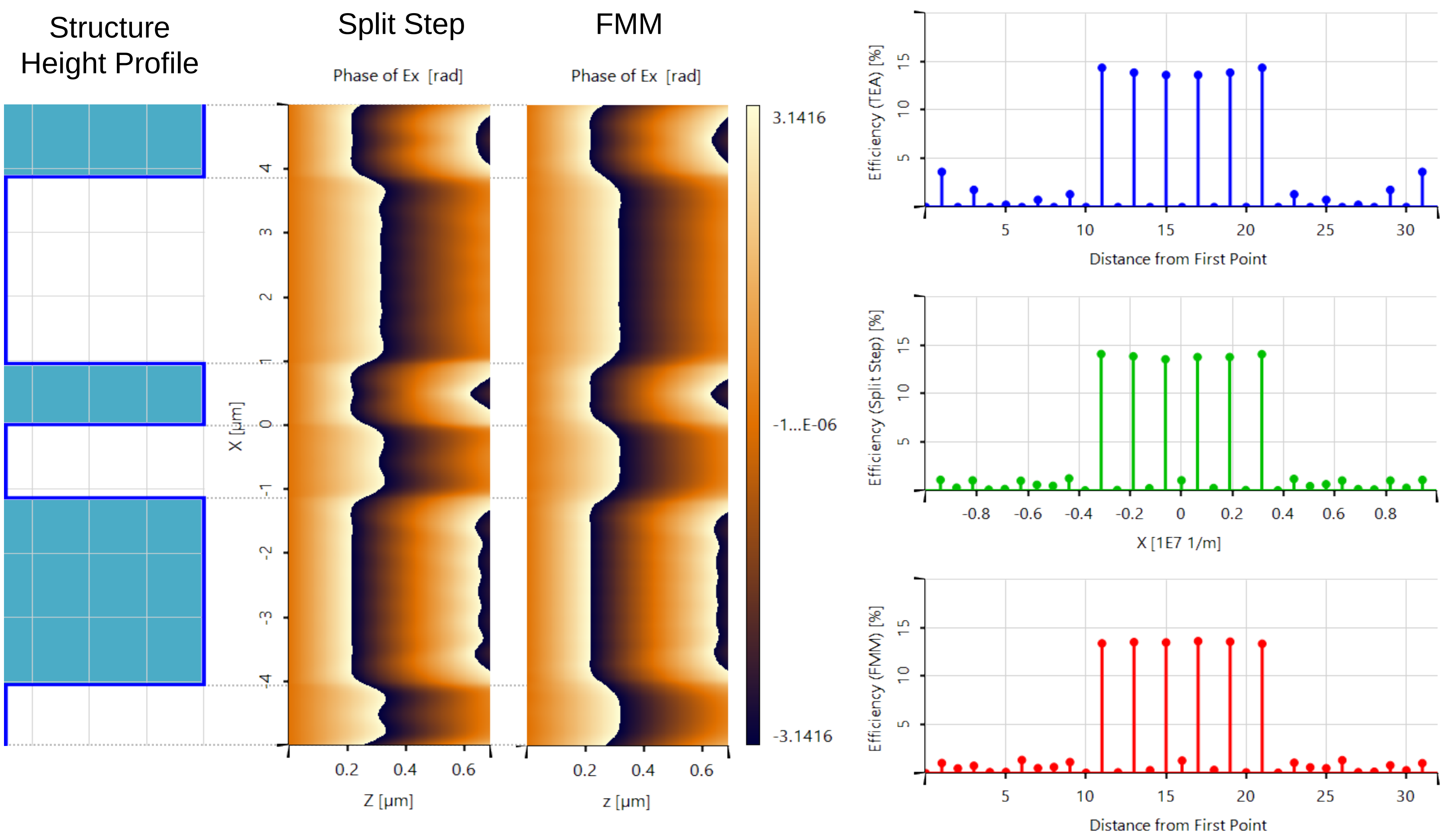
Period = 50µm; Smallest Feature = 4.7410µm



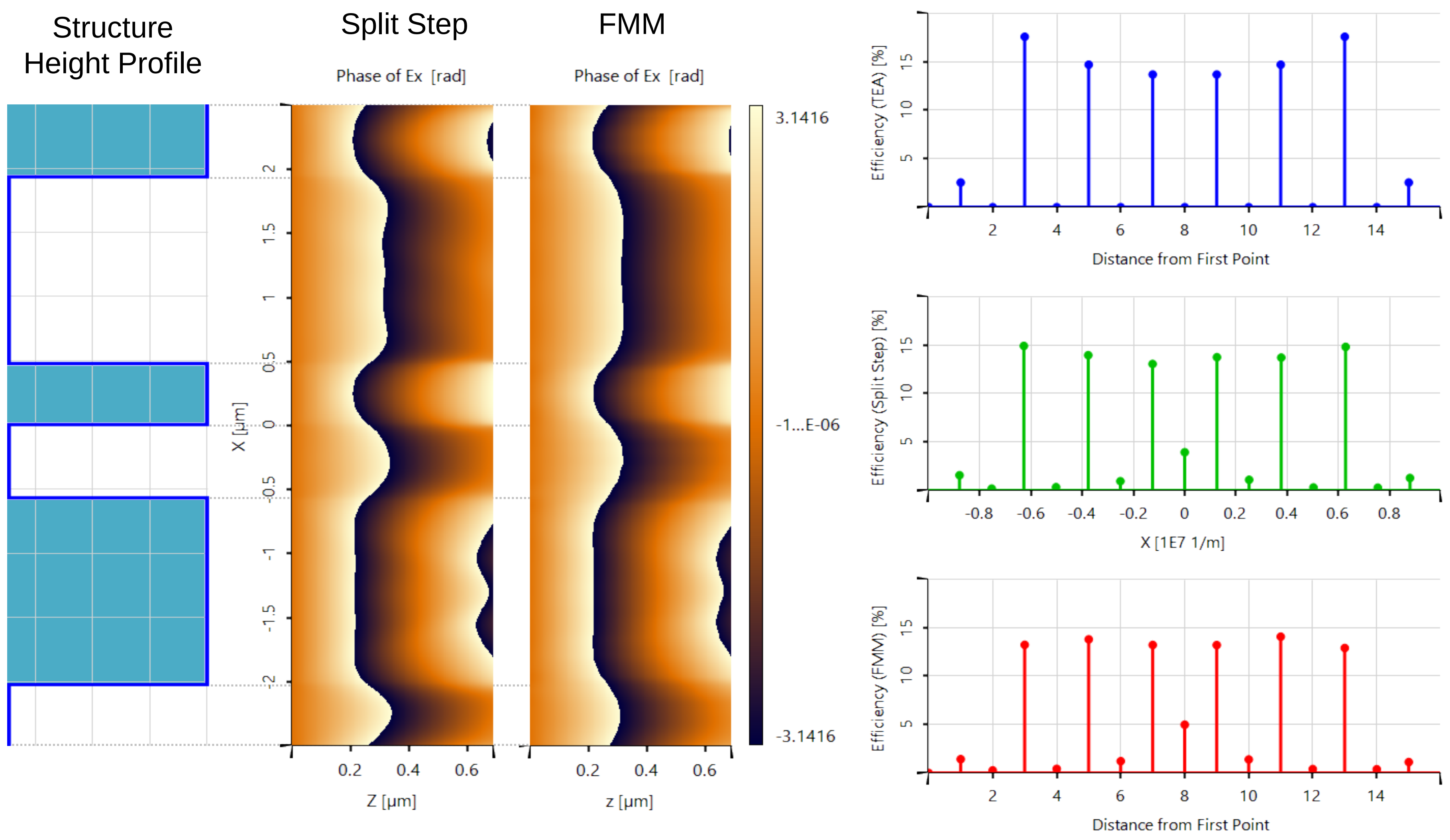
Period = 20µm; Smallest Feature = 1.8964µm



Period = 10µm; Smallest Feature = 0.9482µm



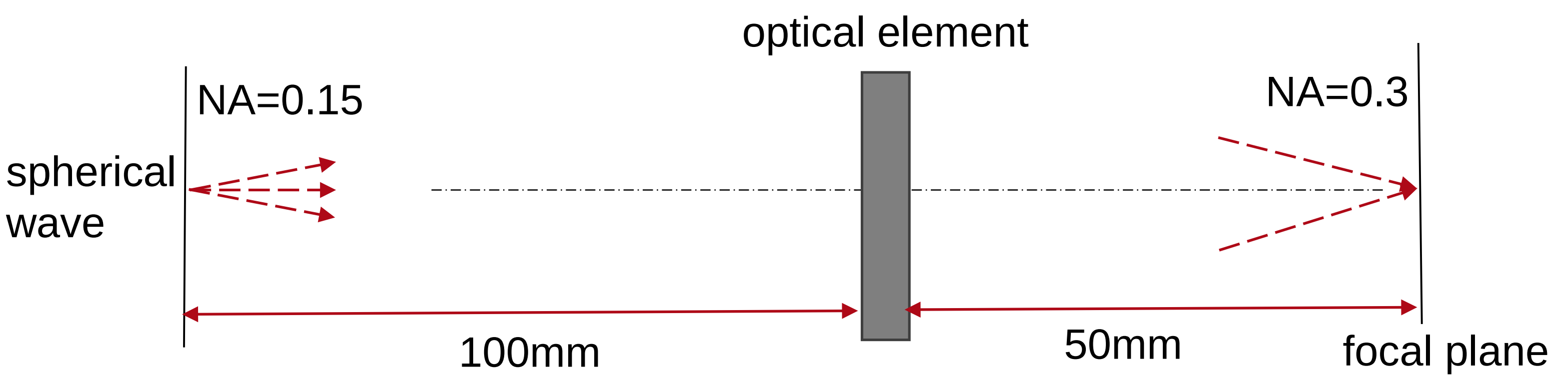
Period = 5µm; Smallest Feature = 0.4741 µm



Design and Modeling of a Diffractive Lens

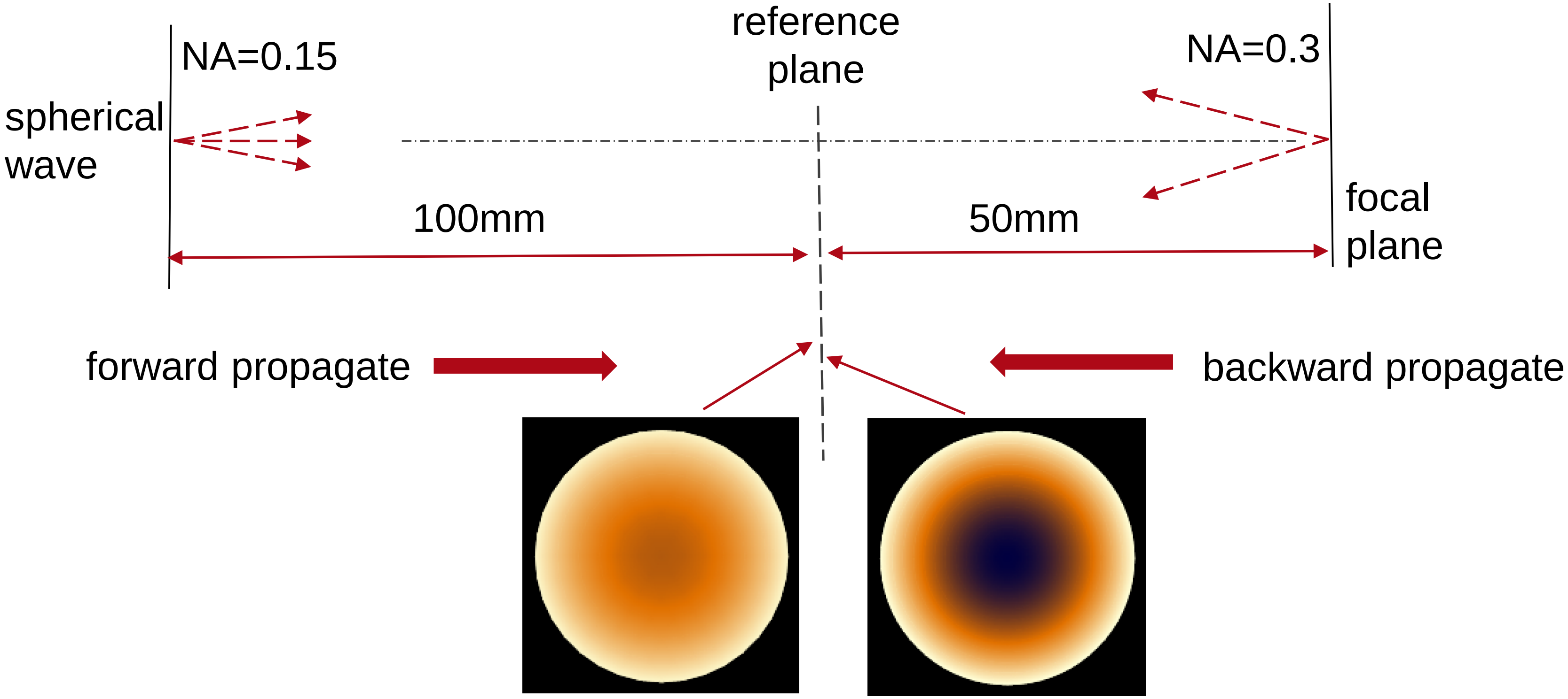
Based on Local Linear Grating Approximation (LLGA)

Task Description



- For a given input spherical wave, to design an optical element to focus the input beam with a specific numerical aperture (NA=0.3) and a required working distance (50mm).

Design Process: Functional Embodiment

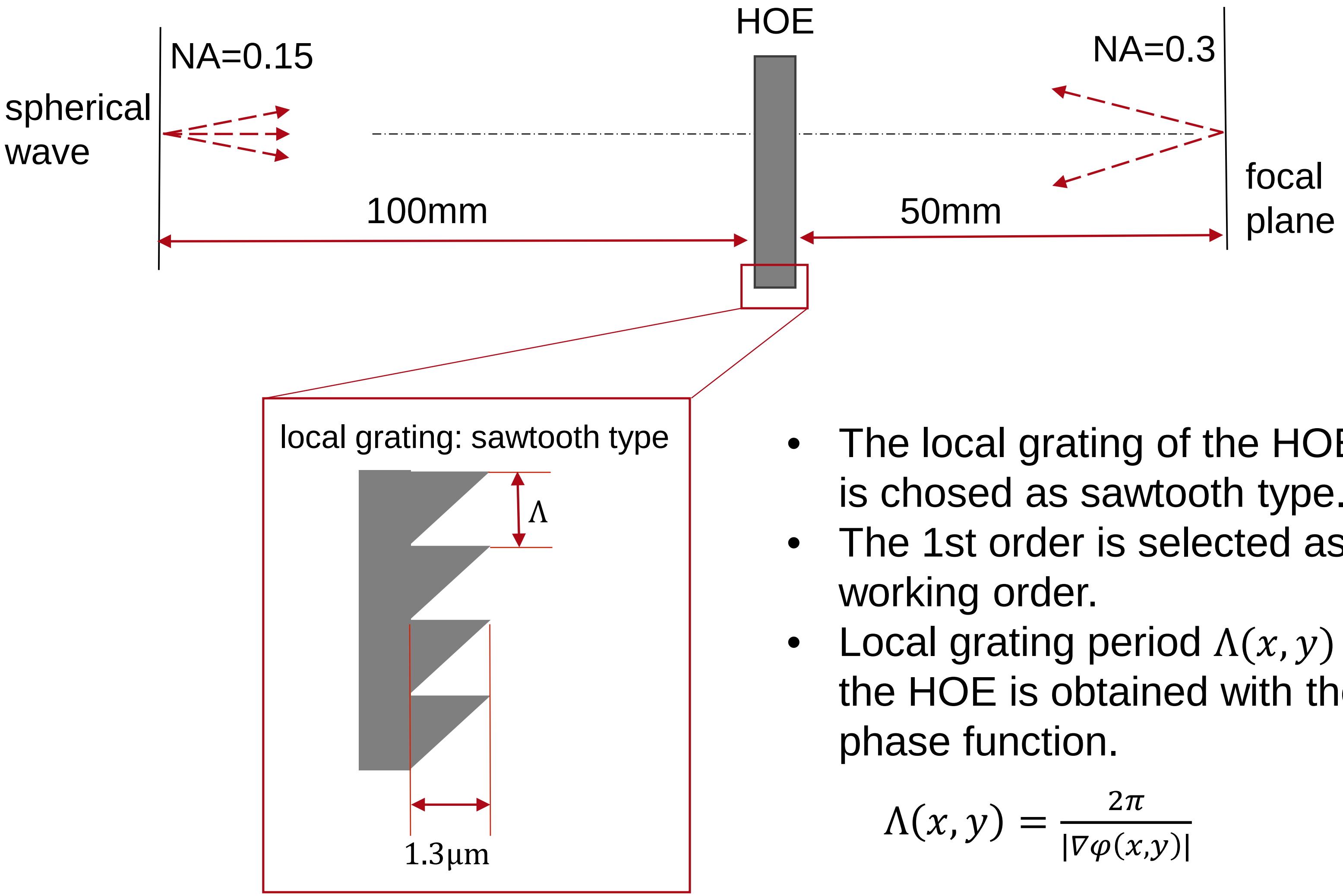


φ^{in}: phase from input field

φ^{out}: phase from output field

The element is consider as a phase only function, which is the subtraction of the phase from input and output field: $\varphi(x, y) = \varphi^{\text{out}}(x, y) - \varphi^{\text{in}}(x, y)$

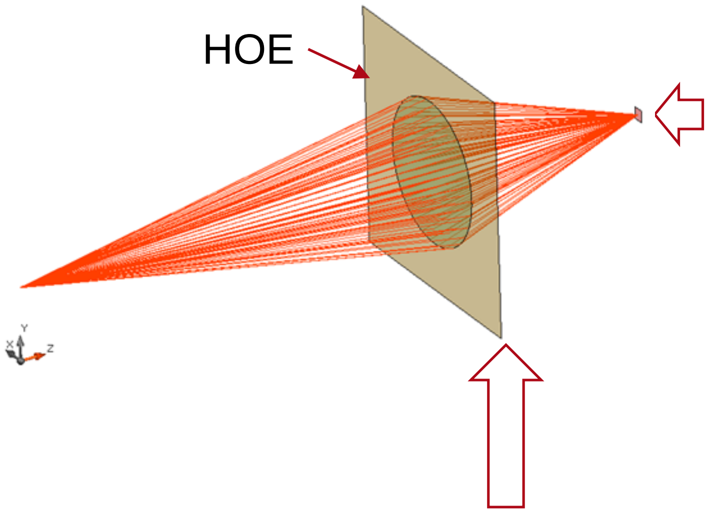
Design Process: Structure Embodiment



- The local grating of the HOE is chosed as sawtooth type.
- The 1st order is selected as working order.
- Local grating period $\Lambda(x, y)$ of the HOE is obtained with the phase function.

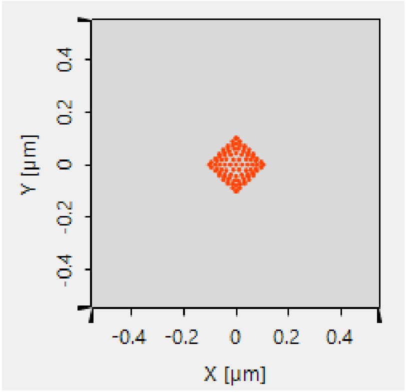
$$\Lambda(x, y) = \frac{2\pi}{|\nabla\varphi(x,y)|}$$

Simulation with Designed Result



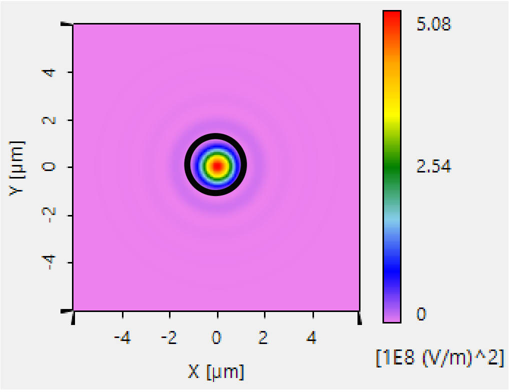
dot diagram

($RMS \approx 100nm$)

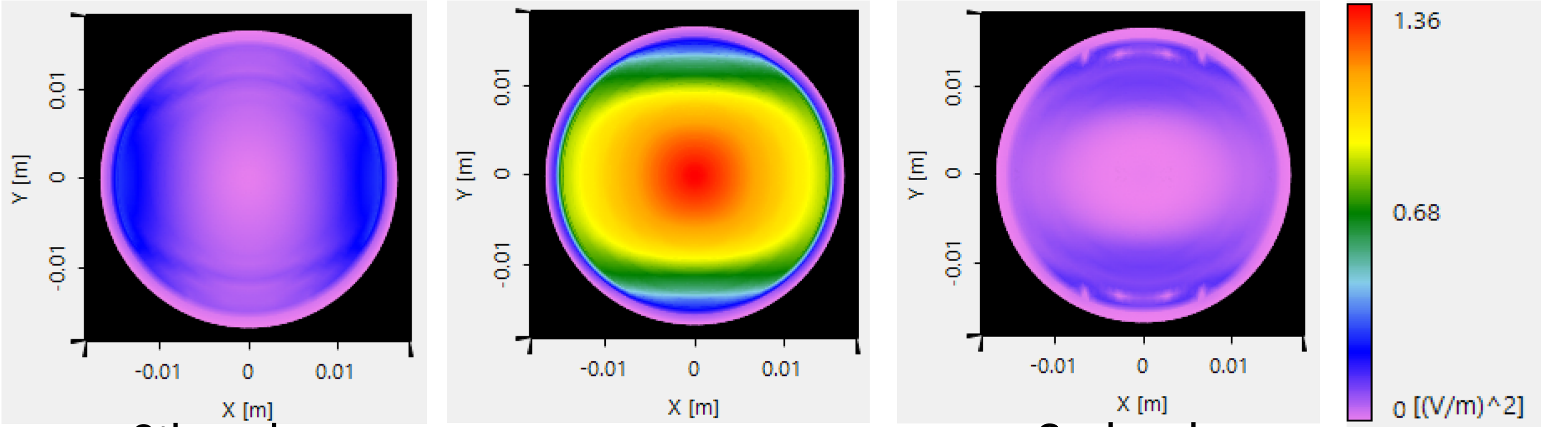


PSF

(Airy disk diameter $\approx 2.5\mu m$)



Intensity After the HOE



0th order 1st order 2nd order

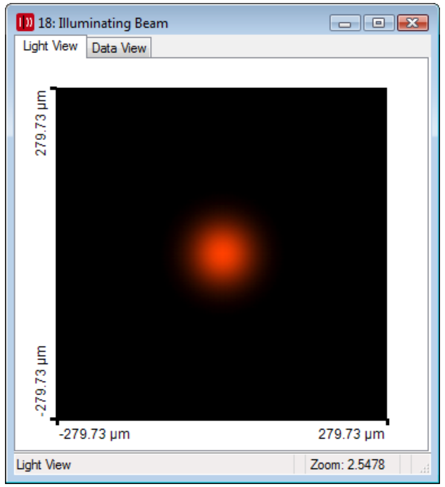
Scenario 90 (3.0)

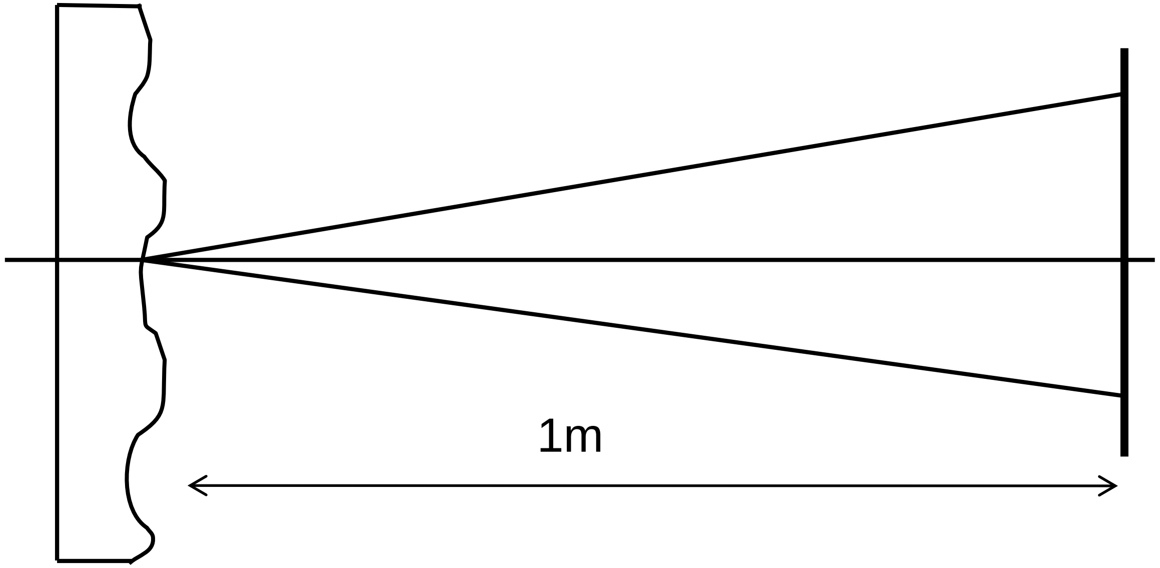
Simulation of Scattering at Rough Surface with Thin Element Approximation (TEA)

Surfaces in VirtualLab are usually smooth. In contrast, real surfaces are always rough to a certain degree.

This application scenario demonstrates the simulation of a Gauss beam that passes a glass plate with a rough surface according to measured height profile data. In 1m distance the scattered light is analyzed.

Modeling Task



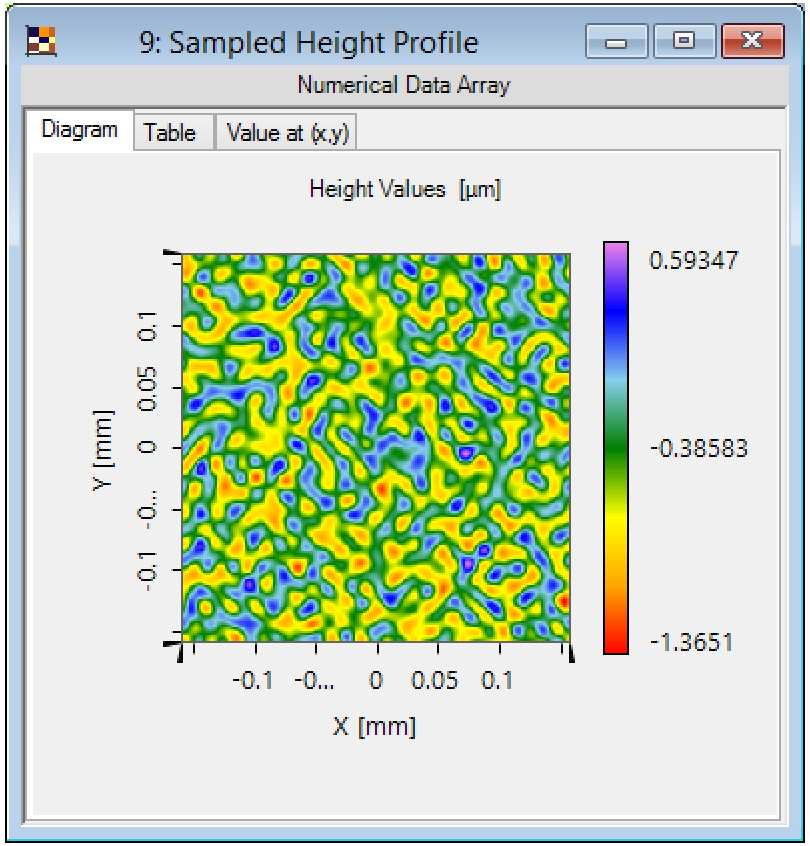


Gaussian laser beam
λ: 632nm
($1/e^2$) diameter: 100µm

Glass Plate
(Fused Silica)
with rough
2nd surface

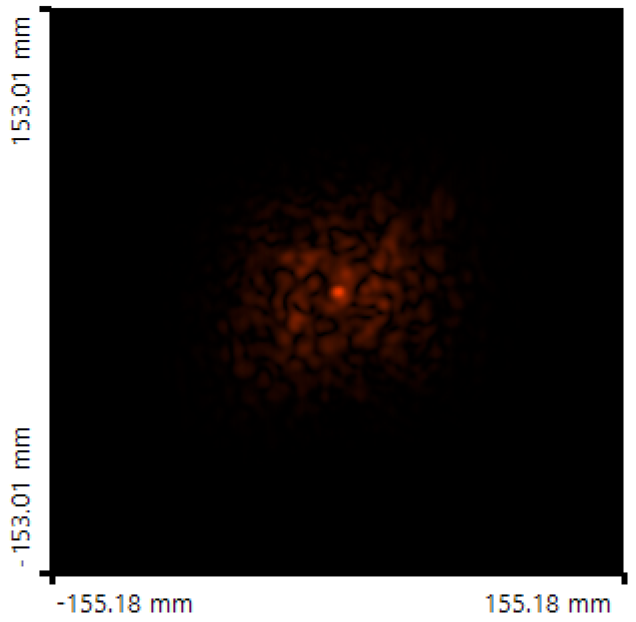
Scatterd Light Field
on Screen=?

Measured Surface Profile Data

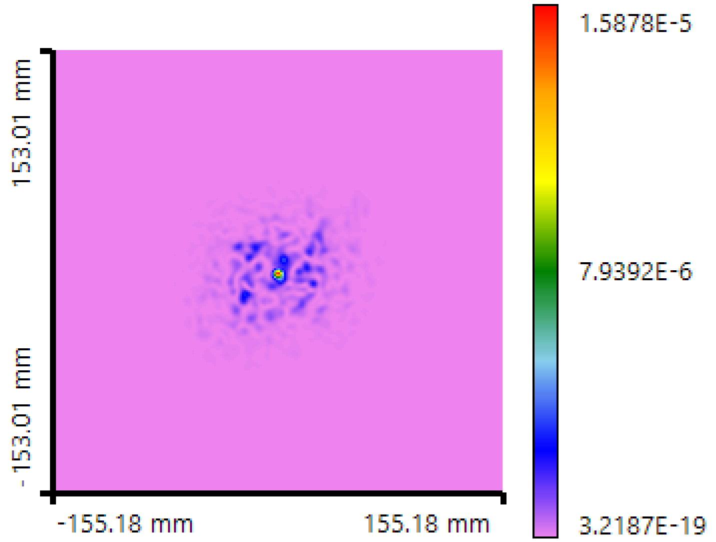


Result: Diffraction Pattern

in real colors



in false (reverse rainbow) colors



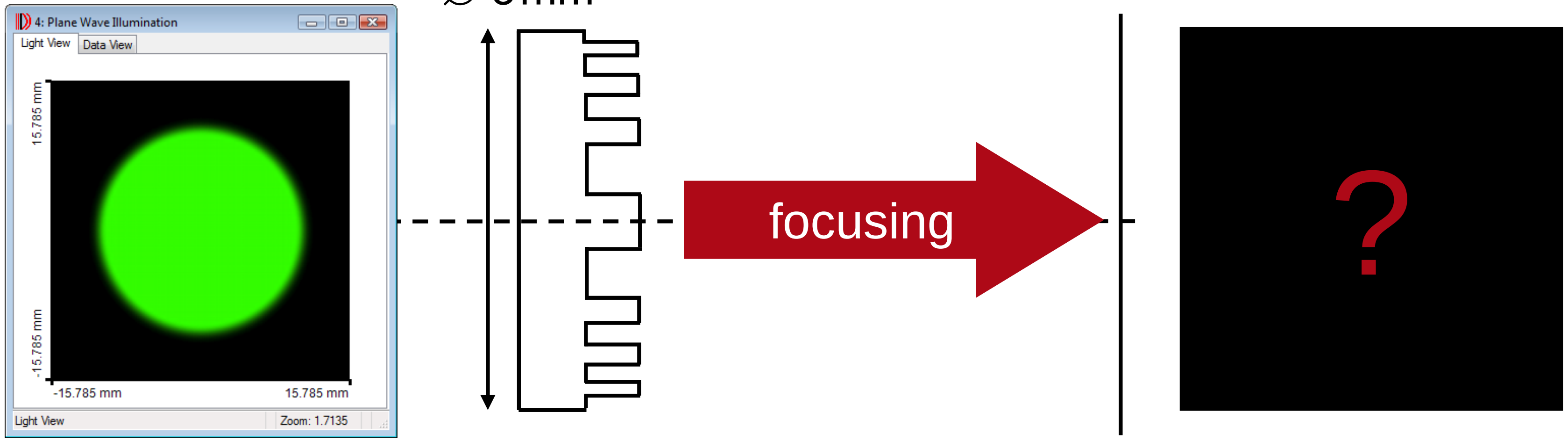
Exercise (v0.9.1)

Analysis of System with Binary Lens

Modeling Task

round
∅ 3 mm

PSF & MTF calculation



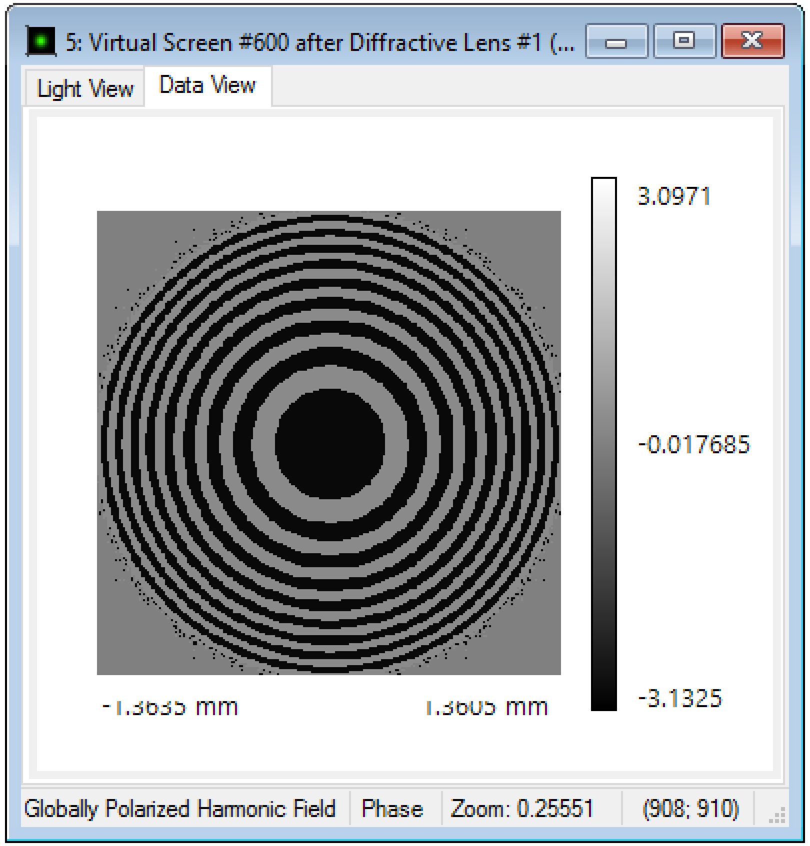
plane wave
wavelength: 532 nm
∅ 2.5 mm
with 5 % edge width

- diffractive lens (based on conical surface)
- 2 levels

focal plane

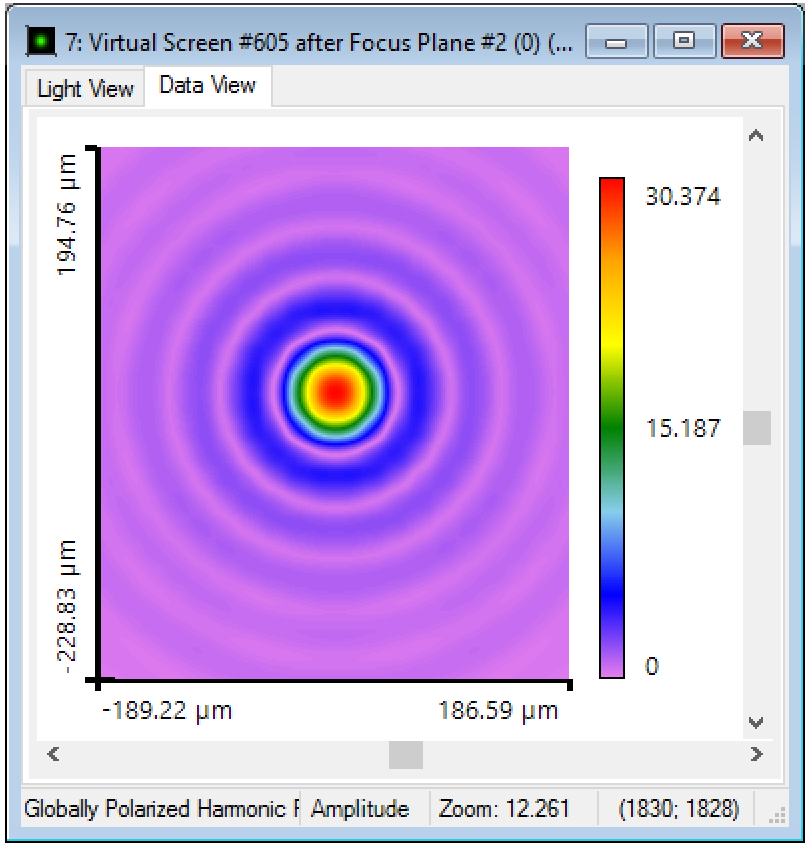
effective focal length f=200 mm

Expected Result: Phase Directly after Lens

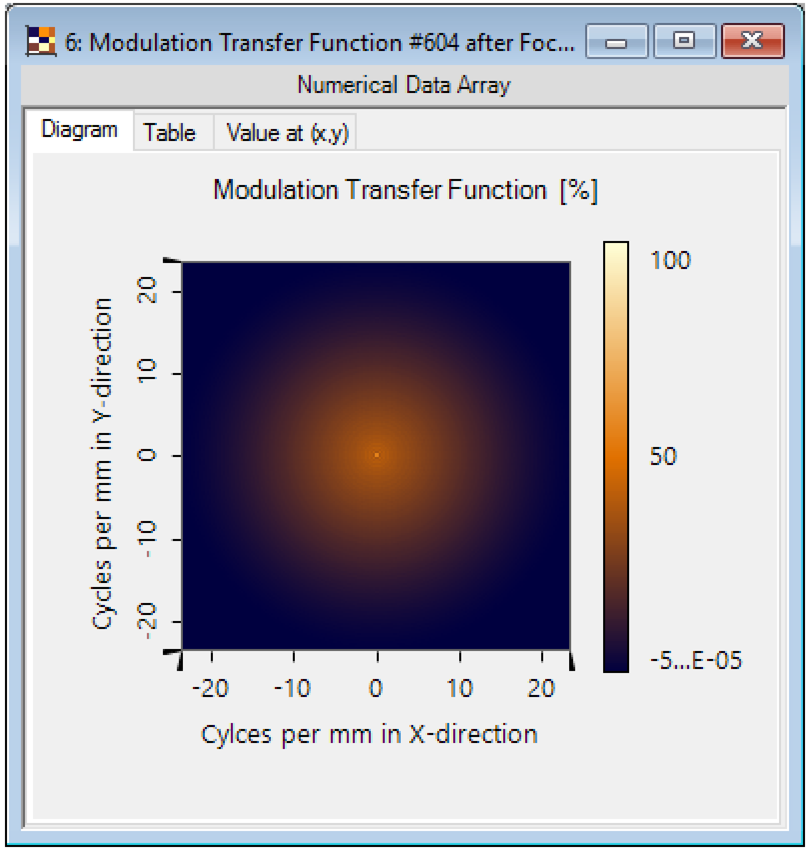


phase of field after lens

Expected Result: PSF & MTF



PSF



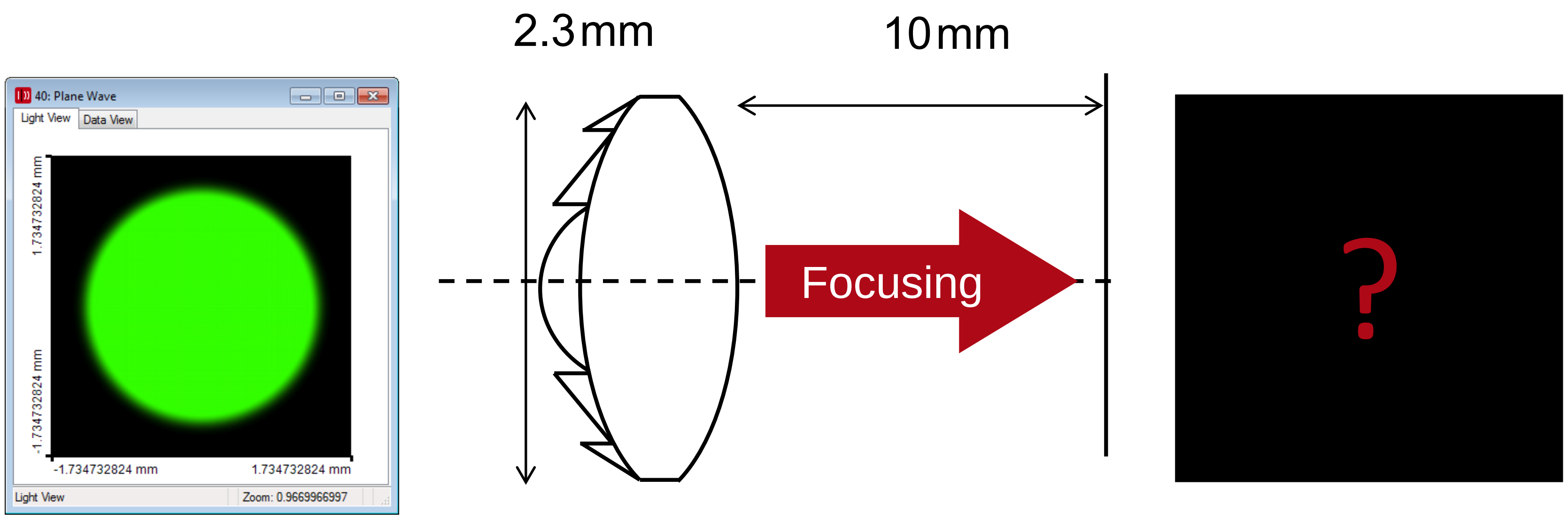
2D MTF

AppS.0009 (1.1)

Simulation of a Bifocal Hybrid Lens

Keywords: bifocal Lens, combined Interface, hybrid lens, multifocal lens, multifocal, bifocal

Task Description

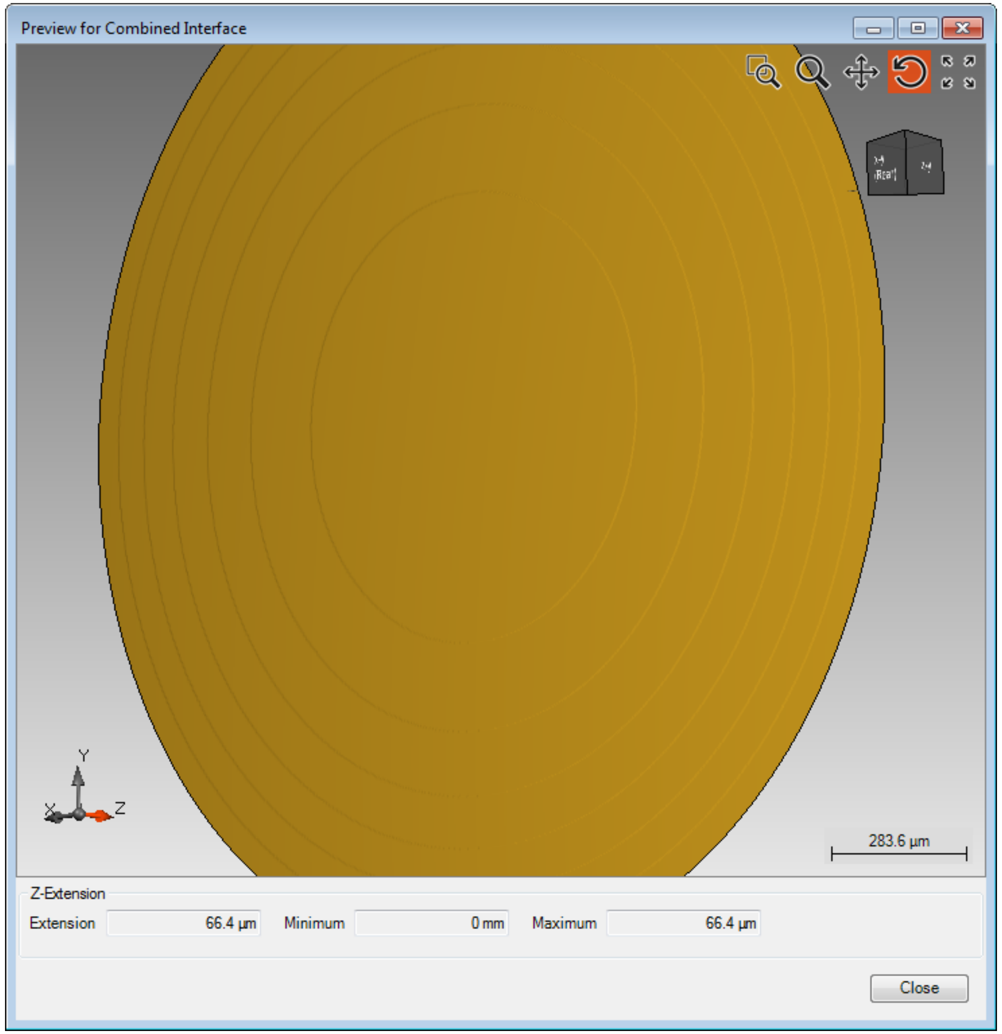


plane wave

bifocal lens with hybrid surface

target plane

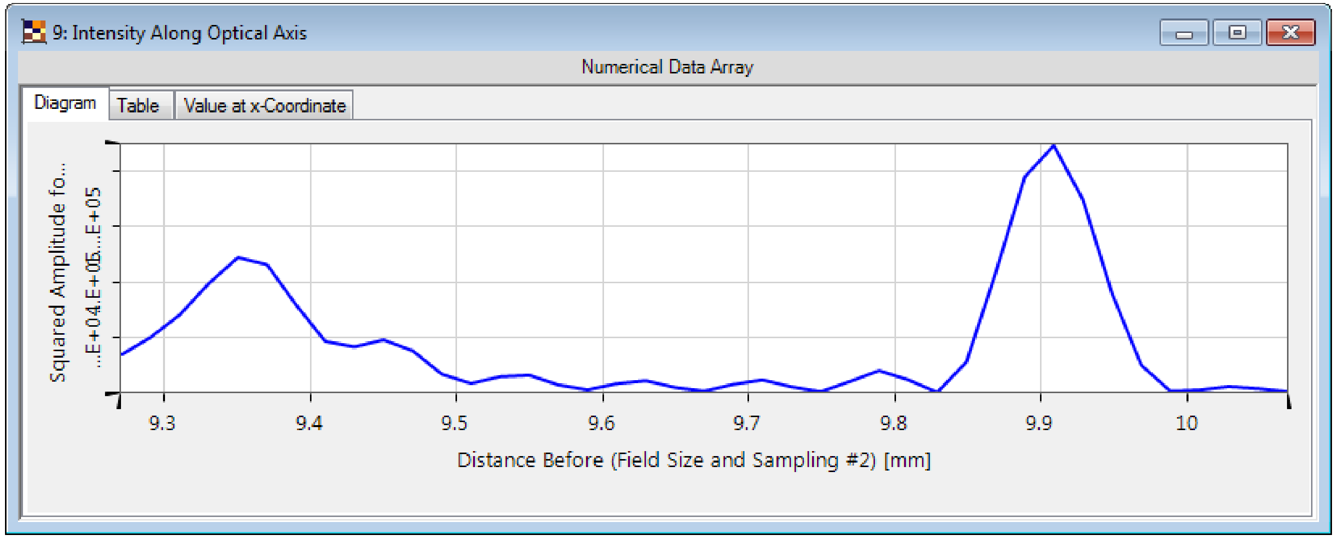
Task Description



- Center thickness of lens: 1 mm.
- Diameter: 2.3 mm
- Radius of curvature of the spherical surface: 10 mm
- Hybrid surface modeled as a superposition of a spherical and a diffractive lens surface.
- Superposition of surface profiles by combined interface of VirtualLab.
- Diffractive lens parameters:
  - Radius: Infinity
  - A2: 0.0022608
  - A4: 0.00038131
  - A6: 2.74E-06

On-Axis Intensity

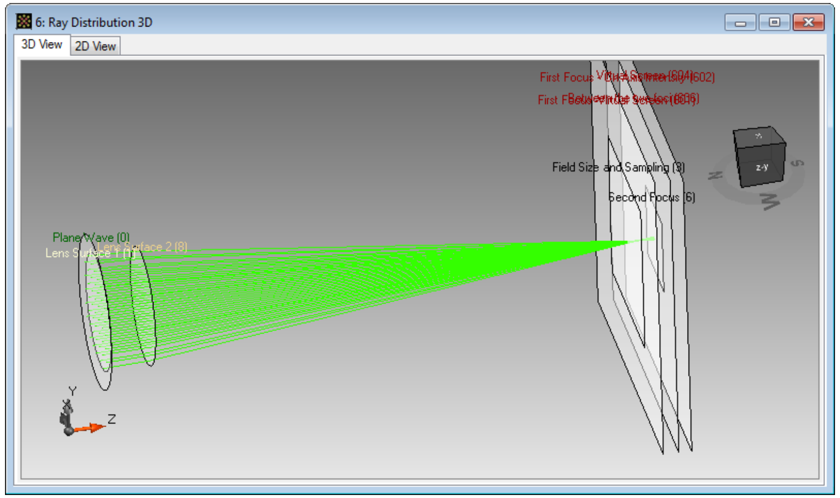
The **intensity along the optical axis** can be taken as indicator for the focal positions. Via **parameter run** the position behind the lens is varied. **To speed up** the simulation, a **separate LPD** with the light distribution 9.37 mm behind the lens as input field is used. Hence, the **muliple propagation through this hybrid lens is avoided**.

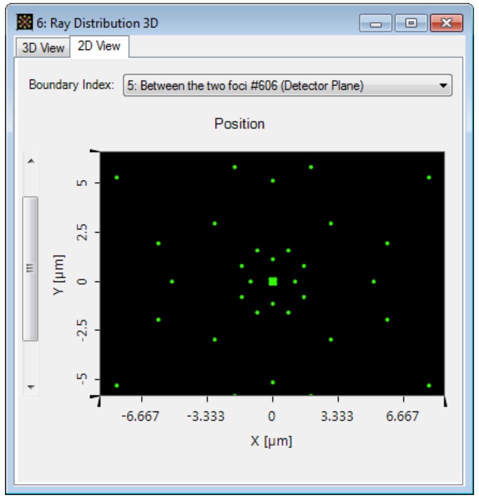


On-axis intensity depending on distance from lens. The two focal points in a distance of 550 µm (at 9.37 mm and 9.91 mm) are visible.

files: AppS.0009_Bifocal_Hybrid_Lens_2.run & …_3.da

Ray Tracing System Analyzer: Results





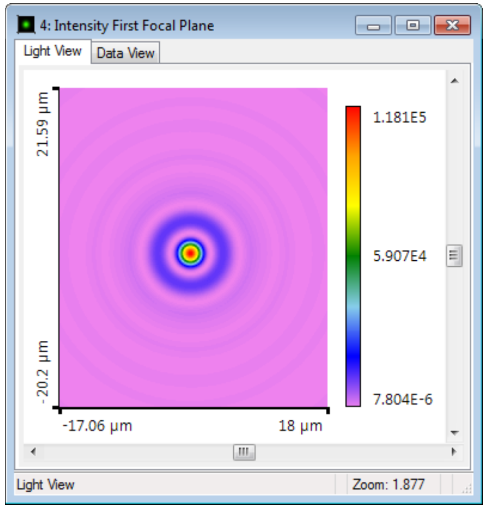
Left figure: 3D ray tracing result

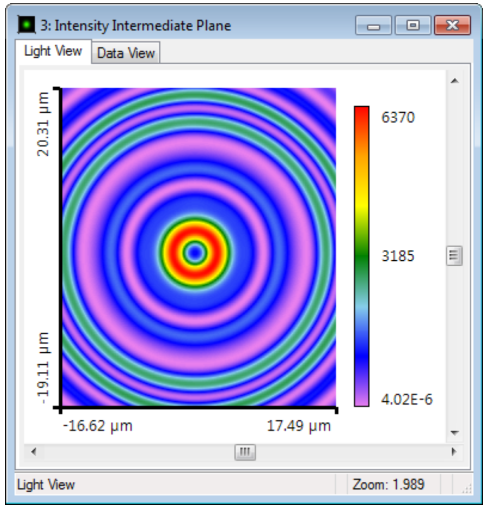
Right figure: Spot diagram somewhere between the intended two focal planes.

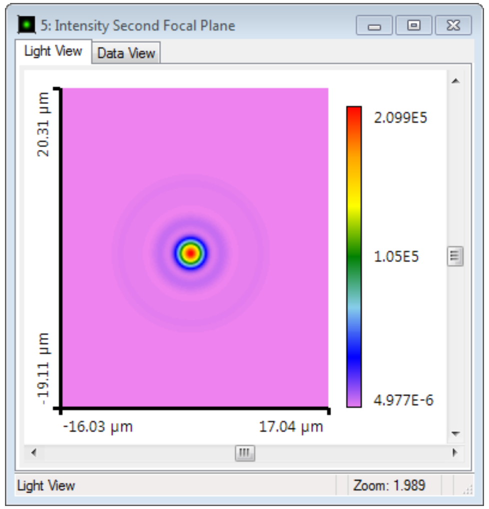
The **position of the two focal planes** and the **point spread function (PSF)** can only be analyzed by classic **field tracing** which includes the consideration of **diffraction effects** due to the microstructured surface part of the hybrid lens (diffractive lens surface).

file used: AppS.0009_Bifocal_Hybrid_Lens_1.lpd

Field Tracing: Point Spread Functions







PSF in 1st focal plane, 9.37 mm after lens

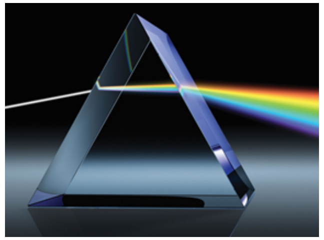
PSF between focal planes, 9.67 mm after lens

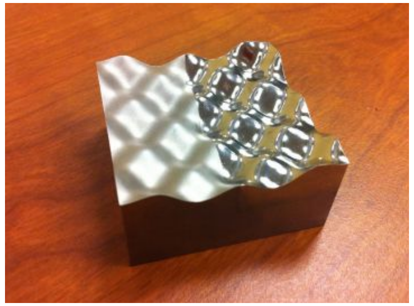
PSF in focal plane 2, 9.92 mm after lens

file used: AppS.0009_Bifocal_Hybrid_Lens_1.lpd

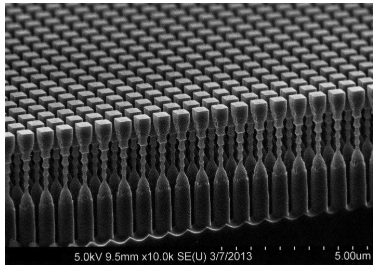
Optical Components

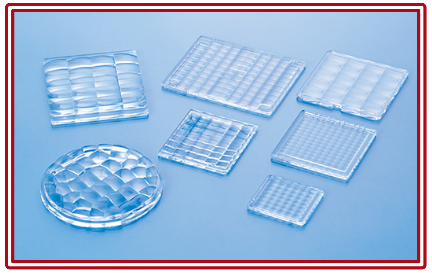
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- **lens arrays**
- crystals
- GRIN media



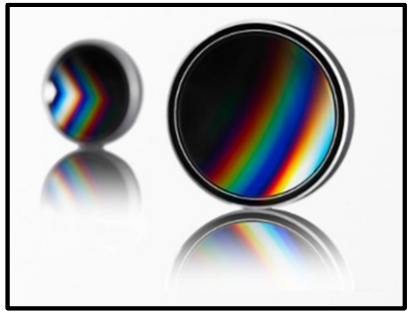


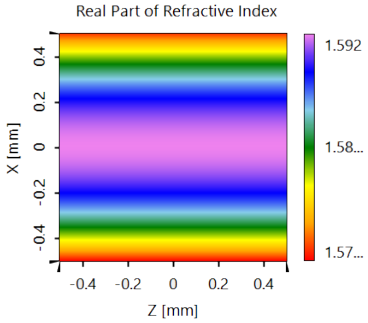
[1] IMS-Mechatronics Lab





[2] ISUZU GLASS

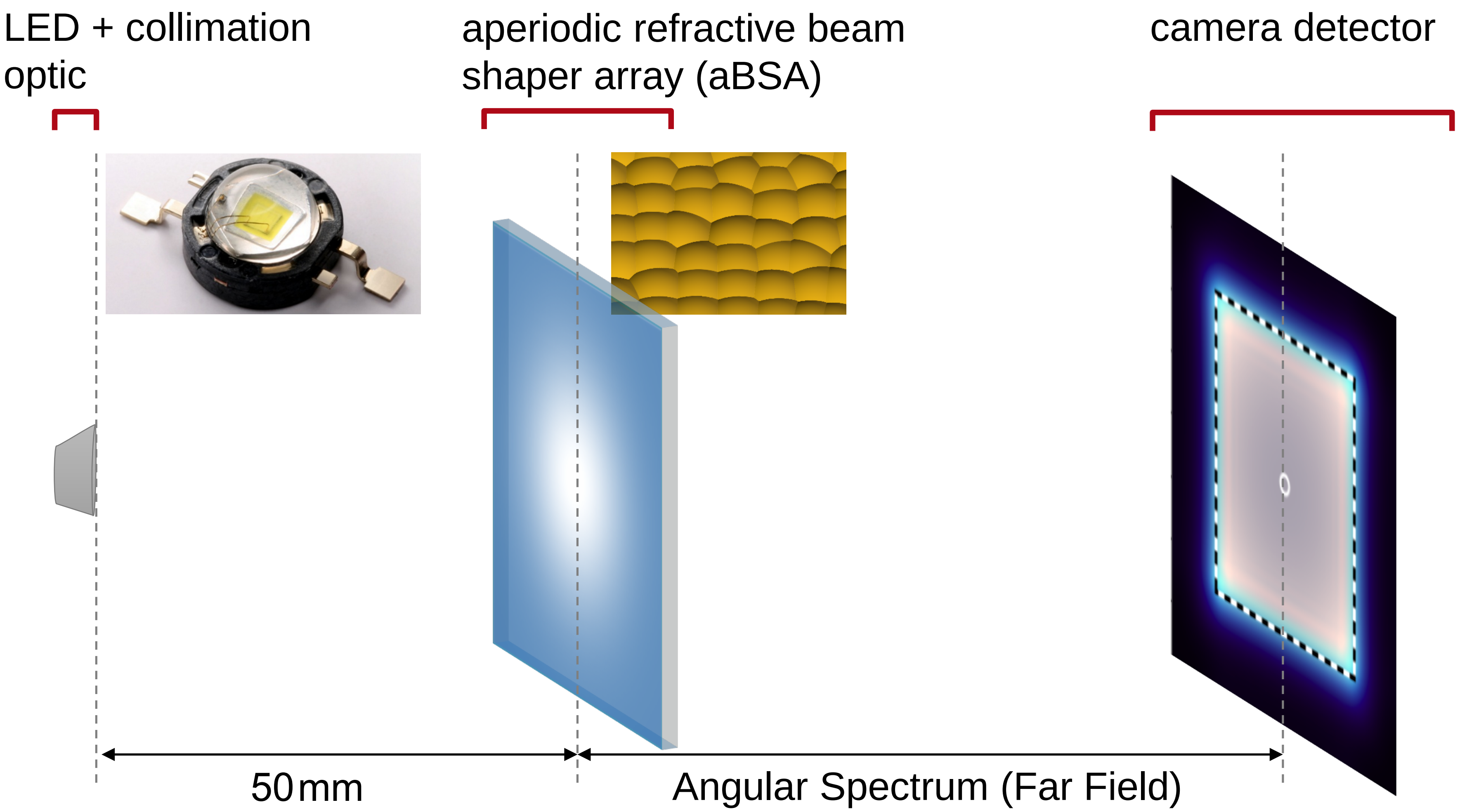




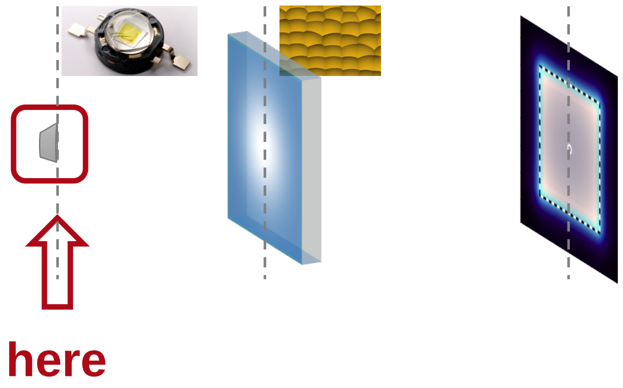
Light Shaping > Aperiodic Microlens Array

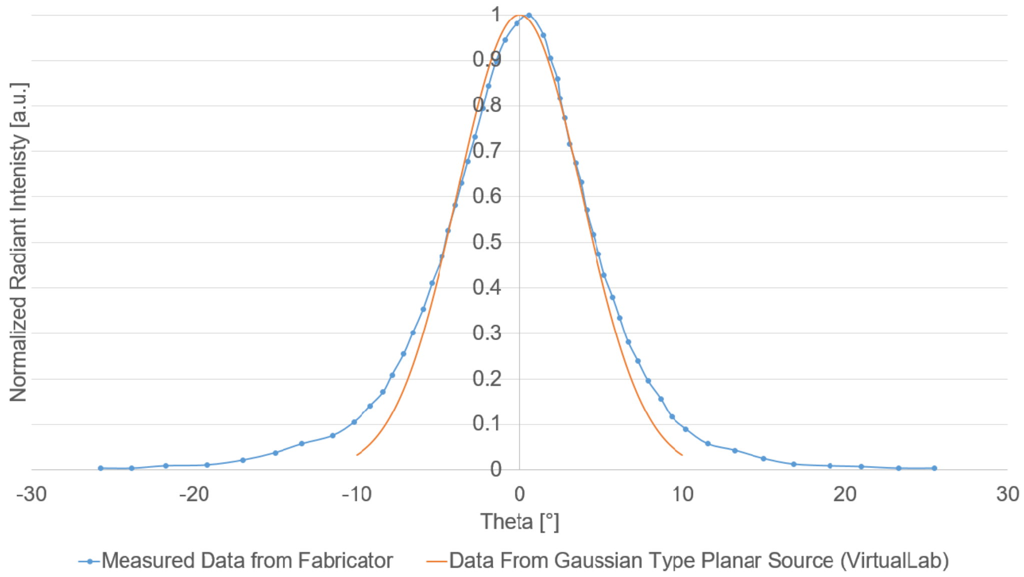
LED Top Hat Generation using Aperiodic Refractive Beam Shaper Array

Task/System Illustration



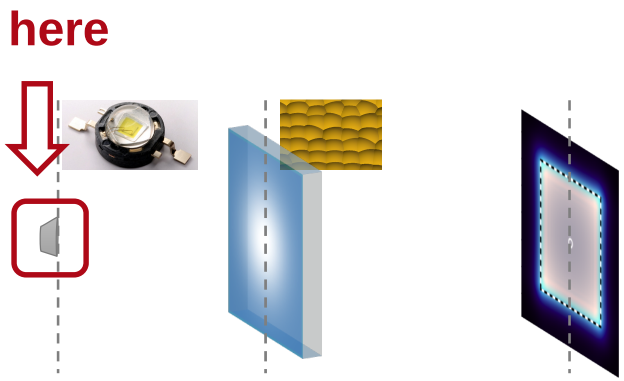
Specs: Light Source





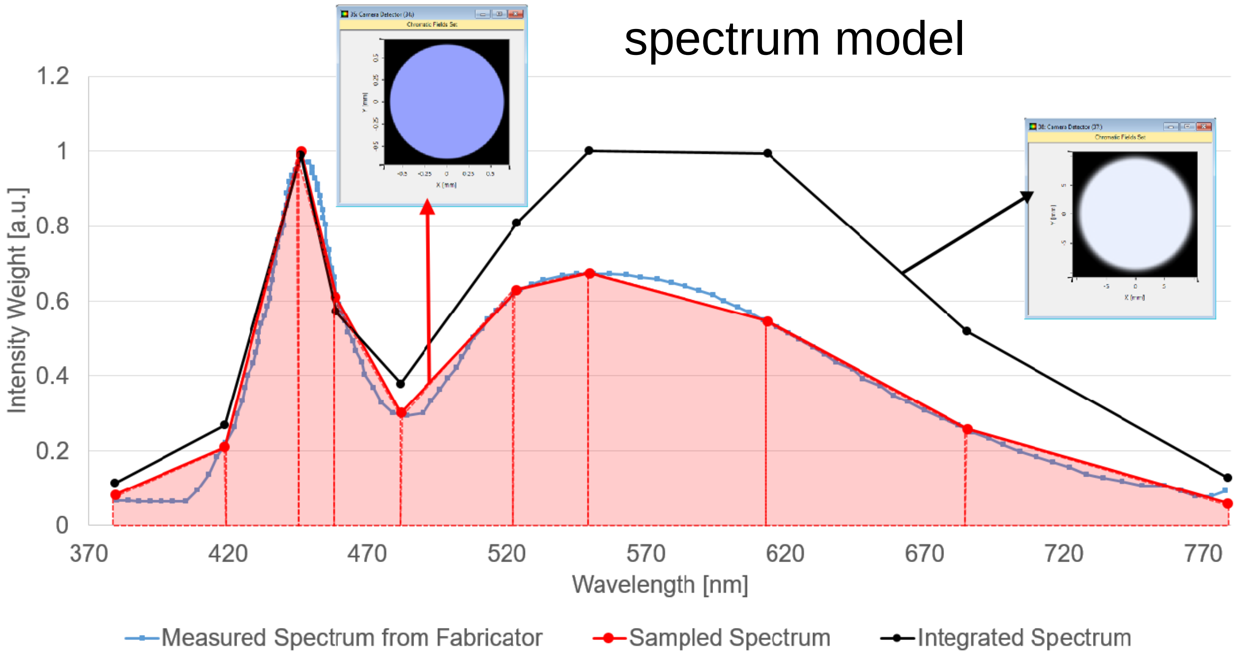
Parameter	Description / Value & Unit
name/type	Seoul Z-LED P4 from Seoul Semiconductors
partially coherent source type	Gaussian type planar source
collimation	TIR lens from Carclo Optics (part no. 10003)
spectrum	pure white light spectrum
FWHM radiant intensity	9°

Specs: Light Source



Highlights

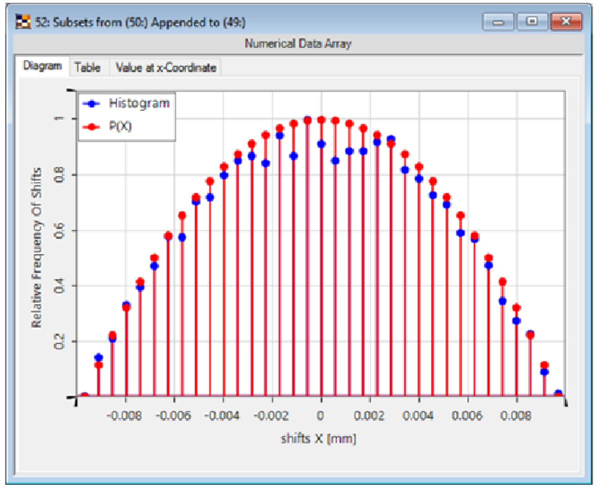
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern



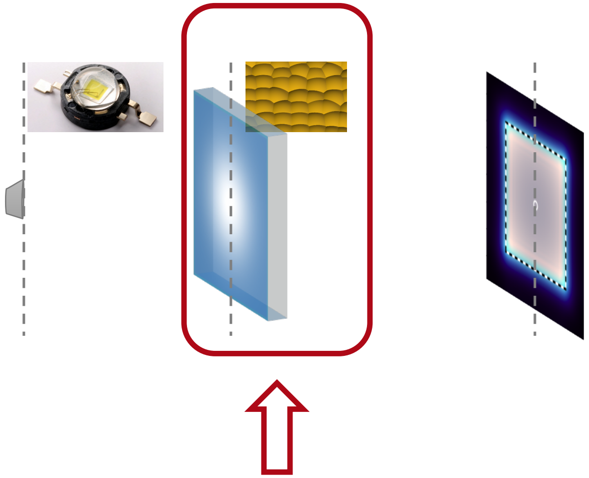
significant performance improvement

non-equidistant sampling of the spectrum

Specs: Aperiodic Refractive Beam Shaper Array



Histogram of Cell Distribution Function



here

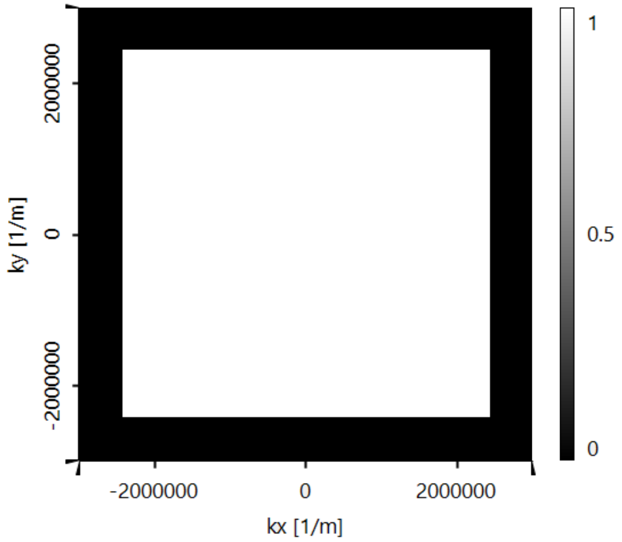
Parameter	Description / Value & Unit
cell array aperture	20x20 mm
number of cells	124x124
cell distribution function	quadratic polynomial
substrate thickness	1 mm
substrate material	fused silica

Highlights

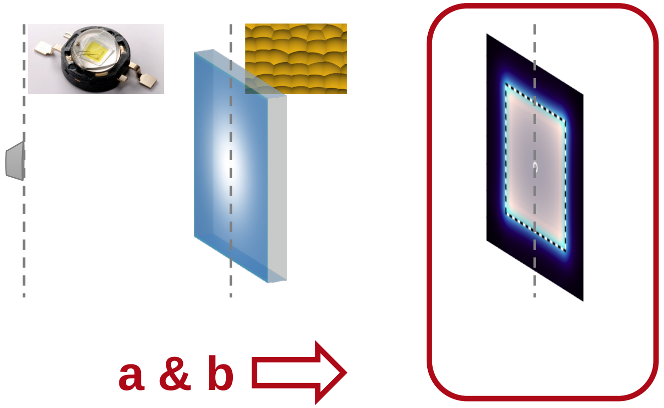
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern

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

Specs: Evaluation

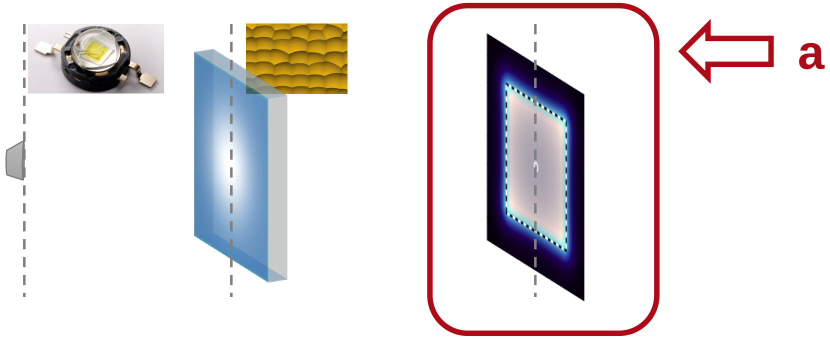


Desired Target Pattern



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

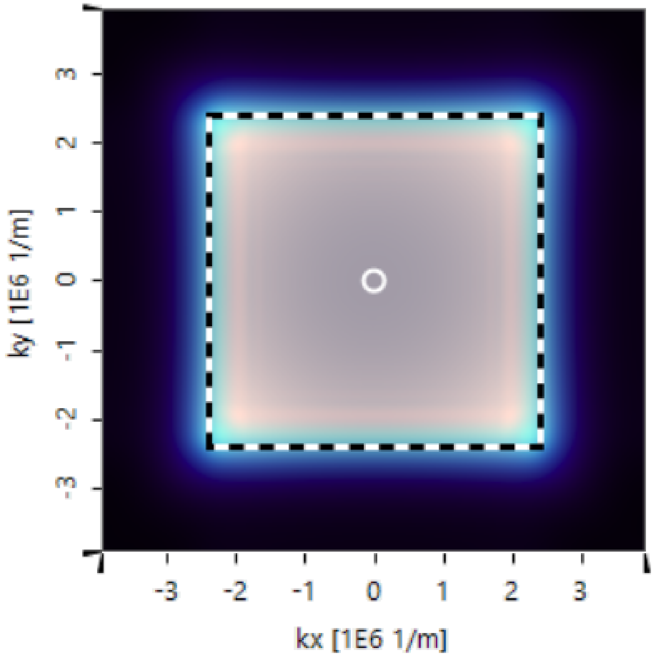
Results: Intensity Pattern (real color view)



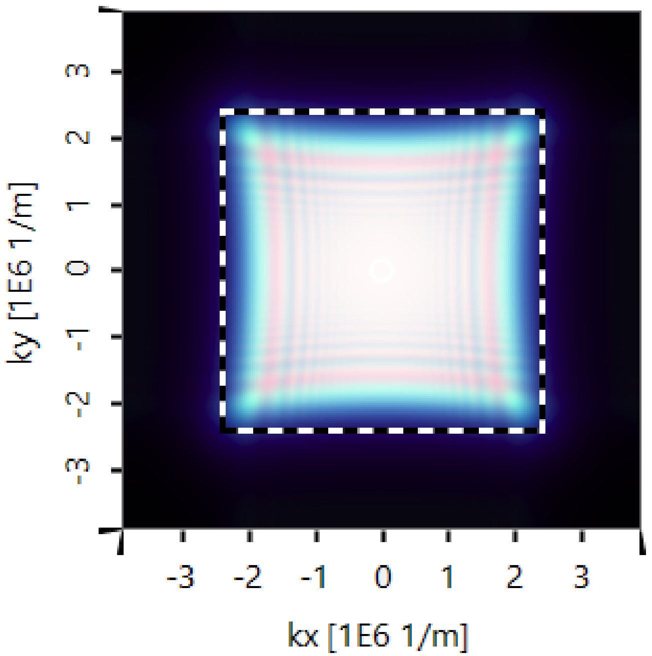
Highlights

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

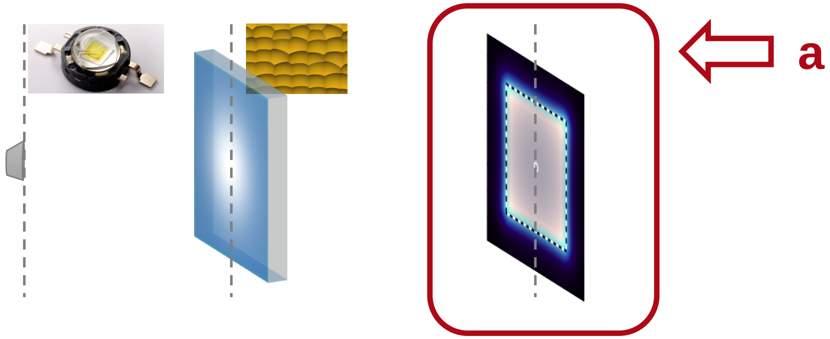
aperiodic beam shaper array



periodic microlens array



Results: Performance Criteria Evaluation



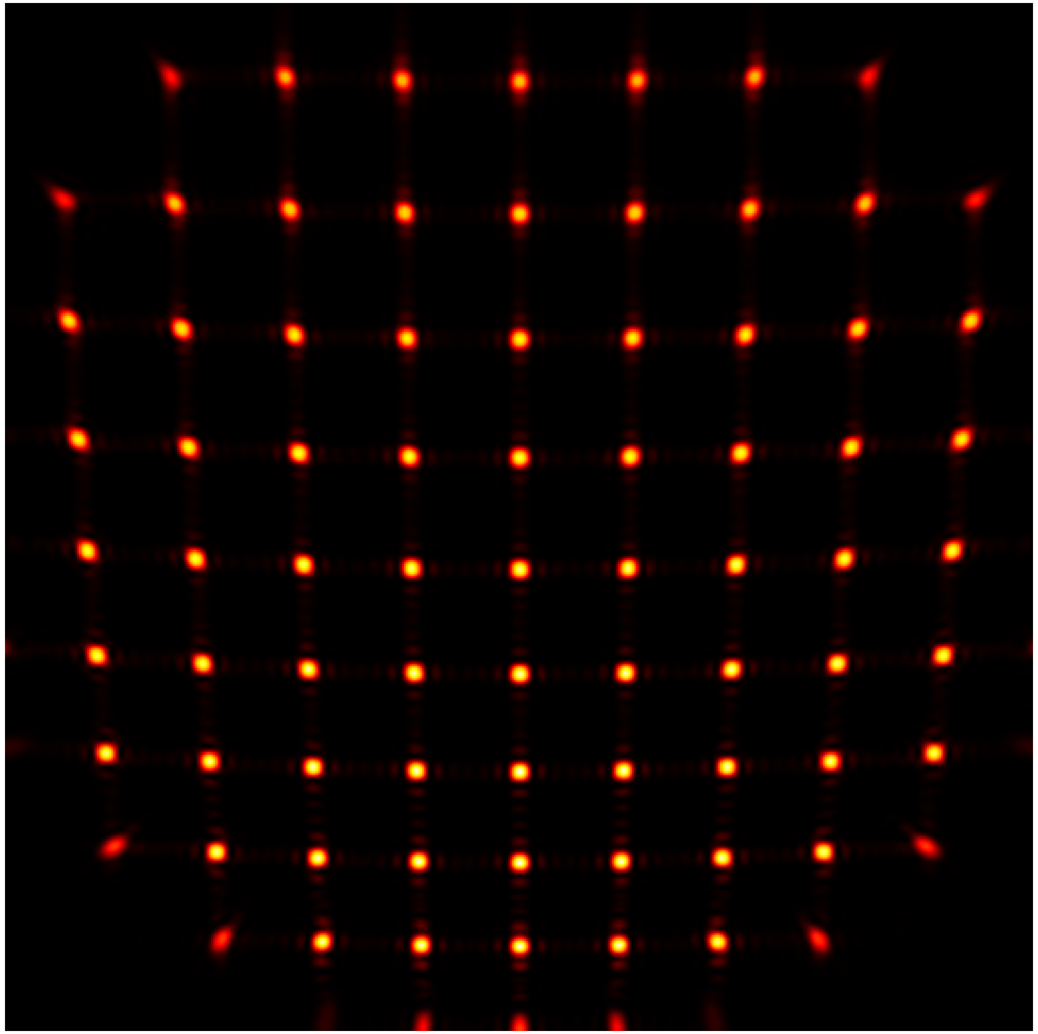
Highlights

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

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

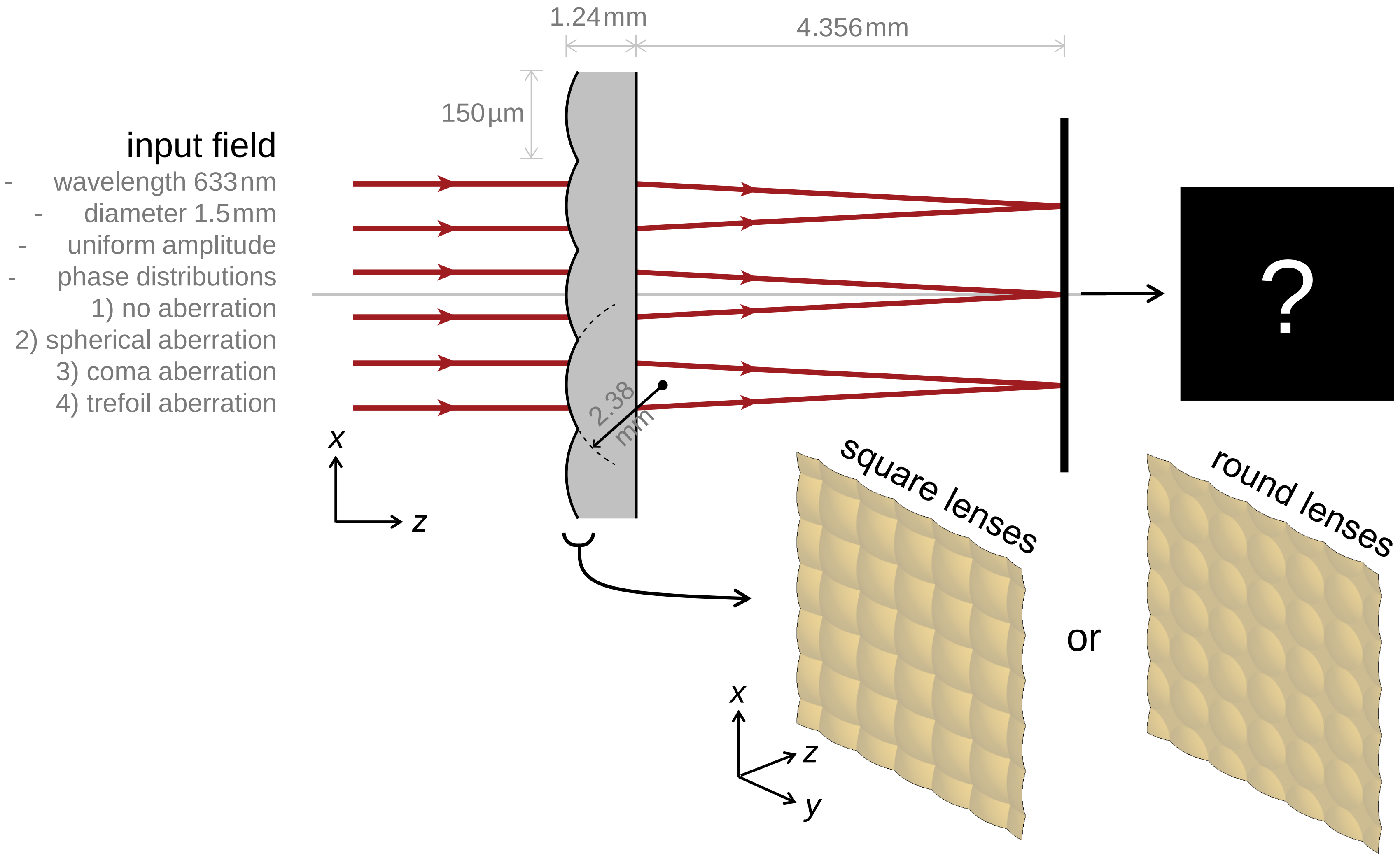
Modeling of Microlens Array with Different Lens Shapes

Abstract



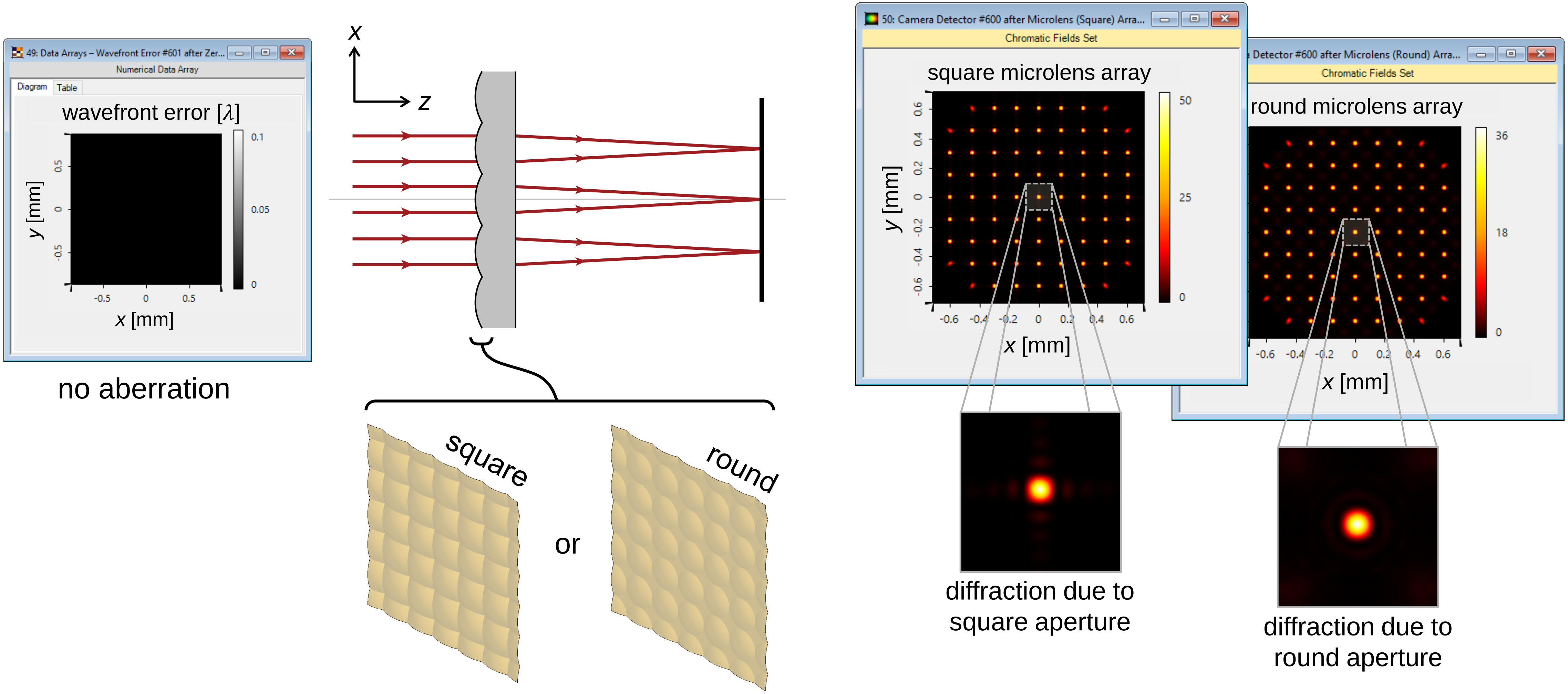
Microlens arrays are useful in many applications, such as imaging, wavefront sensing, light homogenizing, and so on. Due to different fabrication techniques and for different purposes, the microlenses can appear in different shapes. In this example, microlens array with different lens shapes – square and round – are modeled. That leads to apertures in different shapes, and the difference in the focal plane due to aperture effects is shown clearly. The change of the focal spots with respect to the imposed aberration in the input field is demonstrated.

Modeling Task



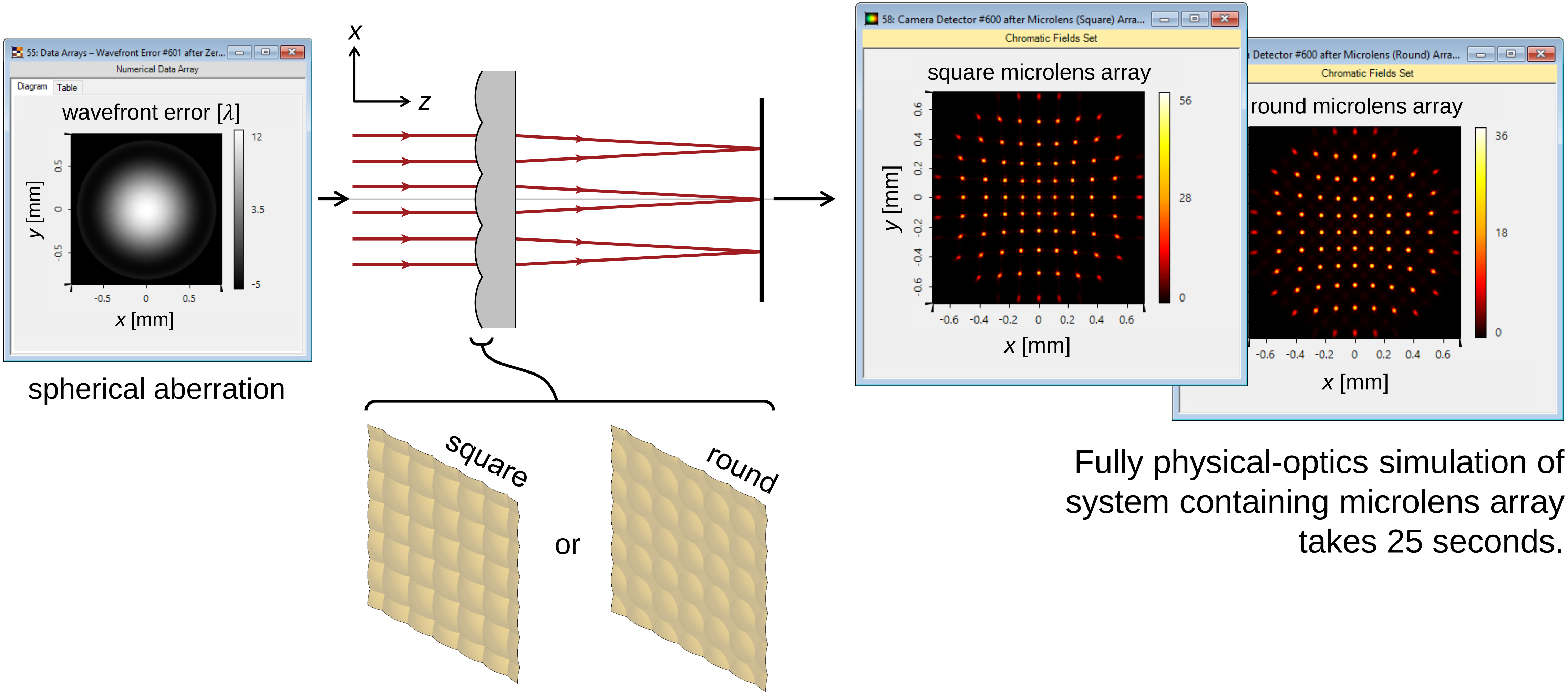
How to calculate field on focal plane behind different types of microlens arrays, and how the spot distribution changes with input field aberration?

Results



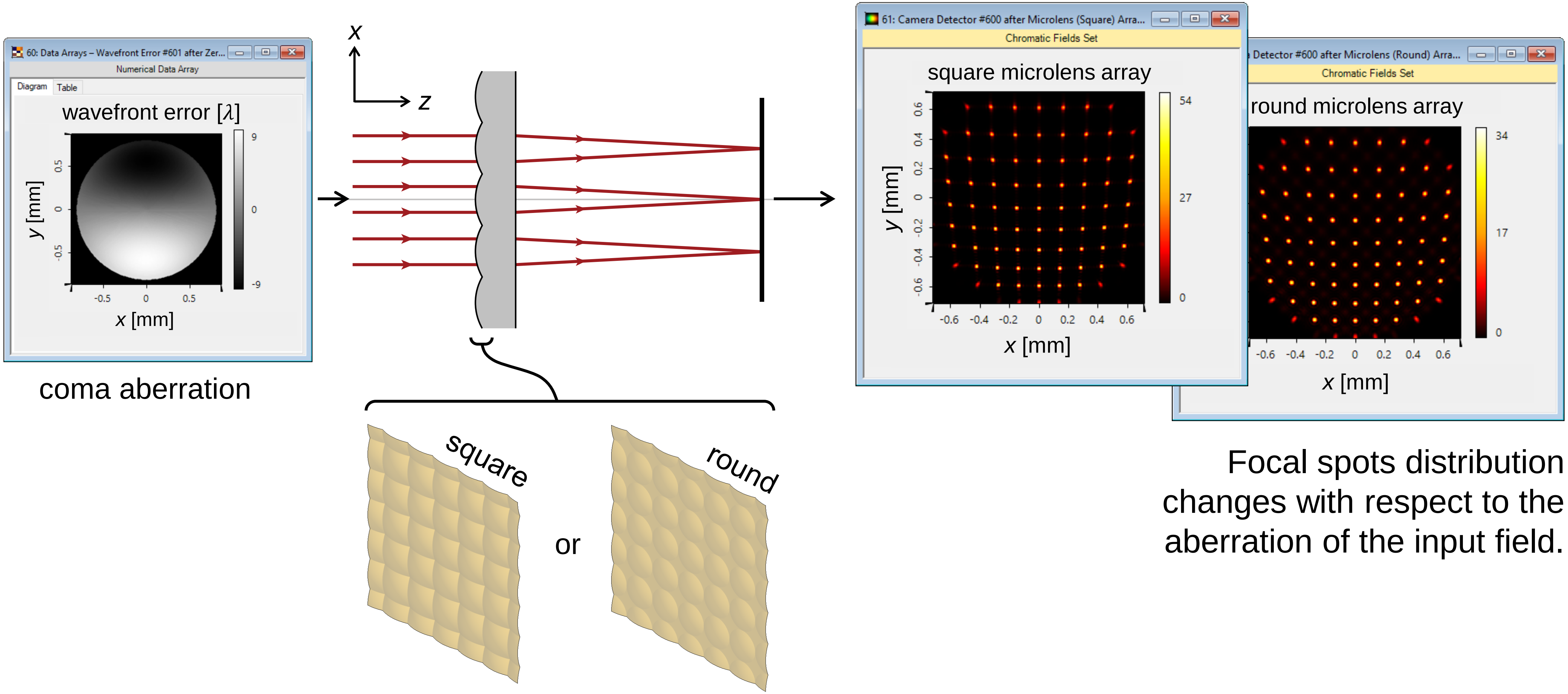
49: Data Arrays – Wavefront Error #601 after Zer...
Numerical Data Array
Diagram
Table
wavefront error [λ]
y [mm]
x [mm]
no aberration
x
z
square
or
round
50: Camera Detector #600 after Microlens (Square) Arra...
Chromatic Fields Set
square microlens array
Detector #600 after Microlens (Round) Arra...
Chromatic Fields Set
round microlens array
diffraction due to square aperture
diffraction due to round aperture

Results



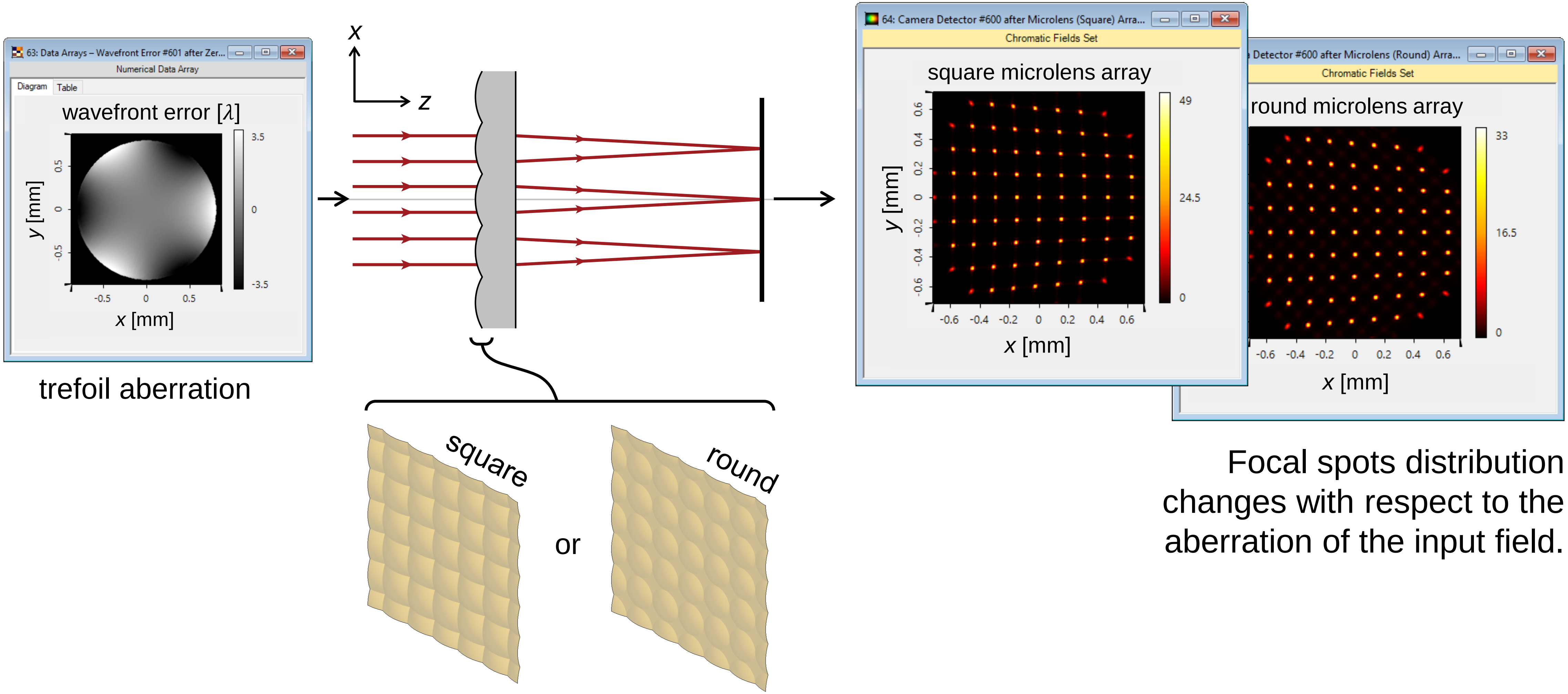
Fully physical-optics simulation of system containing microlens array takes 25 seconds.

Results



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

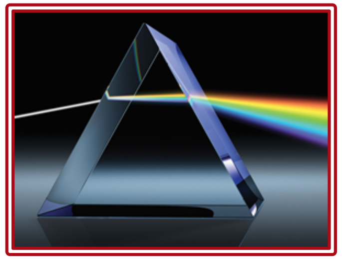
Results

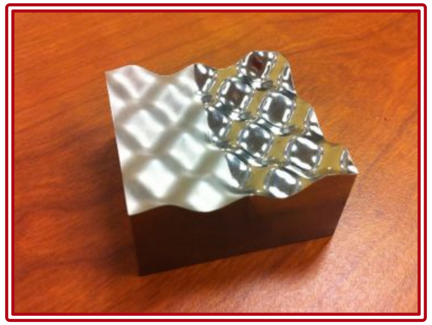


Focal spots distribution changes with respect to the aberration of the input field.

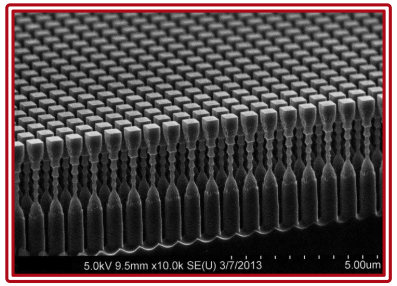
Optical Components

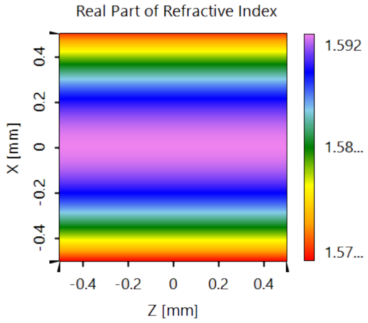
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

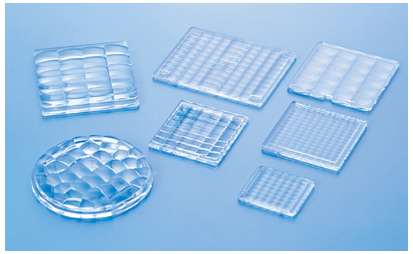




[1] IMS-Mechatronics Lab







[2] ISUZU GLASS

Example – Stress Birefringence

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

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

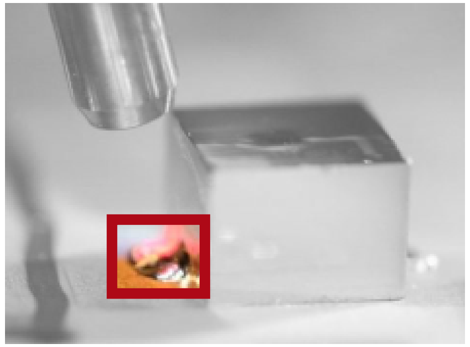


Photo from Fraunhofer IOF

- ANSYS
  - Structural/material definition
  - Transient thermal analysis
  - Stress simulation inside crystal component

- VirtualLab
  - Convert stress into optical permittivity data
  - Simulation of field propagation through birefringent materials

From Stress to Birefringence

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

Stress tensor

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

Permittivity tensor

From Stress to Birefringence

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

Stress tensor

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

Piezo-optic constant

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

Changes in
impermeability tensor

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

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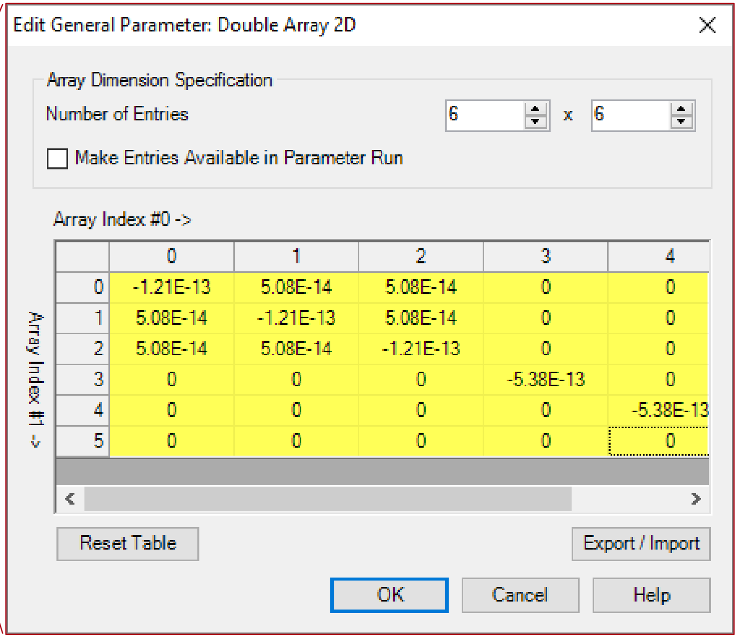


	0	1	2	3	4
0	-1.21E-13	5.08E-14	5.08E-14	0	0
1	5.08E-14	-1.21E-13	5.08E-14	0	0
2	5.08E-14	5.08E-14	-1.21E-13	0	0
3	0	0	0	-5.38E-13	0
4	0	0	0	0	-5.38E-13
5	0	0	0	0	0

Example: piezo-optic constant tensor for YAG crystal

From Stress to Birefringence

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

Stress tensor

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

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

Changes in impermeability tensor

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

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

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

Impermeability tensor

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

From Stress to Birefringence

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

Stress tensor

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

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

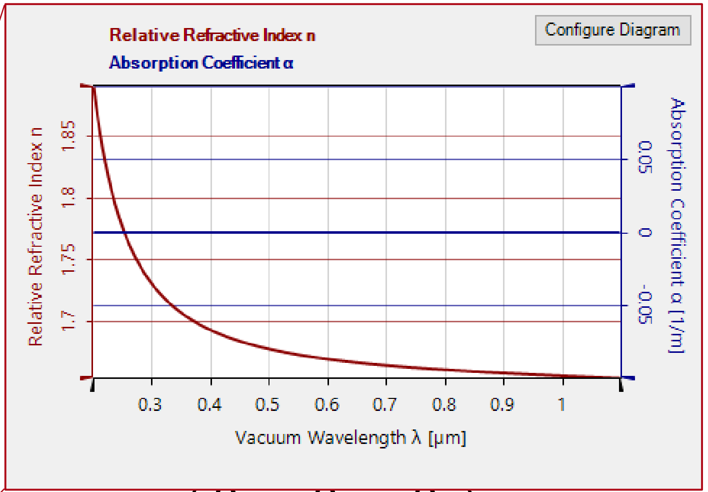
Changes in impermeability tensor

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

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

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

Example: ordinary refractive index for BBO crystal



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

From Stress to Birefringence

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

Stress tensor

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

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

Piezo-optic constant

Changes in impermeability tensor

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

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

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

Impermeability tensor

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

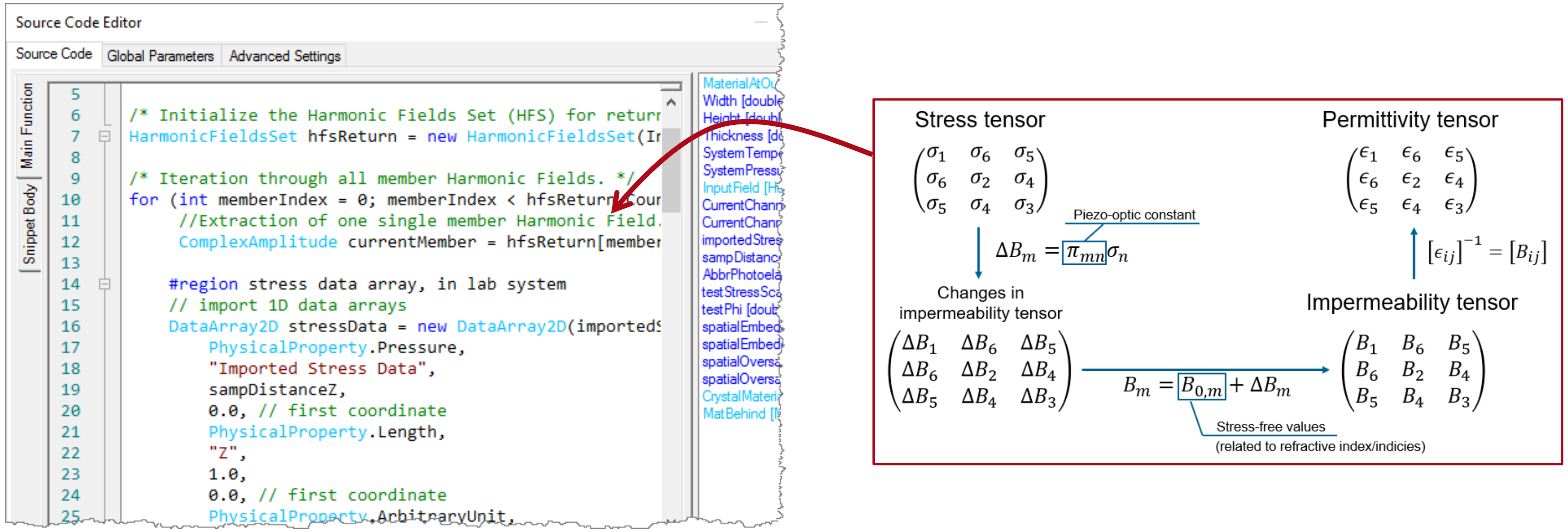
$$[\epsilon_{ij}]^{-1} = [B_{ij}]$$

Permittivity tensor

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

VirtualLab Simulation

- Convert stress to optical permittivity

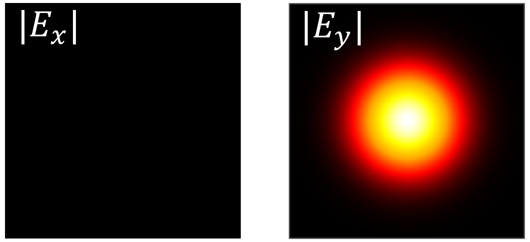


Conversion from stress tensor to the corresponding permittivity tensor is implemented by using the programmable component in VirtualLab

Simulation Results

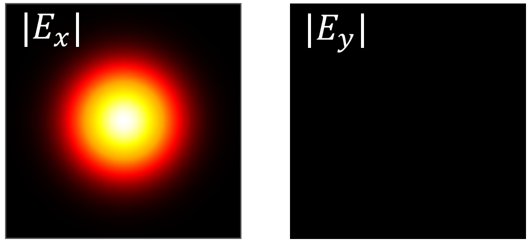
- Input field

1) @1064 nm



(waist radius 50 µm)

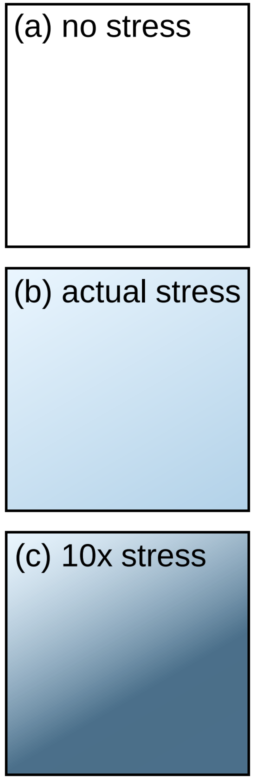
2) @532 nm



(waist radius 50 µm)

Note: we set the polarization according to the SHG configuration

- Applied stress

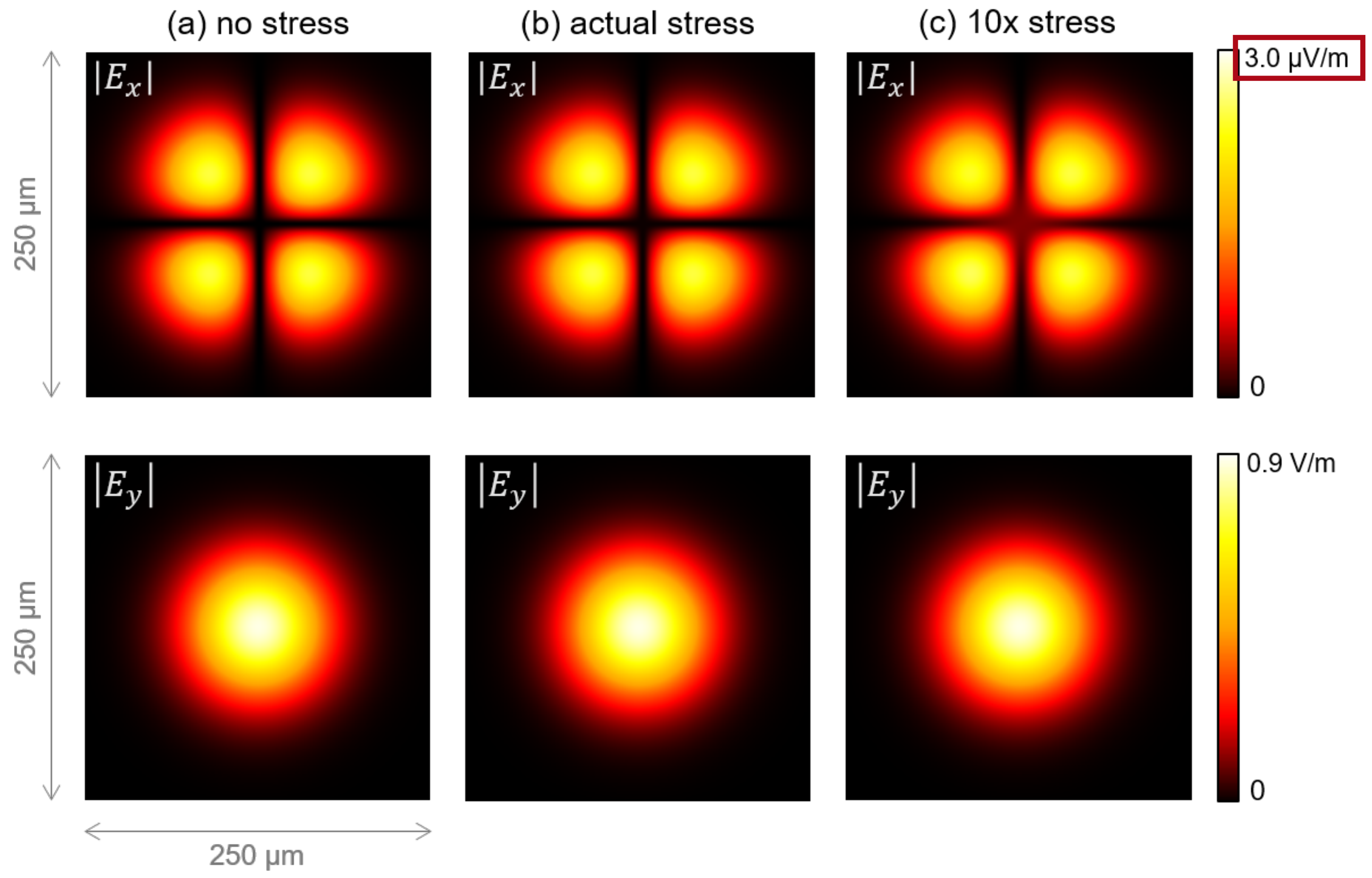


- Output field

?

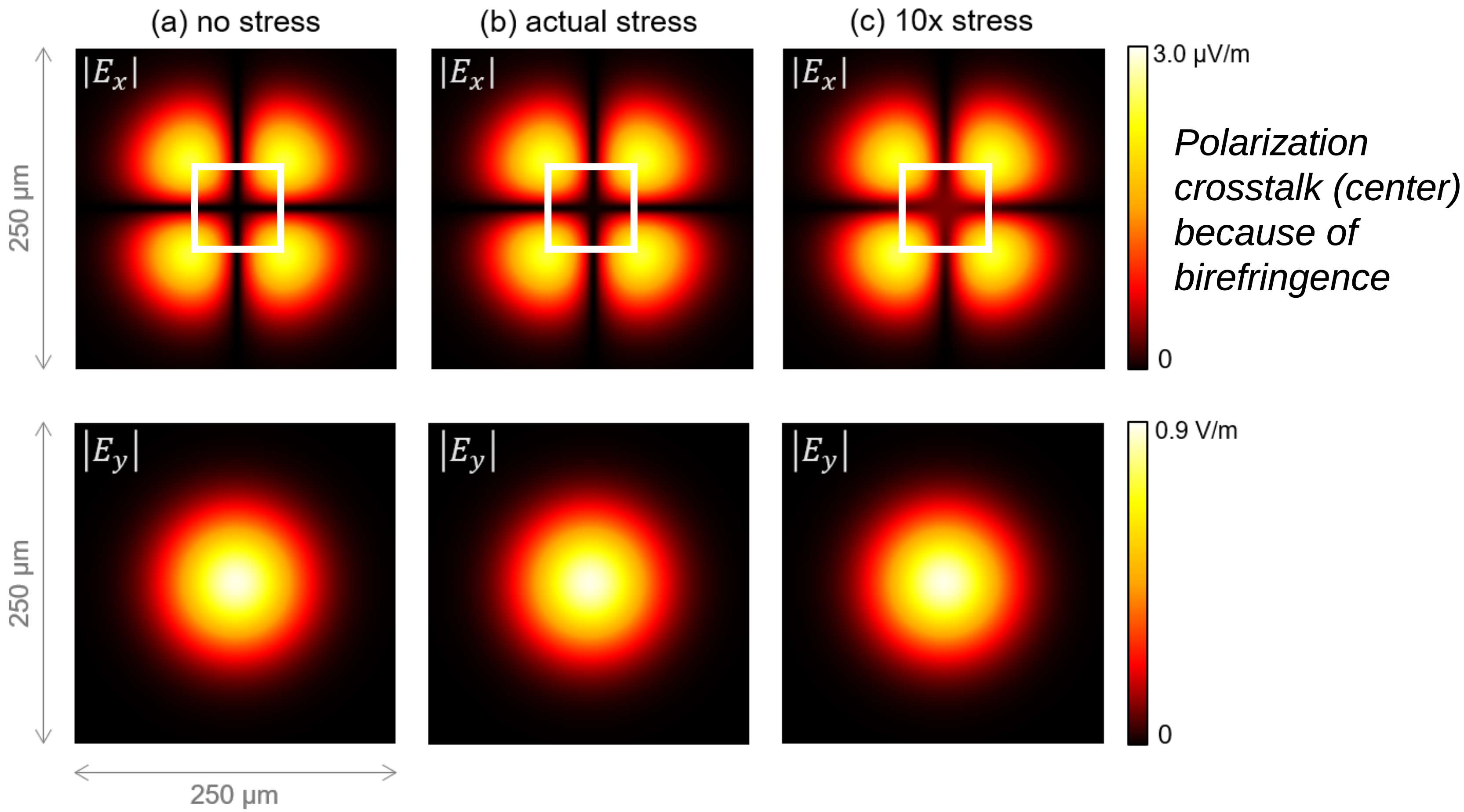
Simulation Results

- YAG crystal with 1064 nm input field (Ey)



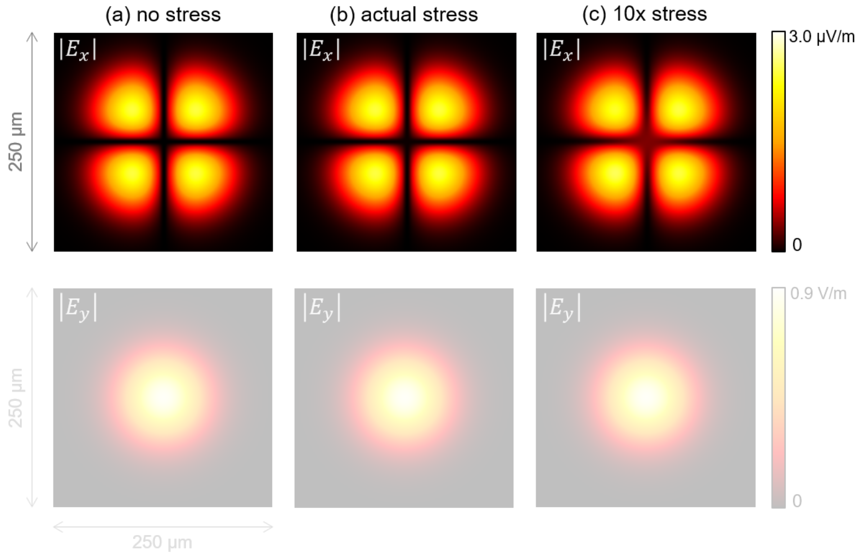
Simulation Results

- YAG crystal with 1064 nm input field (Ey)

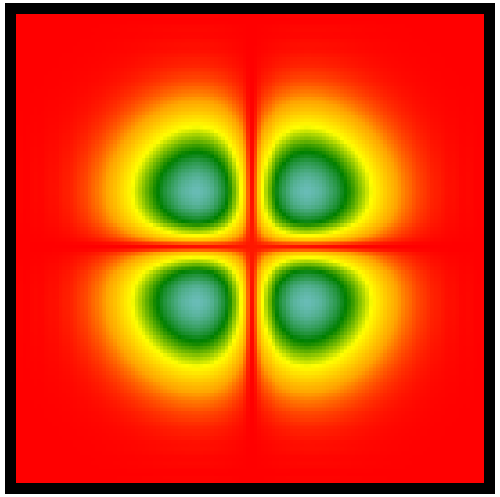


Simulation Results

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



from 1x to 201x stress

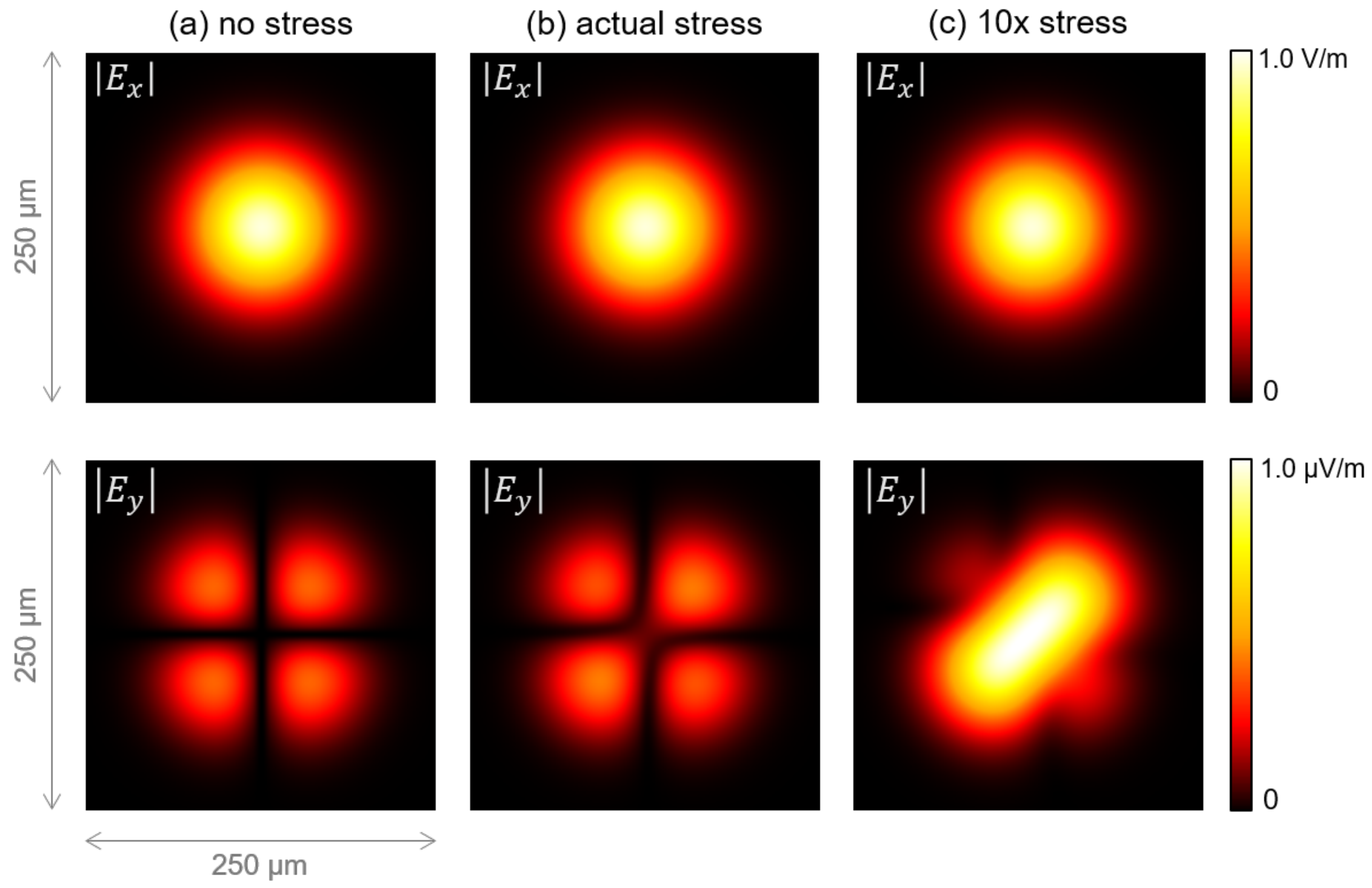


(logarithm color for better visibility)

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

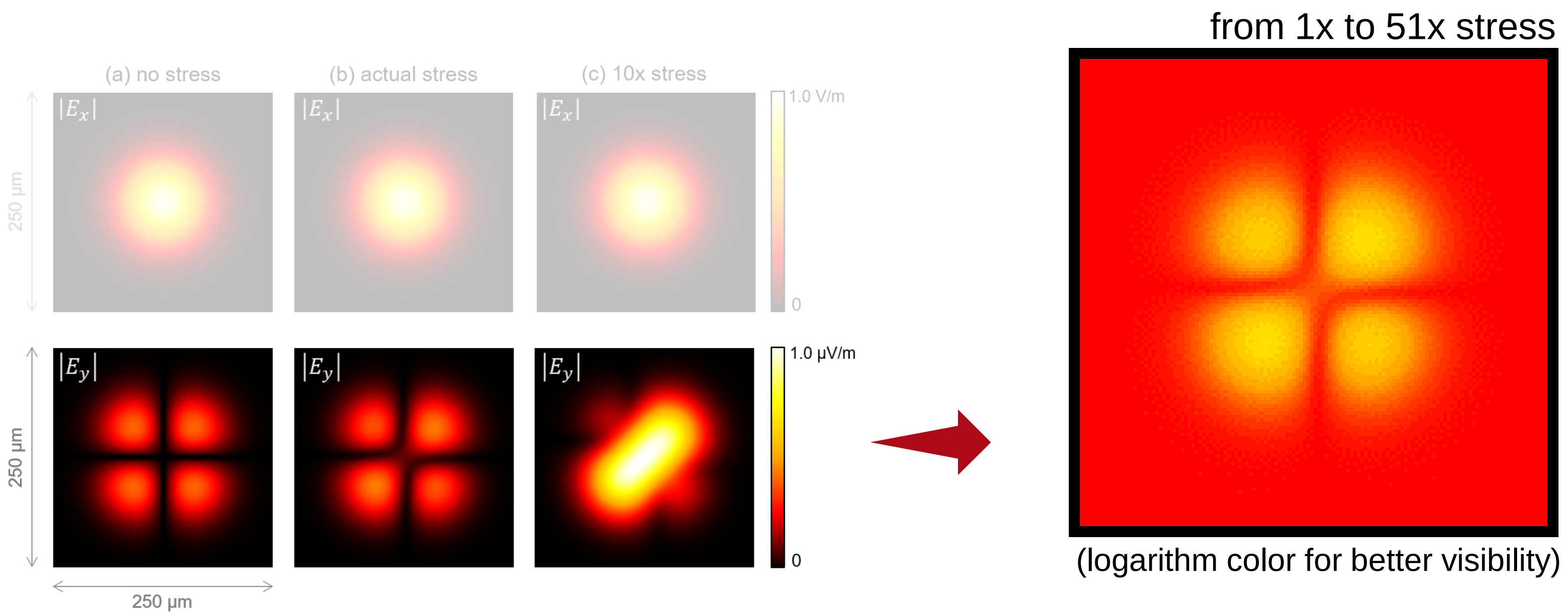
Simulation Results

- YAG crystal with 532 nm input field (Ex)



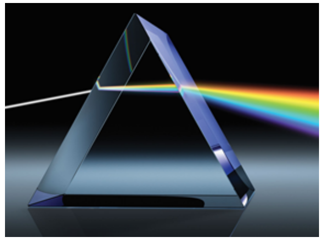
Simulation Results

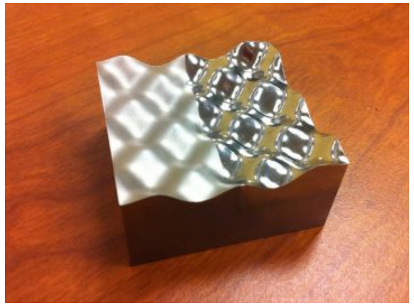
- YAG crystal with 532 nm input field (Ex)
  - Further check on the influence of stress-induced birefringence, we perform parameter run from 1x to 51x stresses (with 101 steps)



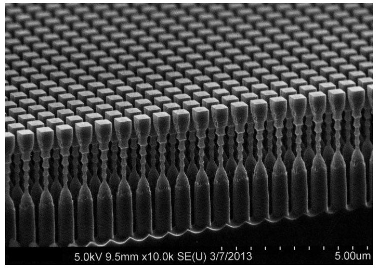
Optical Components

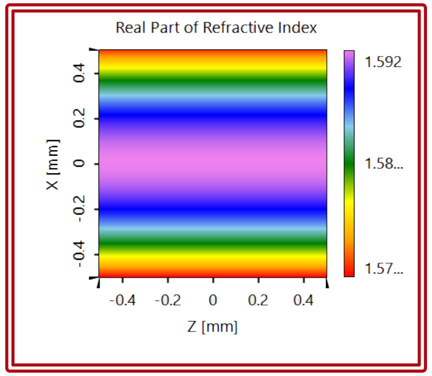
- elements with planar interfaces
- lenses
- freeforms
- gratings
- diffractive optical elements / lenses
- lens arrays
- crystals
- GRIN media

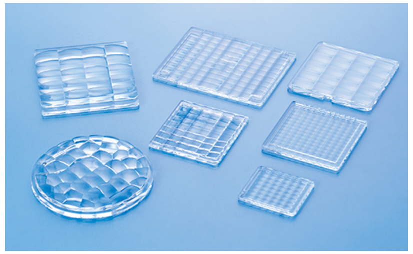




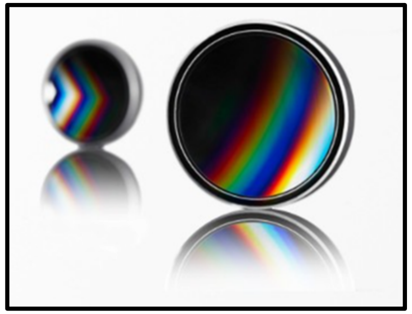
[1] IMS-Mechatronics Lab







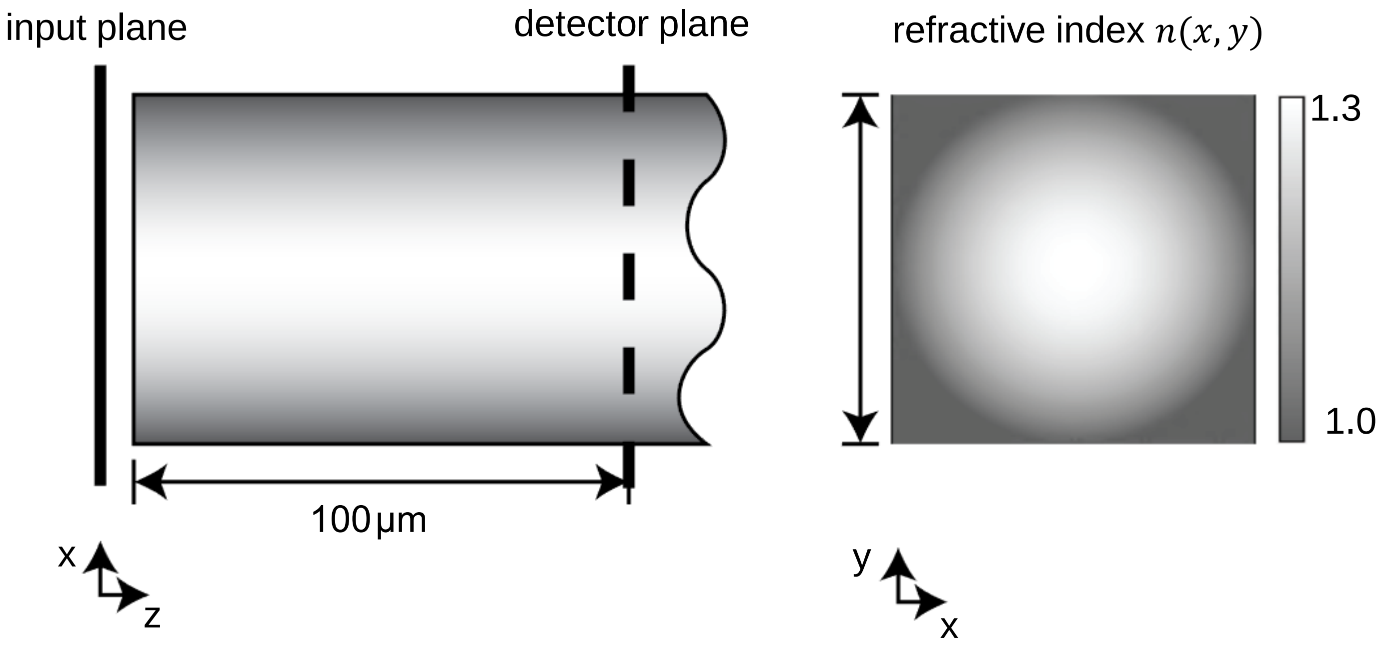
[2] ISUZU GLASS



Laser Systems > Beam Delivery System

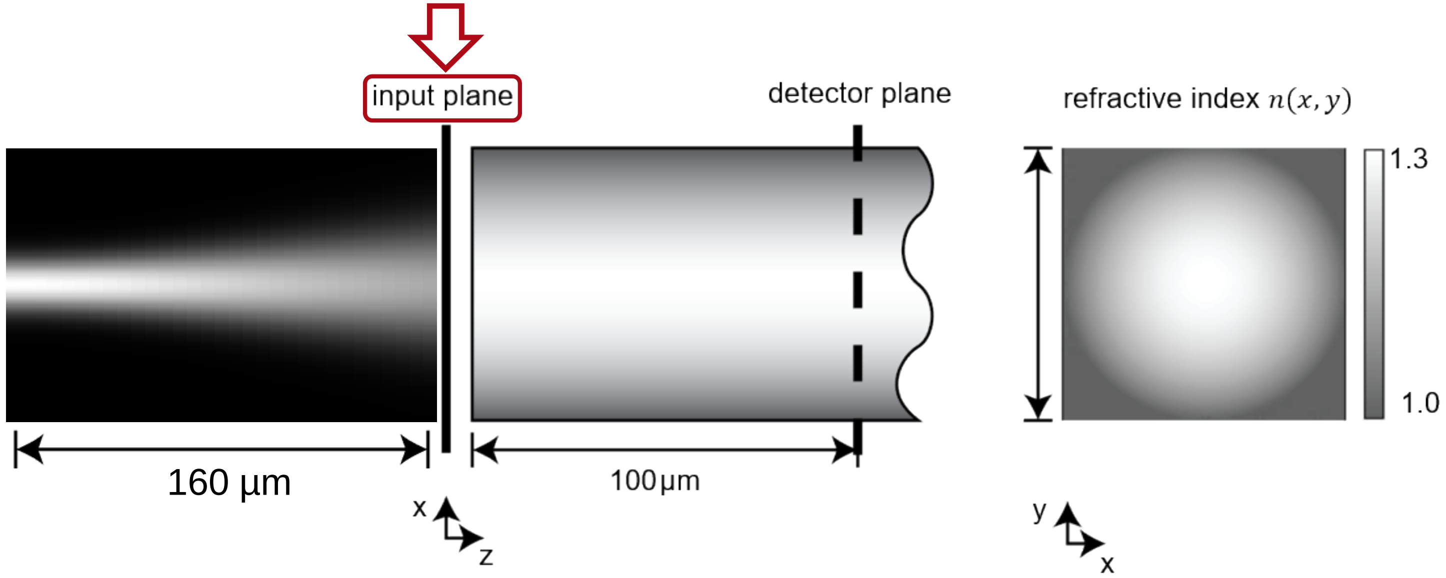
Modeling of Graded-Index (GRIN) Multimode Fiber

Task/System Illustration



- ray propagation through a GRIN fiber
- electromagnetic field propagation through a GRIN fiber by
  - a rigorous Maxwell solver, the Fourier Modal Method (FMM) with Perfectly Matched Layers (PMLs)
  - our newly developed very fast approximated Maxwell solver

Specifications: Light Source



Parameter	Description / Value
coherence/mode	single Hermite Gaussian (0,0) mode
wavelength	532 nm
polarization	linear in y-direction (90°)
distance between beam waist and input plane	160µm

Specifications: GRIN fiber

- refractive index $n(x, y)$

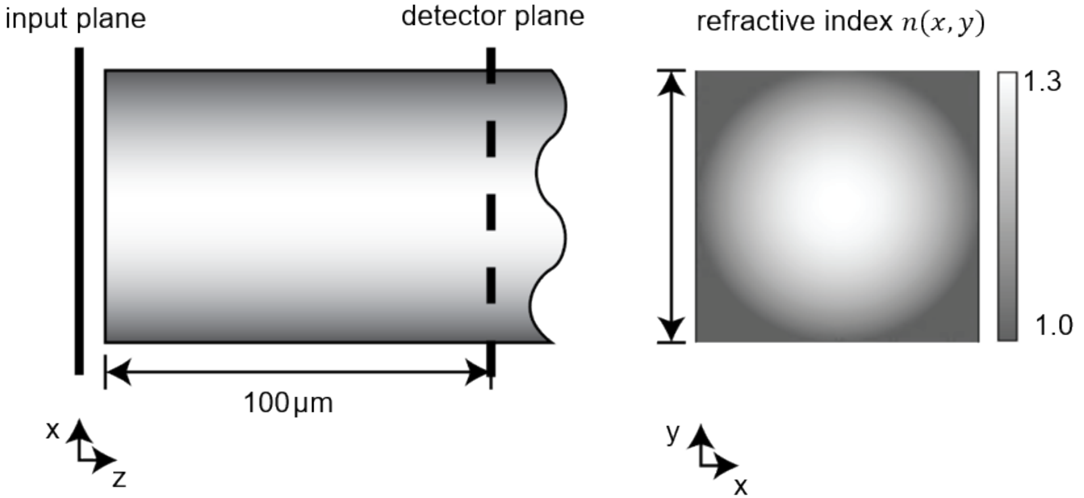
$$n(x, y) = n_0 \sqrt{1 - 2 \cdot \Delta \cdot \frac{r^2}{r_0^2}}$$

with $r = \sqrt{x^2 + y^2}$ and $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$

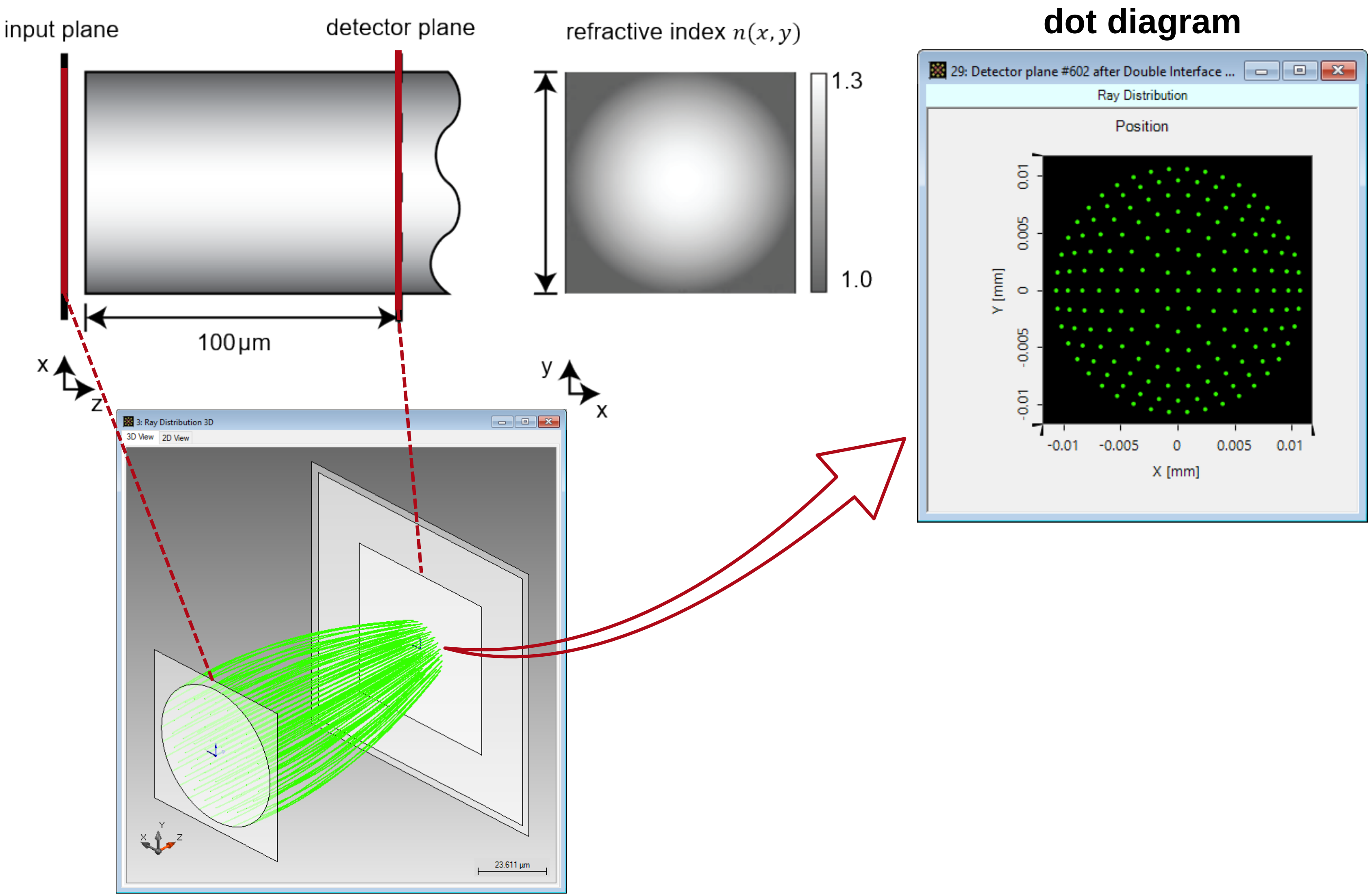
- in this case, $n_1 = 1.3,\ n_2 = 1.0,\ r_0 = 50\,\mu m$

Highlight

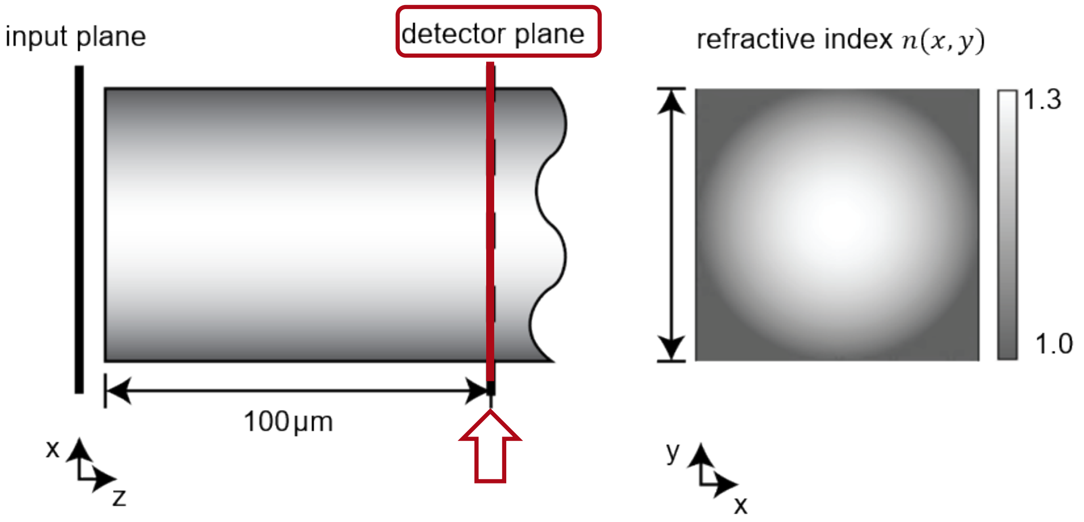
arbitrarily customizable refractive index profile



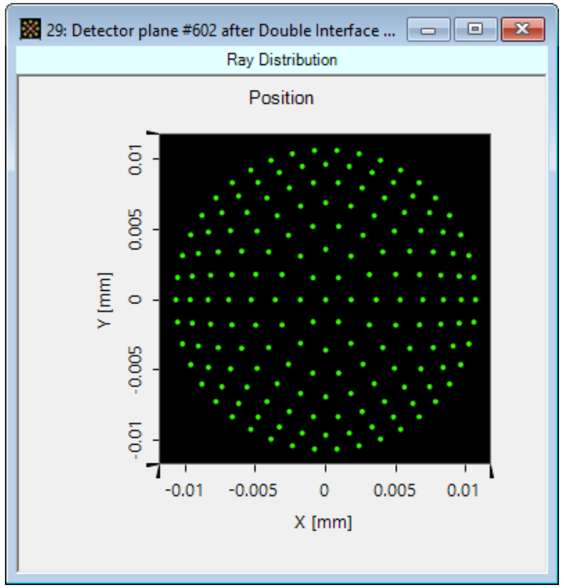
Results: 3D System Ray Tracing



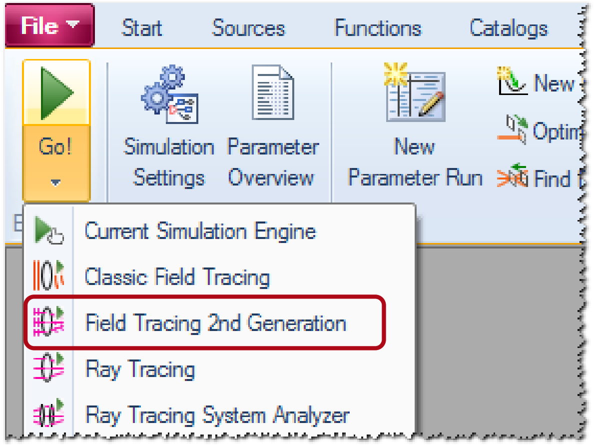
Results: Switching to Our Fast Approach



dot diagram



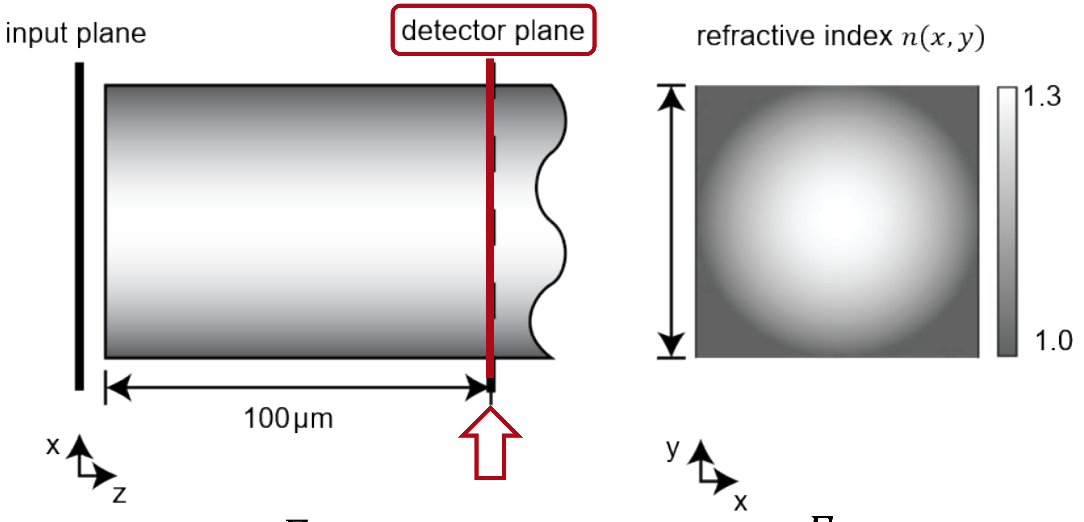
switching from ray tracing to field tracing by just one click

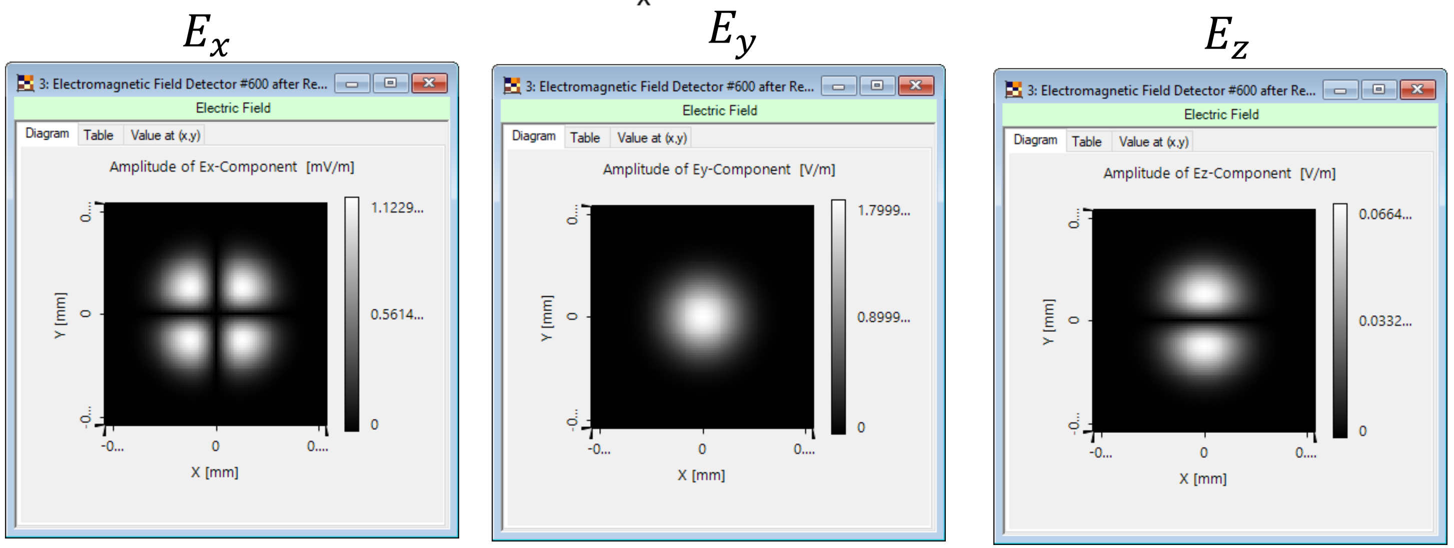


Highlights

easy switching between ray and field tracing

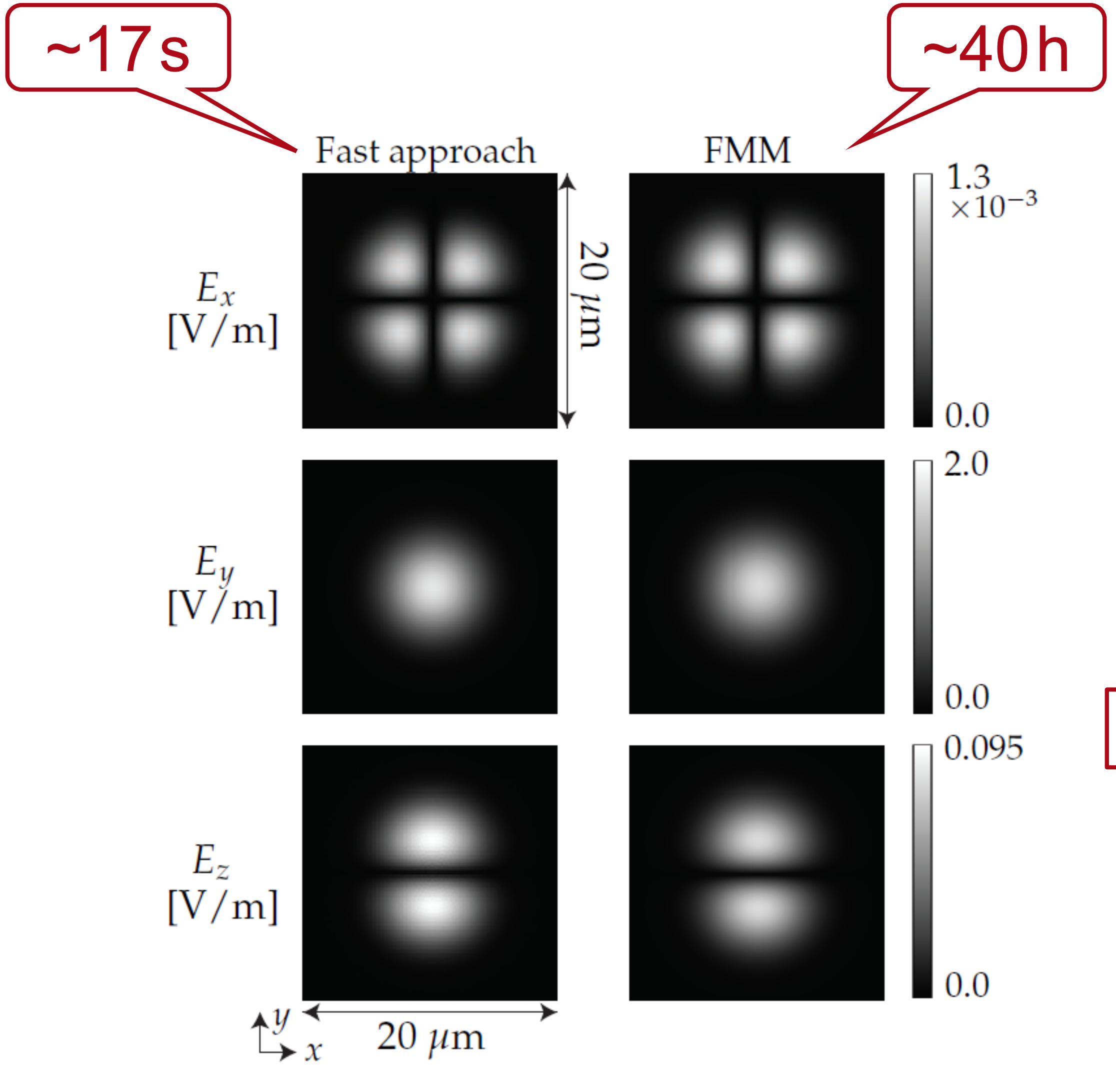
Results: Our Fast Approach





Amplitude [V/m]

Results: Our Fast Approach vs FMM



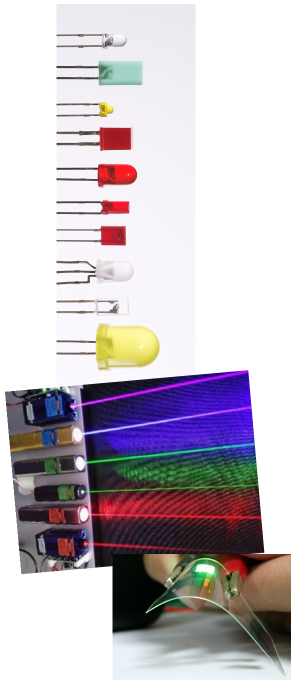
Deviation between results of both approaches is < 1%

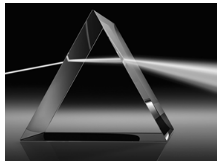
Highlights

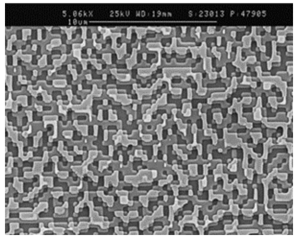
- high accuracy of new propagation method for multimode GRIN fibers
- consideration of polarization crosstalk

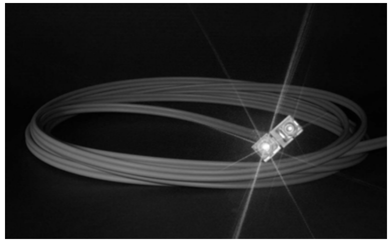
Source and detector modeling

Source

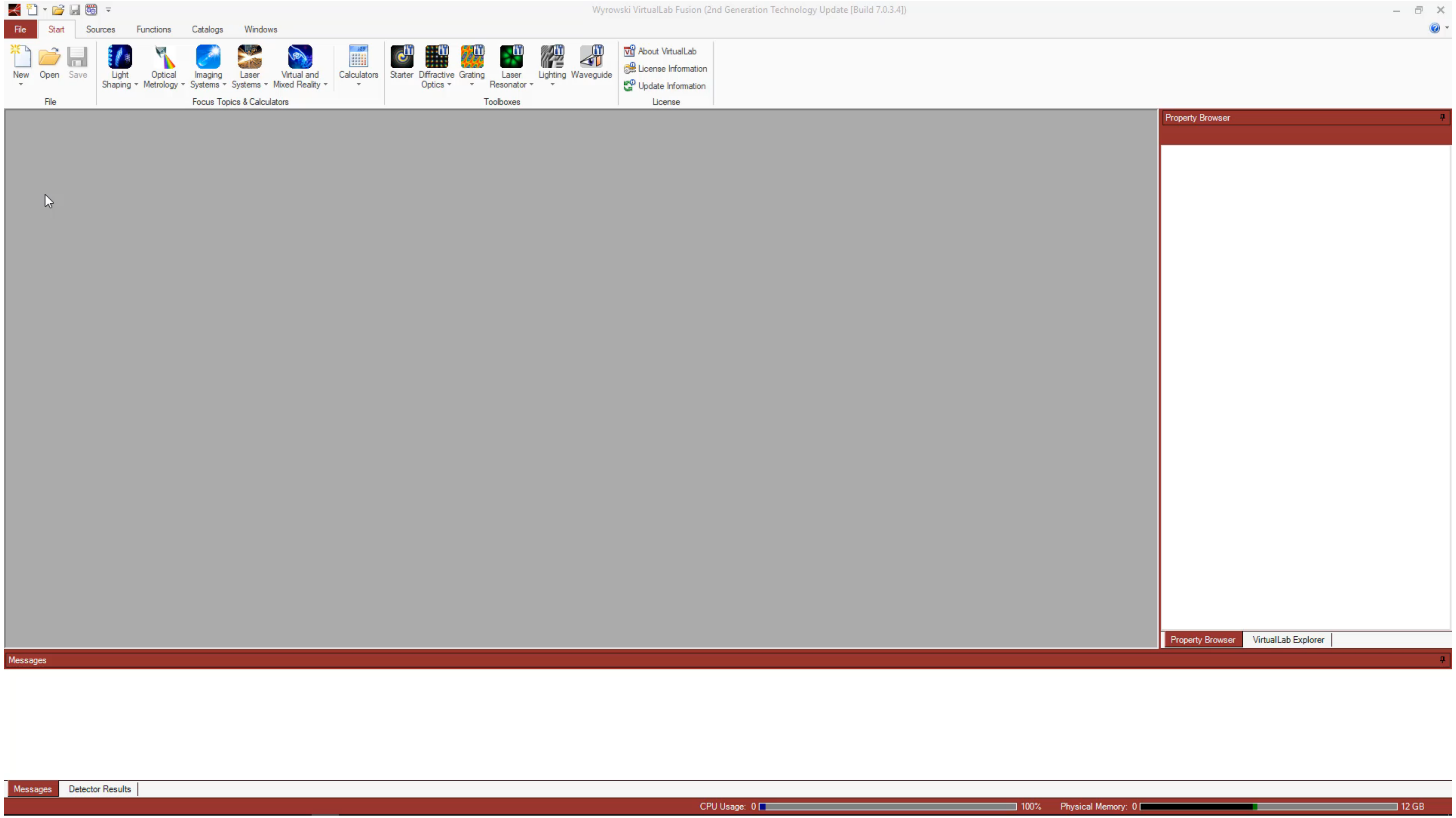




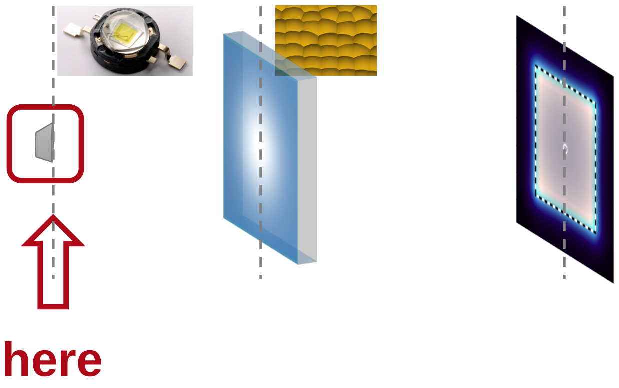




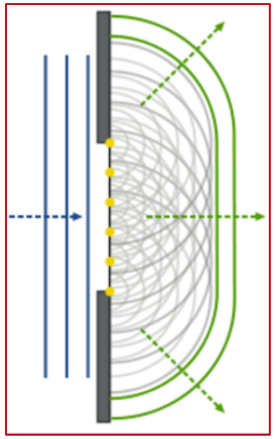
Video of sources



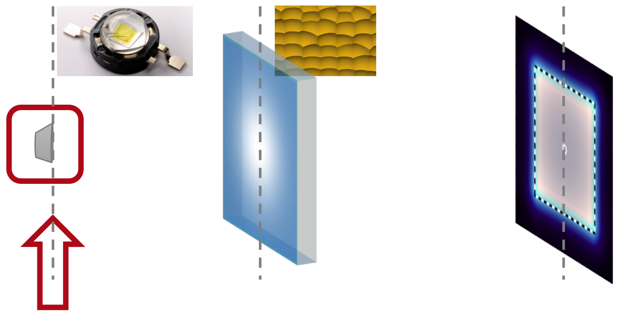
Partially Coherent Source: Lateral Modes



a set of point sources

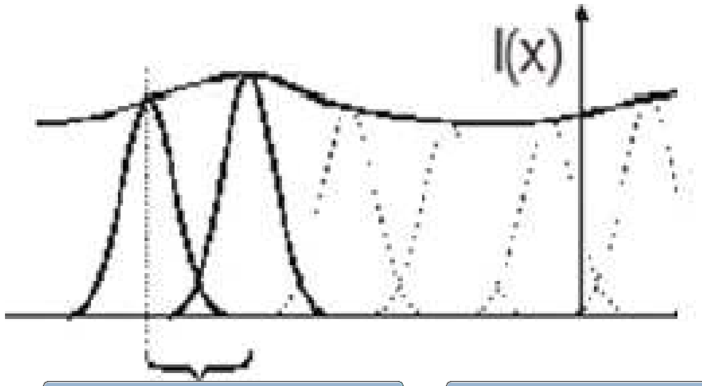


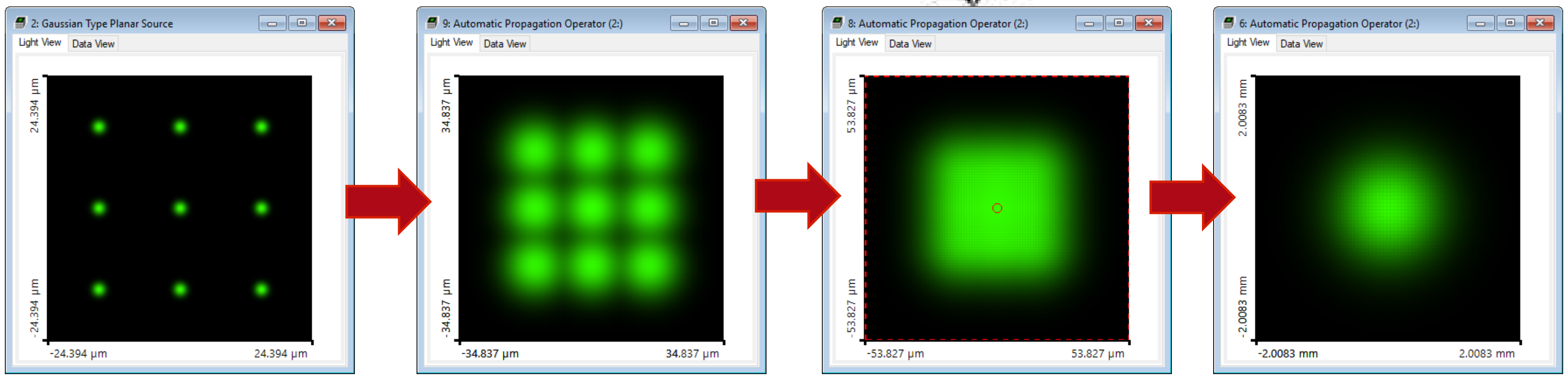
Partially Coherent Source: Lateral Modes



here

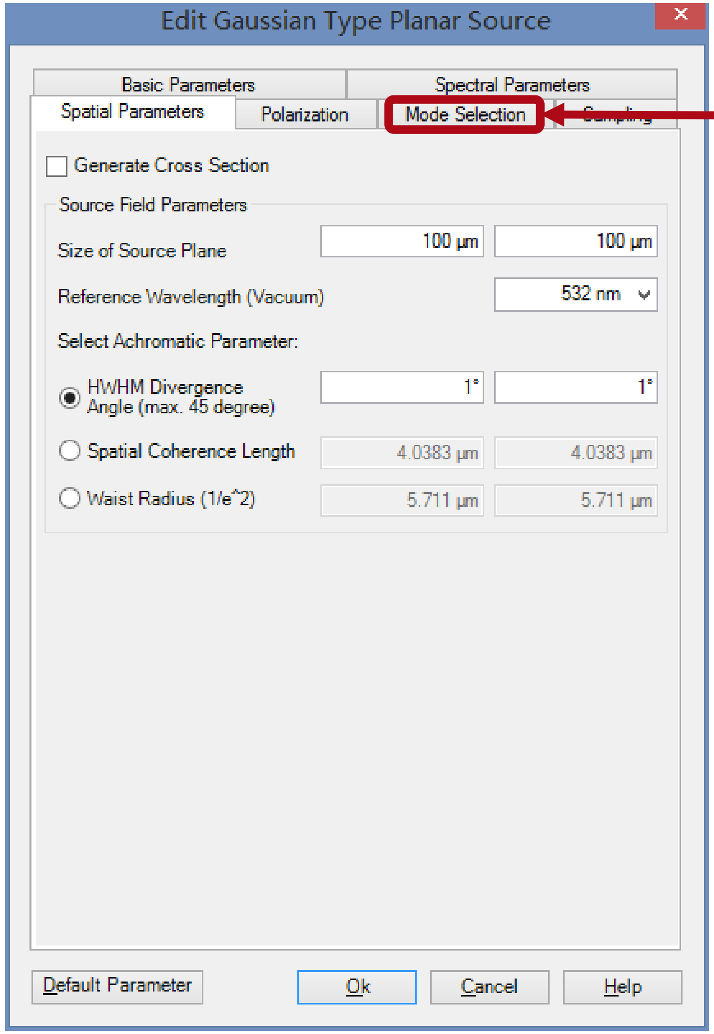
shifted- elementary-mode concept

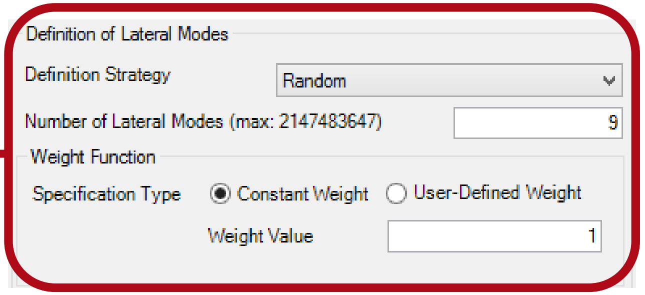


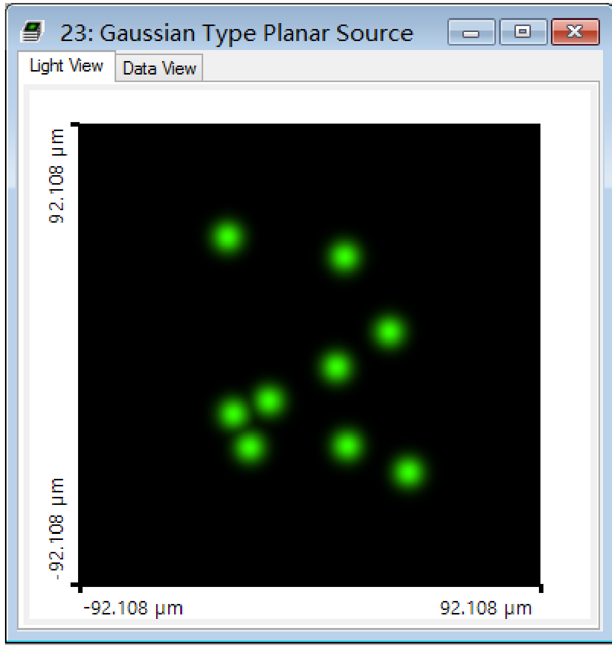


[3] Tervo, J., Turunen, J., Vahimaa, P. and Wyrowski, F. J. Opt. Soc. Am. A 27(9)(2014)

Gaussian Type Planar Source (Example)

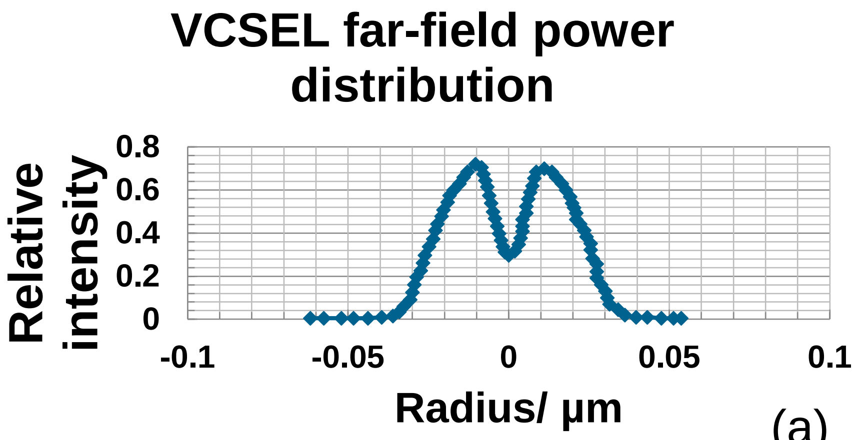




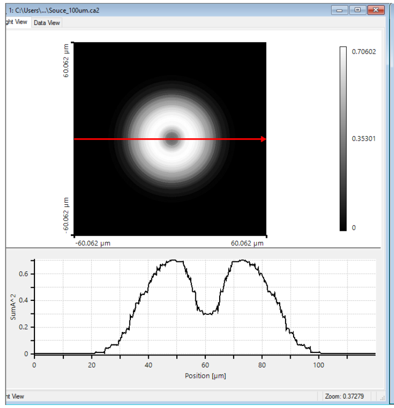


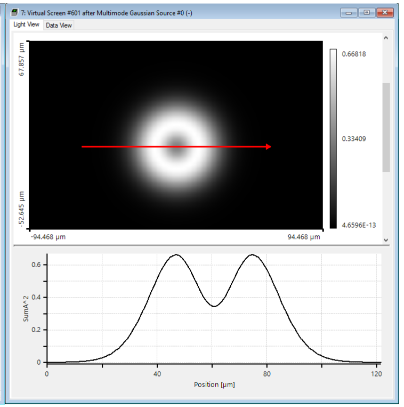
Modelling of Source

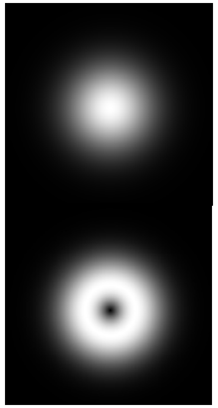
- Modelling of Source
  - Transfer the 1D data(a) into 2D field data (b)
  - Calculate the source modes by using Parametric Optimization.
    - The source contains two Gaussian Laguerre modes (d).
    - The intensity distribution is (c)



(a)

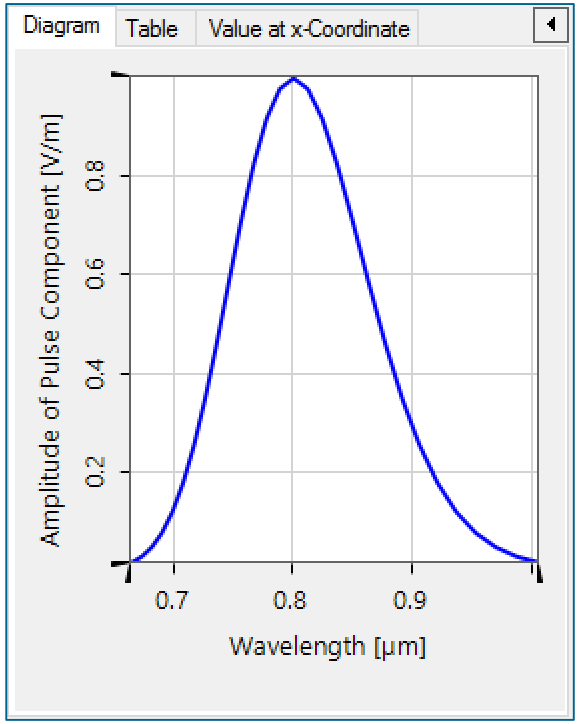

(b)


(c)

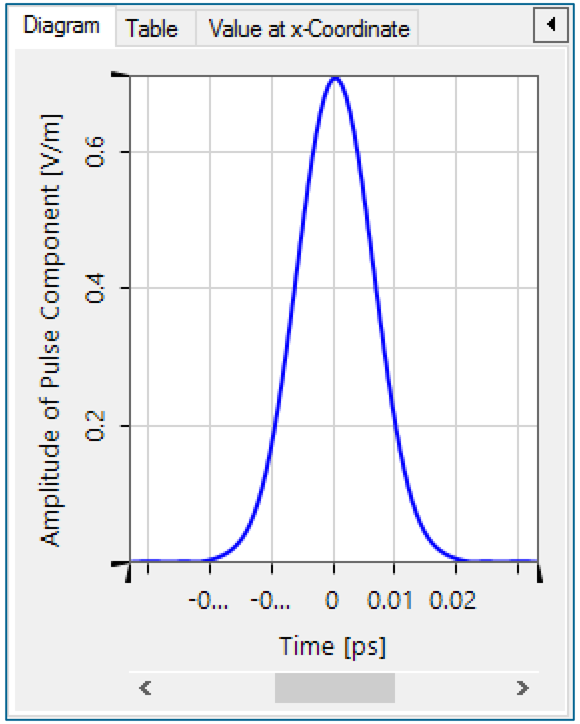

(d)

Pulse in Frequency Domain

- In frequency (wavelength) domain
  - Gaussian pulse

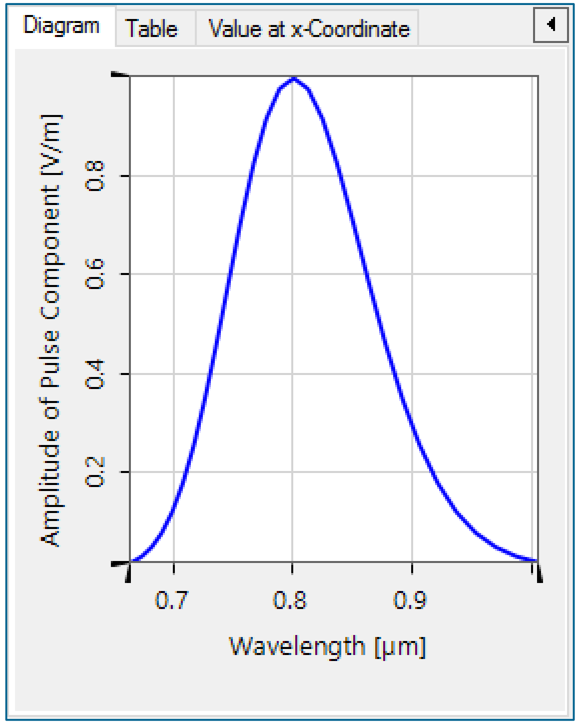


- In time domain (envelop)
  - Fourier transform

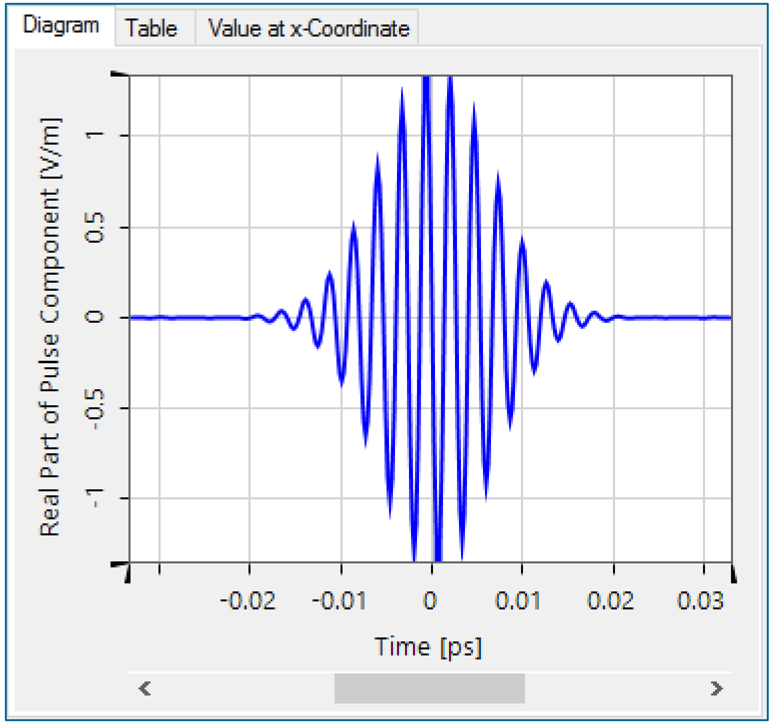


Pulse in Frequency Domain

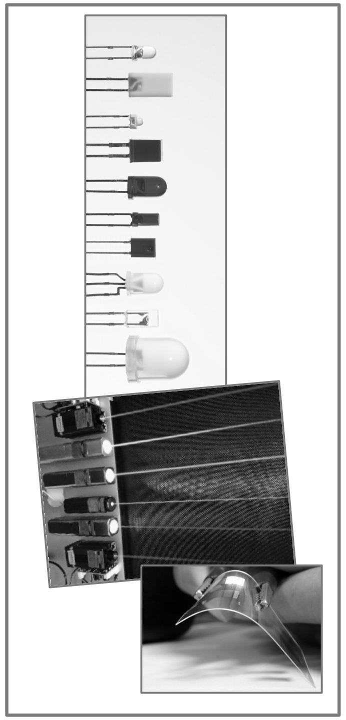
- In frequency (wavelength) domain
  - Gaussian pulse

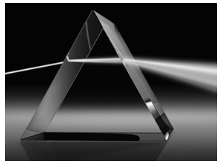


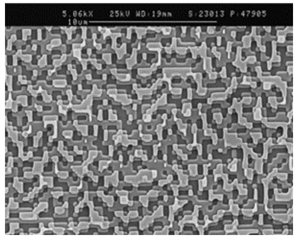
- In time domain
  - Fourier transform

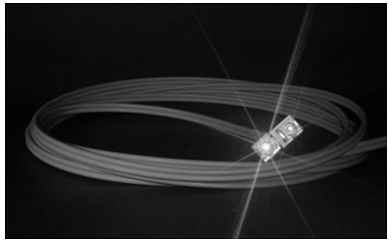


Detectors - Examples





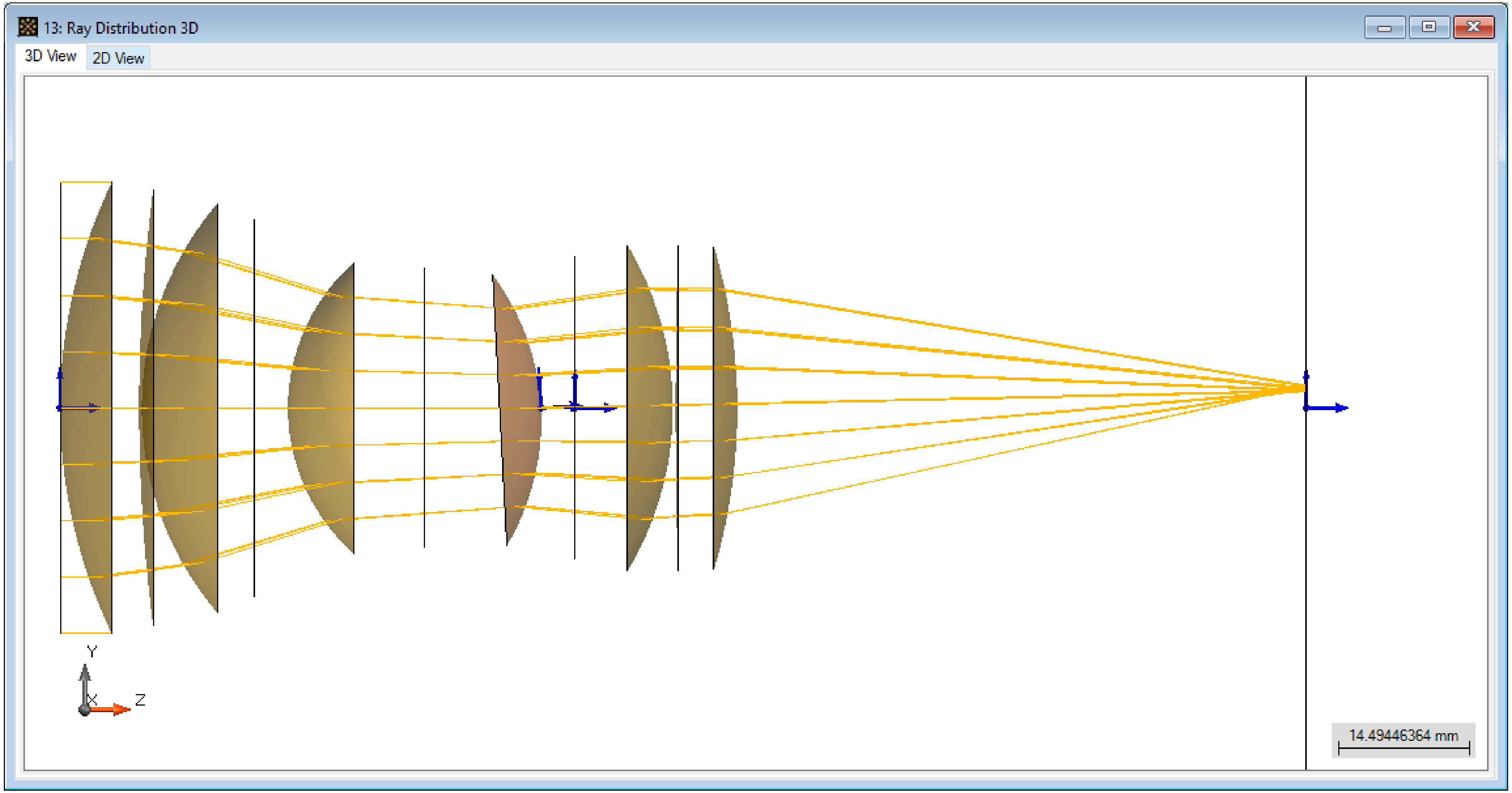




Detector of ray quantities

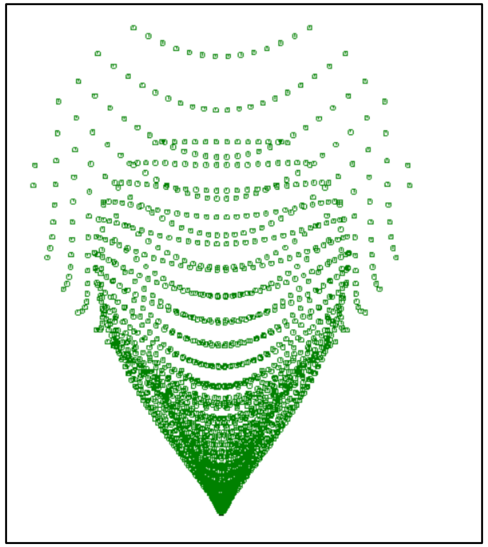
- Ray tracing system analyzer
- Spot diagram
- Spot size

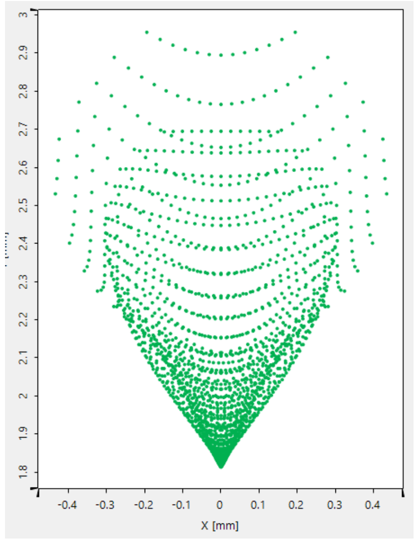
3D Ray Tracing Analyzer: VLF

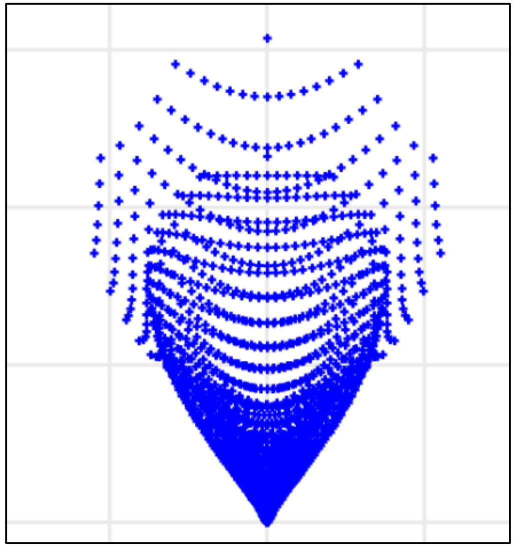


Dot Diagram Comparison: Target Plane

- **VLF** spot size (Beam diameter RMS): 581.25 µm (Centroid as reference)
- **Code V** spot size (RMS): 580.62 µm
- **VLF** spot size (Beam diameter RMS): 880.42 µm (Chief ray as reference)
- **Zemax** spot size (RMS): 880.114 µm







Code V

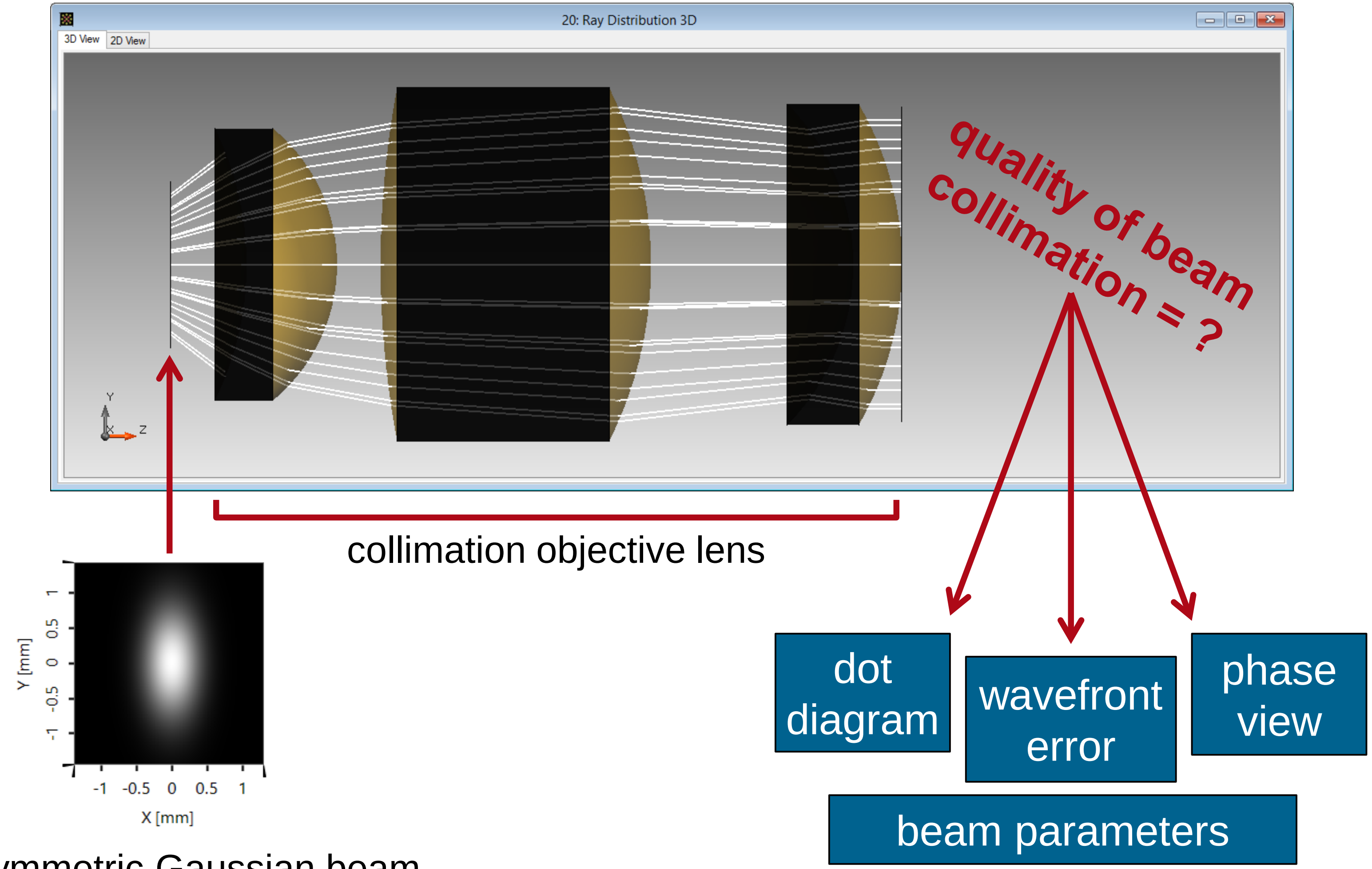
VLF

Zemax

Detector of ray quantities

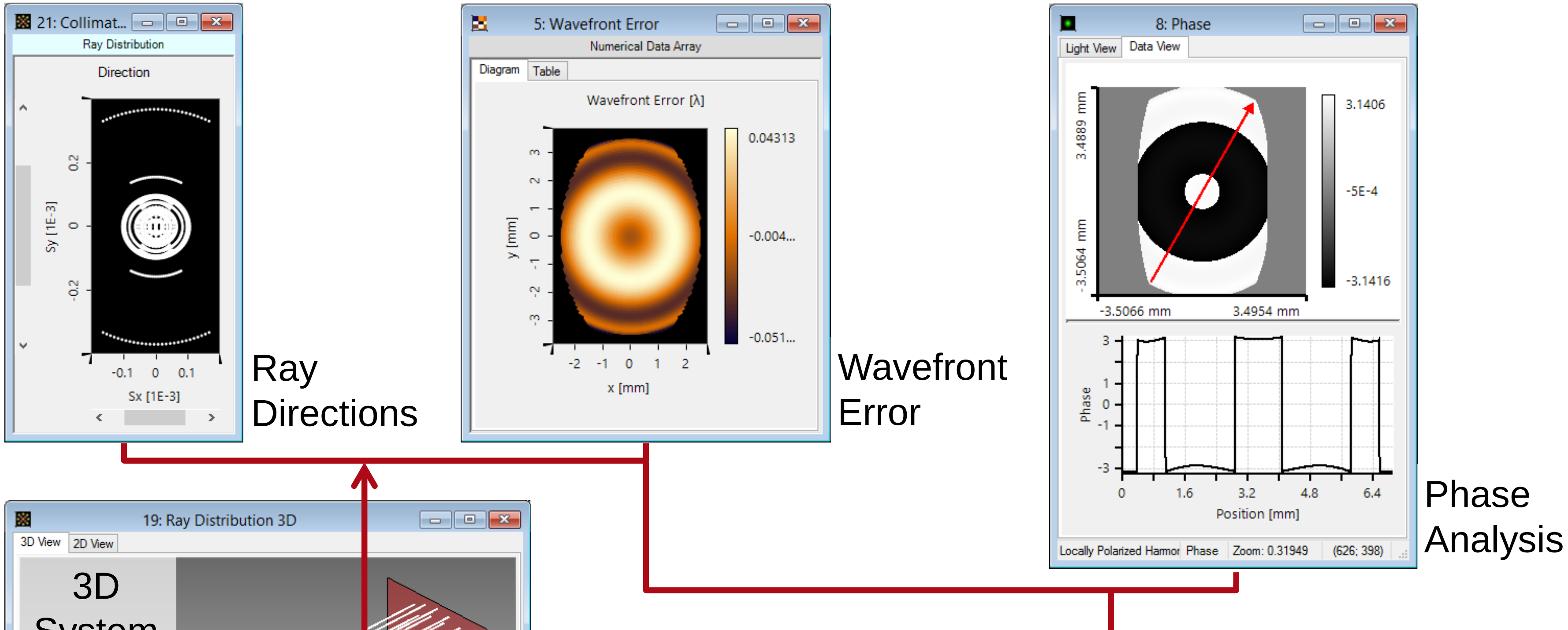
- Ray tracing system analyzer
- Spot diagram
- Spot size
- Wavefront error

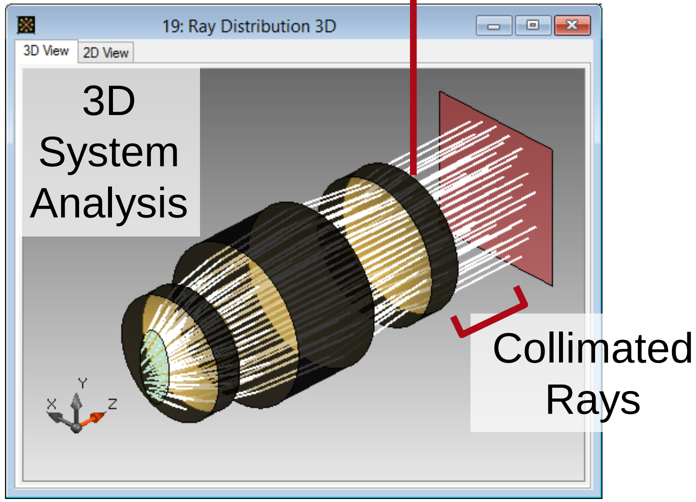
System Illustrations



asymmetric Gaussian beam
of IR laser diode ($M^2 = 1$)

Modeling & Design Results



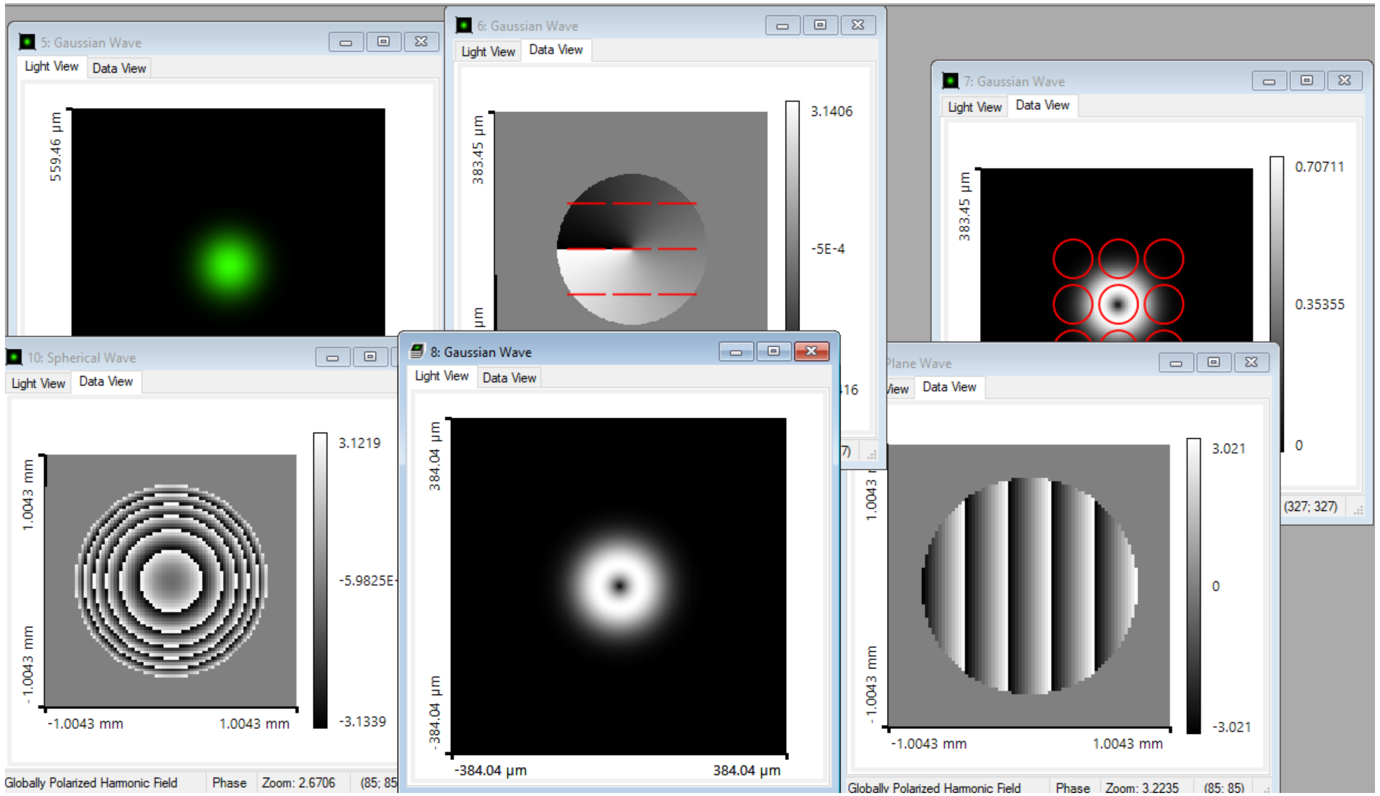


Numerical Detector Results

Quantity	**Value & Unit**
wavefront error (RMS)	0.03λ
divergence Angle X x Y	0.02° x 0.01°
M^2 parameter in X x Y direction	1.0180 x 1.1802

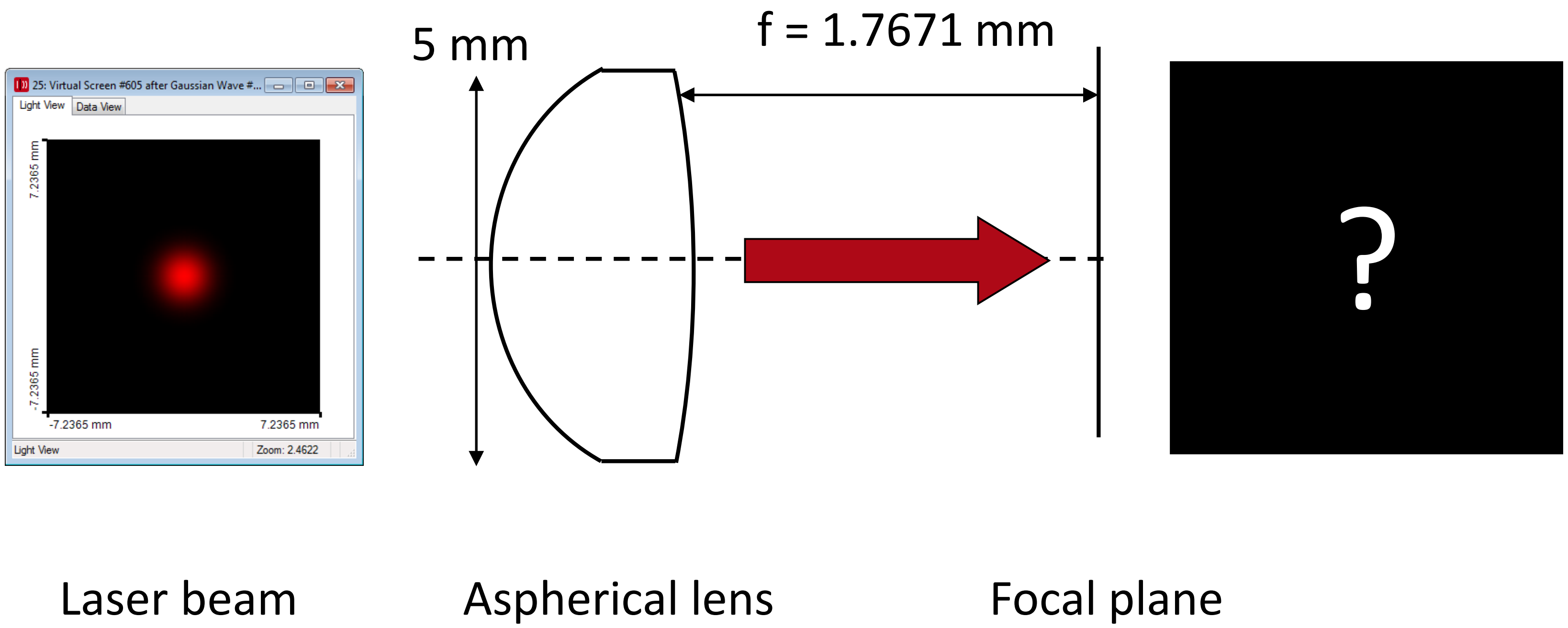
Field Detectors

- Electromagnetic field: amplitude / phase/ real and imaginary part



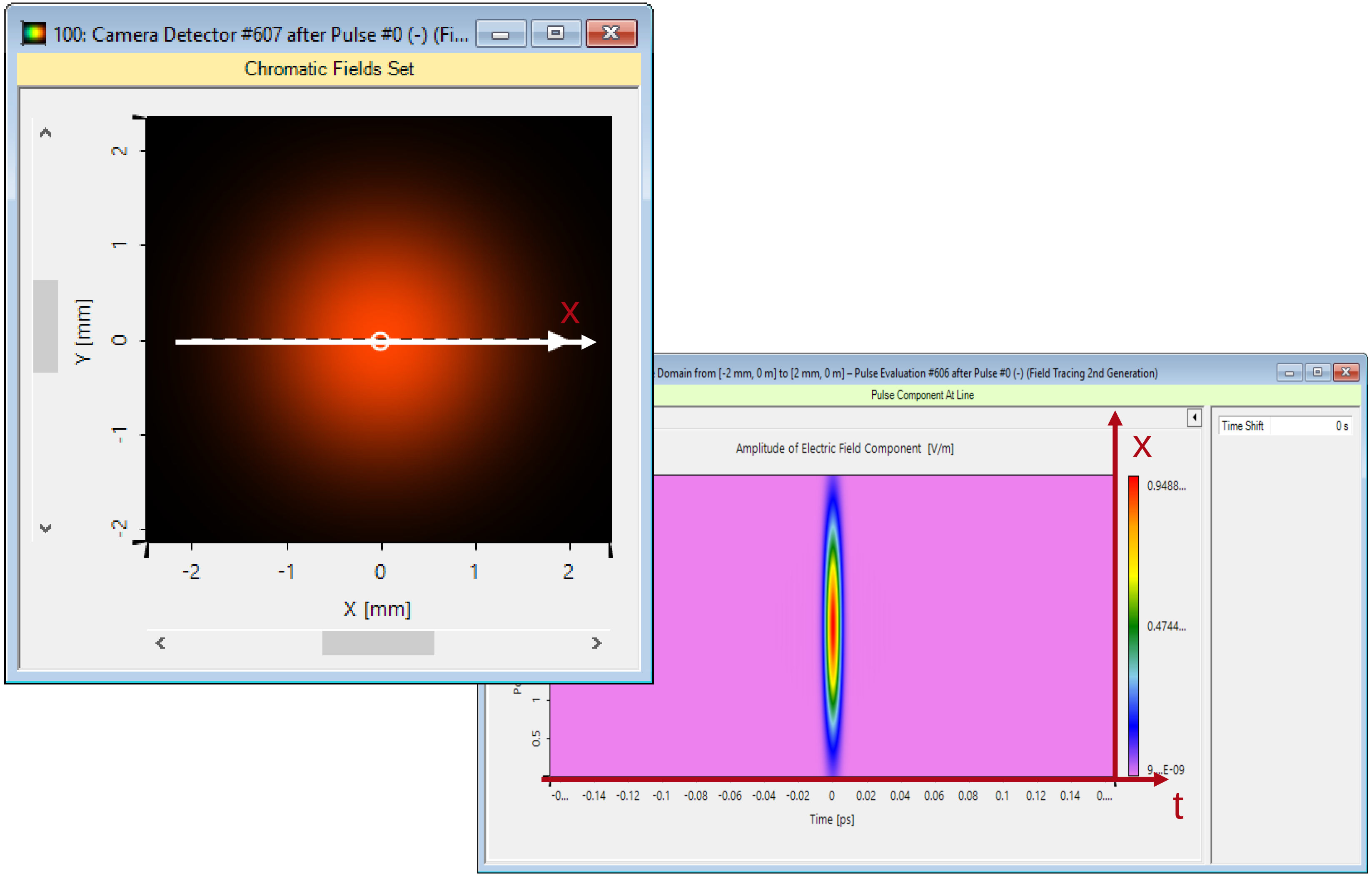
Spatiotemporal Evolution of Femtosecond Pulse Focus

Overview



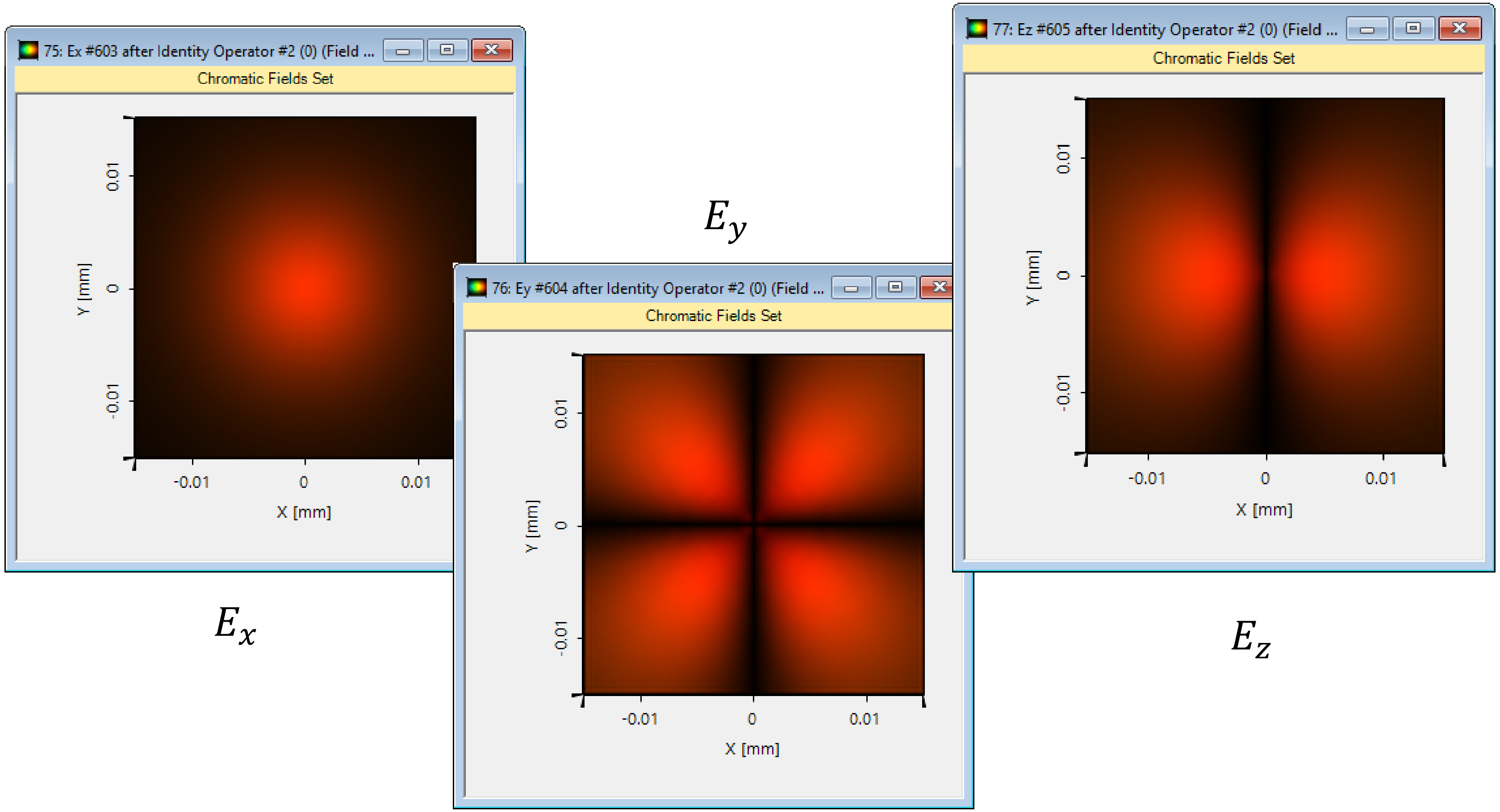
NA=0.68

Input Beam Pulse



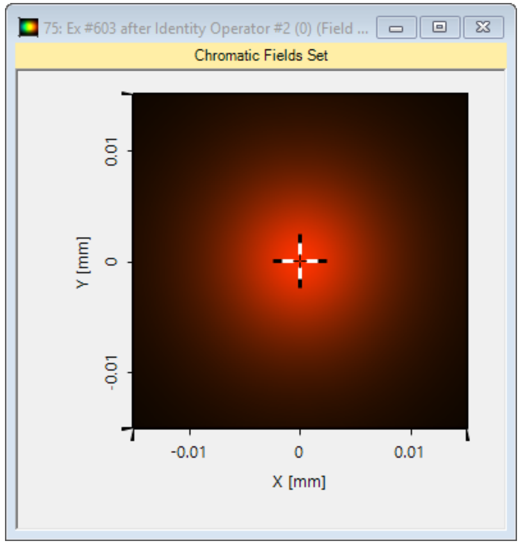
Simulation: Ex, Ey and Ez

- Enable the detectors Ex, Ey and Ez

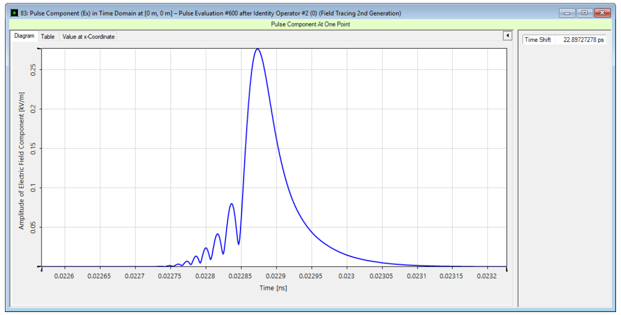


Simulation: Pulse at Point (0,0)

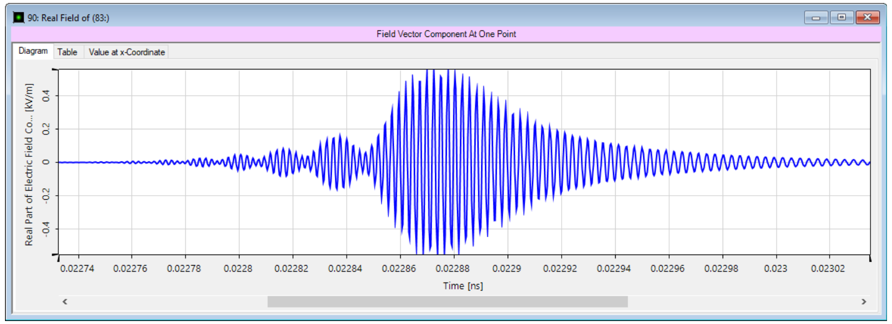
- Enable Detector Pulse Evaluation



E_x

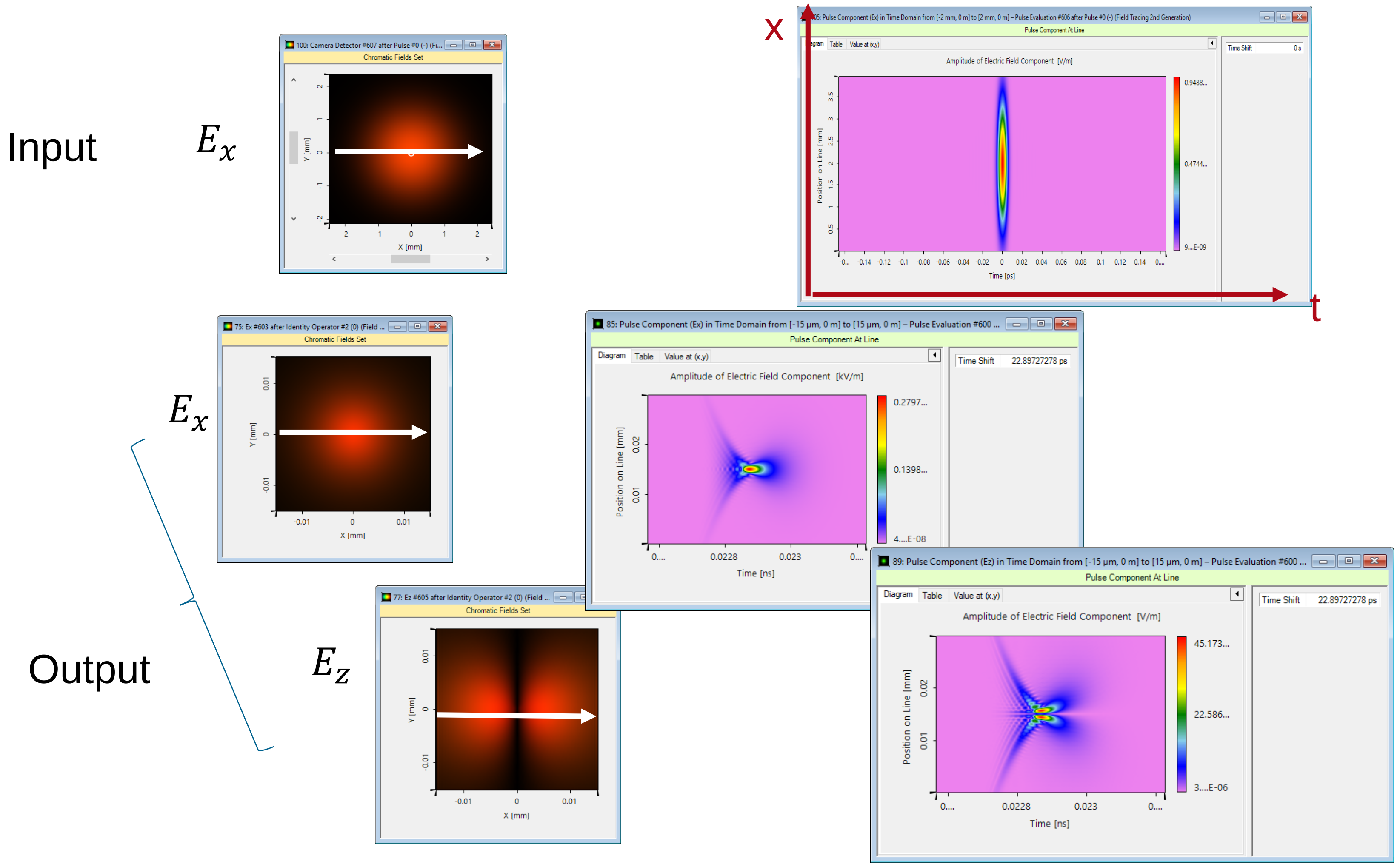


Envelope

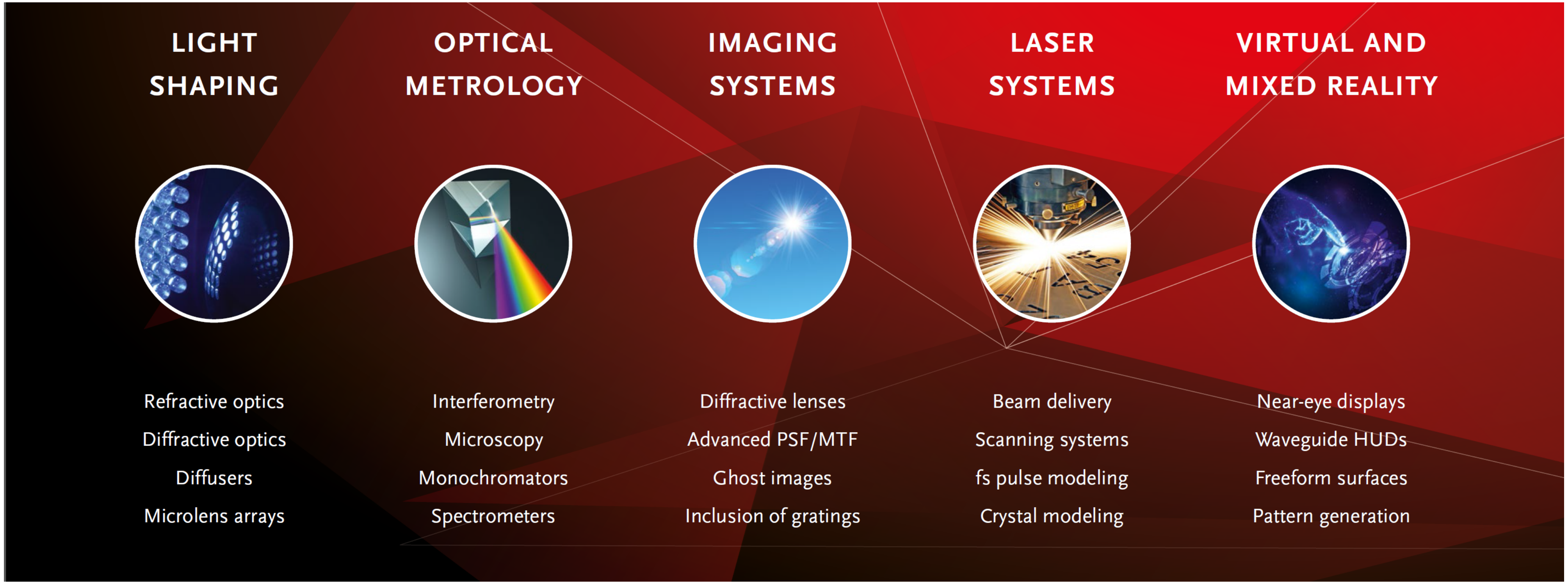


Field

Simulation: Pulse along x-Axis

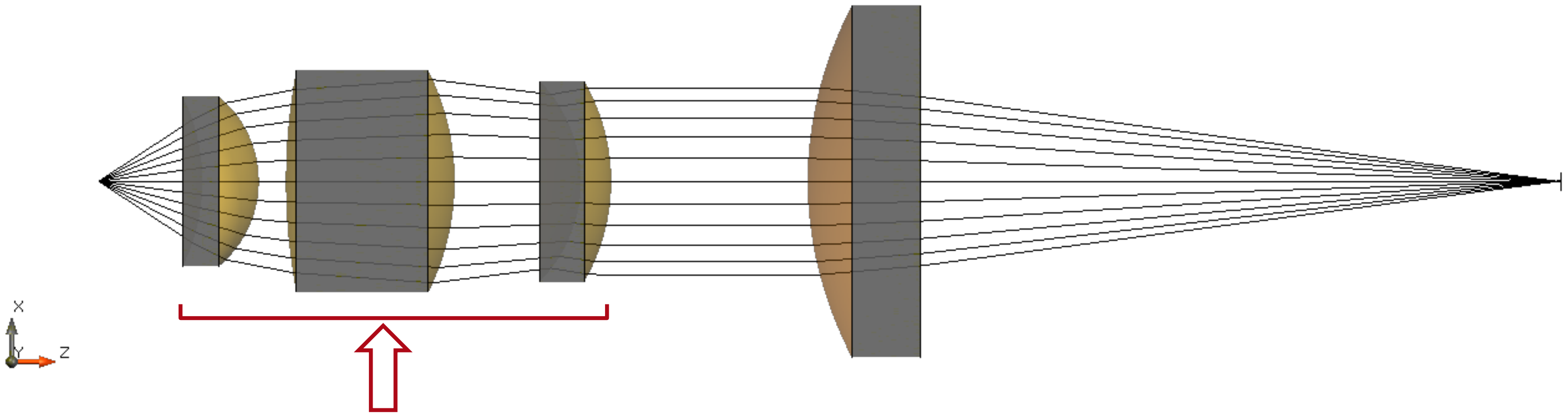


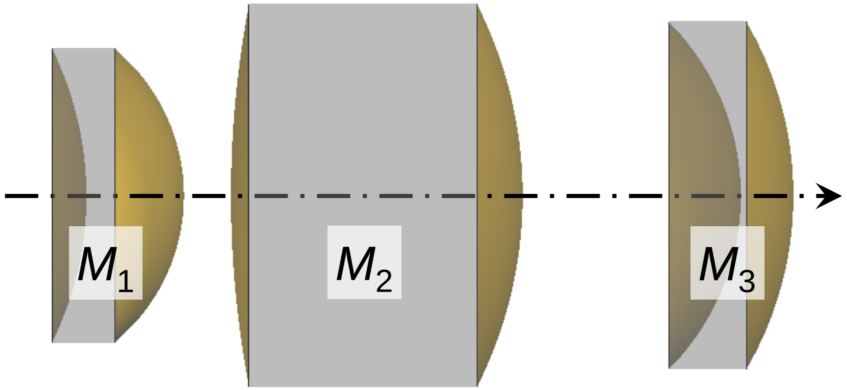
Focused Topics



Imaging and laser systems

Specification: Collimating Lens

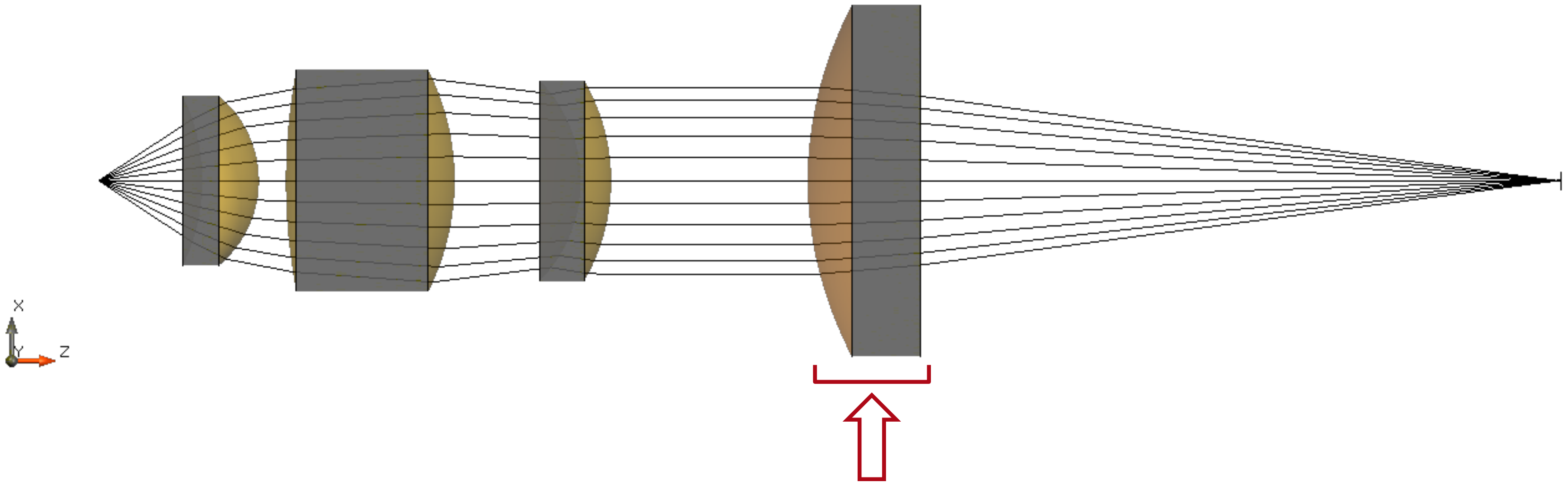




Parameter	Value & Unit
types of lens surfaces	3 lenses with 6 spherical surfaces
numerical aperture (NA)	0.63
materials	M_1: N-SF6* M_2,M_3: N-BK7*

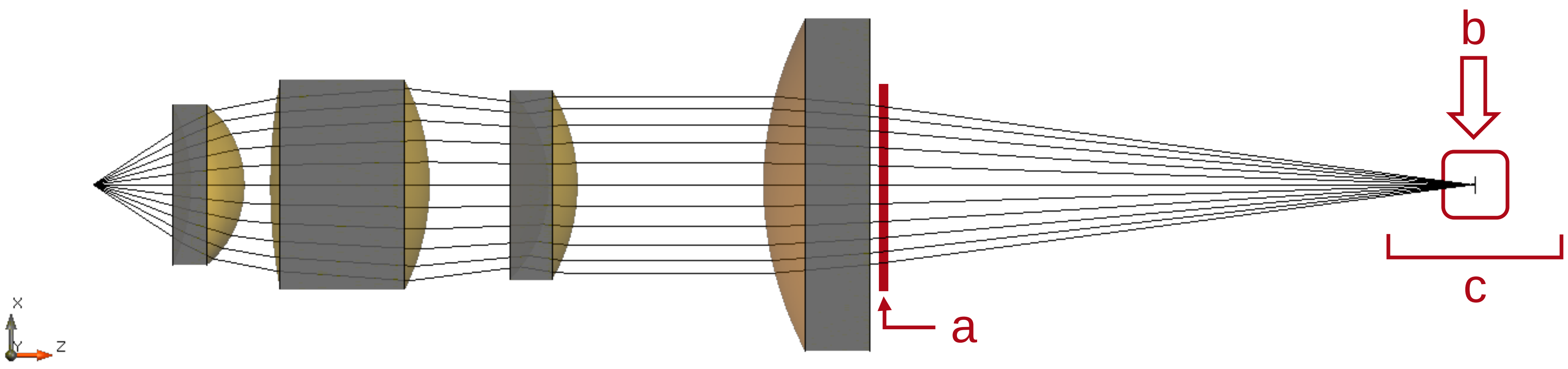
** from catalog "Schott_2014"*

Specification: Focusing Asphere



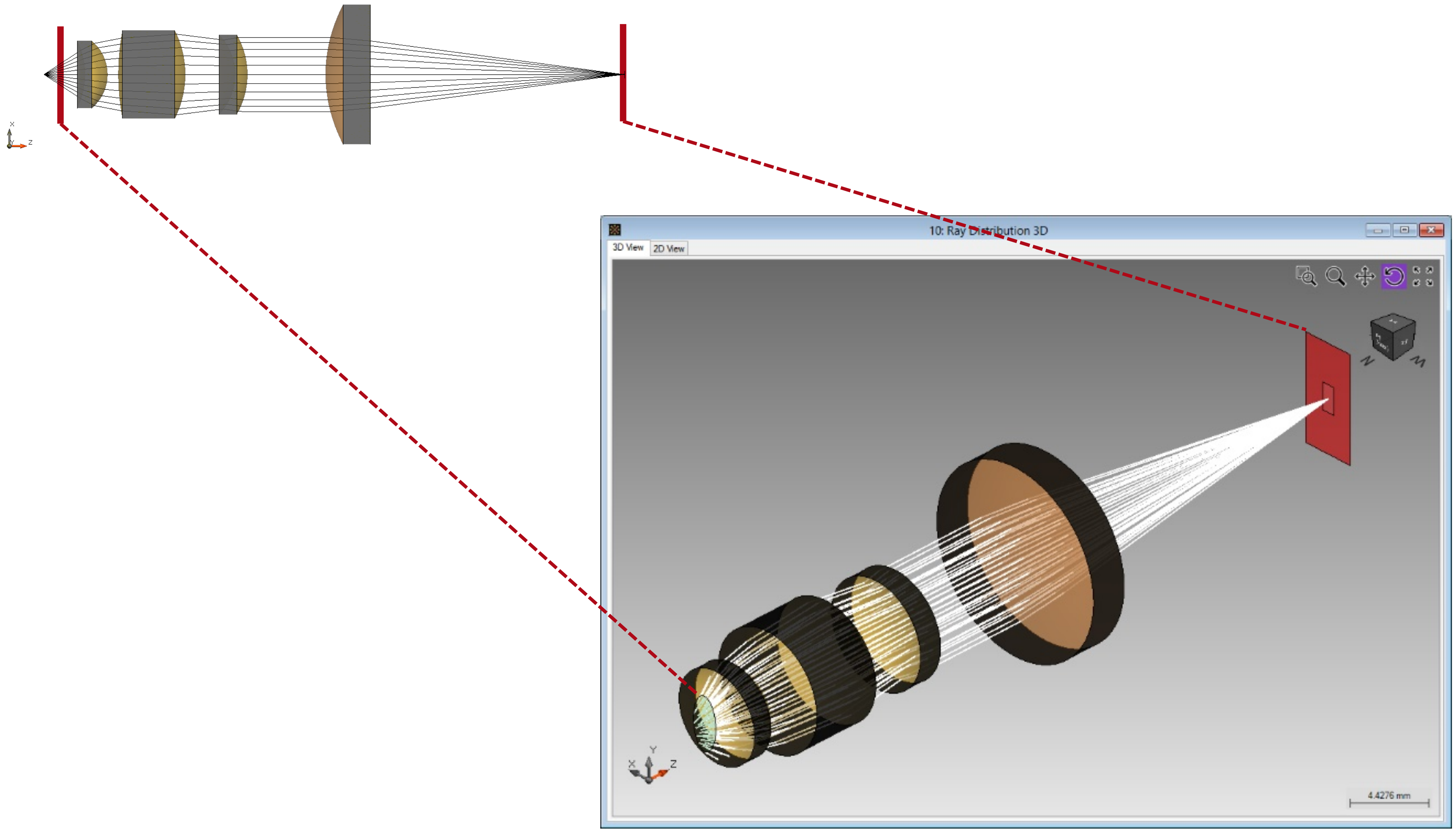
Parameter	Value & Unit
name/type	convex-plano aspherical lens from Asphericon: ALL12-25-S-U (A12-25LPX)
numerical aperture	0.23
material (M)	N-BK7

Specification: Detectors

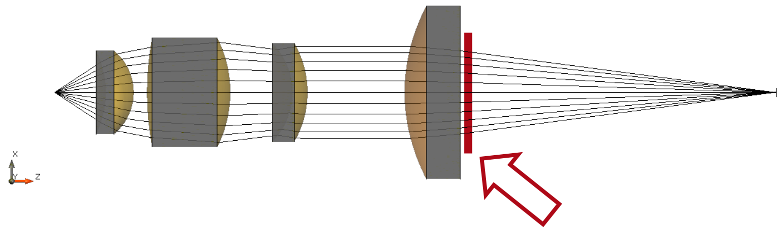


Position	Modeling Technique	Detector/Analyzer
full system	3D system ray tracing	general overview of light behavior in system
a	ray tracing	residual phase aberrations
b	ray tracing	dot diagram & focal beam size (x × y)
b	field tracing	intensity distribution
b	field tracing	focal beam size, M^2 value (x × y)
c	field tracing	focal region analysis by multiple 1D cross sections in x- & y-direction

Results: 3D System Ray Tracing



Results: Field behind Asphere

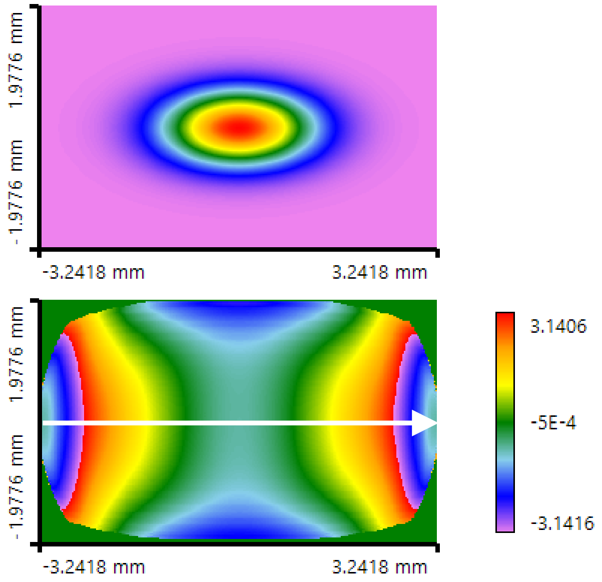


Highlights

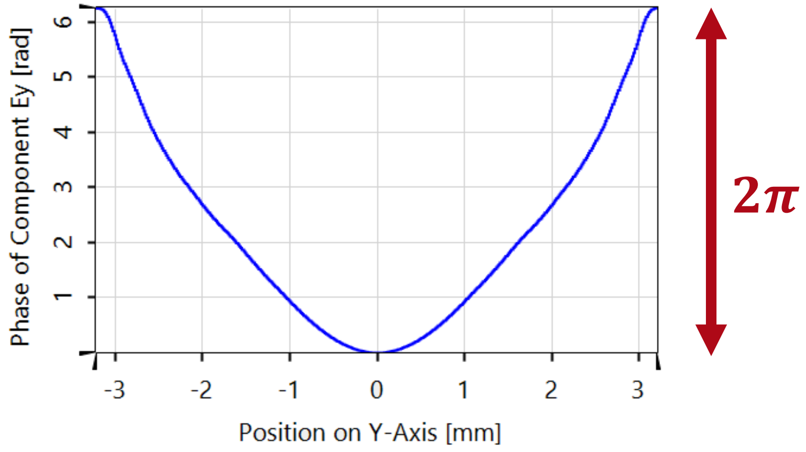
- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis

intensity

residual phase

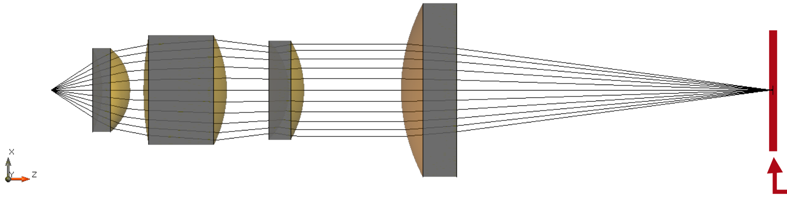


Simulation Time ~2s



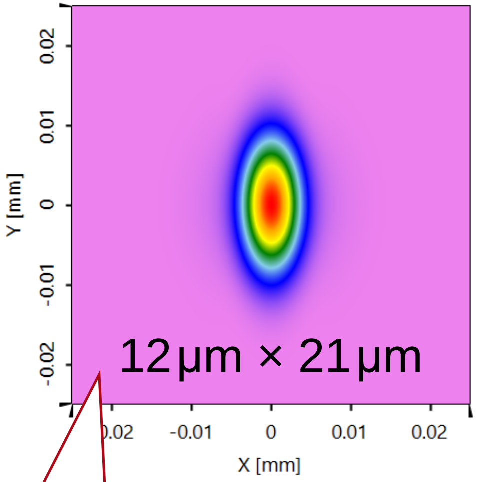
1D cross section of remaining phase

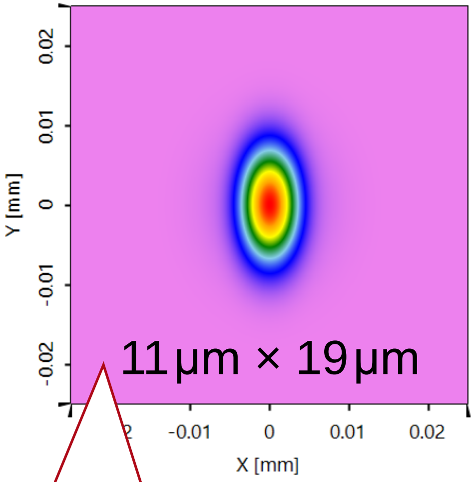
Results: Comparison with/without Astigmatisms



Highlights

- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis

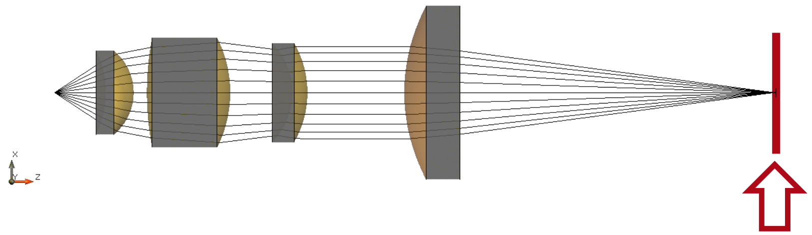




with astigmatism (11.6 µm)

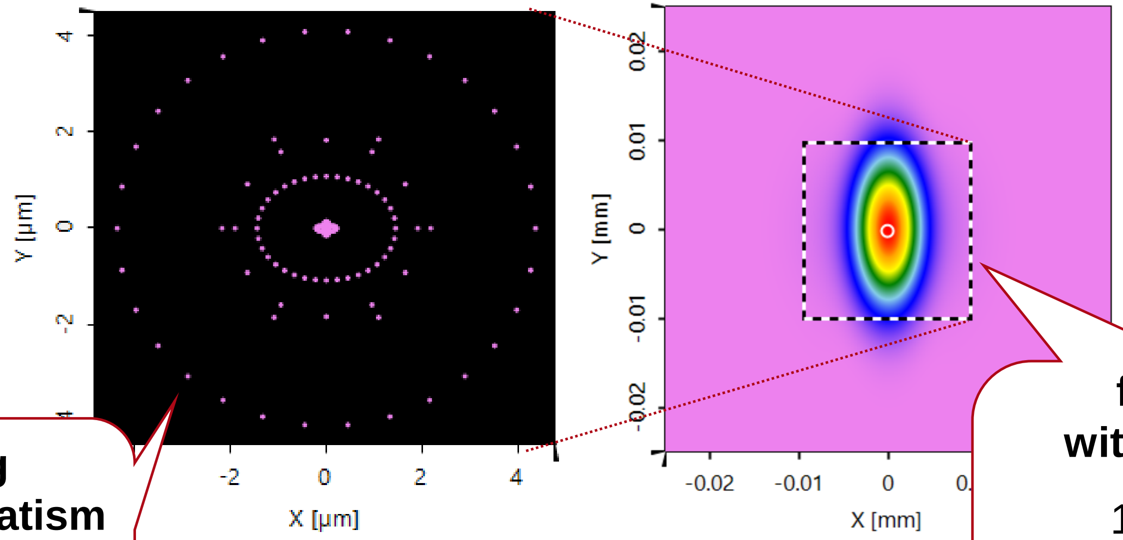
without astigmatism

Results: Focus Spot (PSF) & Parameters



Highlights

- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis



ray tracing without astigmatism

RMS diameter
(x × y) = 6µm × 6µm

dot diagram of ray positions

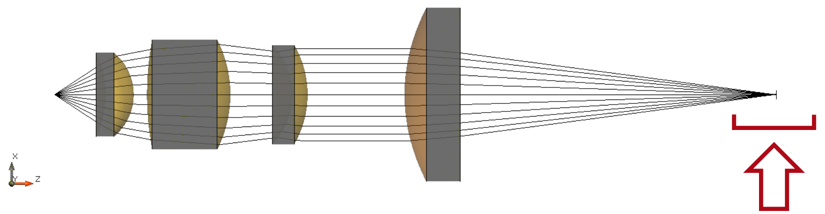
intensity

field tracing with astigmatism

$1/e^2$ diameter
(x × y) = 11µm × 19µm

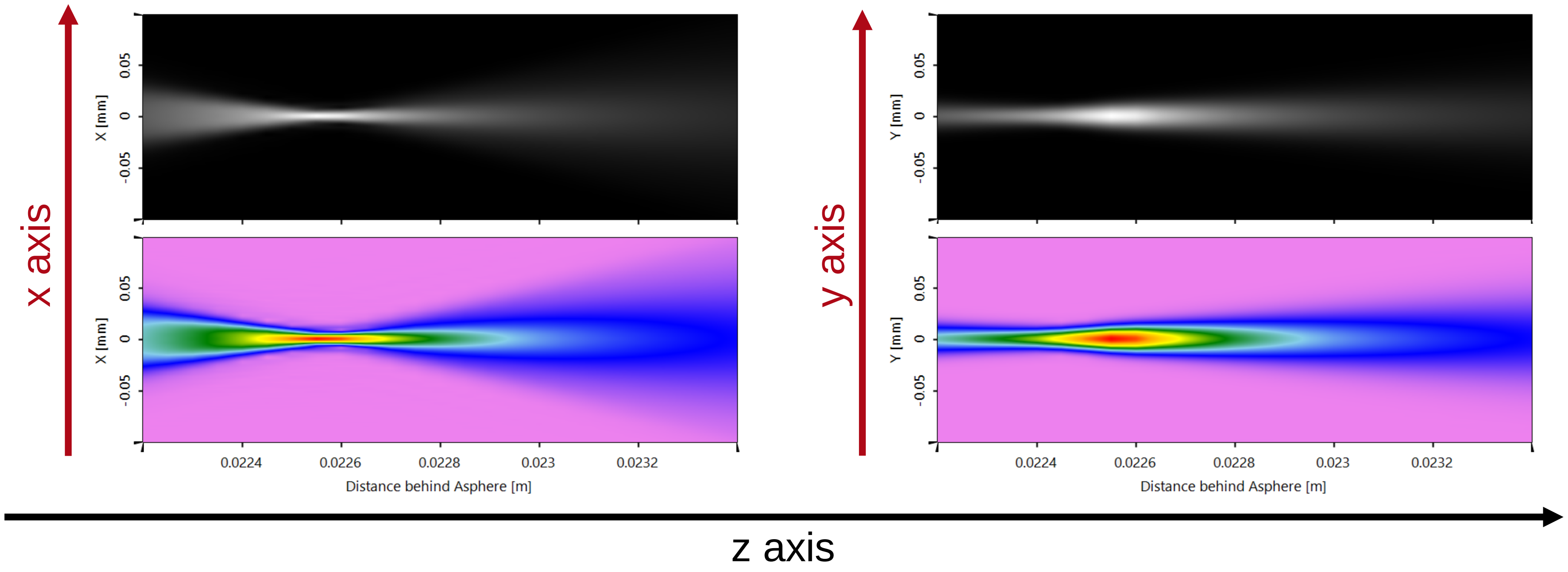
beam quality
M2 = 1.07 × 1.01

Results: Field Analysis in Focal Region 1D



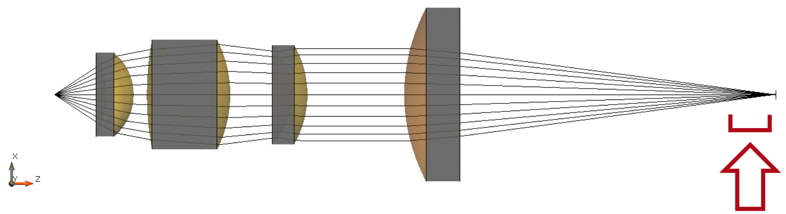
Highlights

- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis



(amplitudes in grey and inverse rainbow colors)

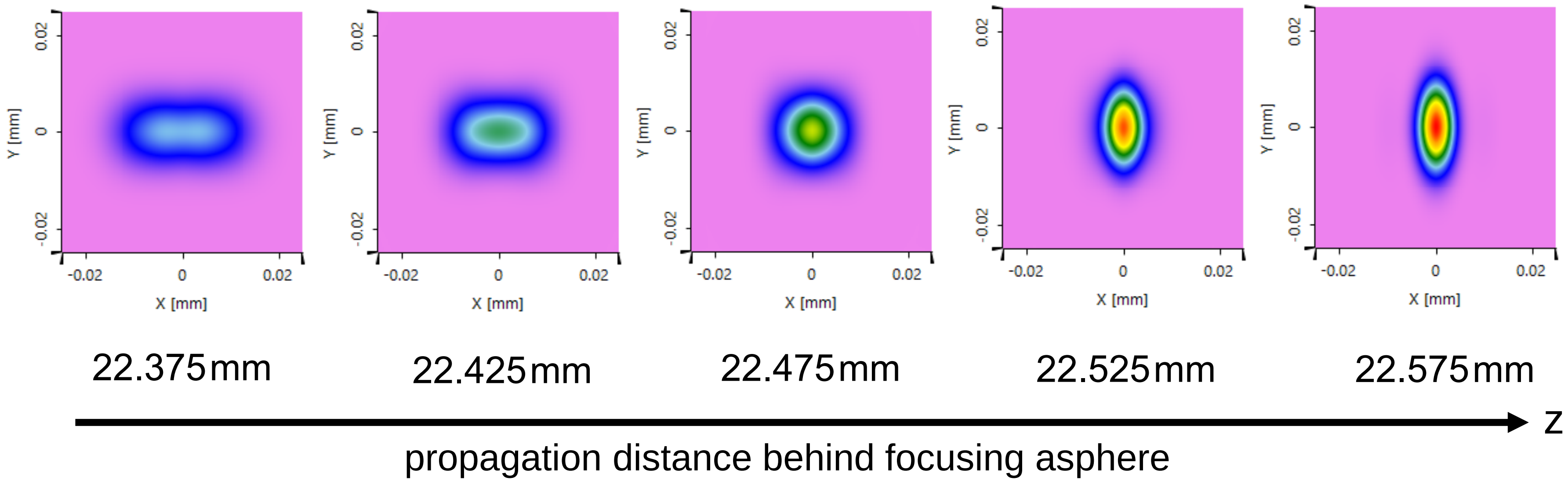
Results: Field Development in front of Focus 2D



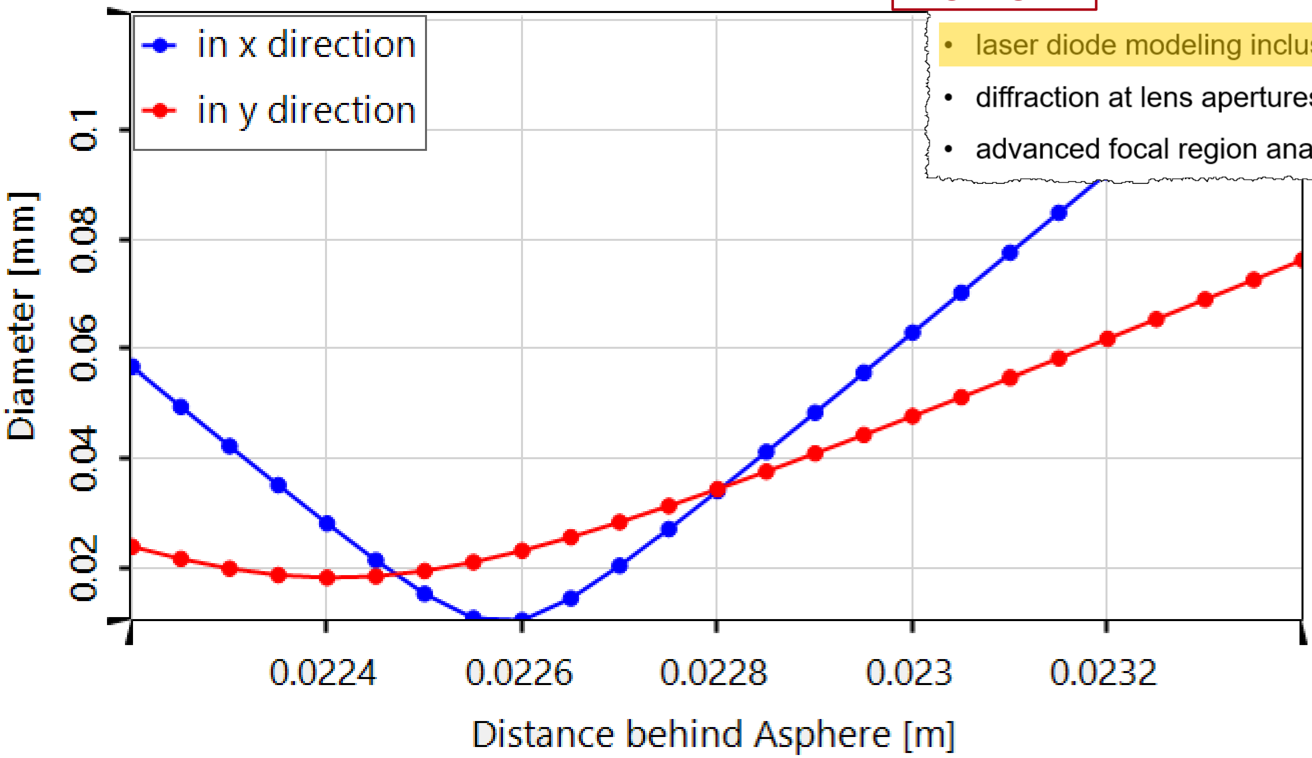
Highlights

- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis

principal axis of beam ellipse changes from y- to x-direction.



Results: Focus Position in X vs Y Direction



Highlights

- laser diode modeling inclusive astigmatism
- diffraction at lens apertures
- advanced focal region analysis

z-position of smallest spot diameter
is different for x- and y-direction

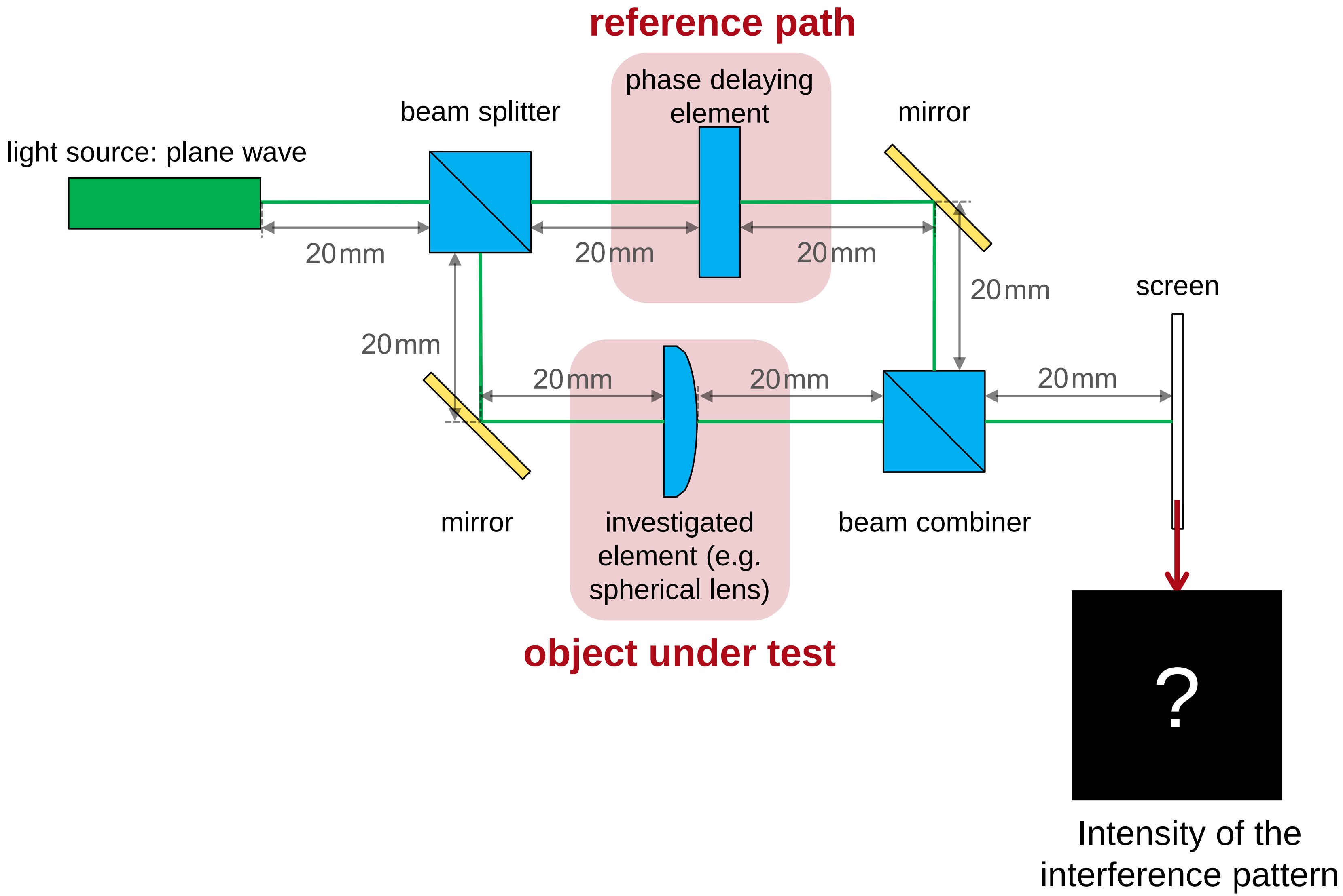
Document & Technical Info

code	BD.0002
version of document	1.0
title	Focus Investigation behind Aspherical Lens
category	Laser Systems > Beam Delivery (BD)
author	Hartwig Crailsheim (LightTrans)
used VL version	7.0.0.29

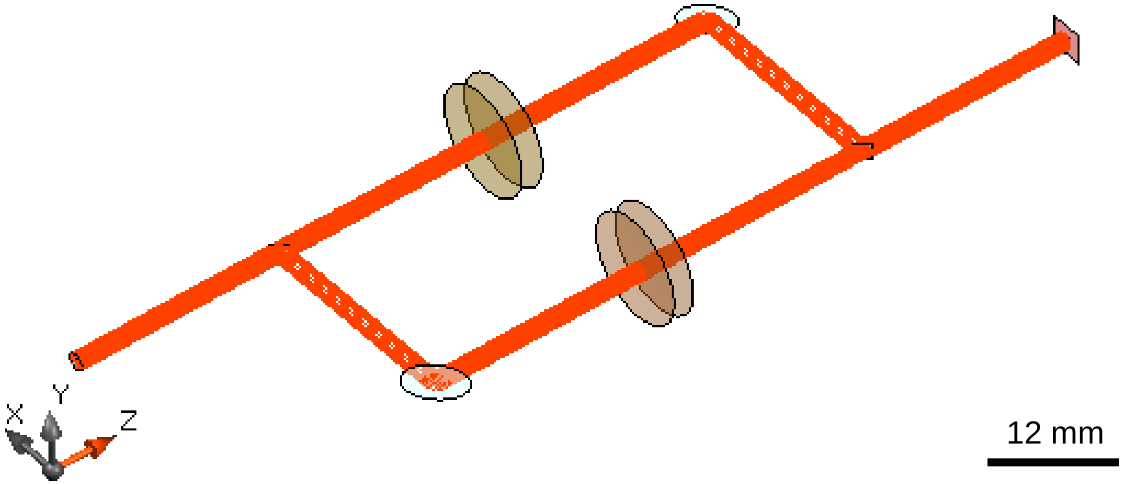
Specifications of PC Used for Simulation	
Processor	i7-4910MQ (4 CPU cores)
RAM	32 GB
Operating System	Windows 10

Mach-Zehnder Interferometer Using Coherent Light

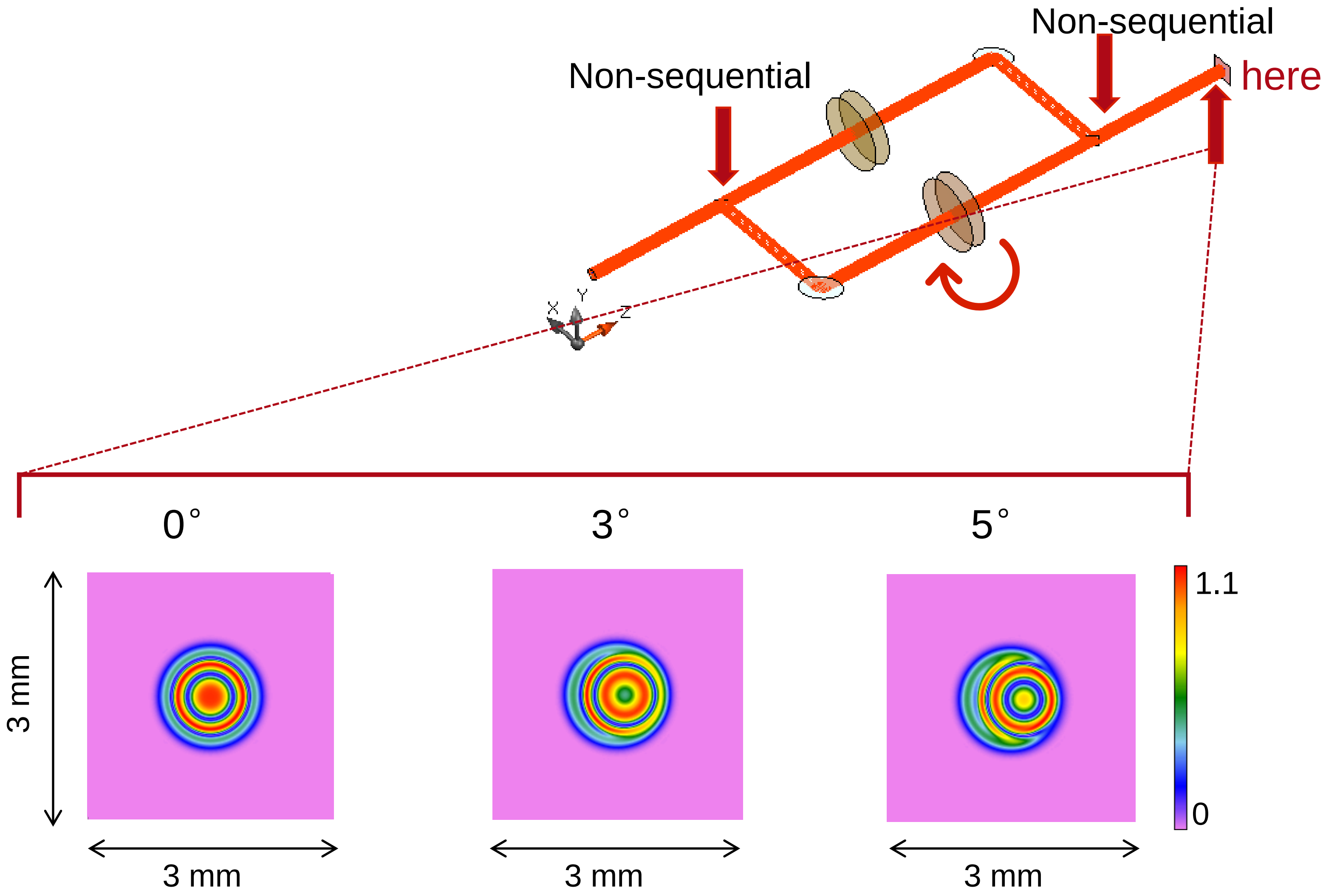
Task/System Illustration



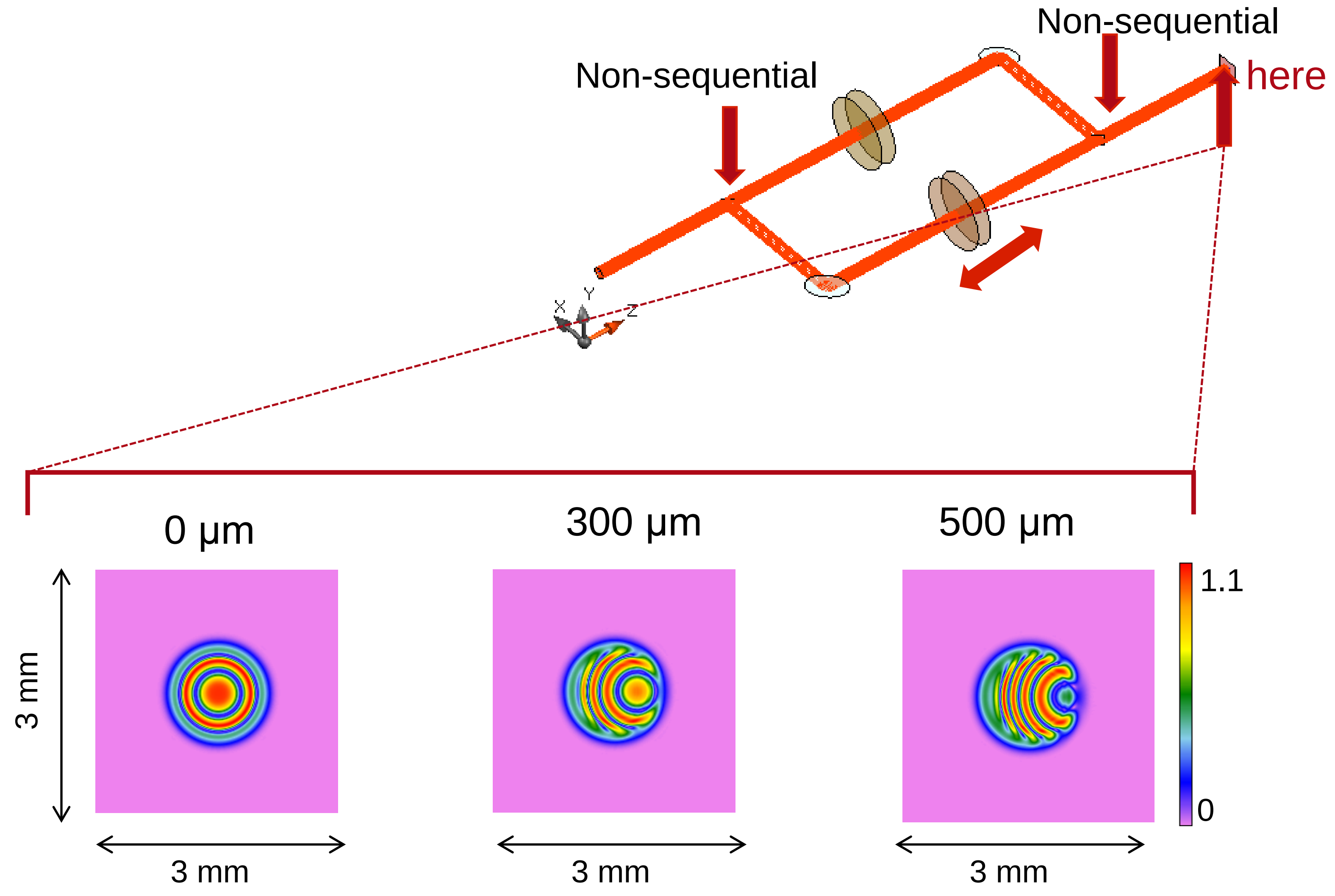
Results: 3D System Ray Tracing



Results: Field Tracing with Tilt of the Object

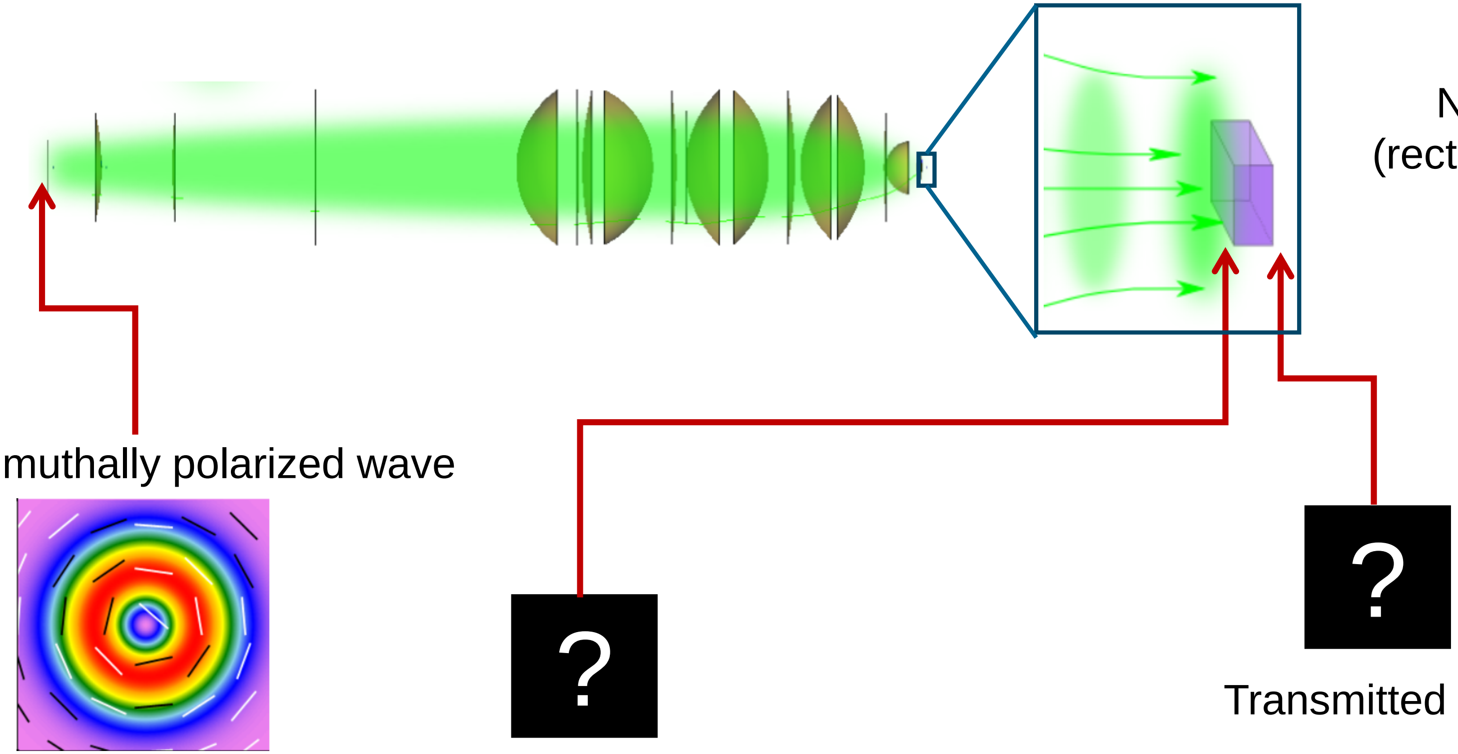


Results: Field Tracing Lateral Shift of the Object

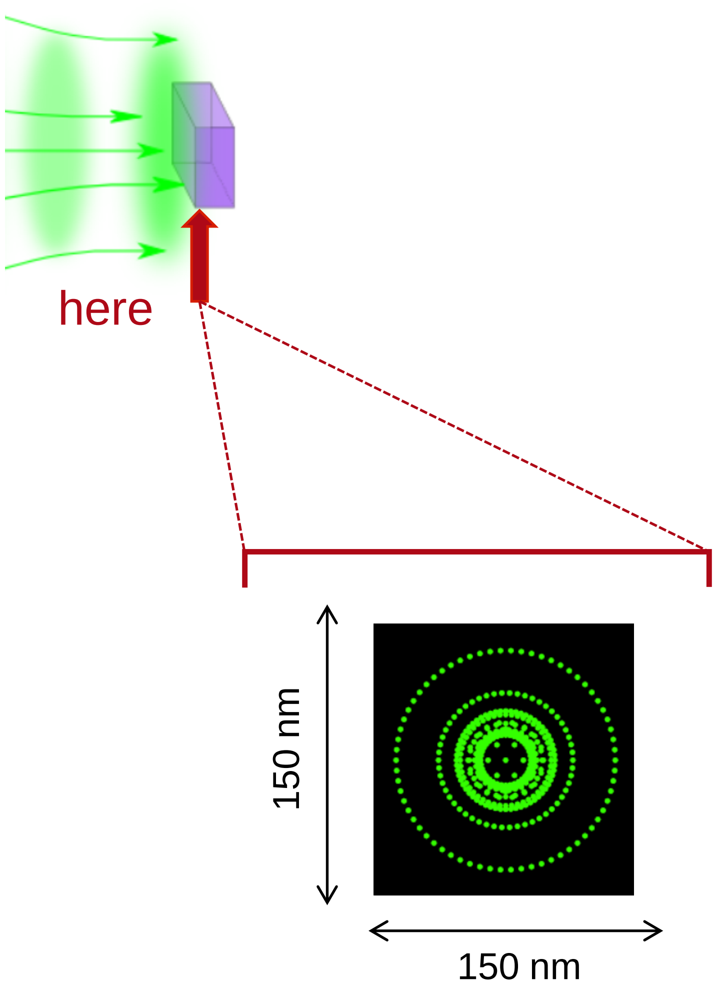


Interaction of Highly Focused Azimuthally polarized Field with Nano Particle

Task/System Illustration



Dot Diagram at Focal Plane: NA=0.85



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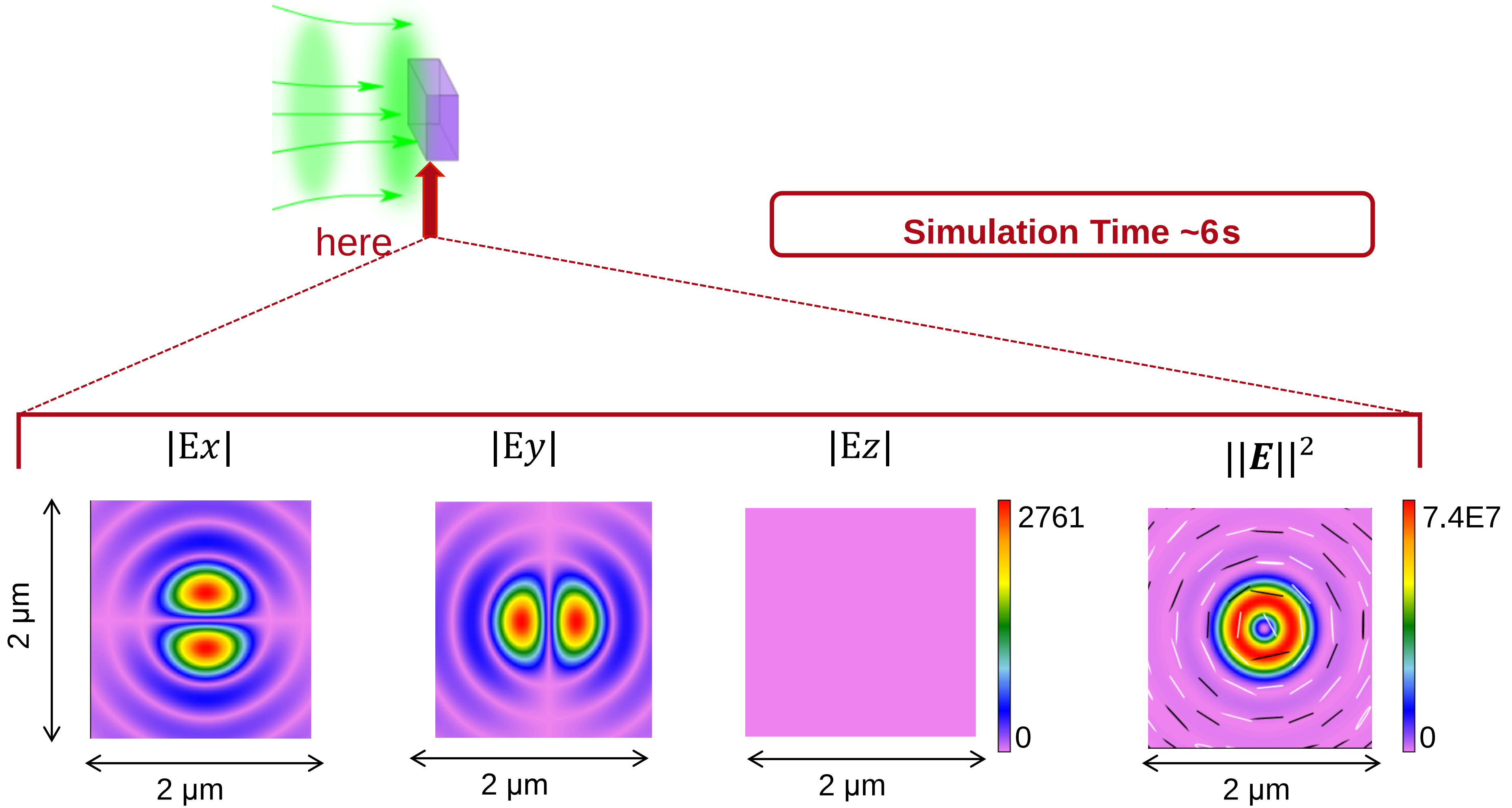
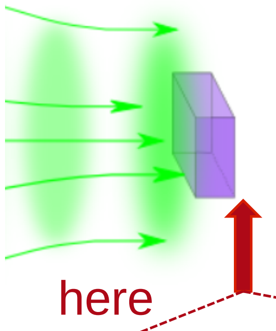
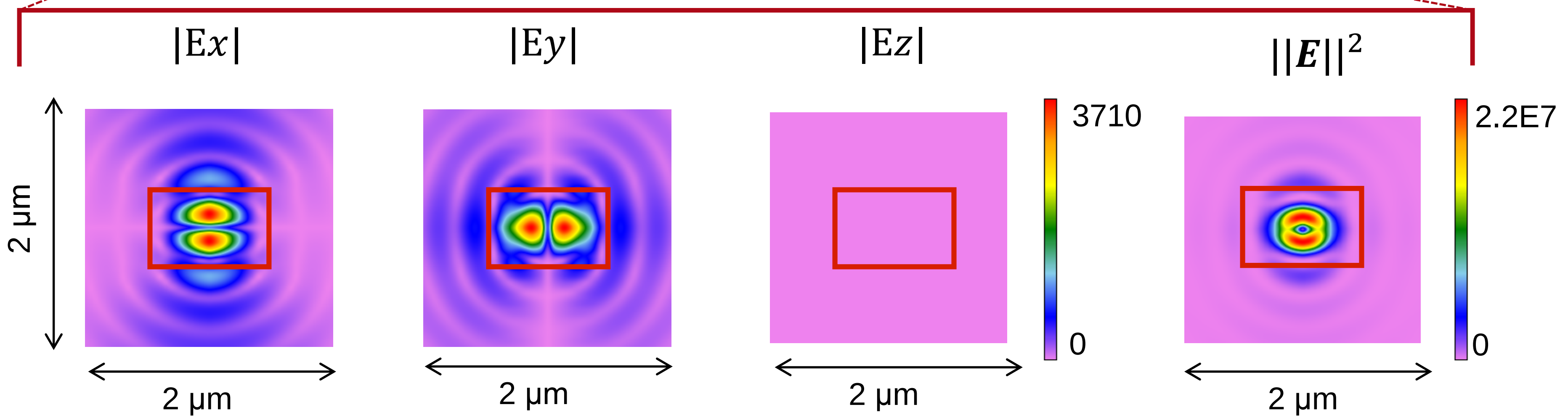
Field at Focal Plane: NA=0.85



Transmitted Near Field



Size of particle: 900 nm × 600 nm × 300 nm



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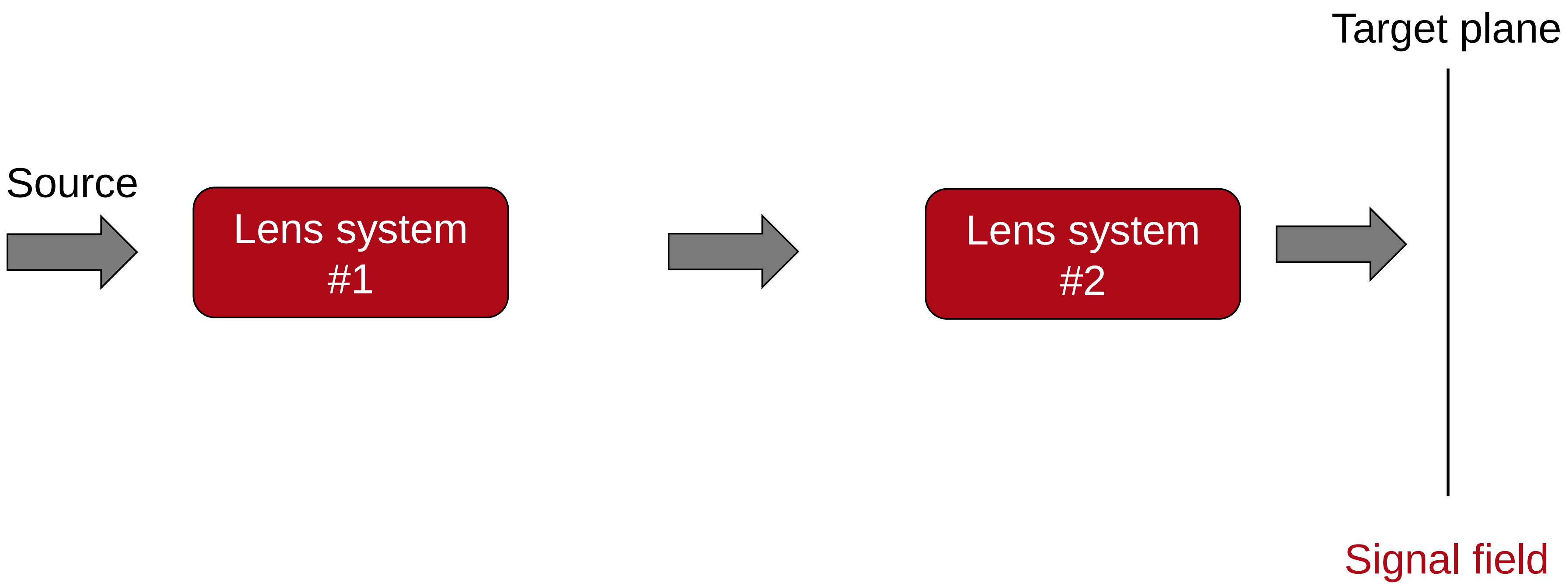
 www.LightTrans.com

Light Shaping

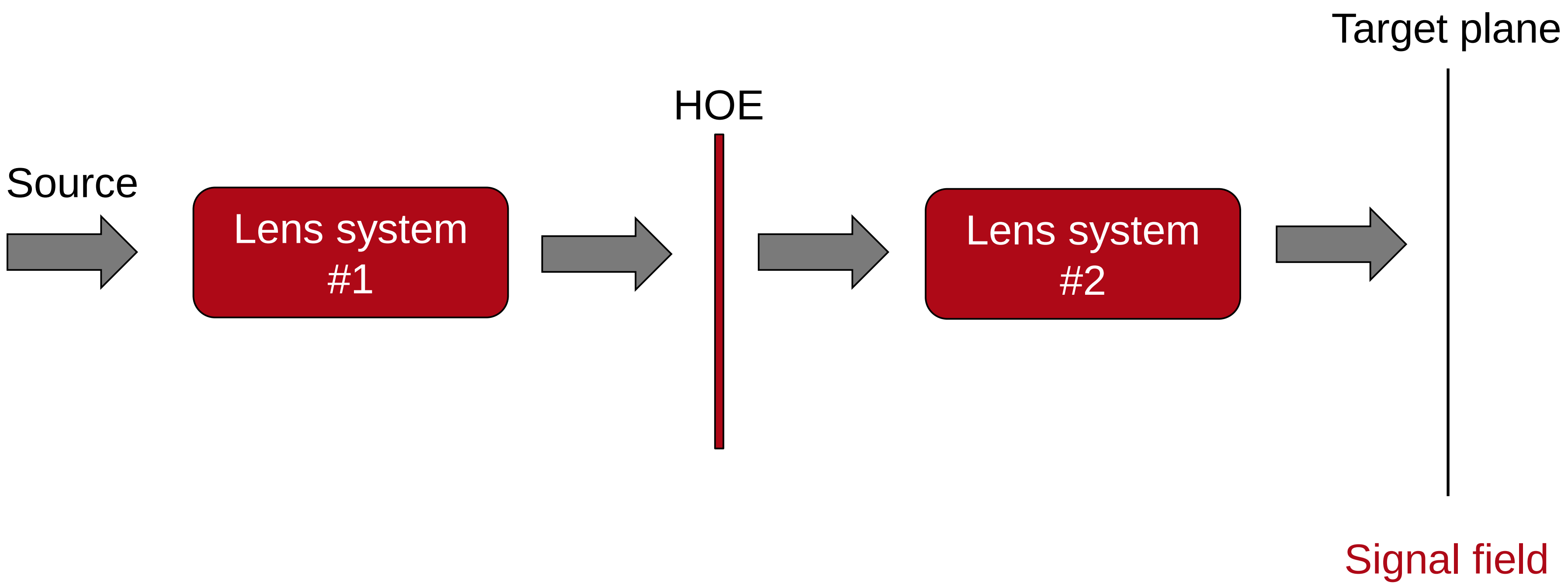
Light shaping by inverse approach

Concept of amplitude matching and consequences

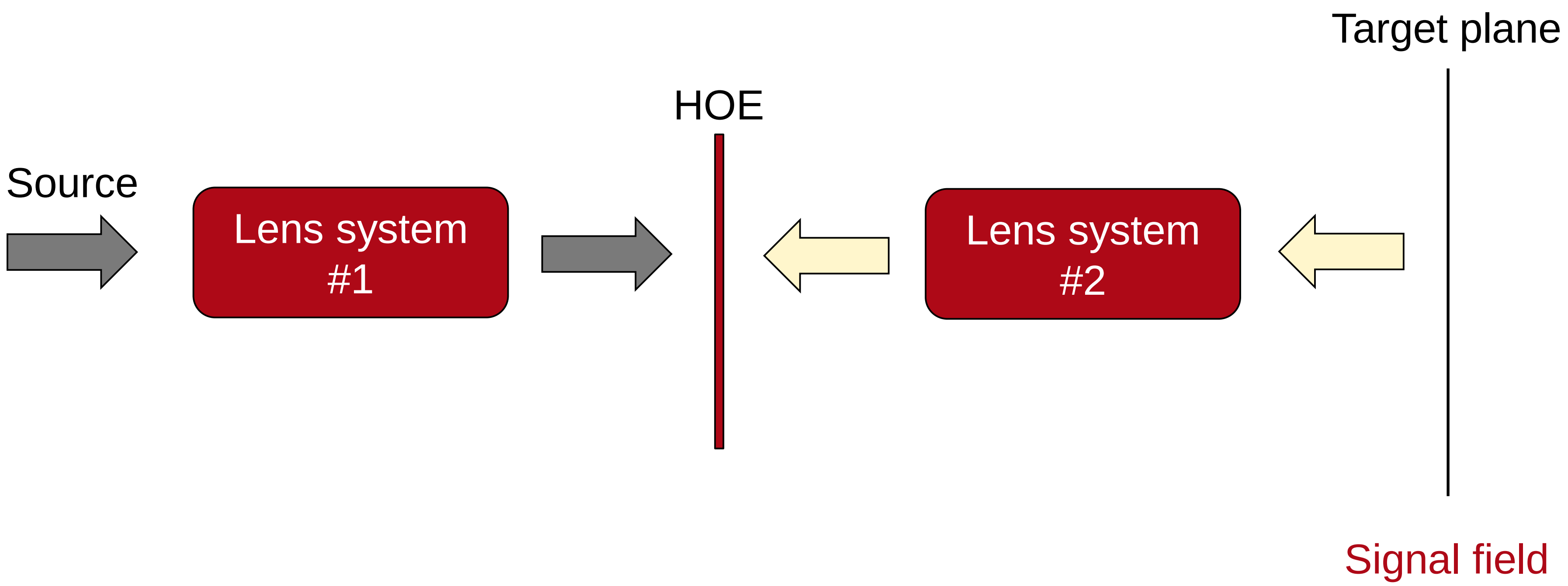
Inverse Design Concept: HOE and Freeform



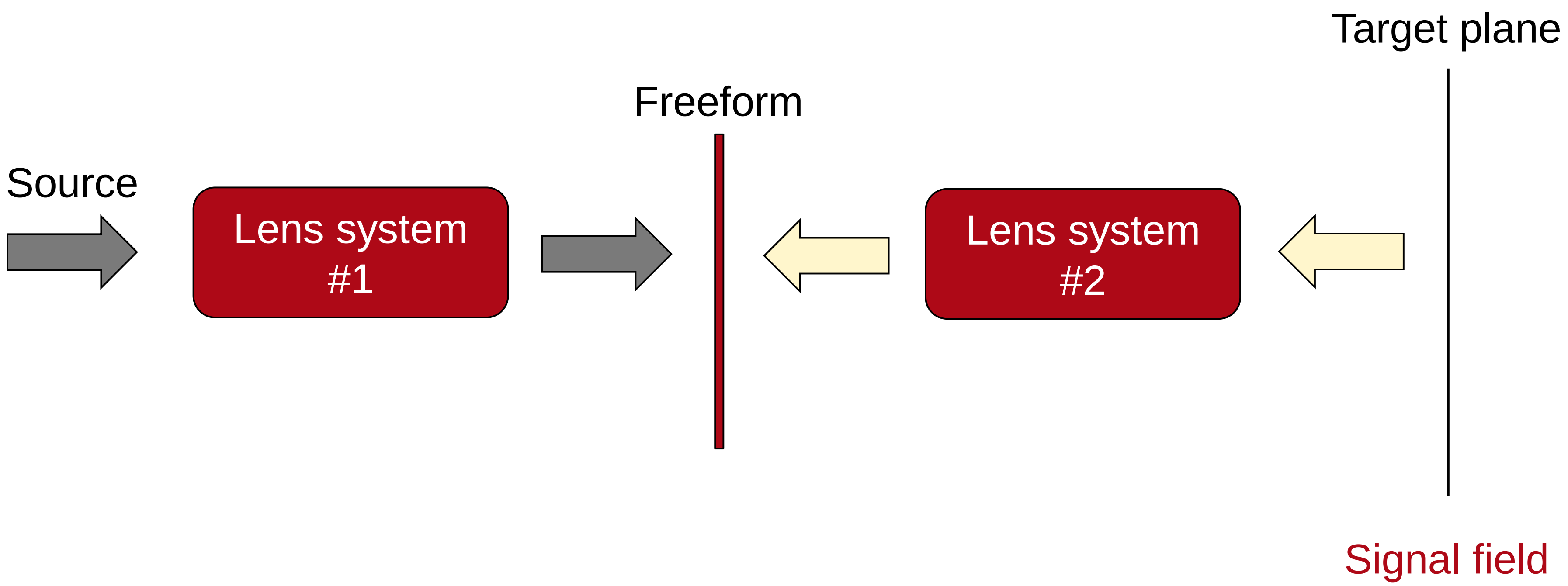
Inverse Design Concept: HOE and Freeform



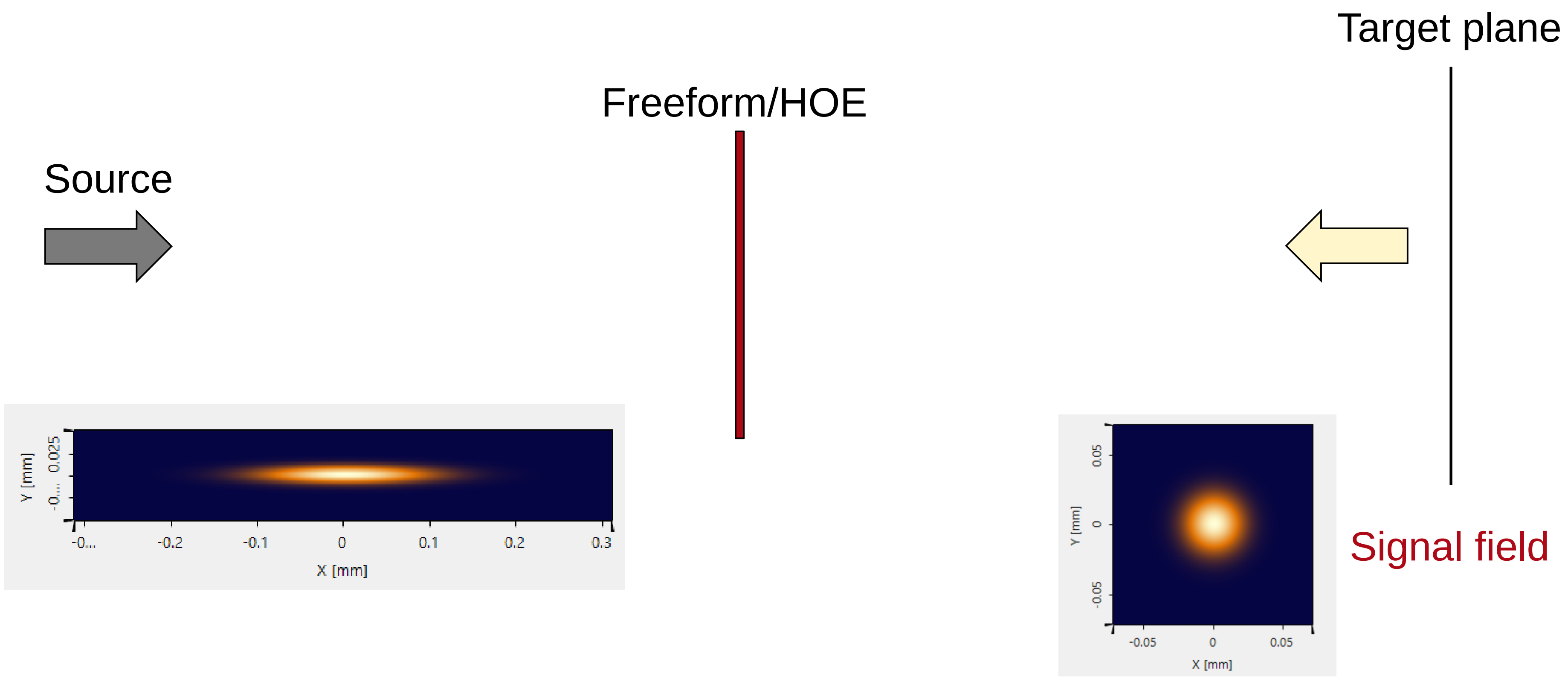
Inverse Design Concept: HOE and Freeform



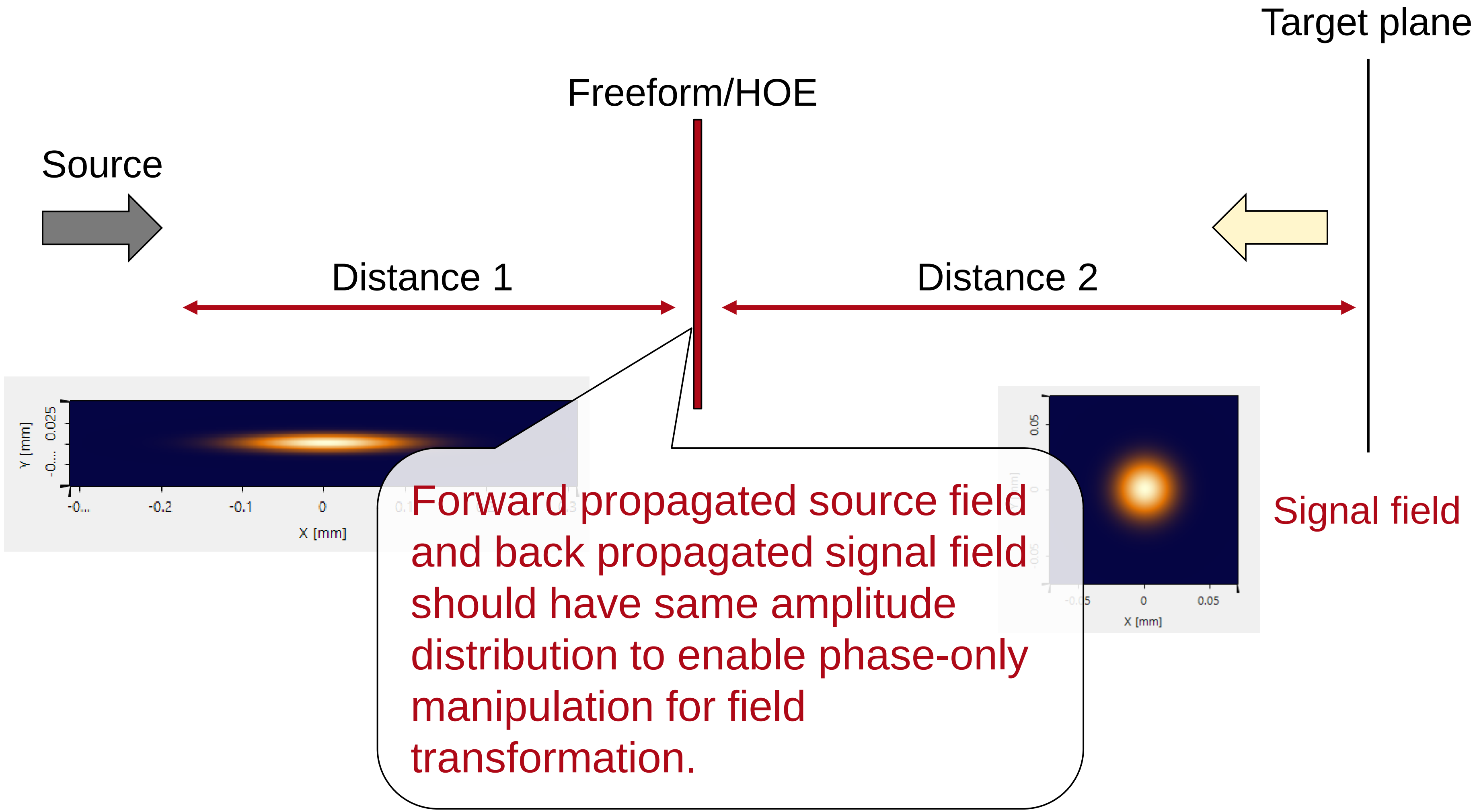
Inverse Design Concept: HOE and Freeform



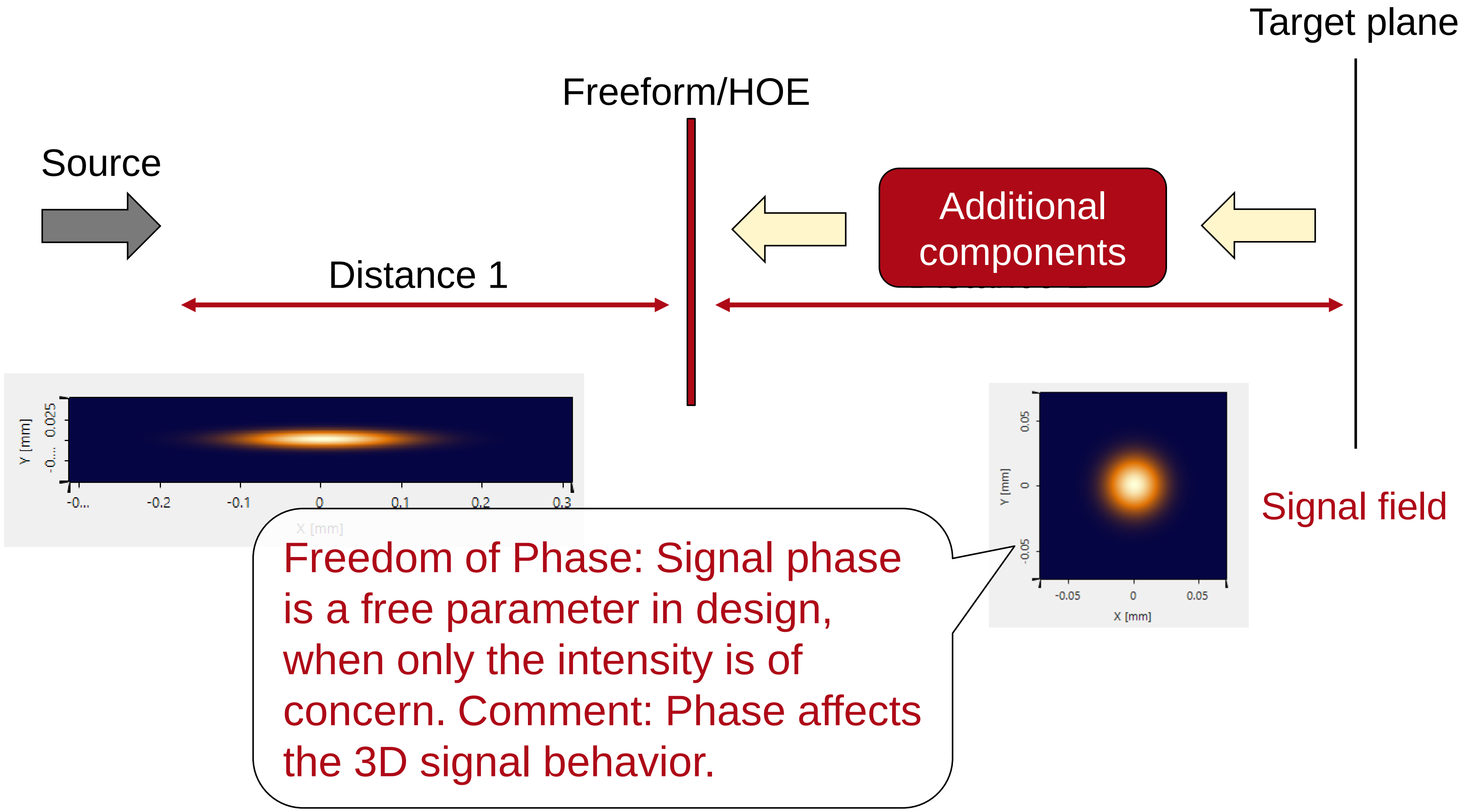
Inverse Design Concept: HOE and Freeform



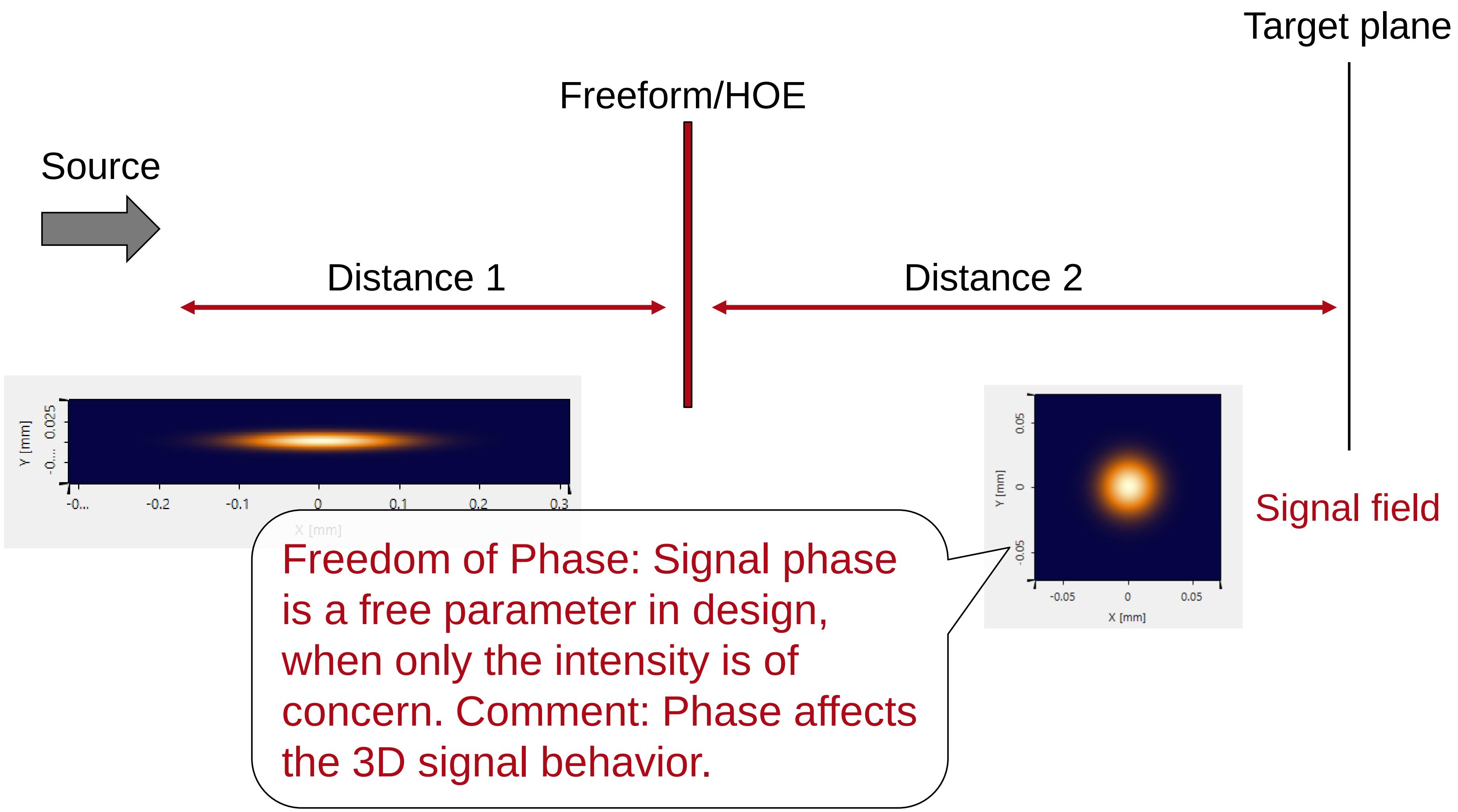
Inverse Design Concept: HOE and Freeform



Inverse Design Concept: HOE and Freeform



Inverse Design Concept: HOE and Freeform

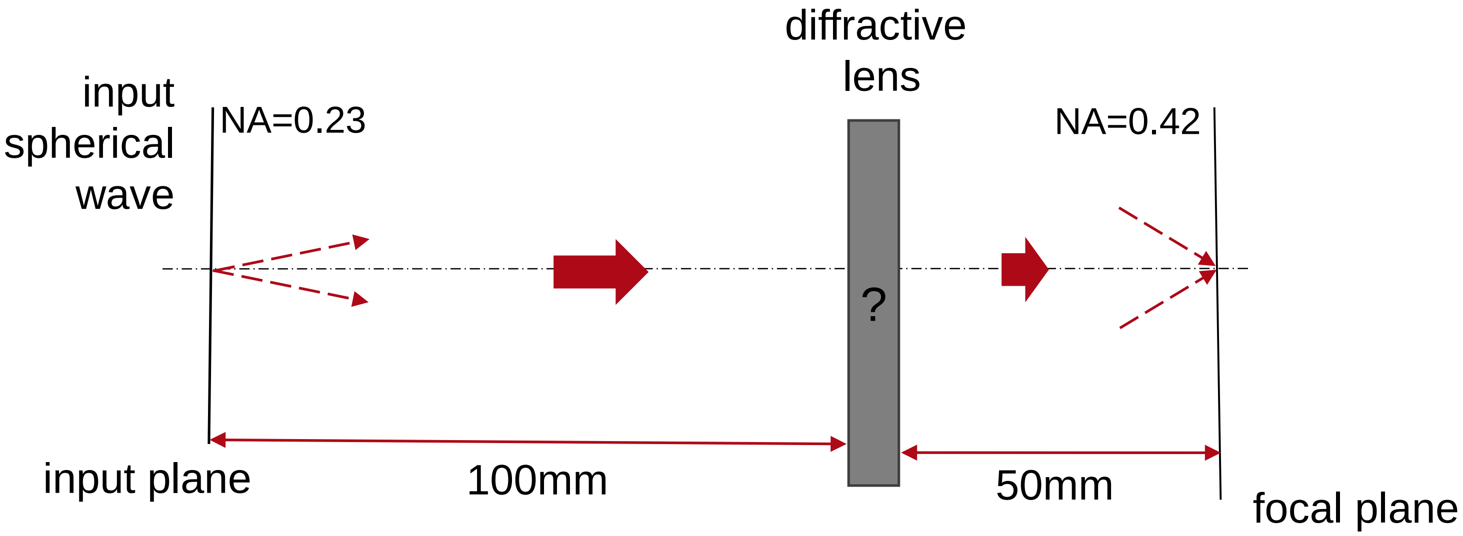


Imaging System Examples

1. single lens design
2. off-axis aberration control

1. single lens design

- Desing task: For a given spherical wave input, how to design a diffractive lens to focus it with required NA and focal length.

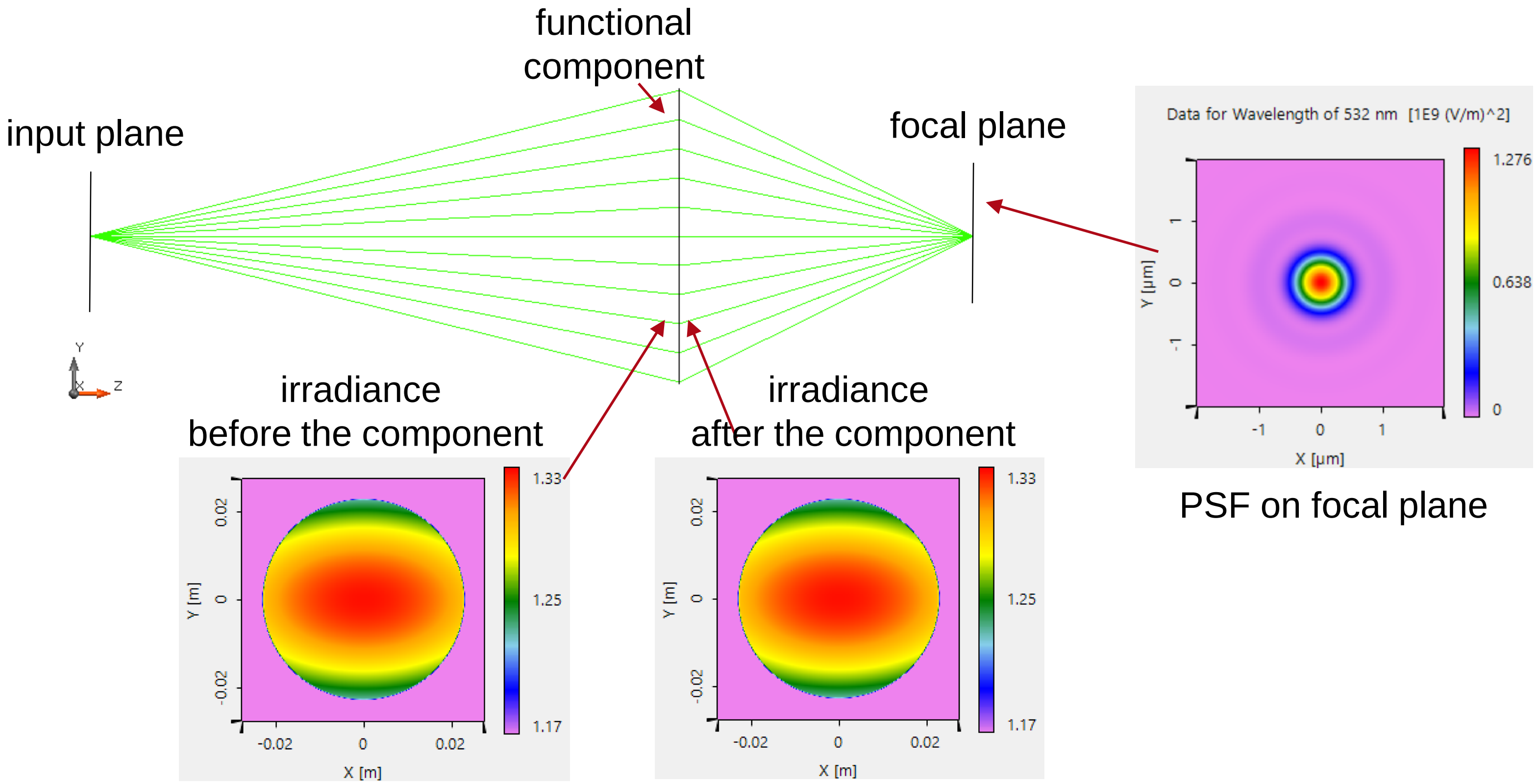


1. single lens design

a. functional embodiment : a phase-only functional component

The phase function $\varphi(x, y)$ is obtained by the subtraction of the input field and the required signal field.

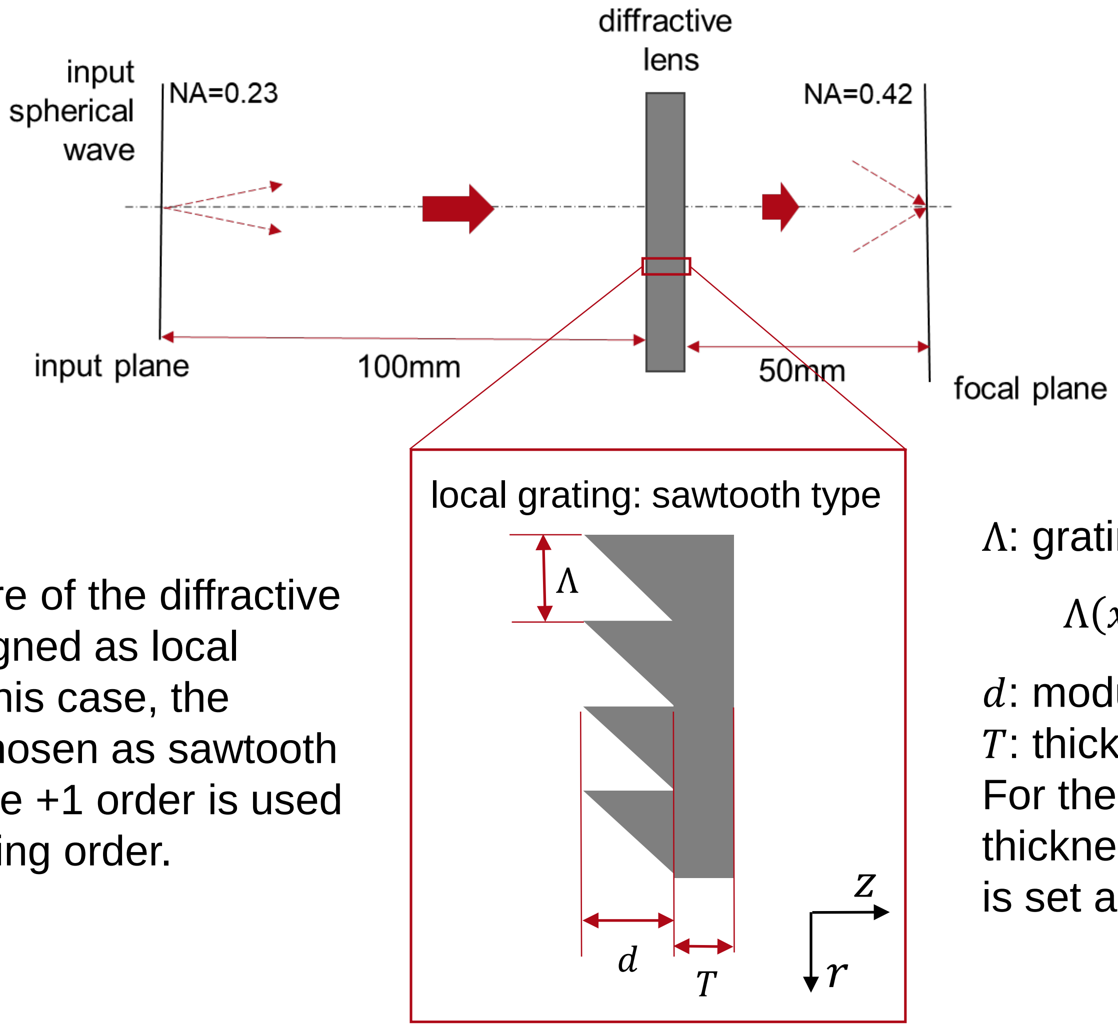
The functional component gives the required phase for the input spherical wave, and keep the input irradiance as remained according to energy conservation.



PSF on focal plane

1. single lens design

b. structure: HOE



The structure of the diffractive lens is designed as local grating. In this case, the grating is chosen as sawtooth type, and the +1 order is used as the working order.

Λ: grating period

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

d: modulation depth

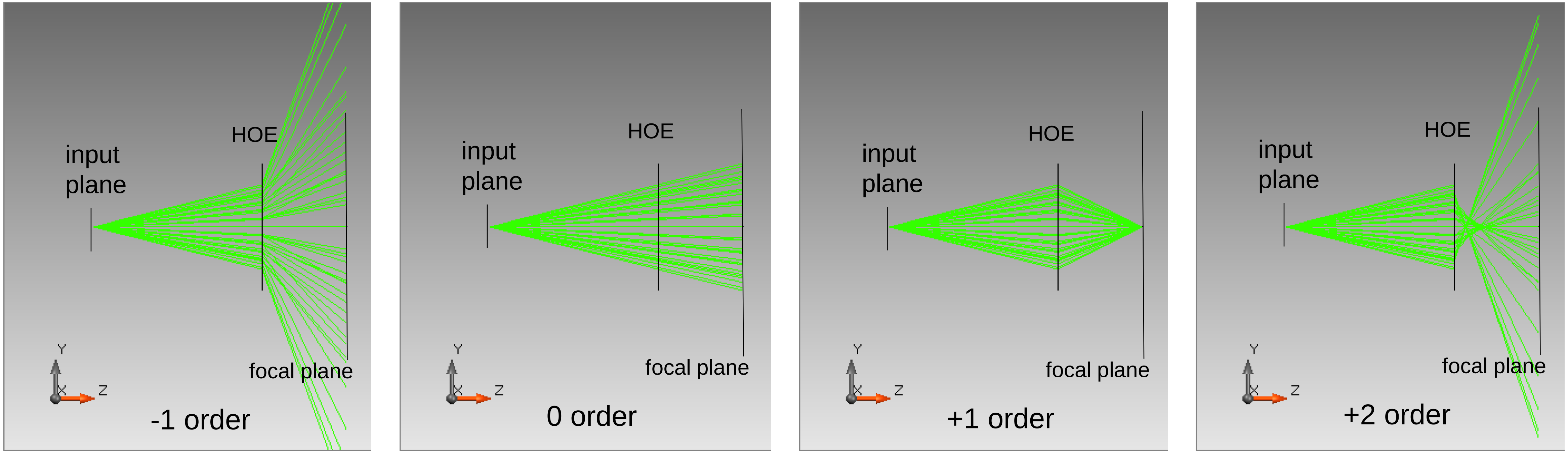
T: thickness of base block.

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

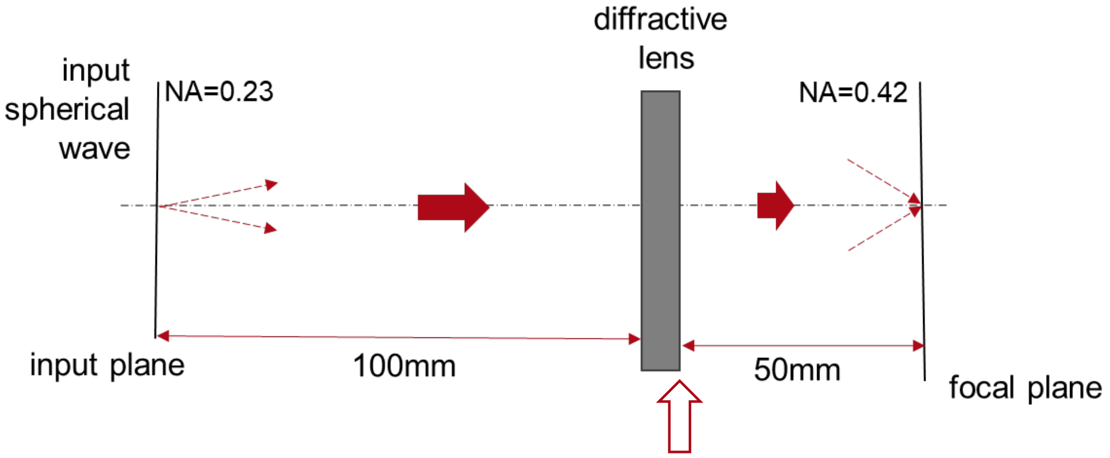
1. single lens design

b. structure: HOE

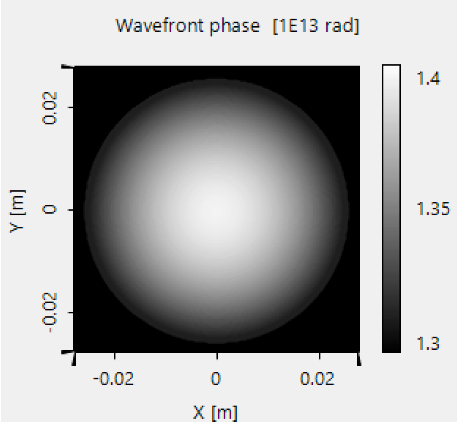
ray tracing result with HOE (with the working order of +1 order)



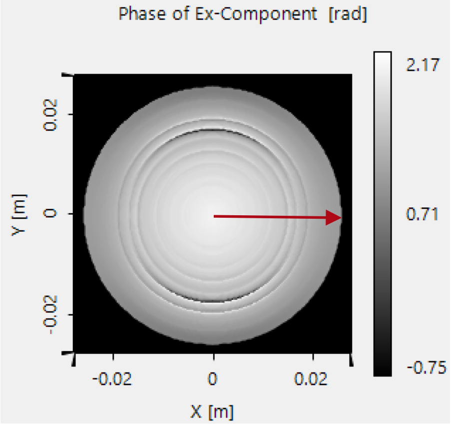
1. single lens design



phase of the working order behind the diffractive lens

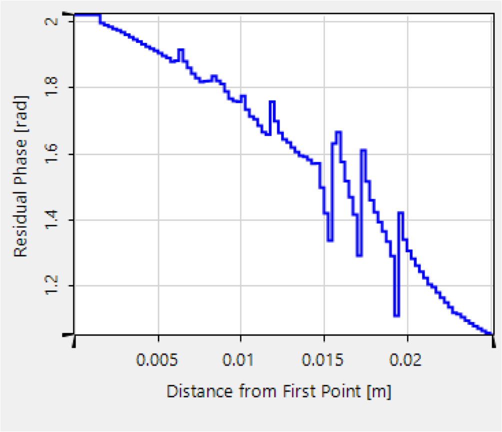


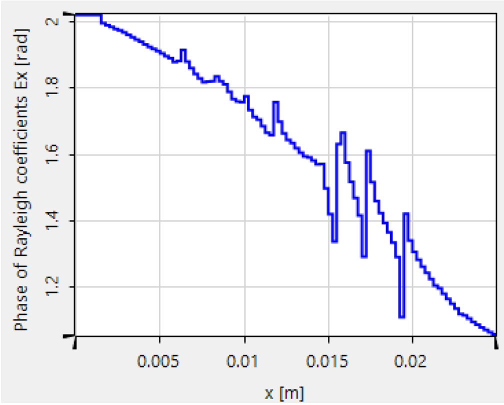
wavefront phase



residual phase

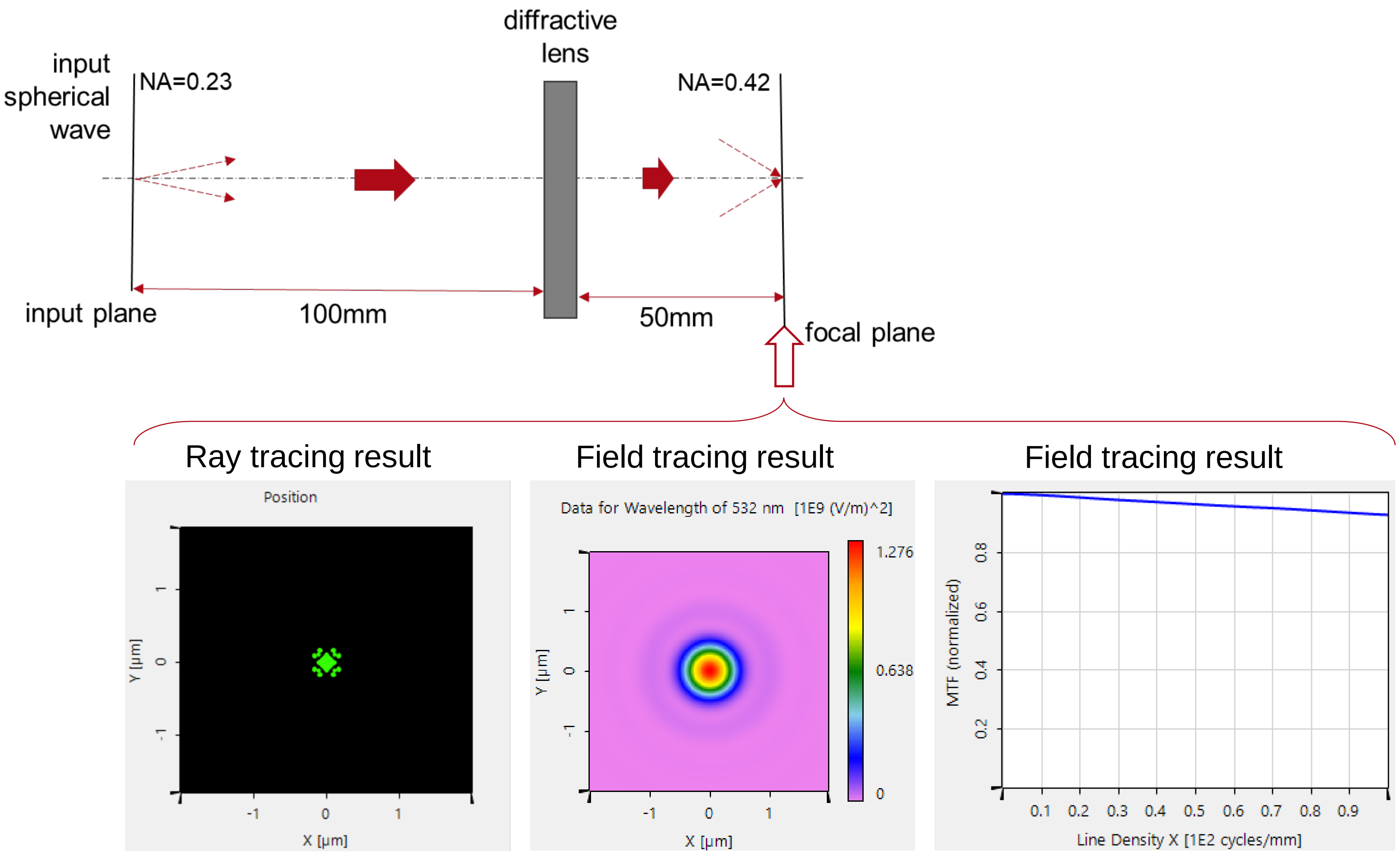
calculated phase of Rayleigh coefficient of Ex





residual phase along cross-section

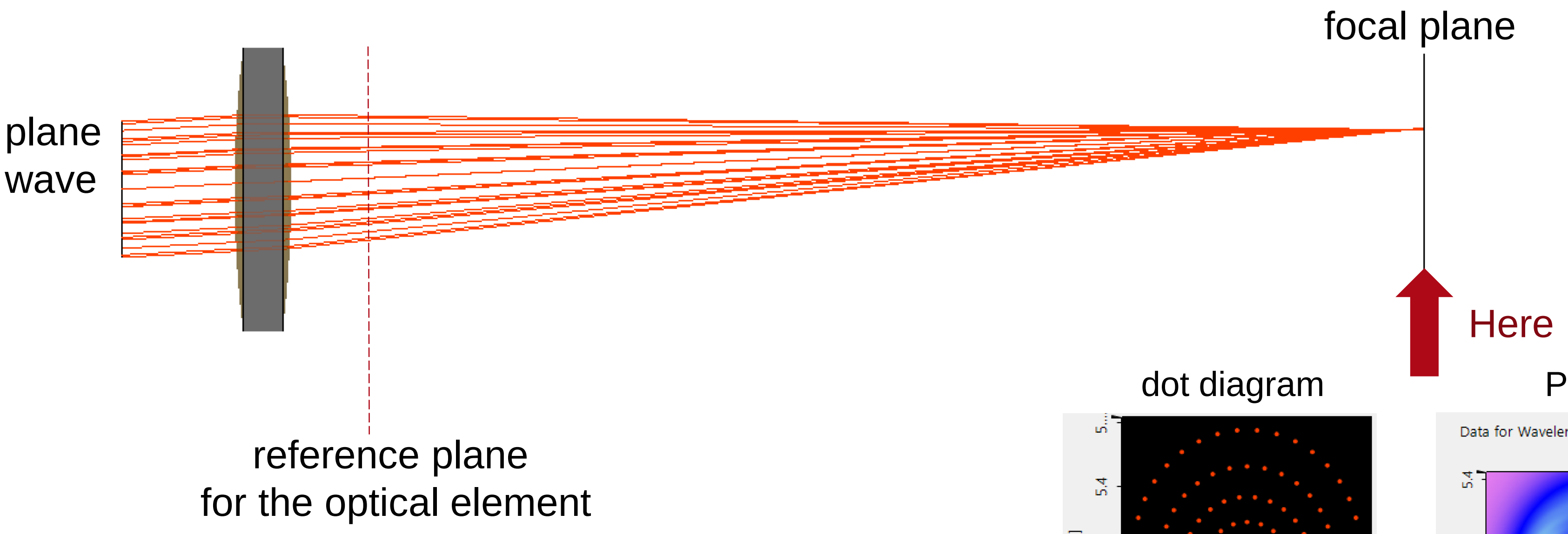
1. single lens design



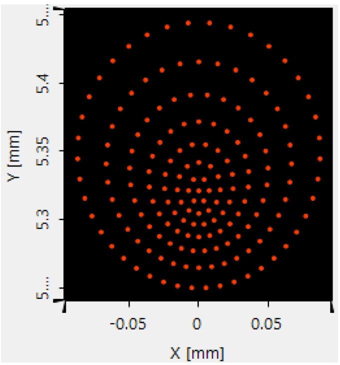
Dot pattern of the working order PSF MTF

2. aberration control

Task description: design a optical element to correct the aberration of a spherical lens illuminated with off-axis input plane wave

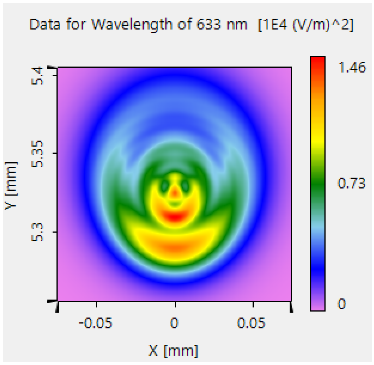


dot diagram



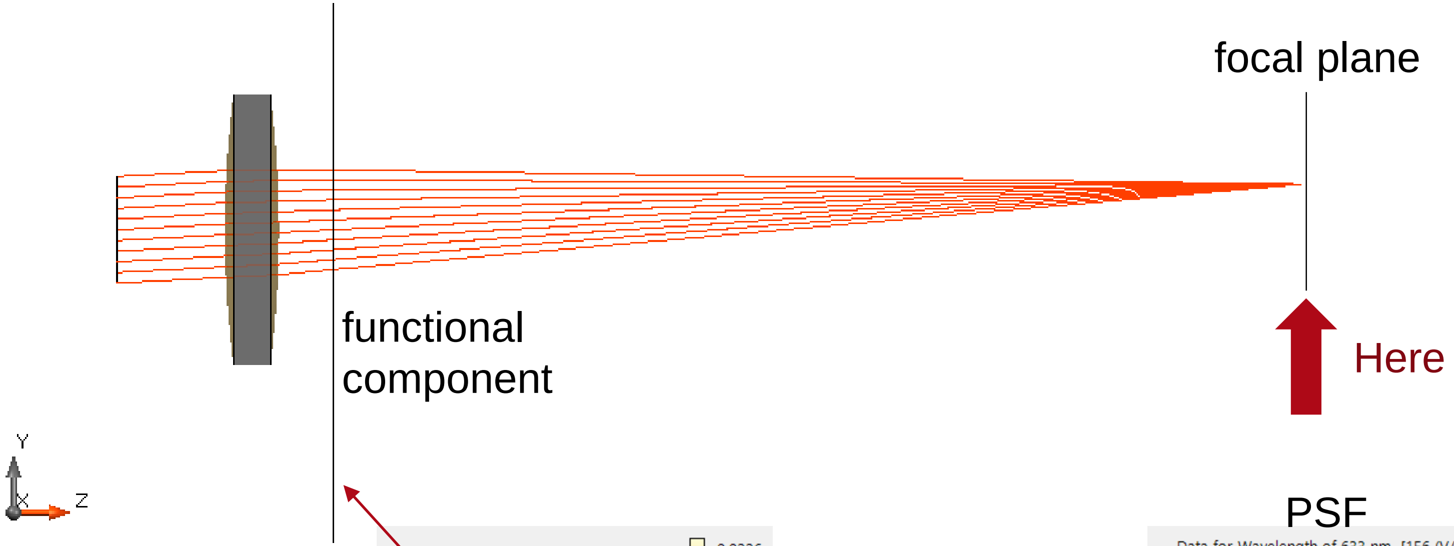
$RMS = 127.9\mu m$

PSF

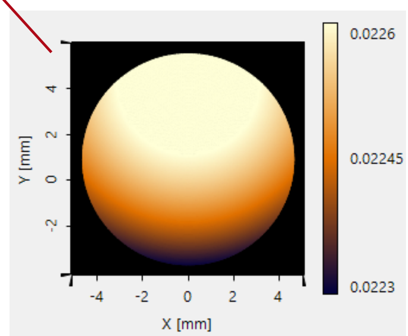


2. aberration control

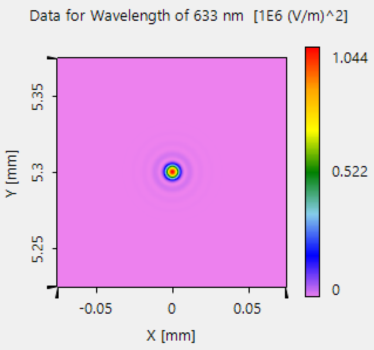
a. functional embodiment



PSF

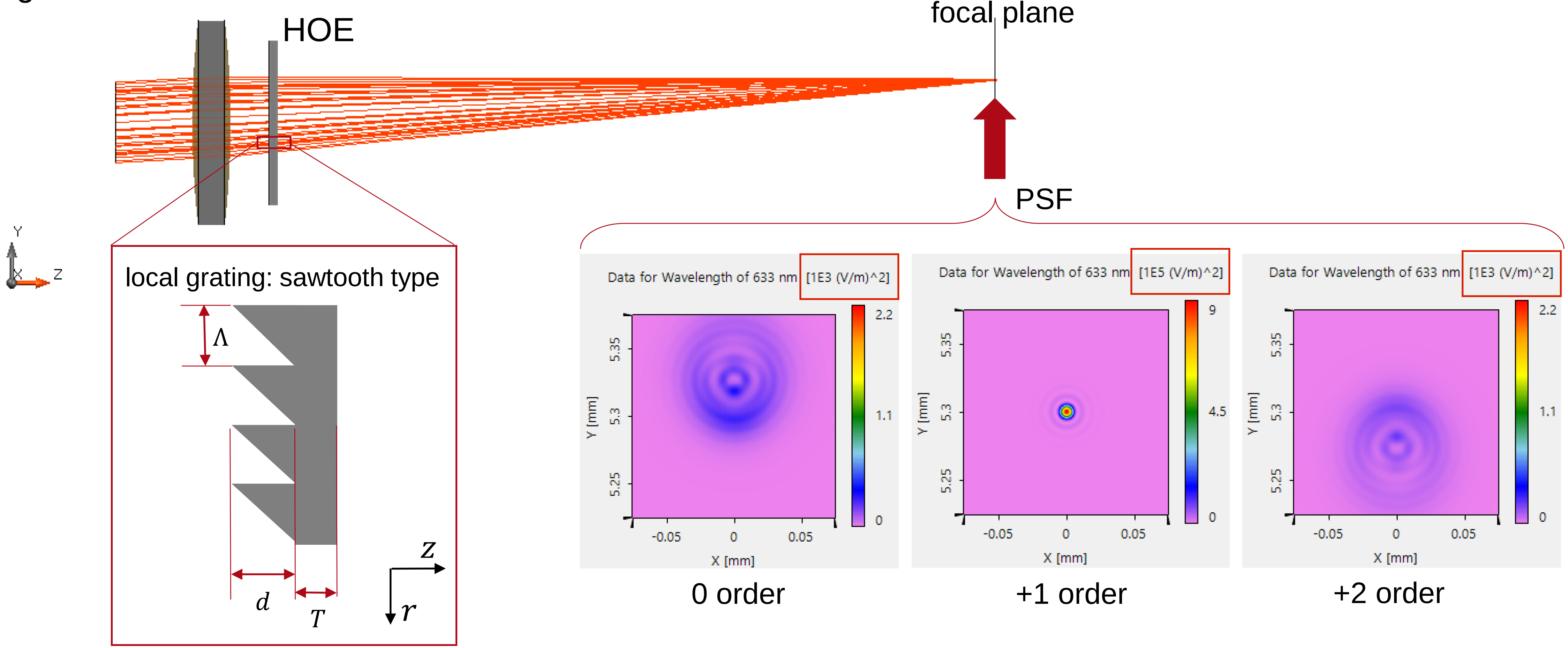


wavefront phase behind the functional component



2. aberration control

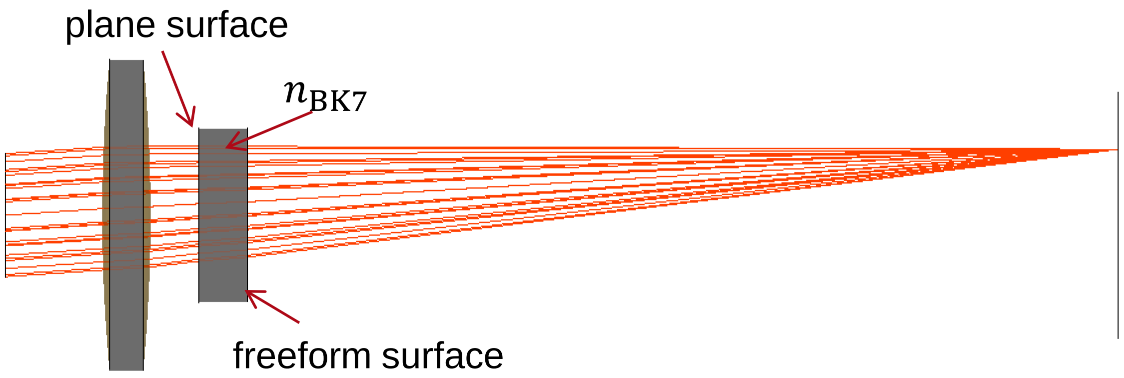
b. design HOE

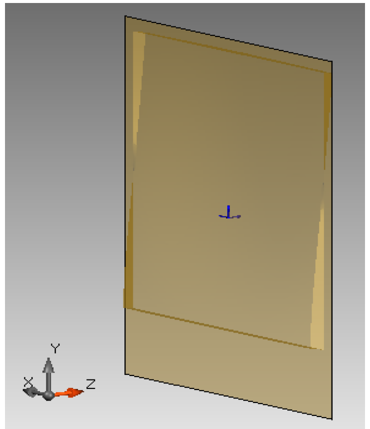


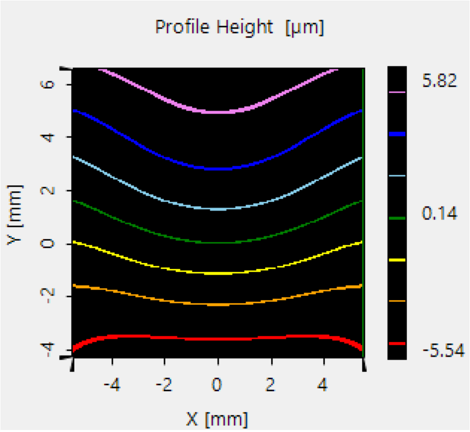
the +1 order is used as working order

2. aberration control

c. design freeform surface



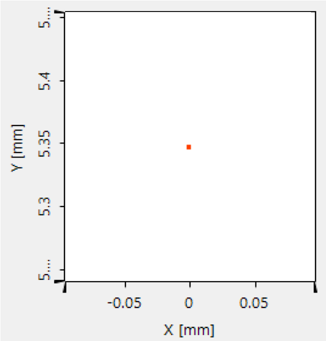




Height Profile (3D view)

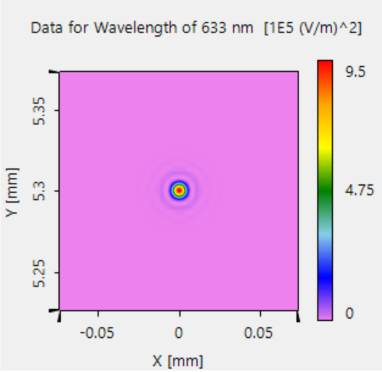
Height Profile (2D Contour line)

dot diagram

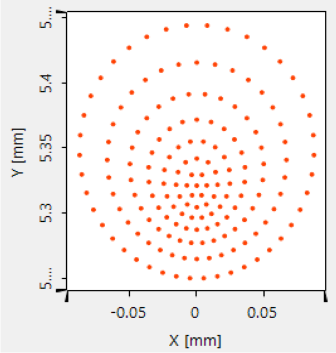


$\text{RMS} = 0.76\mu m$

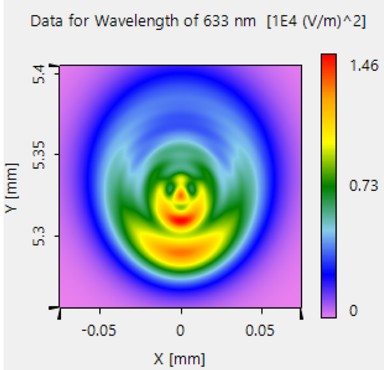
PSF



result without correction



$\text{RMS} = 127.9\mu m$



Light Shaping Concepts

- tailored aberrations (beam shaping)
- stored scanning process (diffuser & splitter)
- multichannel concept (cells array)

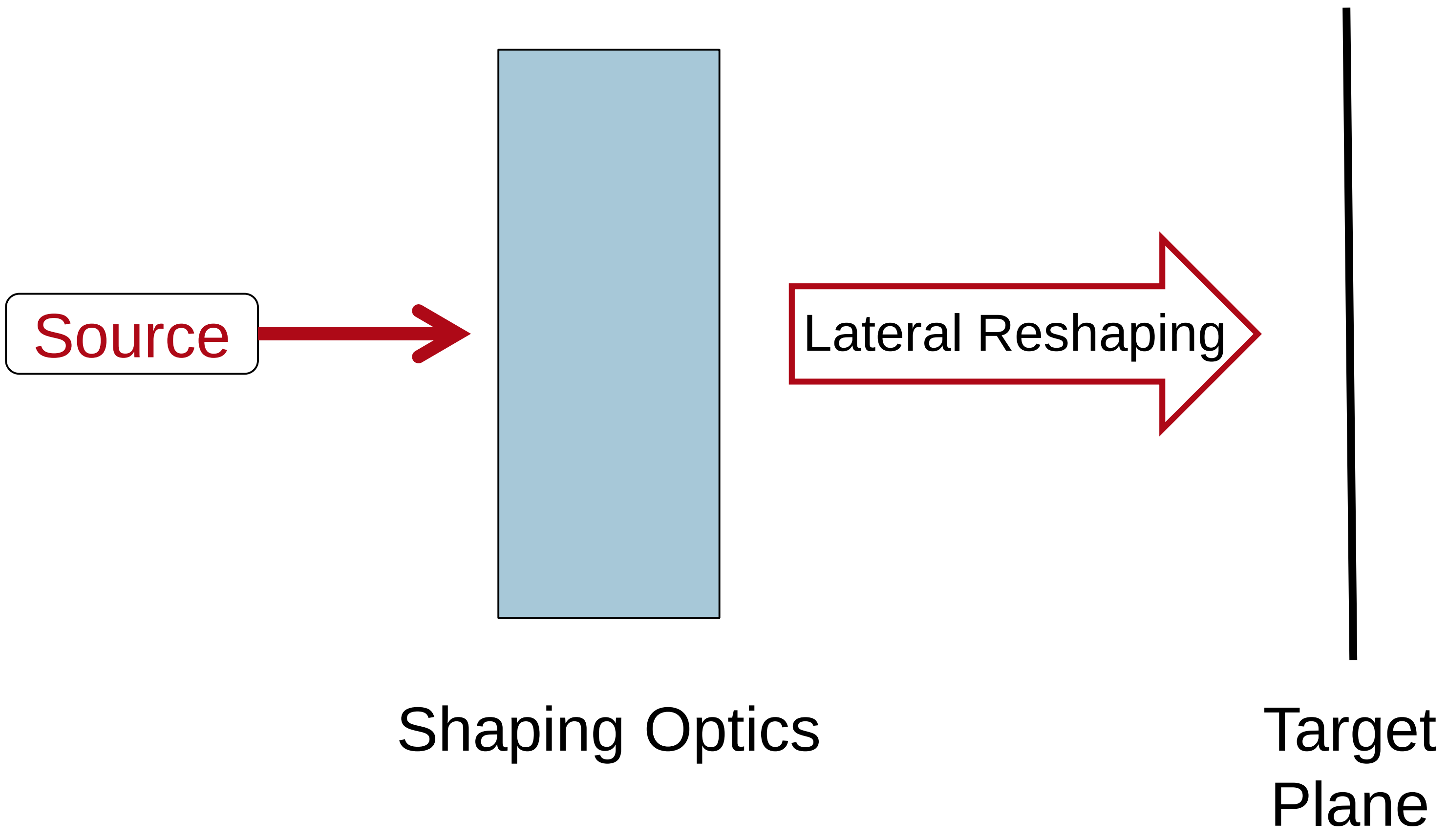
Light Shaping Concepts

- tailored aberrations (beam shaping)
- stored scanning process (diffuser & splitter)
- multichannel concept (cells array)

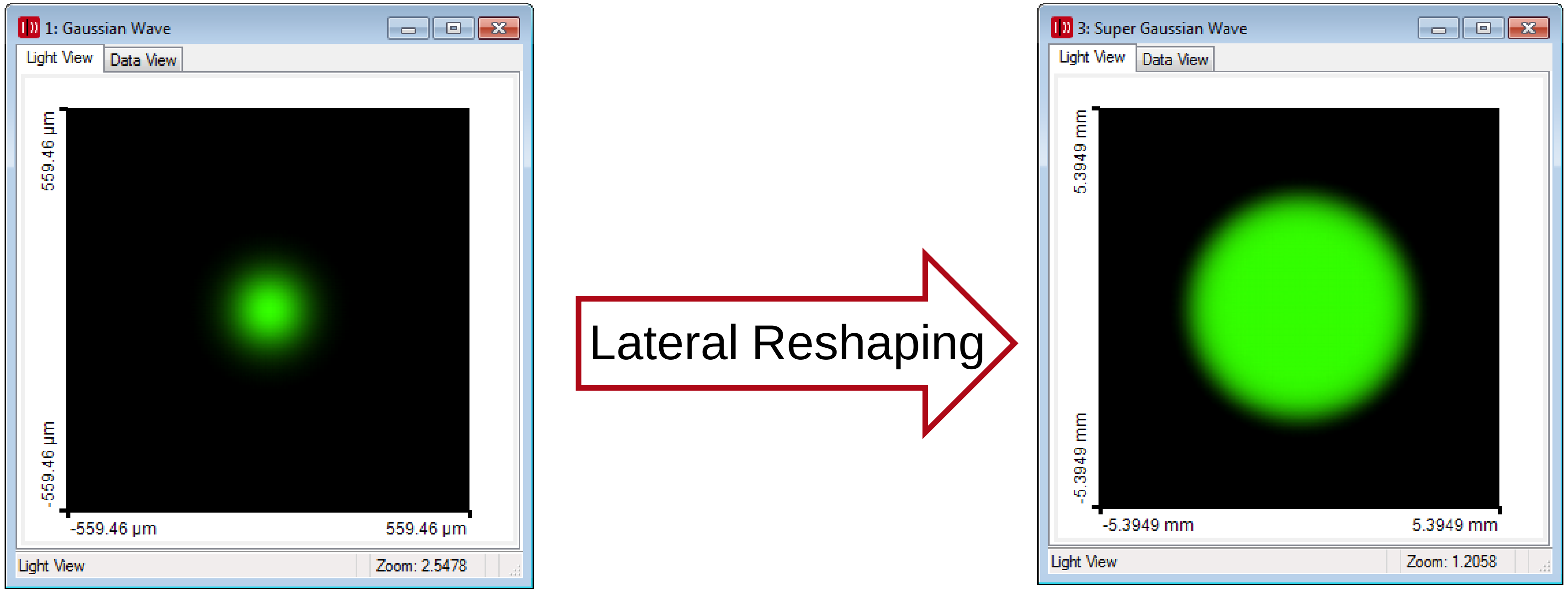
Light shaping by tailored aberrations

Refractive and diffractive optical elements

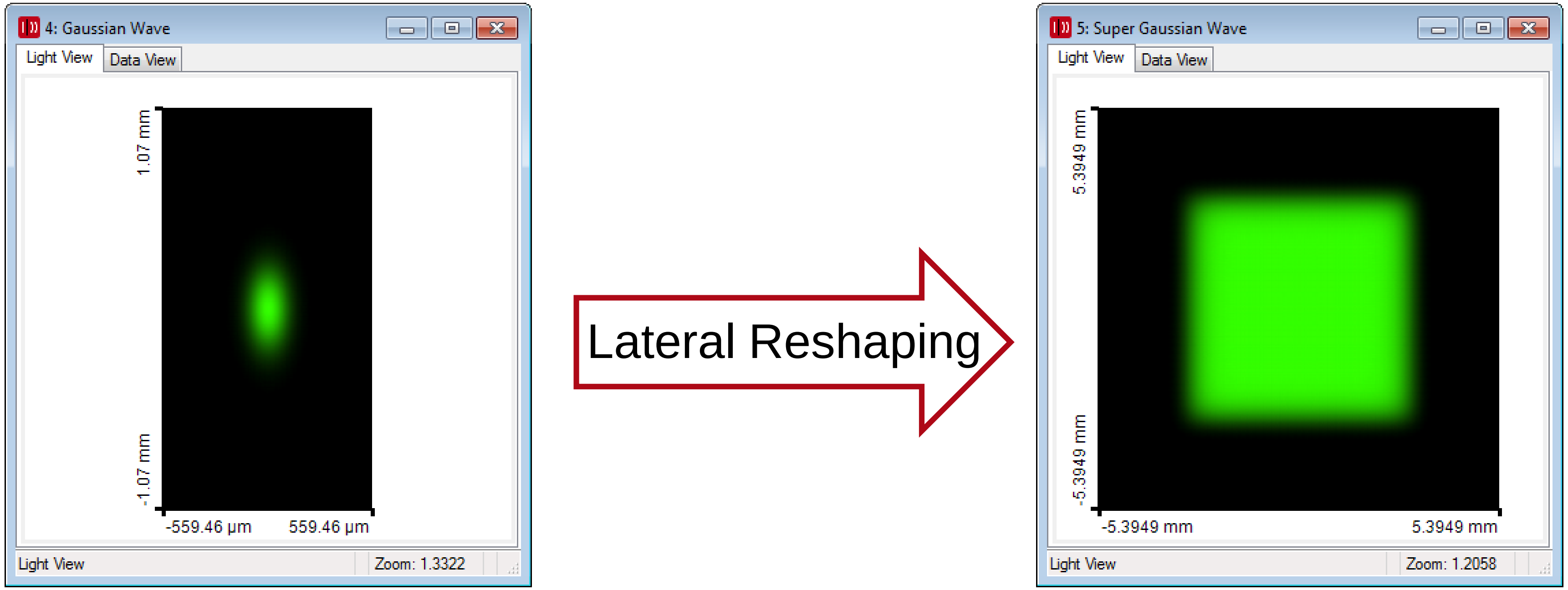
Beam Shaping: The Task



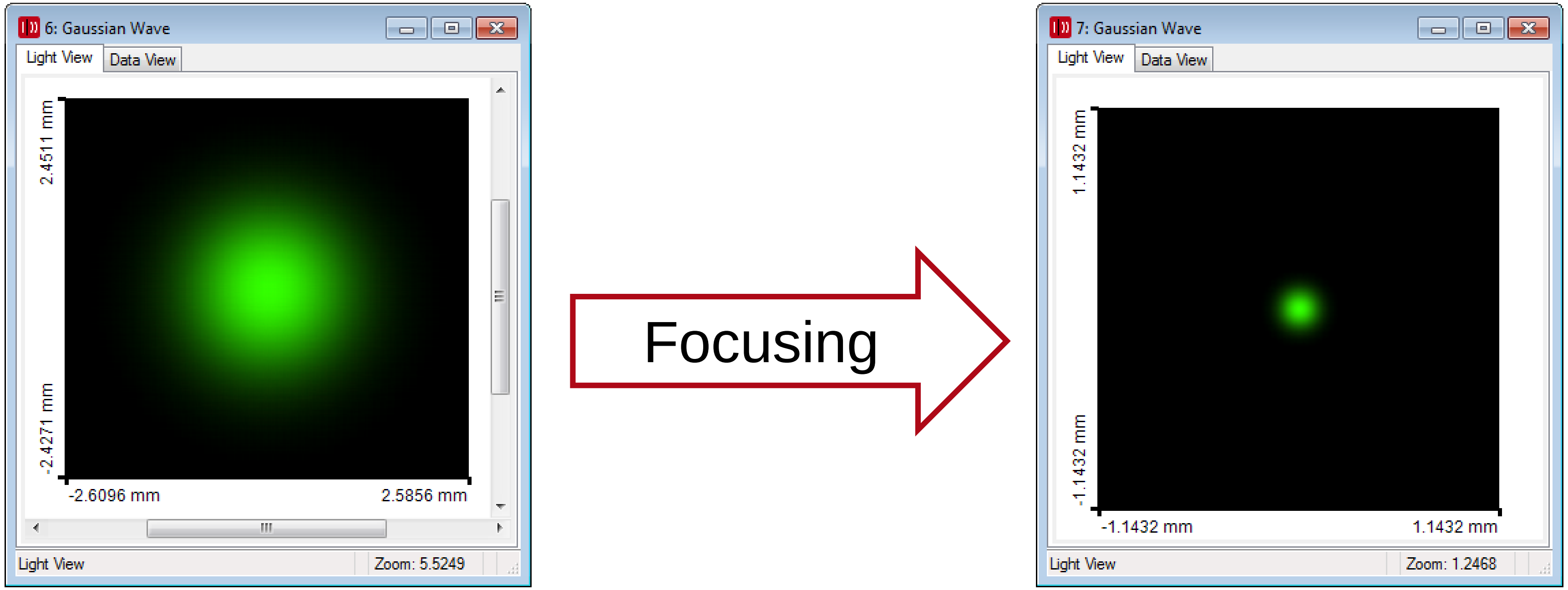
Beam Shaping: The Task



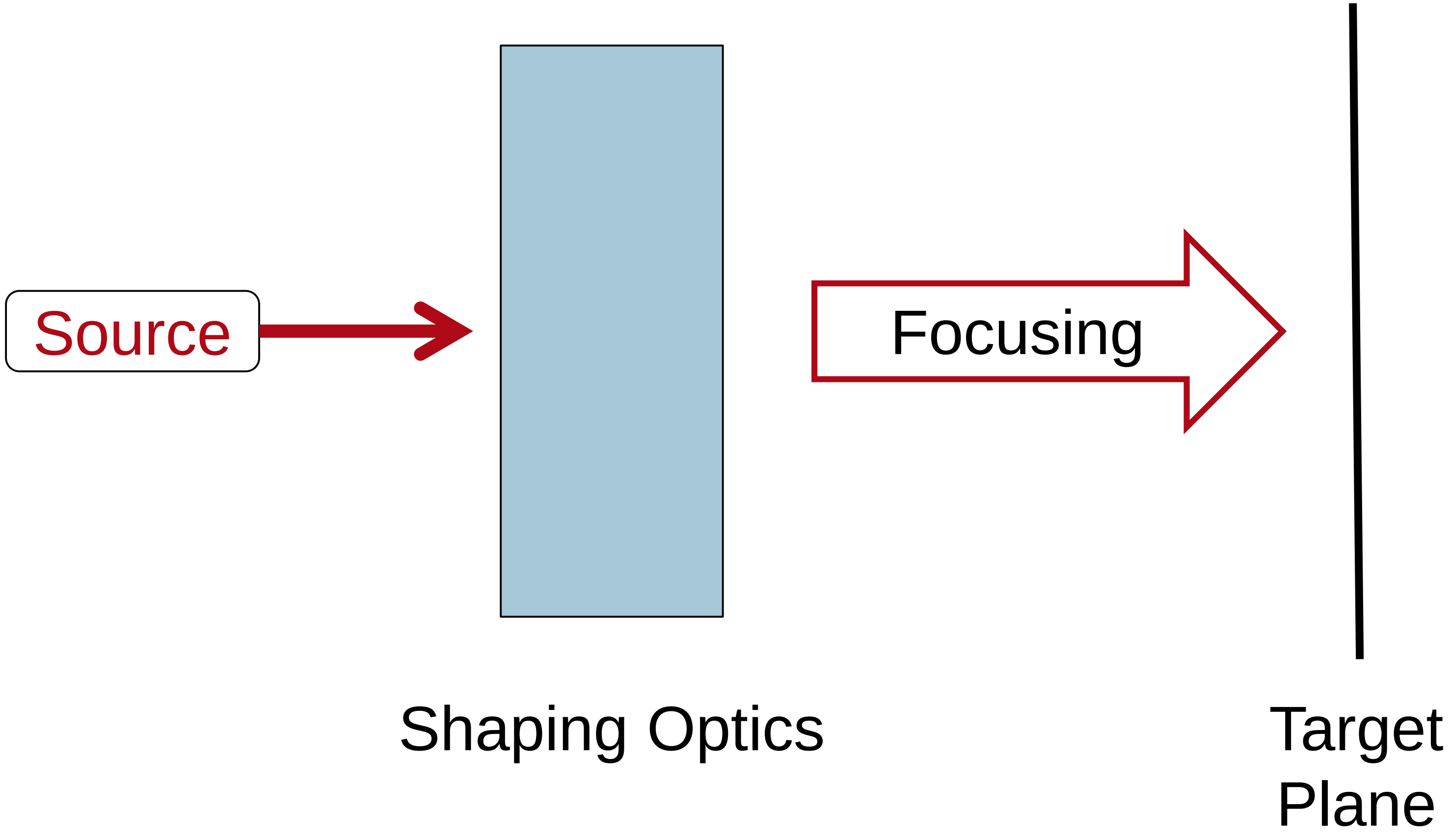
Beam Shaping: The Task



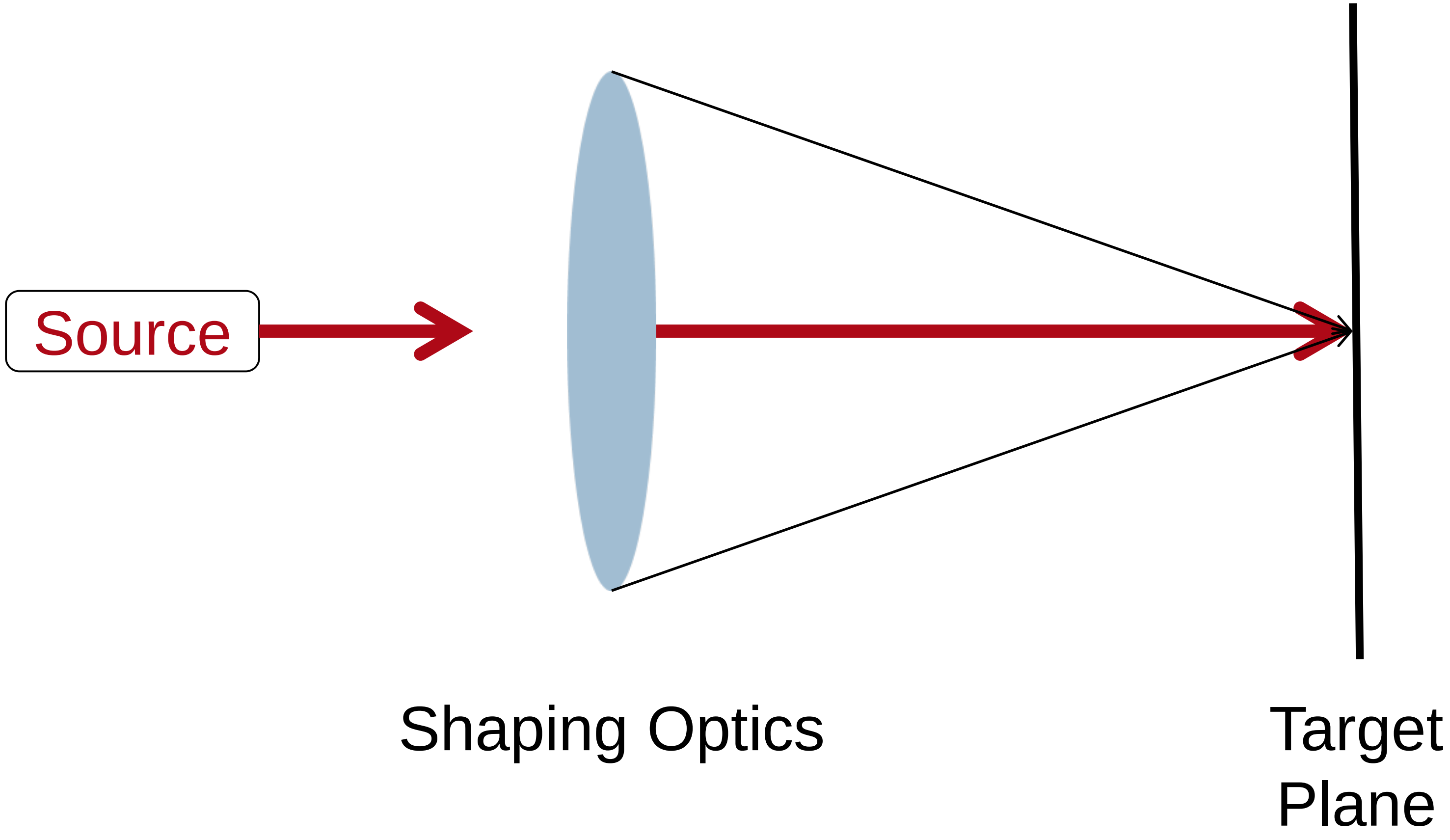
Basic „Beam Shaping“ Task: Focusing



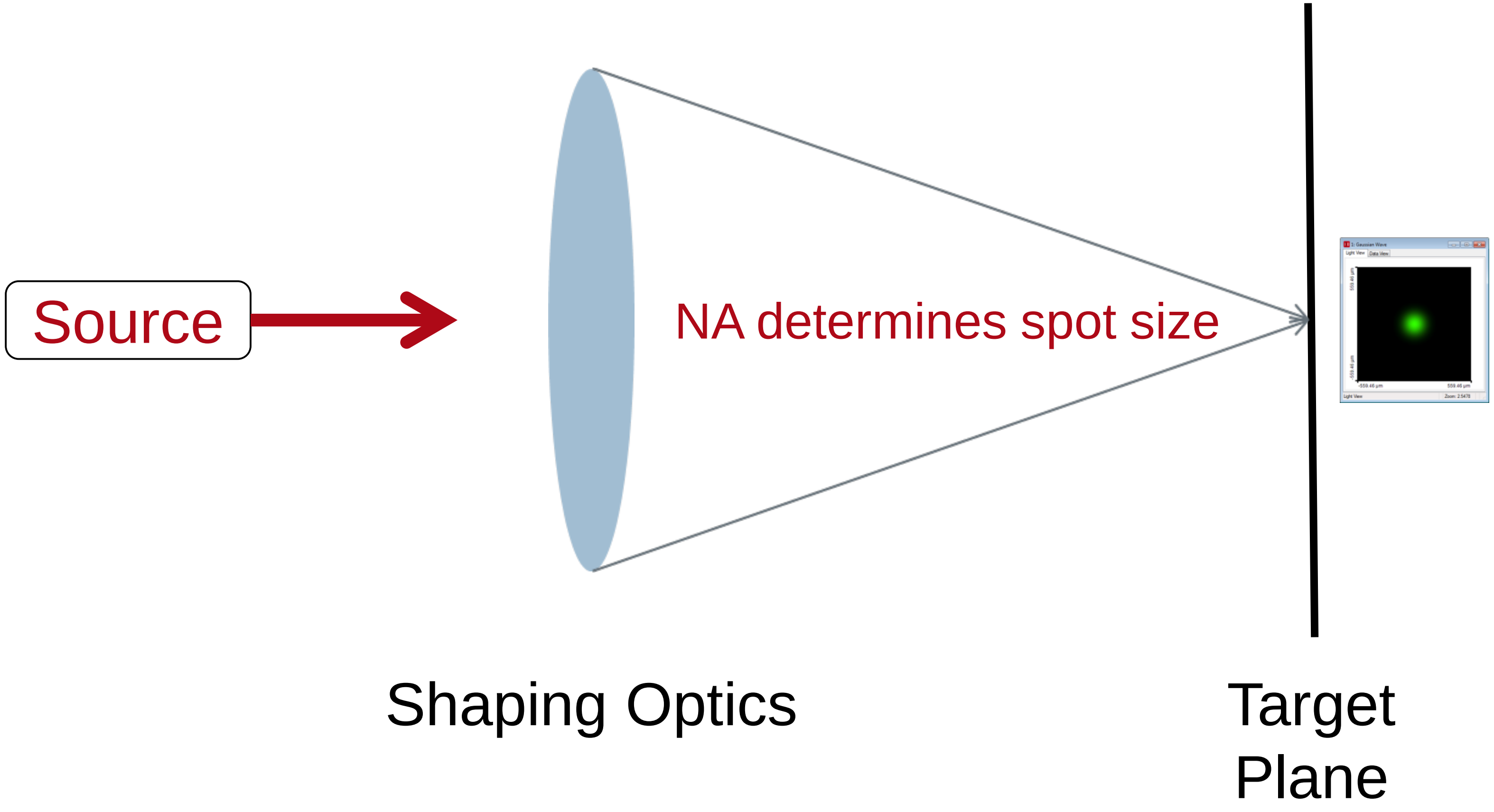
Basic „Beam Shaping“ Task: Focusing



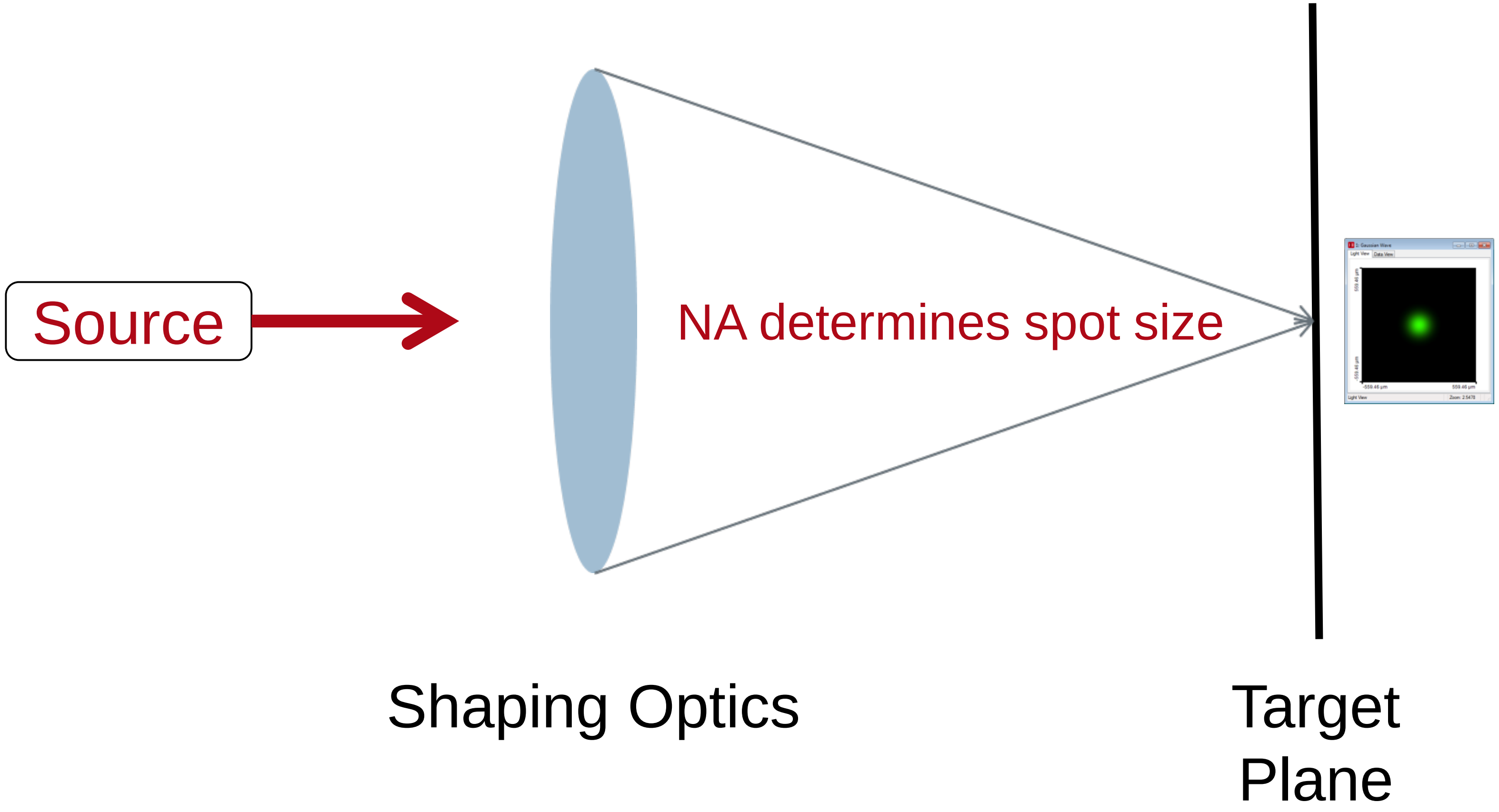
Basic „Beam Shaping“ Task: Focusing



Basic „Beam Shaping“ Task: Focusing

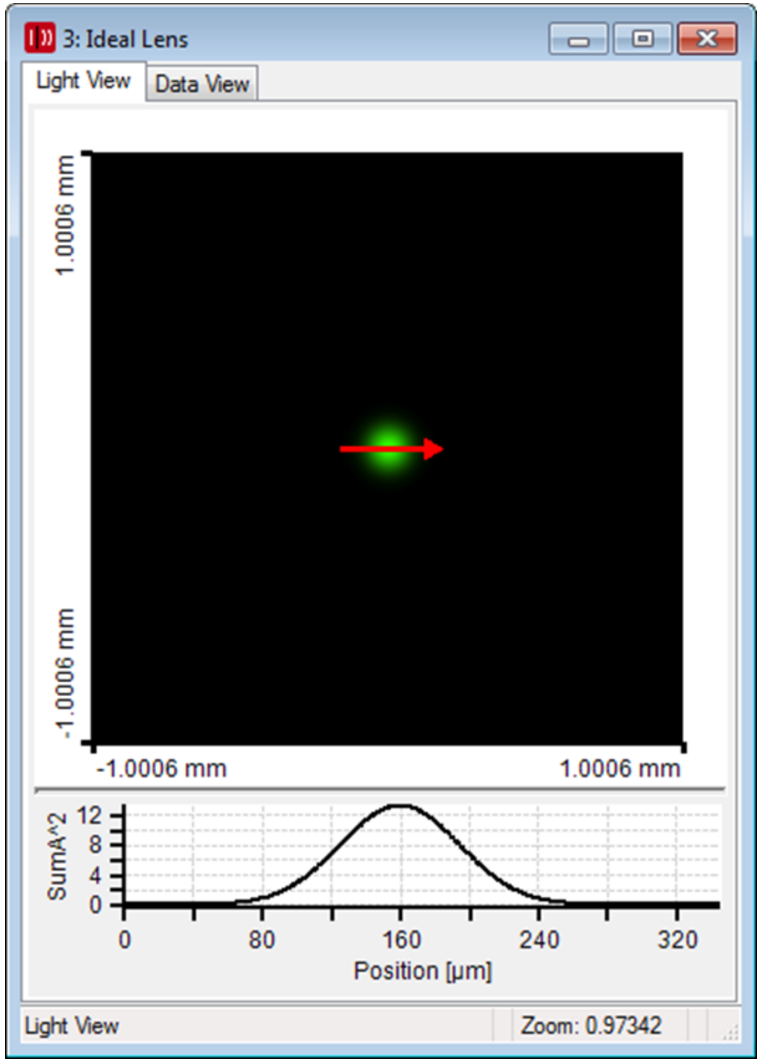


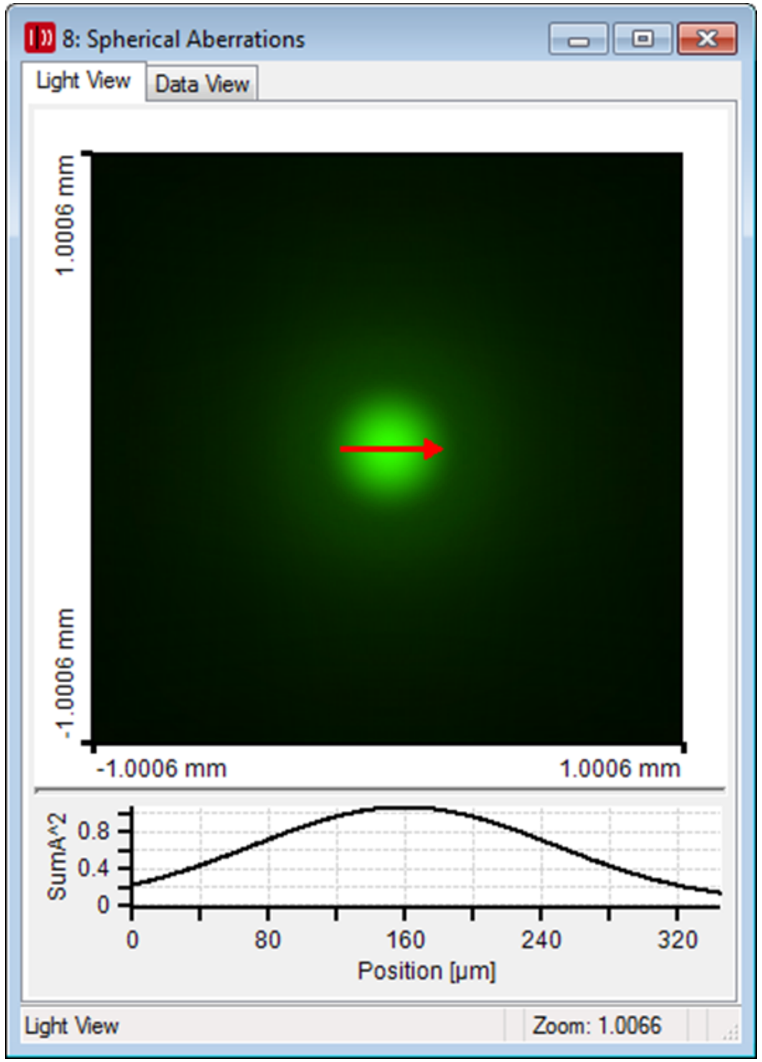
Light Shaping by Aberrations



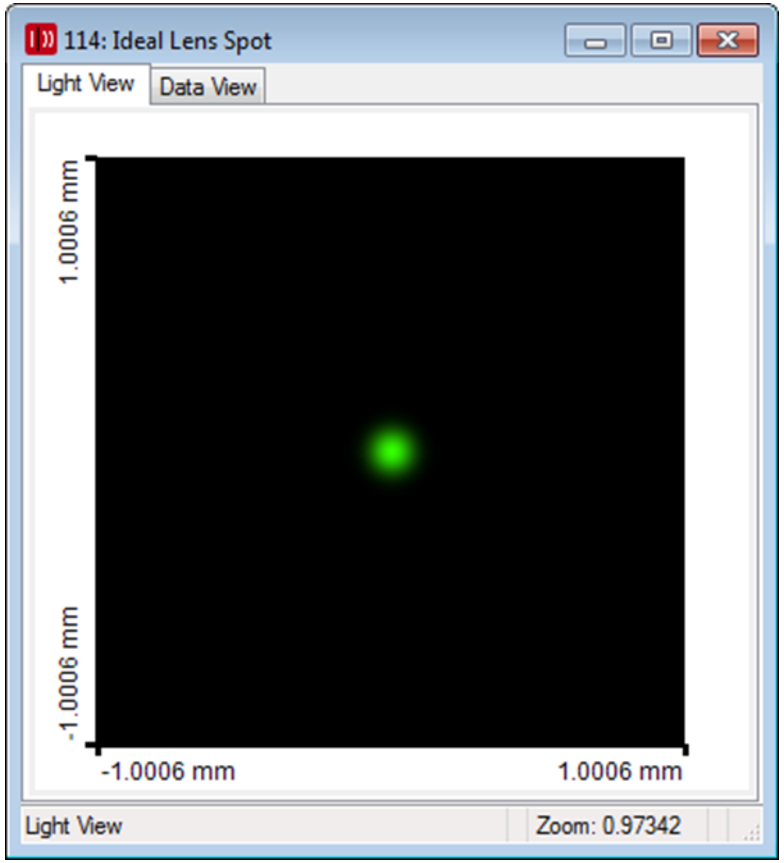
Beam shaping can be understood as the introduction of aberrations to shape the focus!

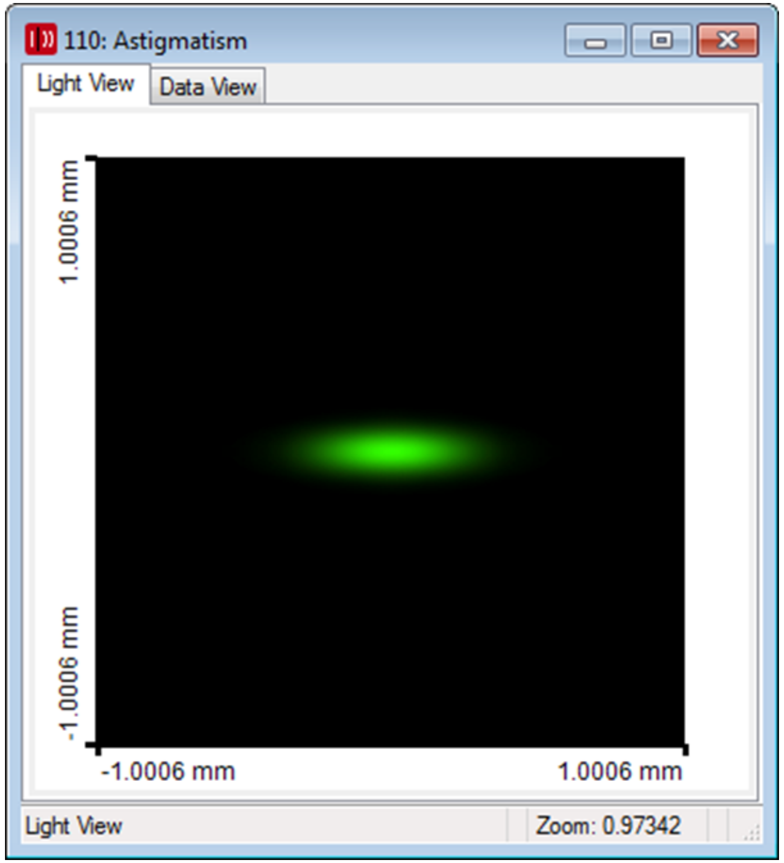
Ideal Lens vs. Spherical Aberrations



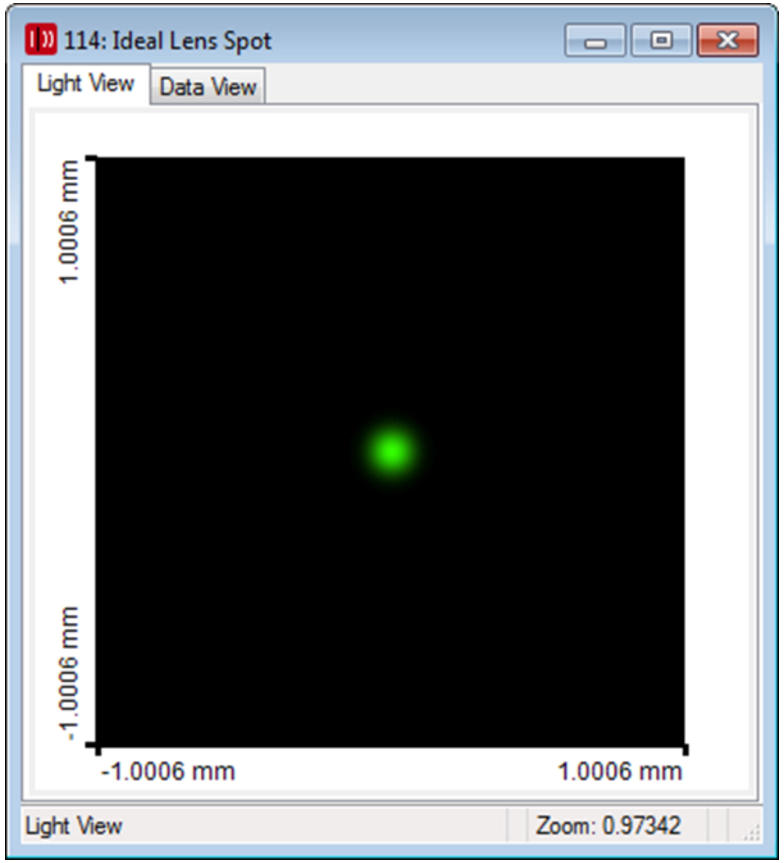


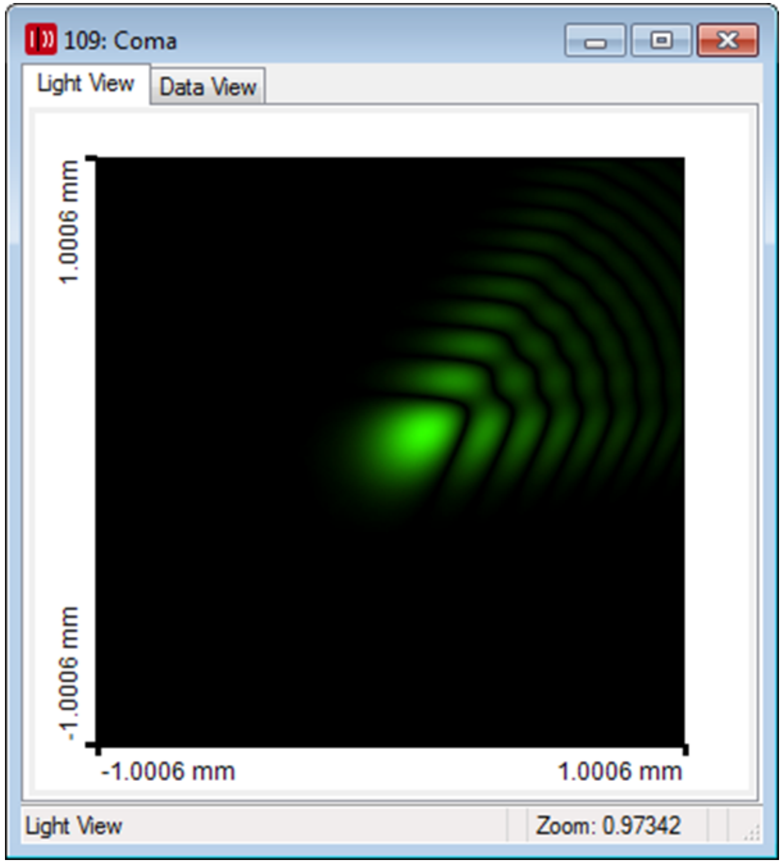
Ideal Lens vs. Astigmatism



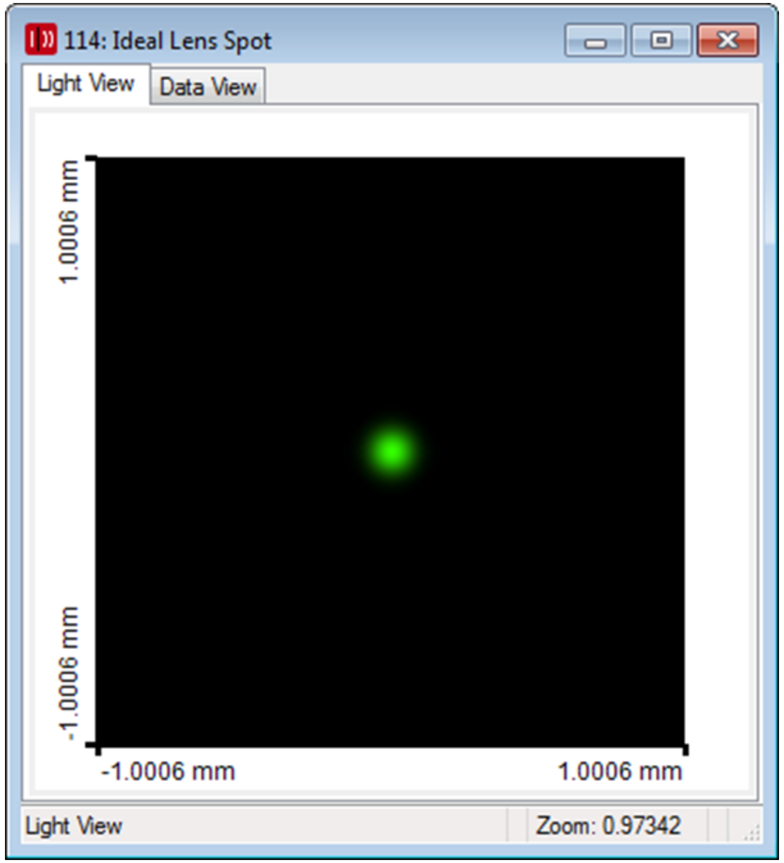


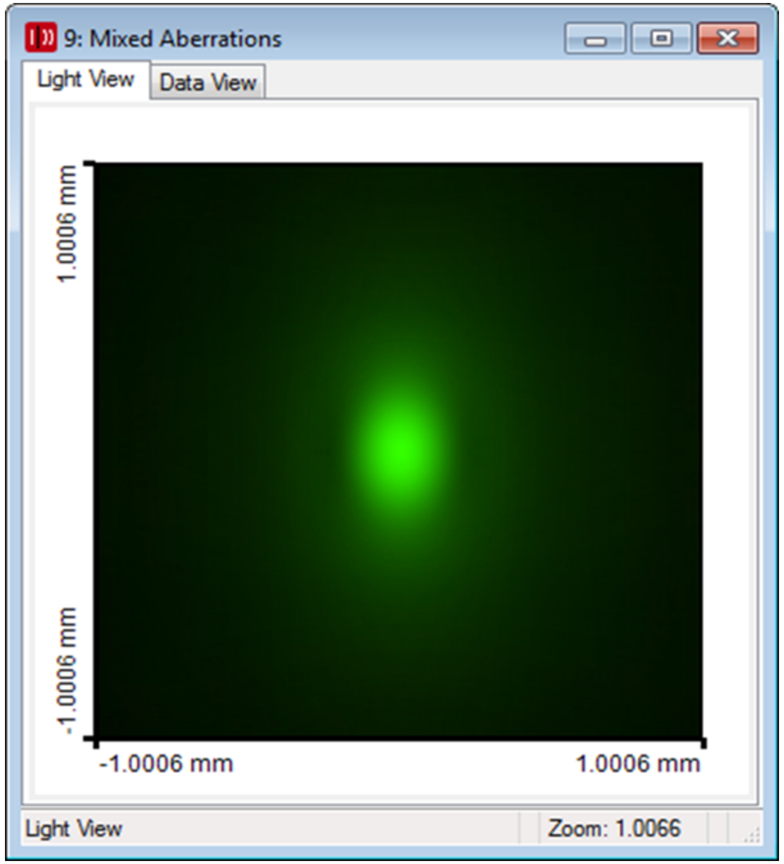
Ideal Lens vs. Coma





Ideal Lens vs. Mixed Aberration



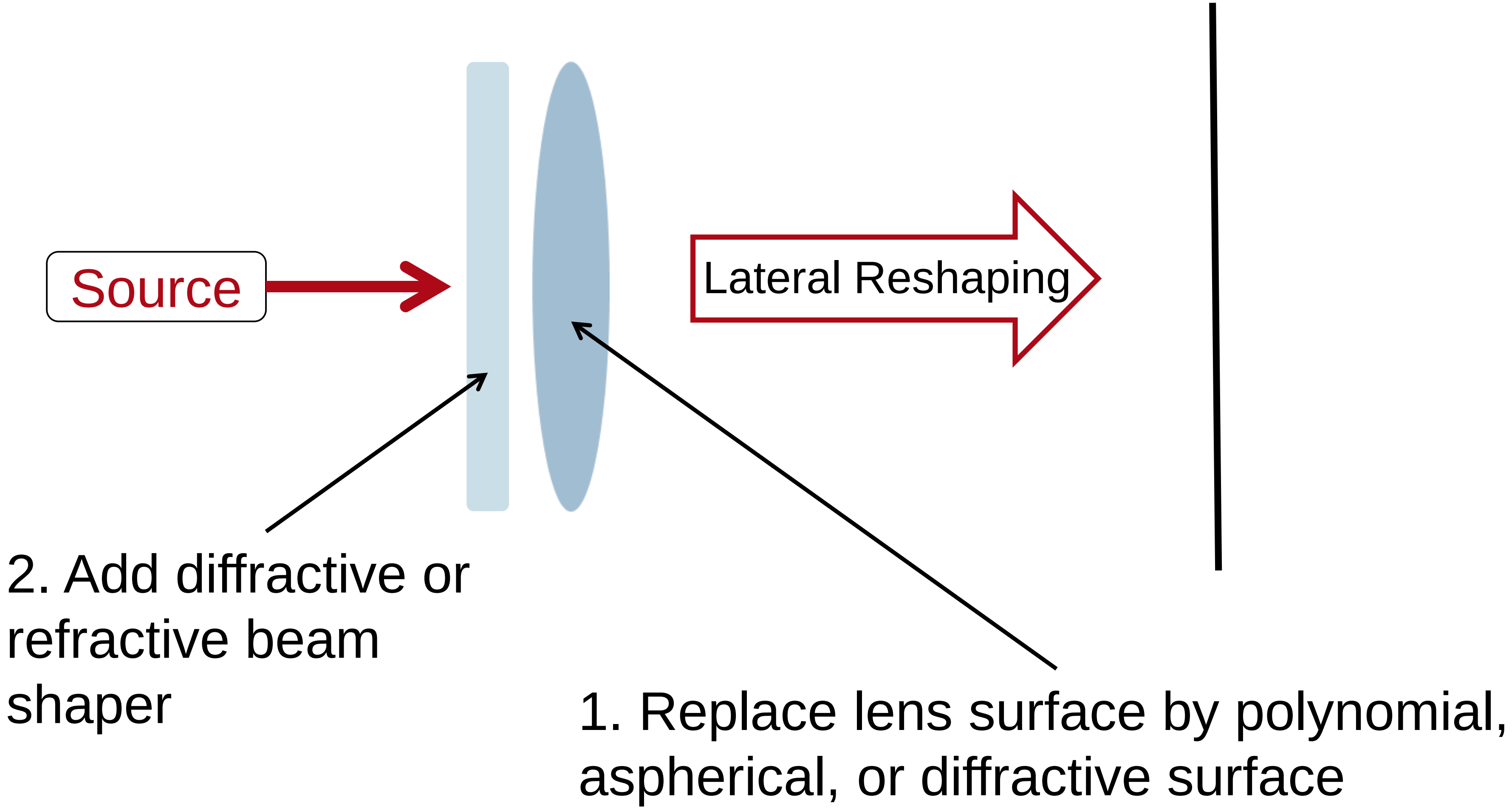


Conclusions for Beam Shaping

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

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

Introduction of Aberrations



What Kind of Aberrations Are Needed?

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

Geometrical Distortion Concept

Analytical beam shaping with application to laser-diode arrays

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

Geometrical Distortion Concept

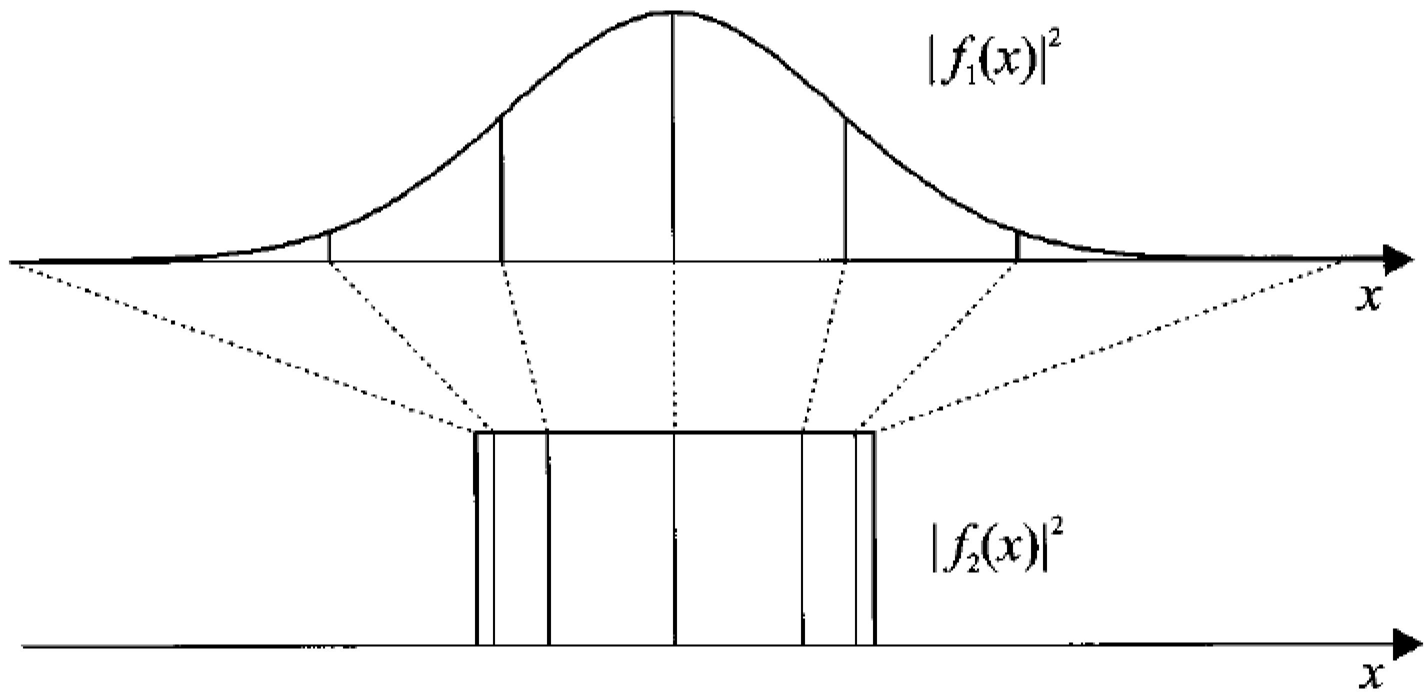

Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

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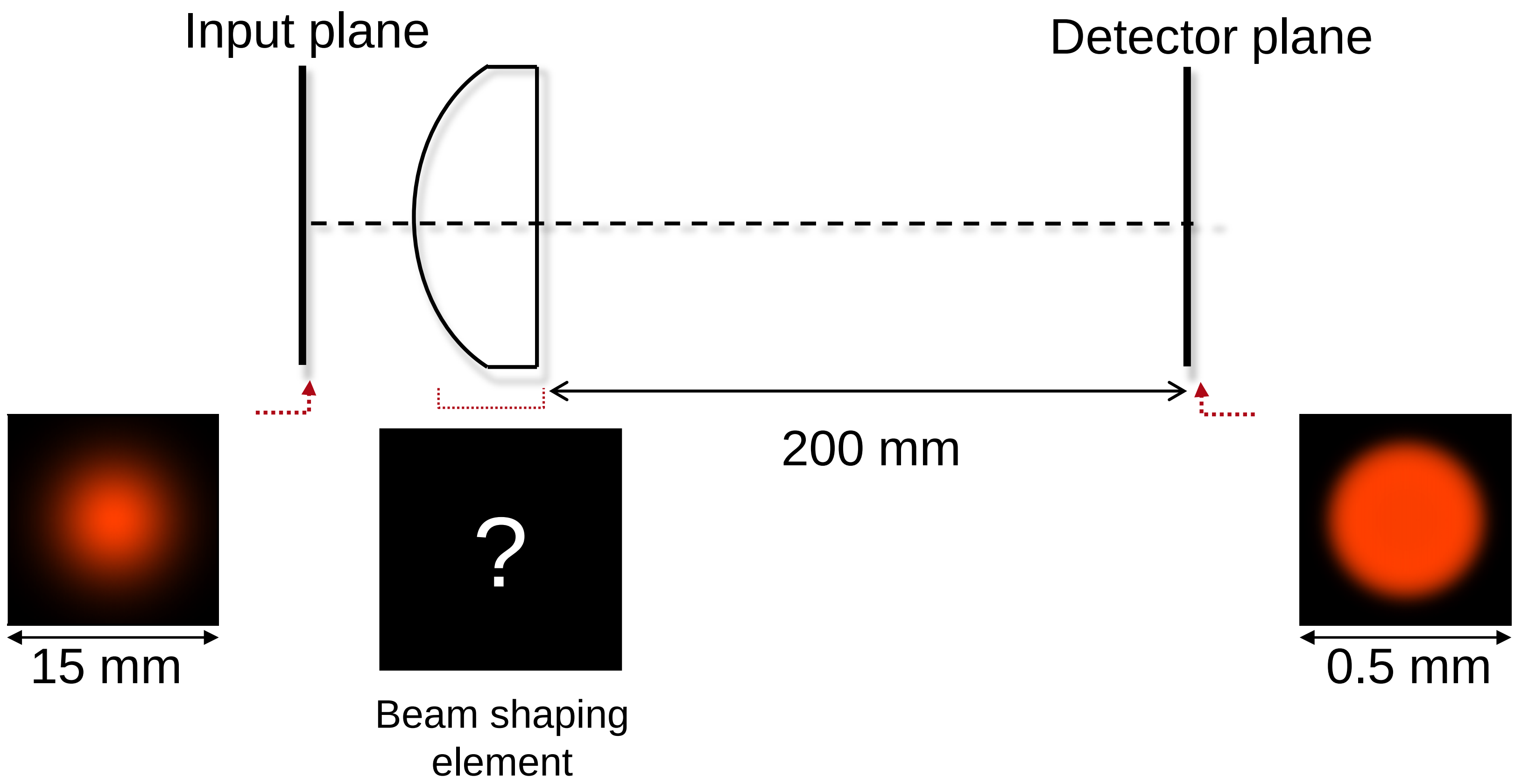
Light Shaping > Refractive Optics

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

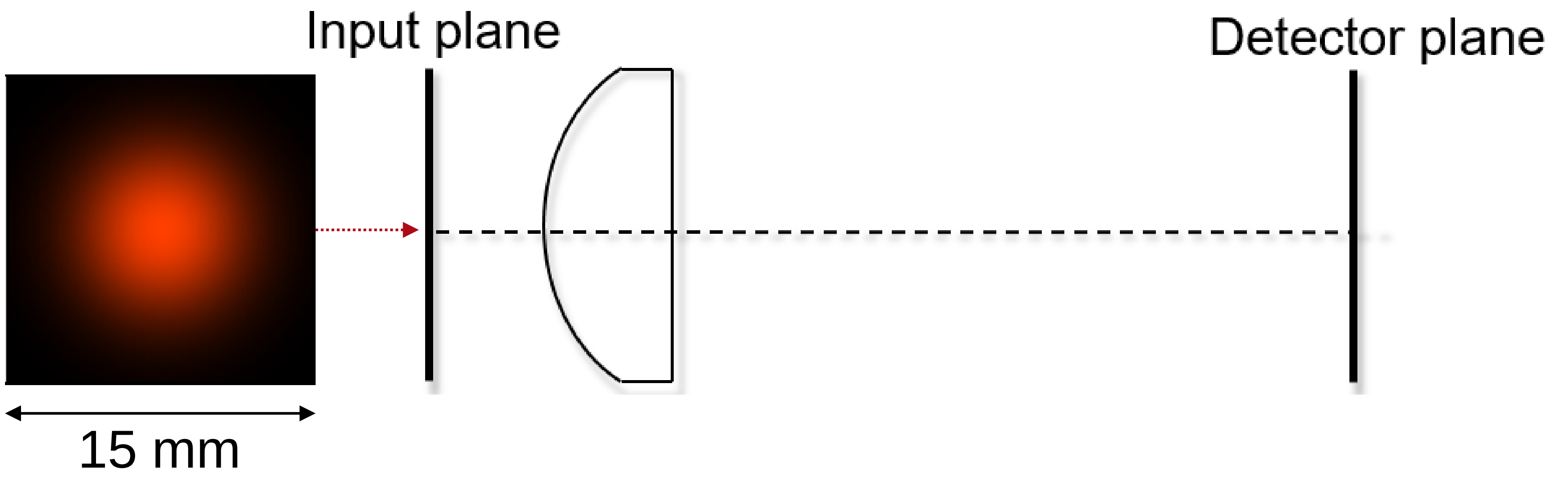
LightTrans International UG

Task Illustration



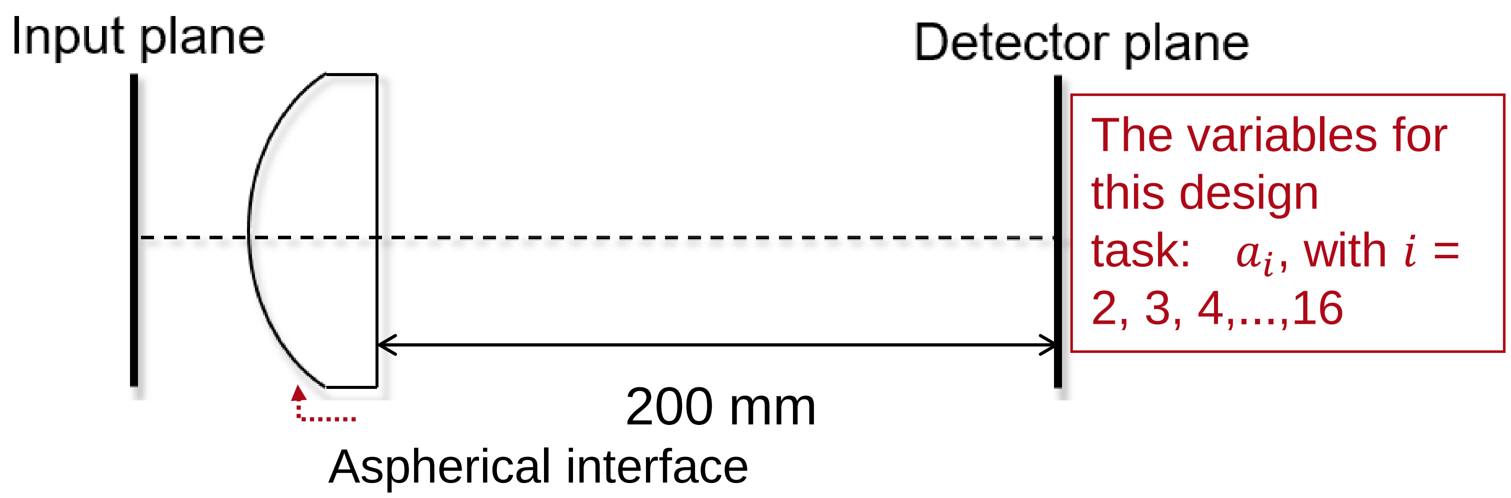
- Design a beam shaping element to shape a laser beam (fundamental mode) to a circular Top-Hat.

Specification: Light Source



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

Specification: Beam Shaper Element



- Aspherical interface:

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

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

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

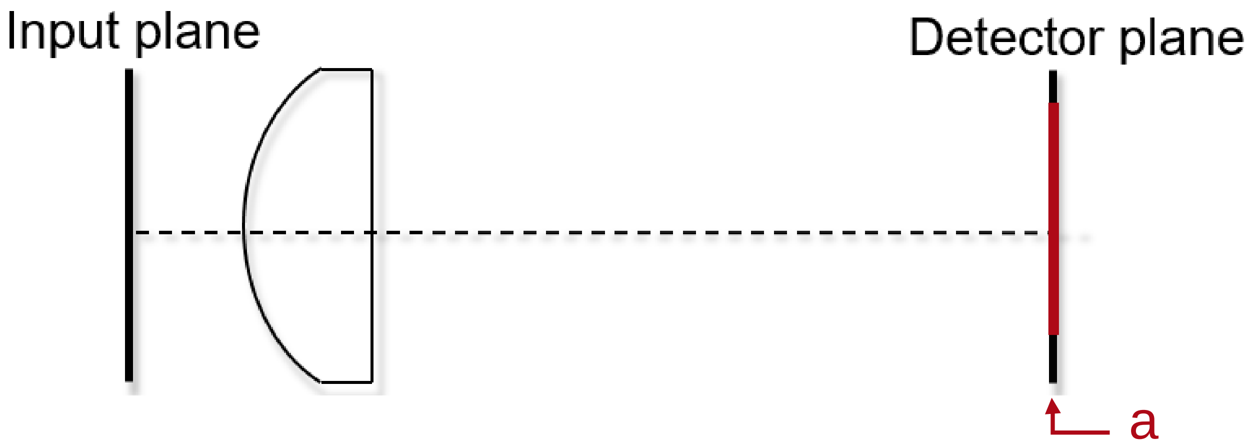
Specification: Desired Pattern

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

Specifications: Merit Functions for Design

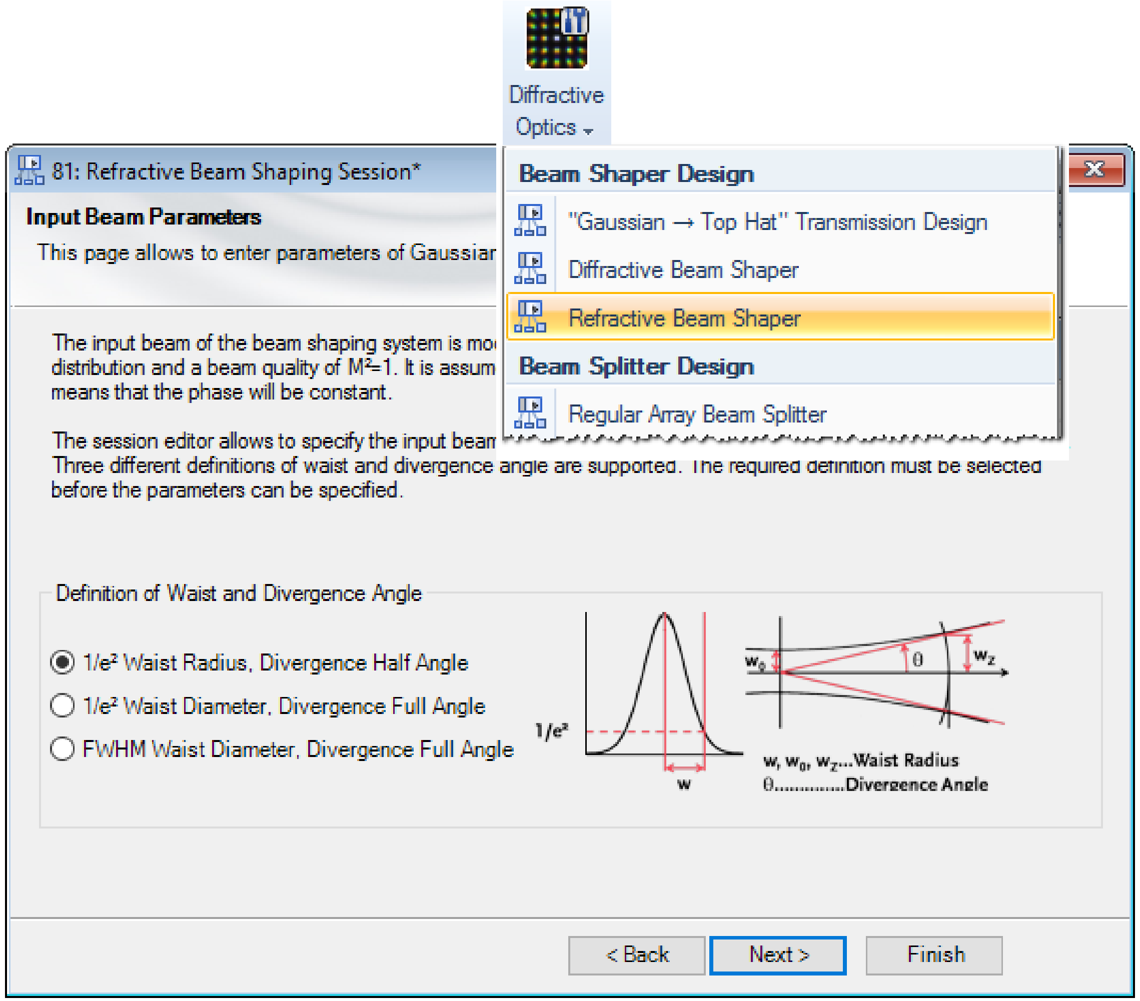
Parameter	Description / Value & Unit
conversion efficiency	> 90%
signal to Noise Radio (SNR)	> 22 dB
maximum relative intensity of stray light	< 10%

Specifications: Detector



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

Optimization Process

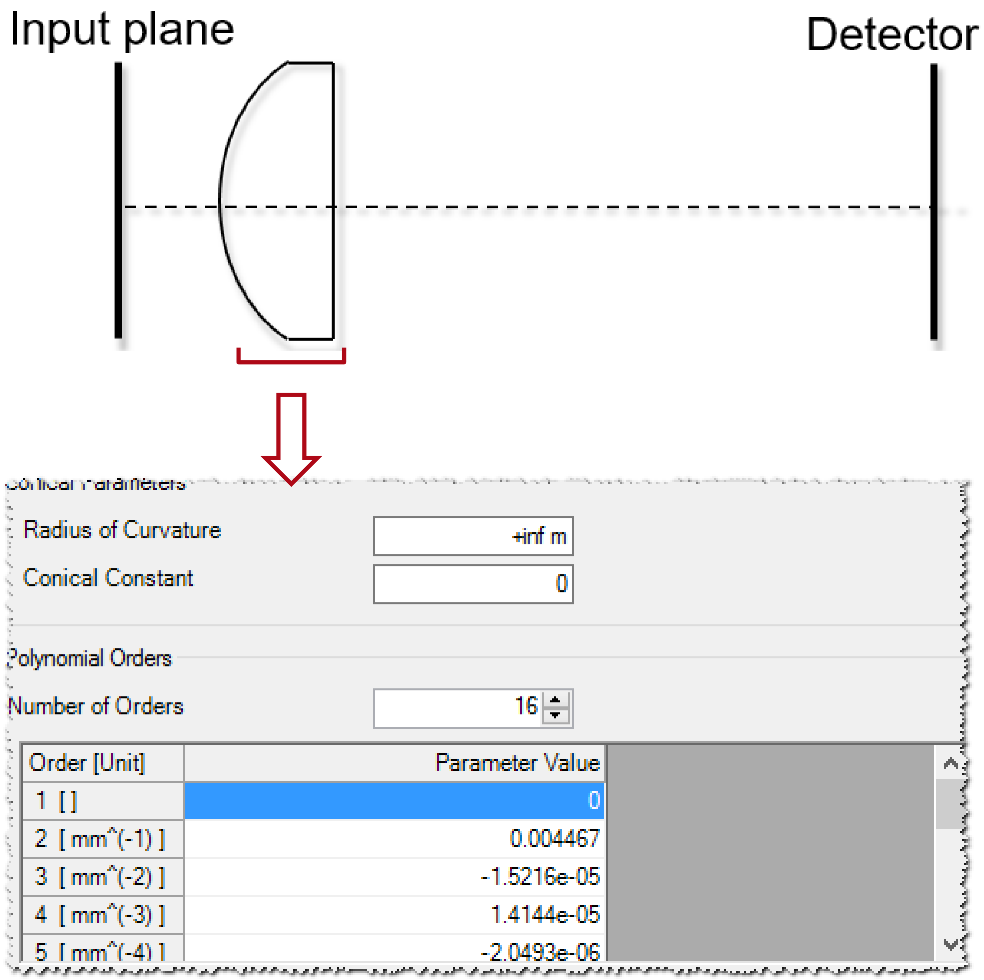


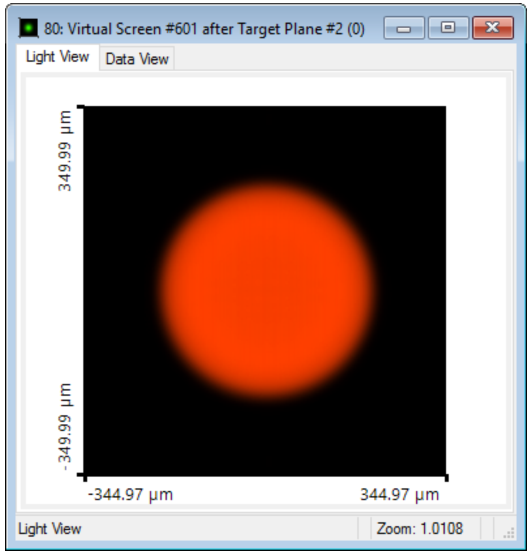
- Design Process is easily done by using the *Refractive Beam Shaping Session*.
  - Fill the parameters in illustration
  - Next!
- Click *Finish*, the beam shaper design is done immediately.

Design time → ~0.016 s !!!

* RO.0001_Refractive_Top_Hat_Beam_Shaper_Session_Editor.seditor

Results: Refractive Beam Shaper





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

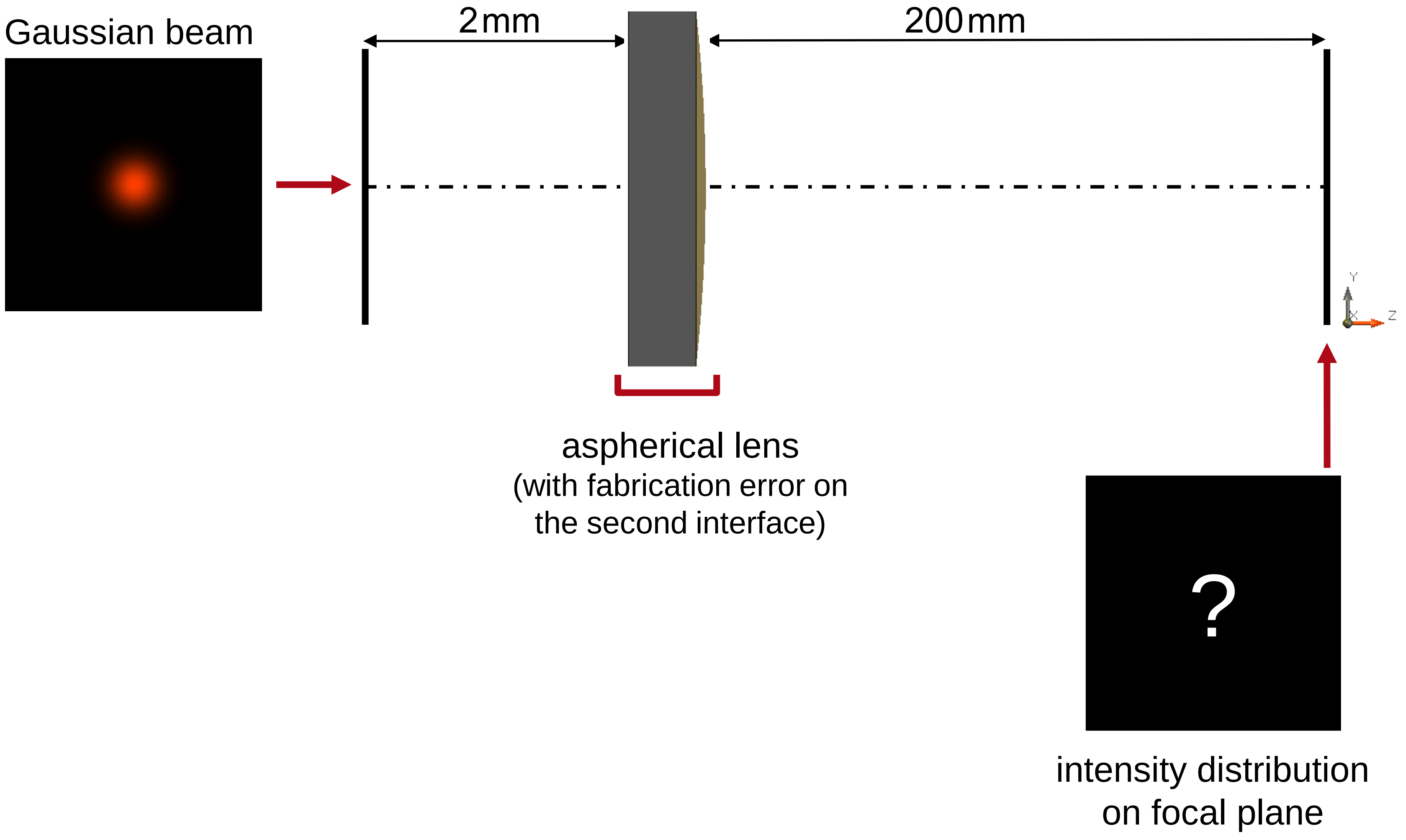
*RO.0001_Refractive_Top_Hat_Beam_Shaper_LPD.lpd

Light Shaping > Refractive Optics

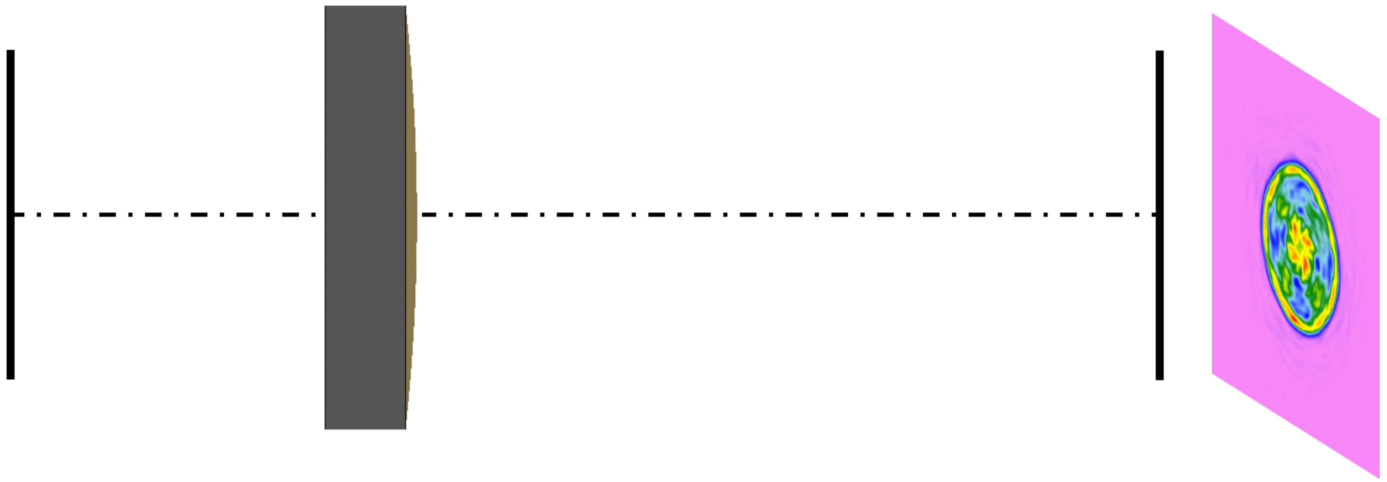
Modeling of a Refractive Beam Shaper with Measured Height Profile

LightTrans International UG

Task/System Illustration

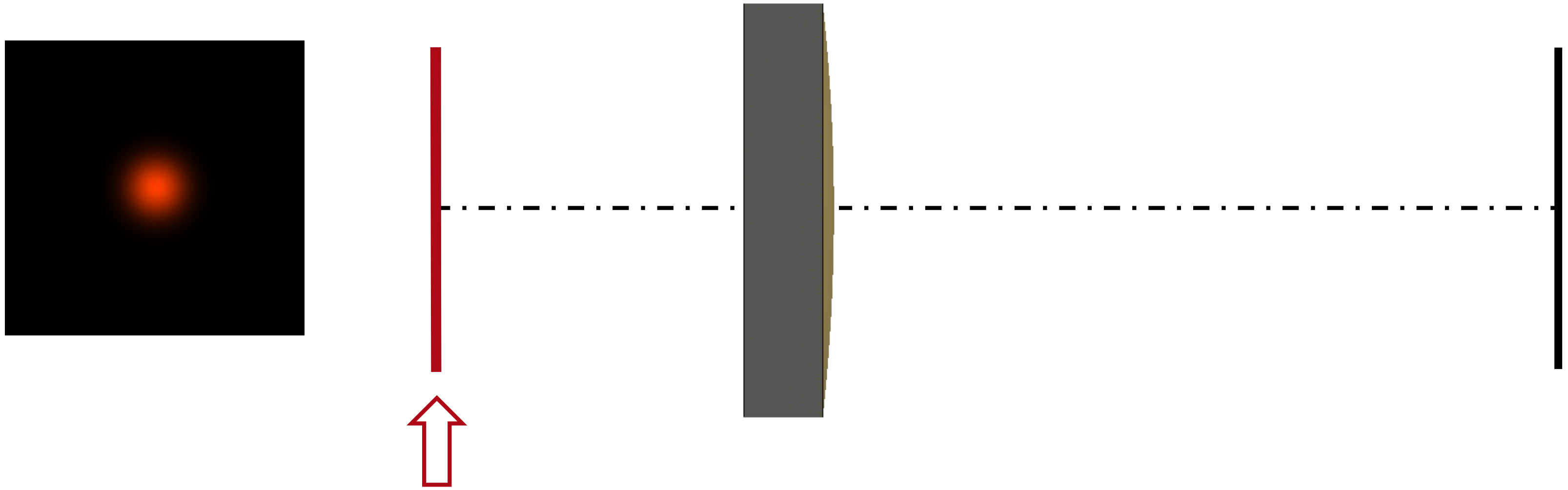


Highlights



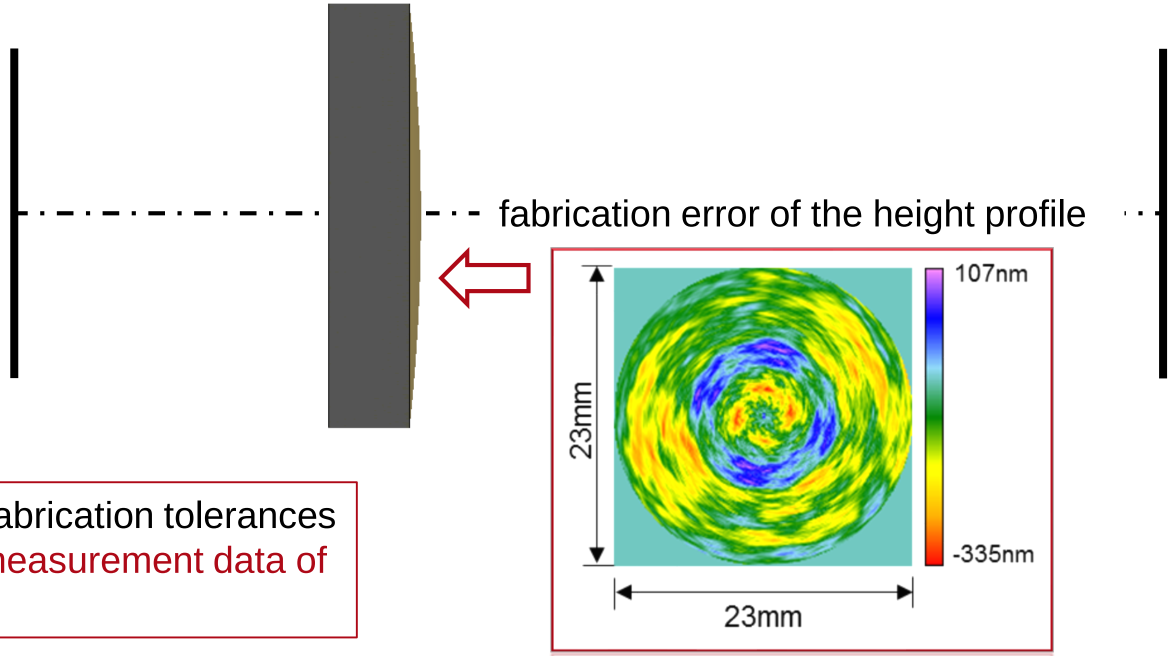
- simulation of fabrication tolerances by importing measurement data of height profiles

Specification: Light Source



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

Specification: Focusing Asphere

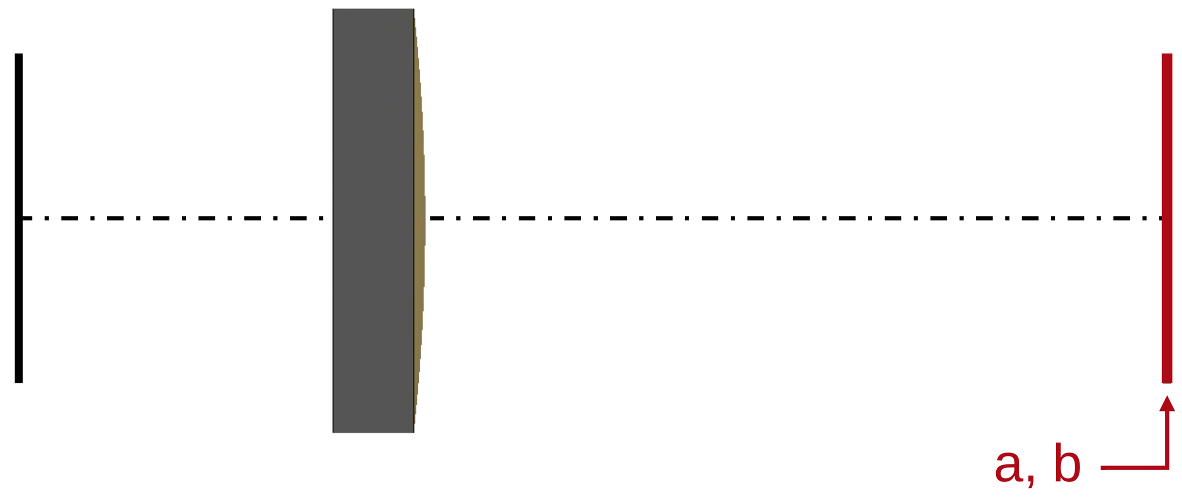


Highlights

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

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

Specification: Detectors

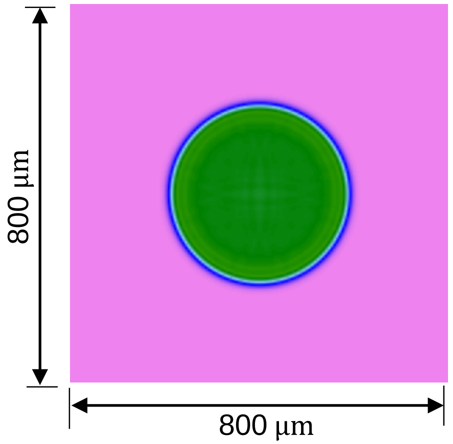


Position	Modeling Technique	Detector/Analyzer
a	field tracing	intensity distribution
b	field tracing	merit function detector

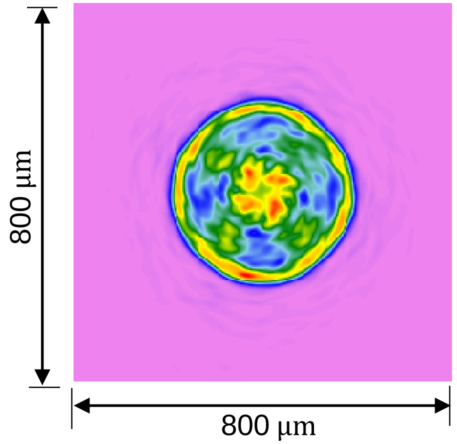
Results: Intensity Distribution

Highlights

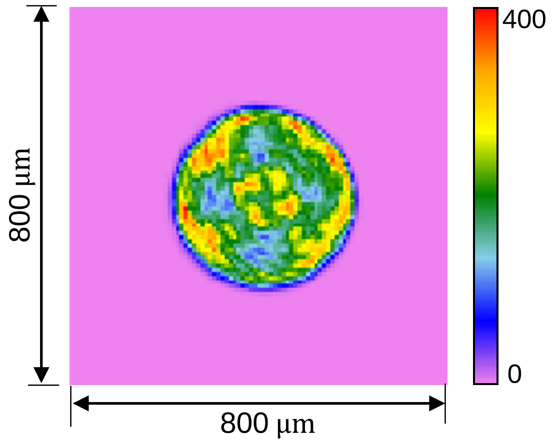
- simulation of fabrication tolerances by importing measurement data of height profiles



intensity of field at focal plane (without fabrication tolerances)



intensity of field at focal plane (with fabrication tolerances)



measured intensity at focal plane (with fabrication tolerances)

Results: Merit Function Detector

Highlights

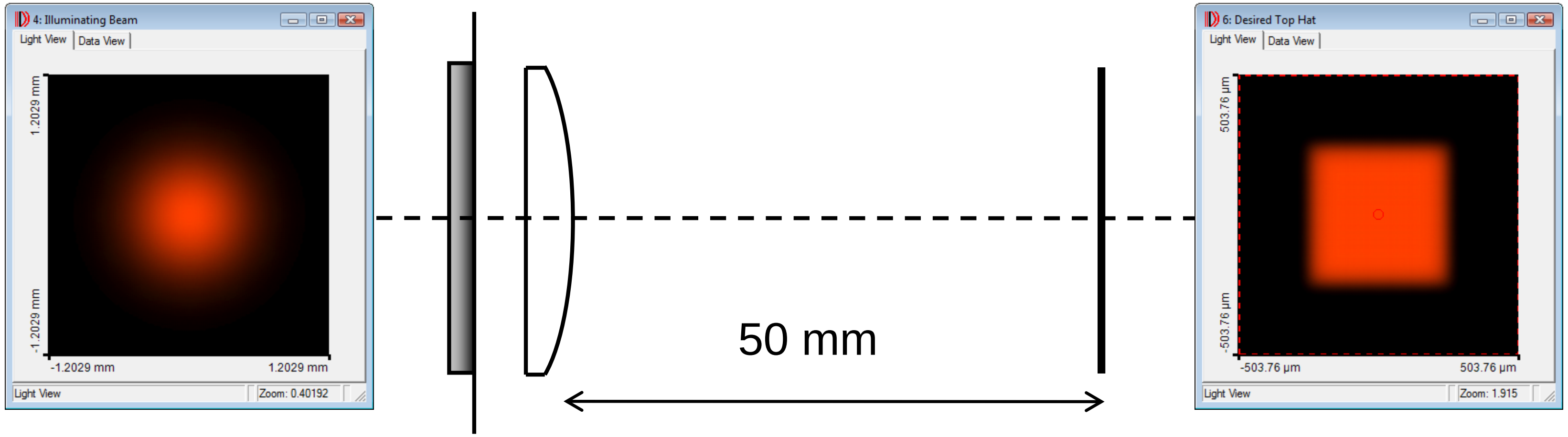
- simulation of fabrication tolerances by importing measurement data of height profiles

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

Modeling Task

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

Target
Plane



Illuminating Beam
Intensity

1f-Setup
Focal Length f=50 mm

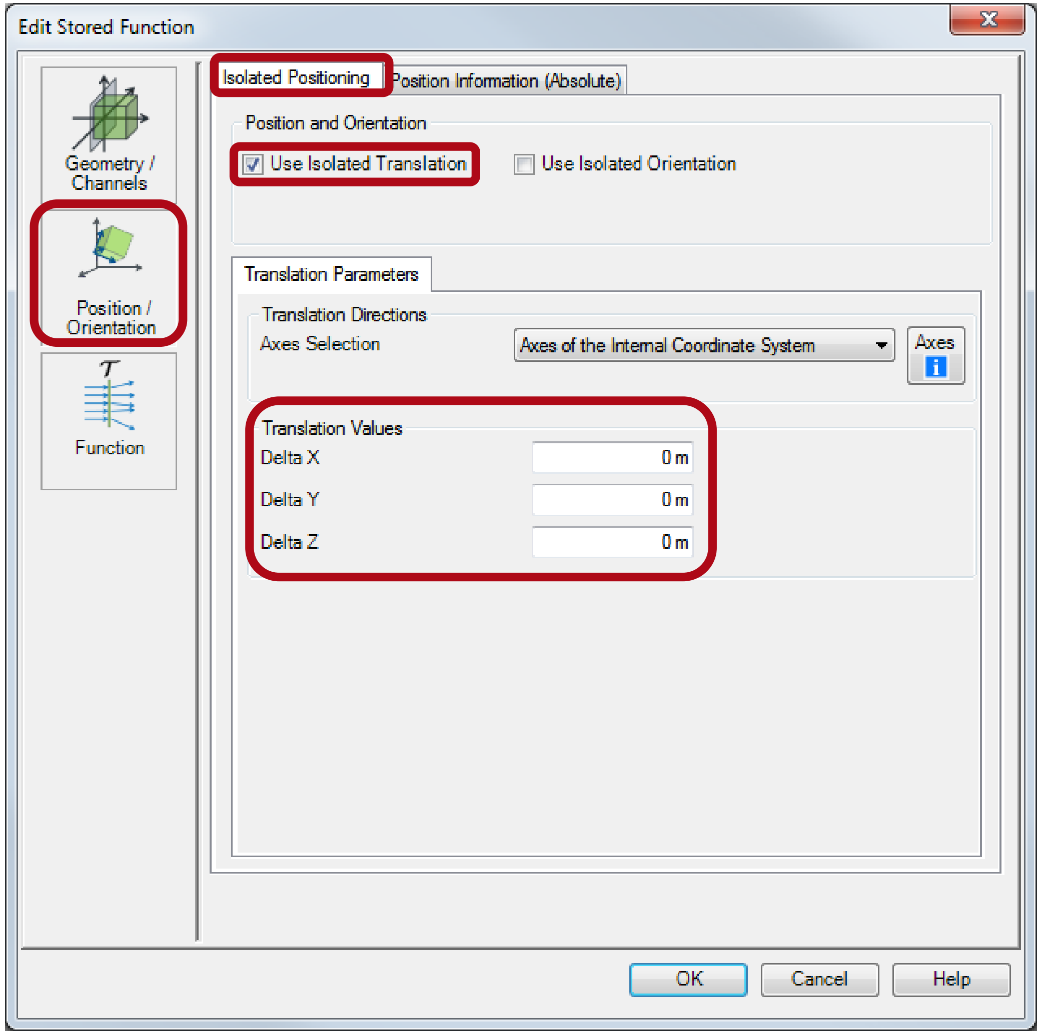
Top Hat Intensity
(free of speckles)

Modeling Task

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

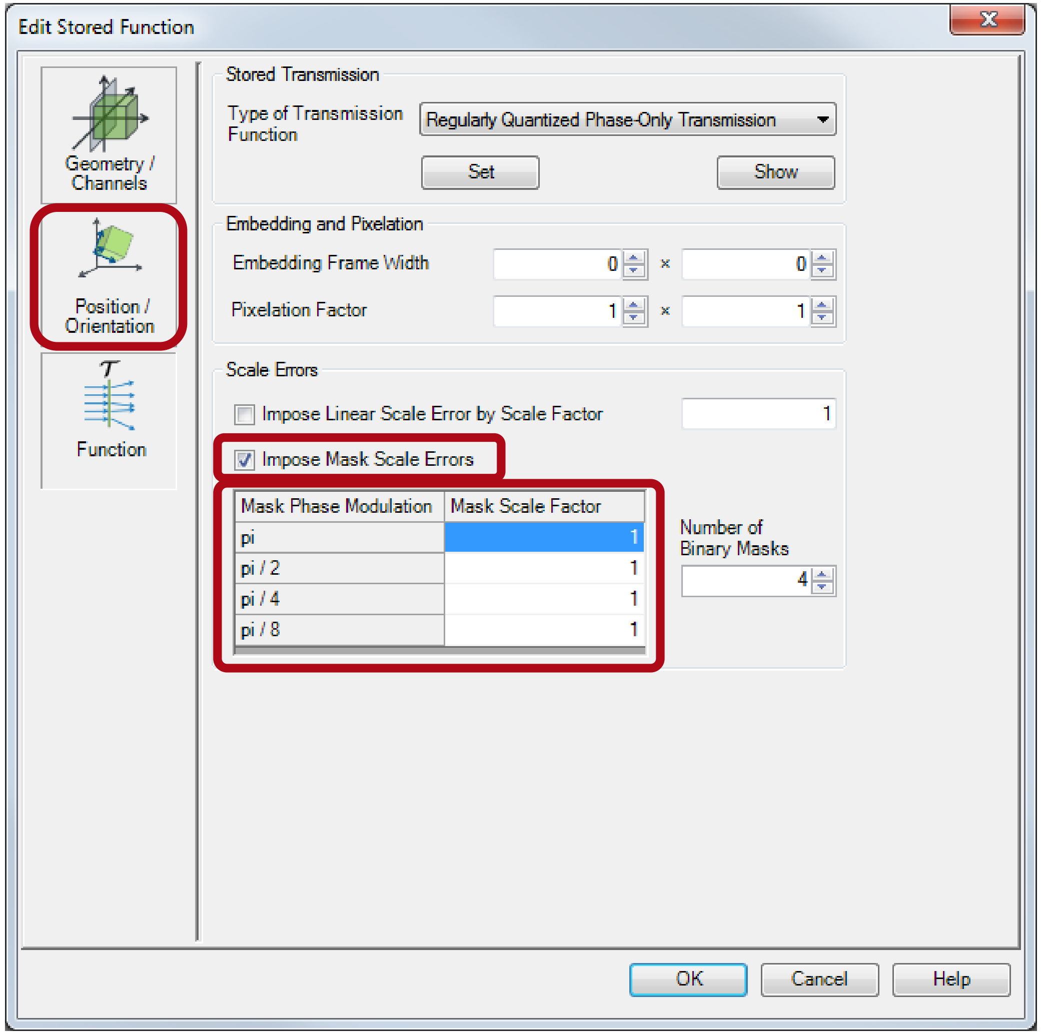
Varied Parameters	Value and Tolerances
Waist Radius of Input Beam	(500 ± 25) µm
Etching Depths of all 4 Binary Masks	± 2 % of original height
x-Position of Beam Shaper	(0 ± 10) µm
y-Position of Beam Shaper	(0 ± 10) µm
Focal Length of Lens	(50 ± 0.5) mm

Simulation of Alignment Tolerances



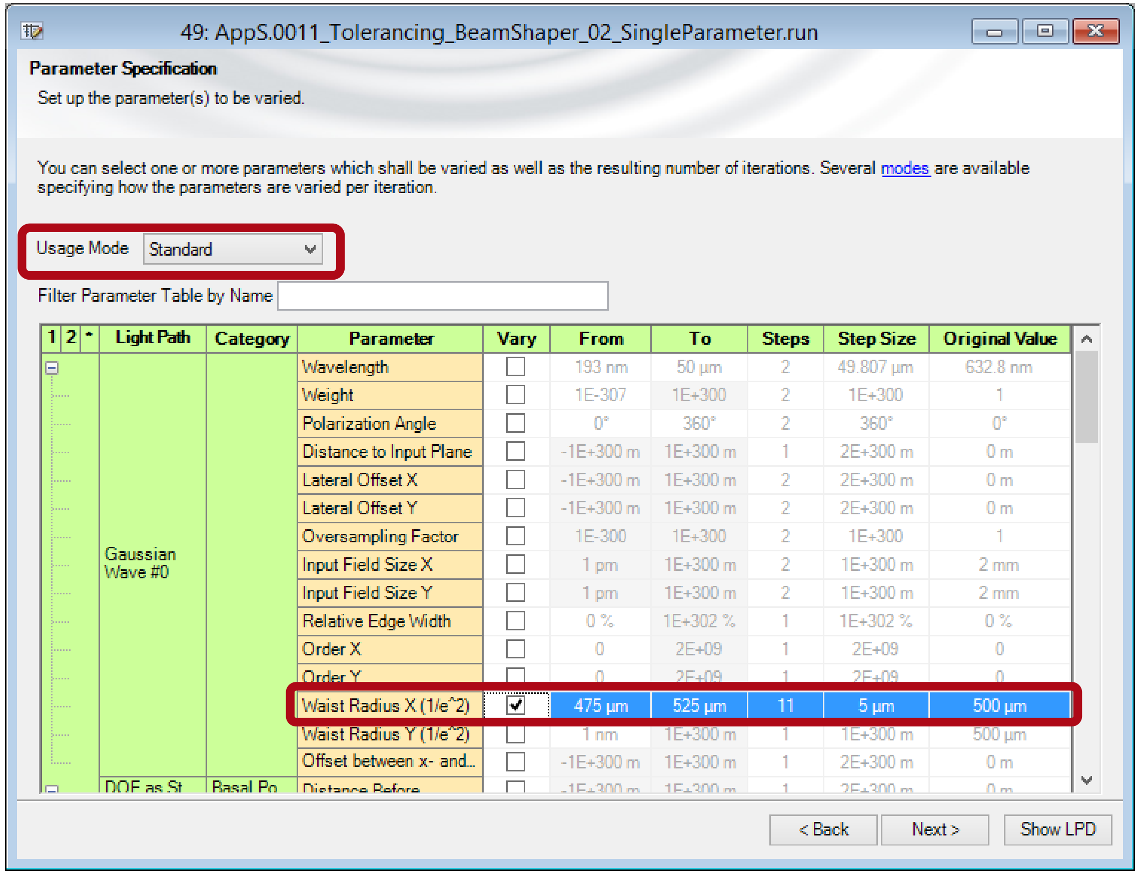
- Simulation of shift tolerances must be activated on *Tolerancing* page of *Stored Function* component and *Target Plane* component.
- Tolerance values are varied by *Parameter Run.* The values set in the component dialog are ignored.

Simulation of Etching Depth Tolerances



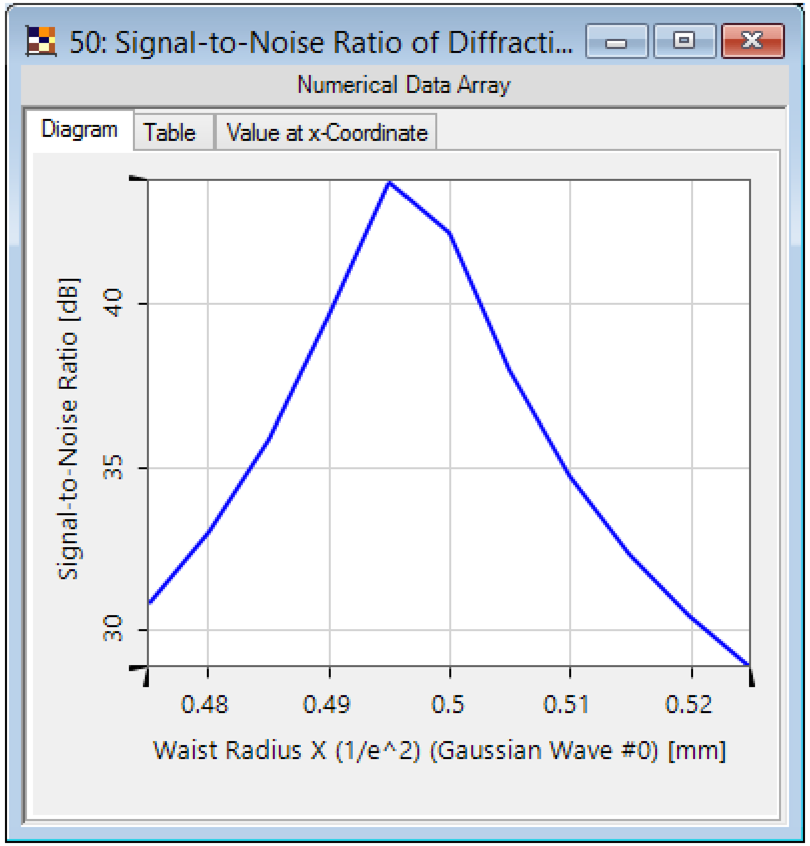
- Simulation of mask etching depth errors must be activated on *Function* page of *Stored Function* component.
- Tolerance values are varied by *Parameter Run*. The respective settings in the component dialog are ignored.
- A tolerance value of 1 represents an optimum etching depth.

Single Parameter Variation



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

Single Parameter Variation

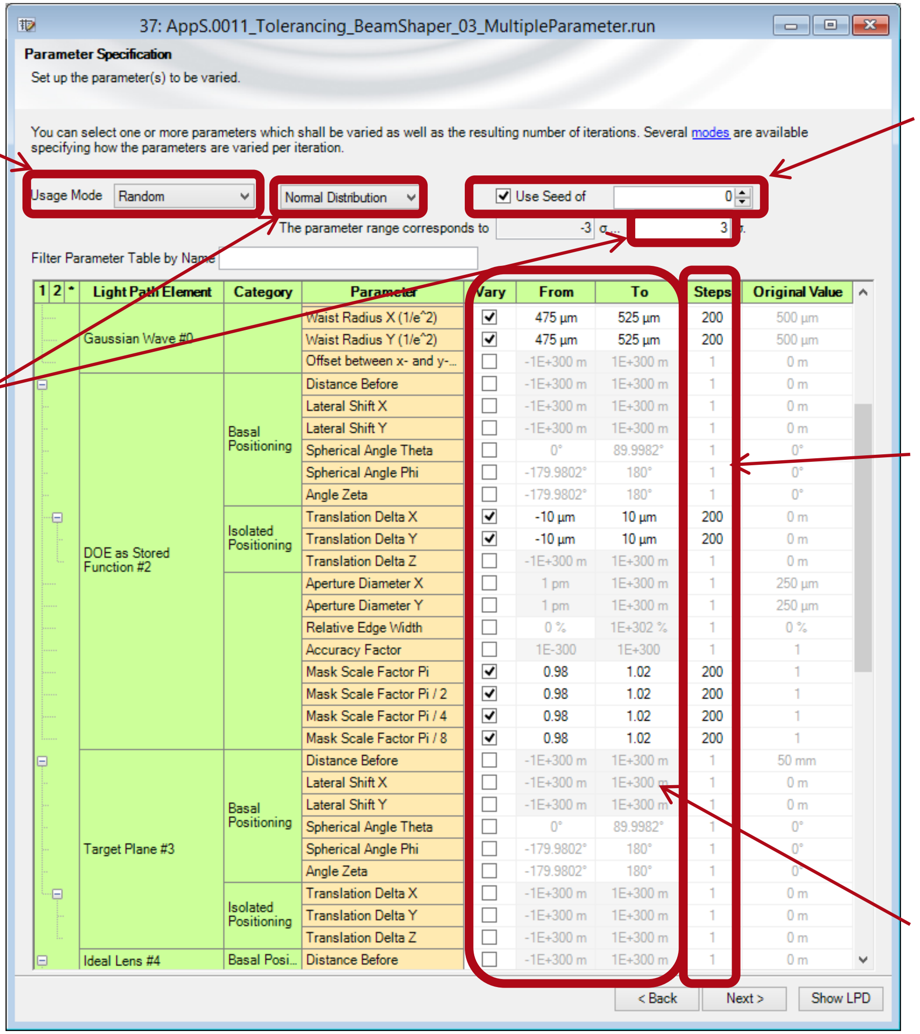


- The beam shaping system shows a strong sensitivity for a variation of the laser beam radius.
- The Signal to Noise Ratio (SNR) will drop to 28.8dB.

Monte-Carlo Simulation

Random mode for Monte Carlo simulation

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

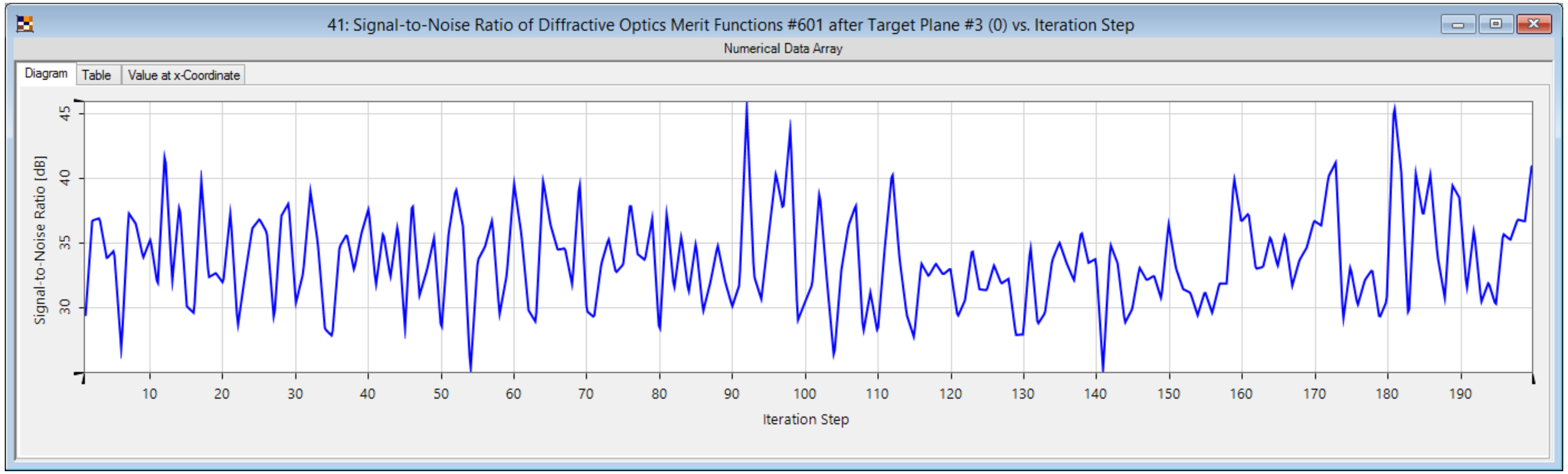


A Seed can be used for reproducible results of the 'random' series.

Total number of variations

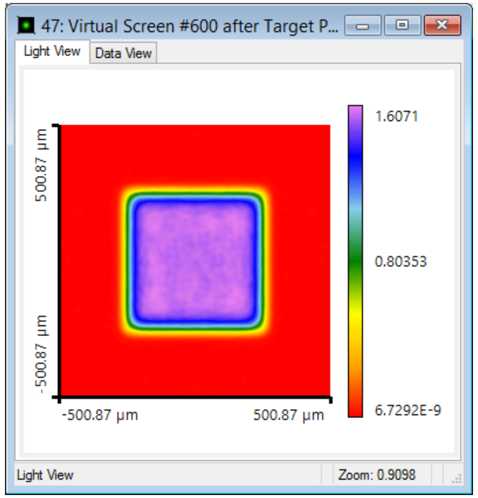
Minimum and maximum value of all tolerances defined by $\pm 3\sigma$

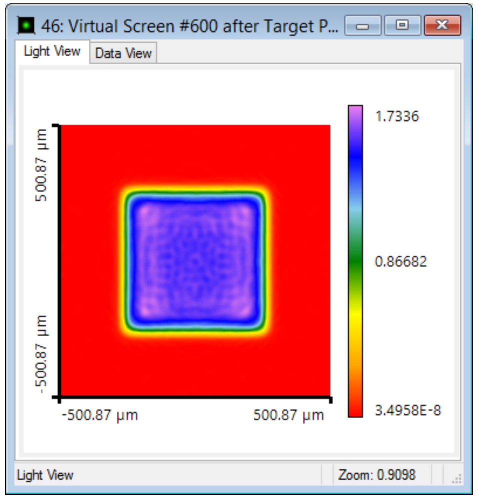
Monte-Carlo Simulation



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

Resulting Field Distributions





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

Light shaping by stored scanning process

Diffractive optical elements

Light Shaping Concepts

- tailored aberrations (beam shaping)
- stored scanning process (diffuser & splitter)
- multichannel concept (cells array)

Function Principle of DOE

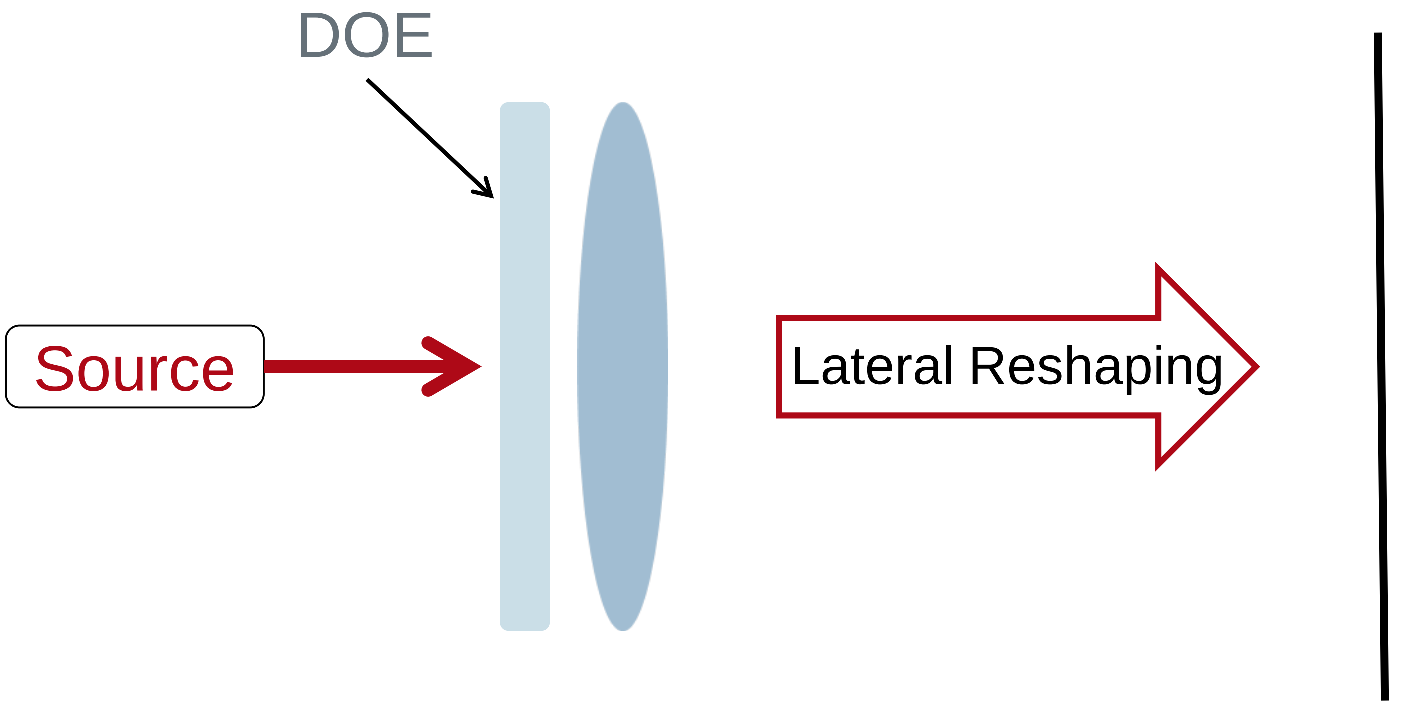


Illustration of Deflection

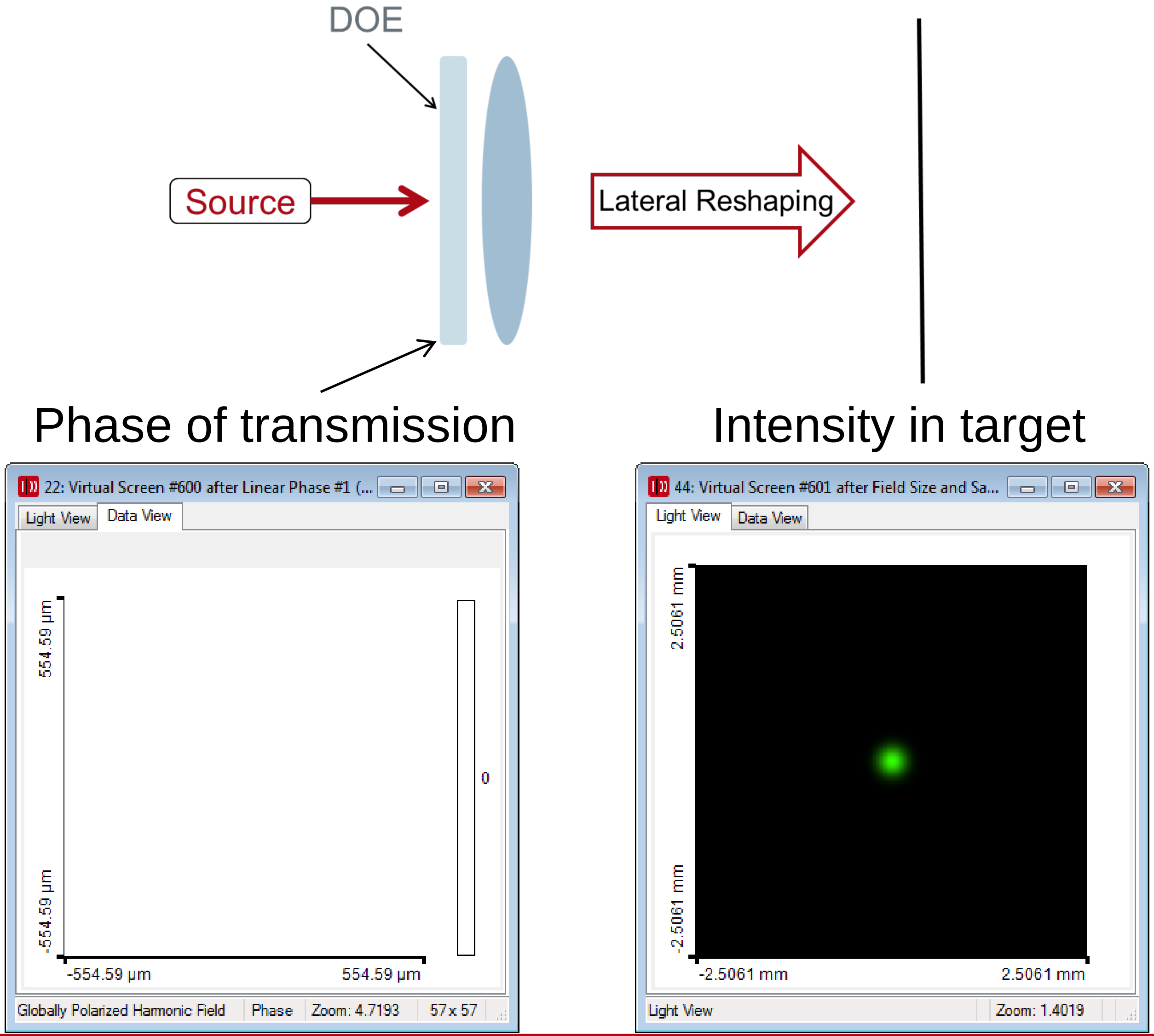
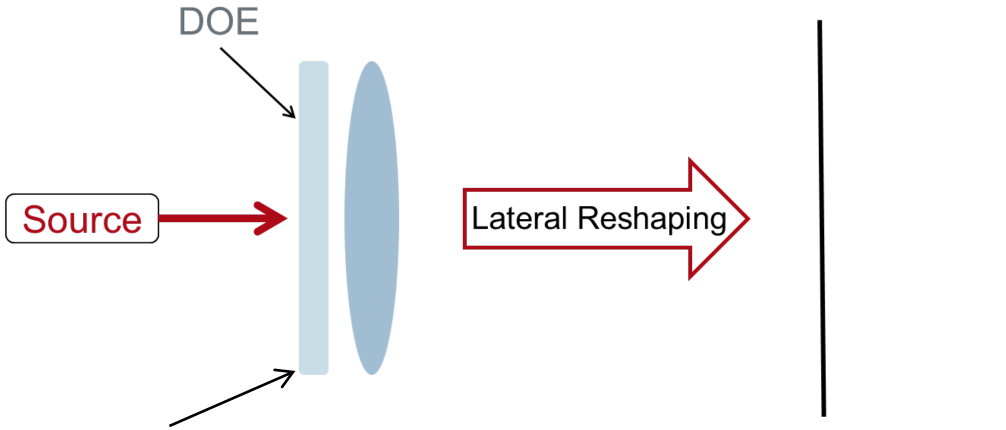
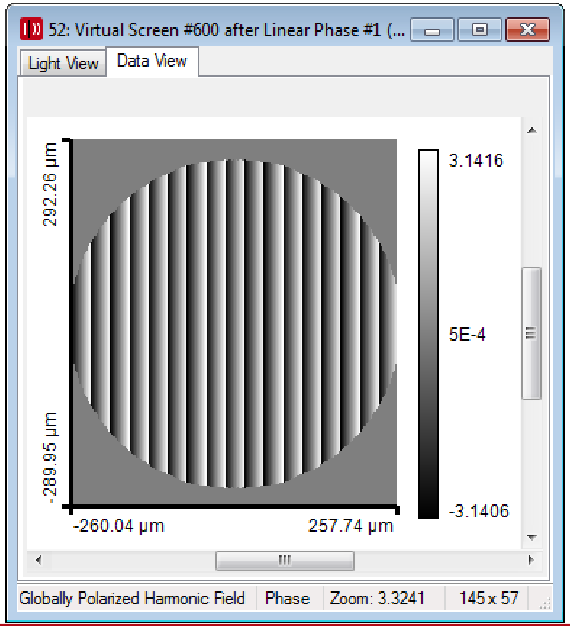


Illustration of Deflection



Phase of transmission



Intensity in target

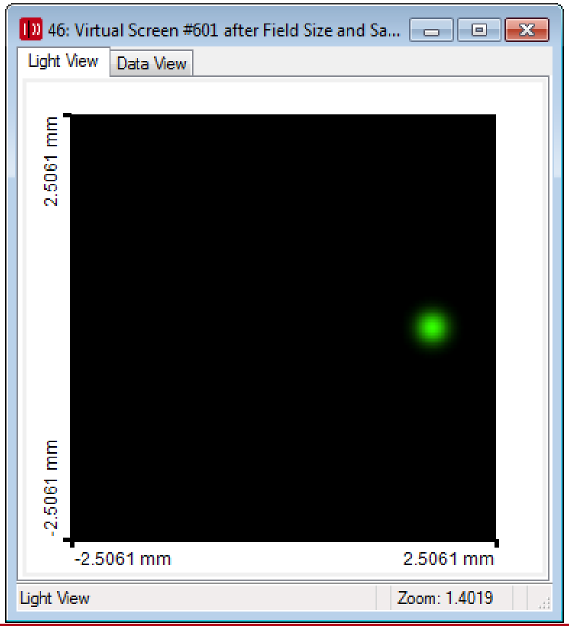


Illustration of Deflection

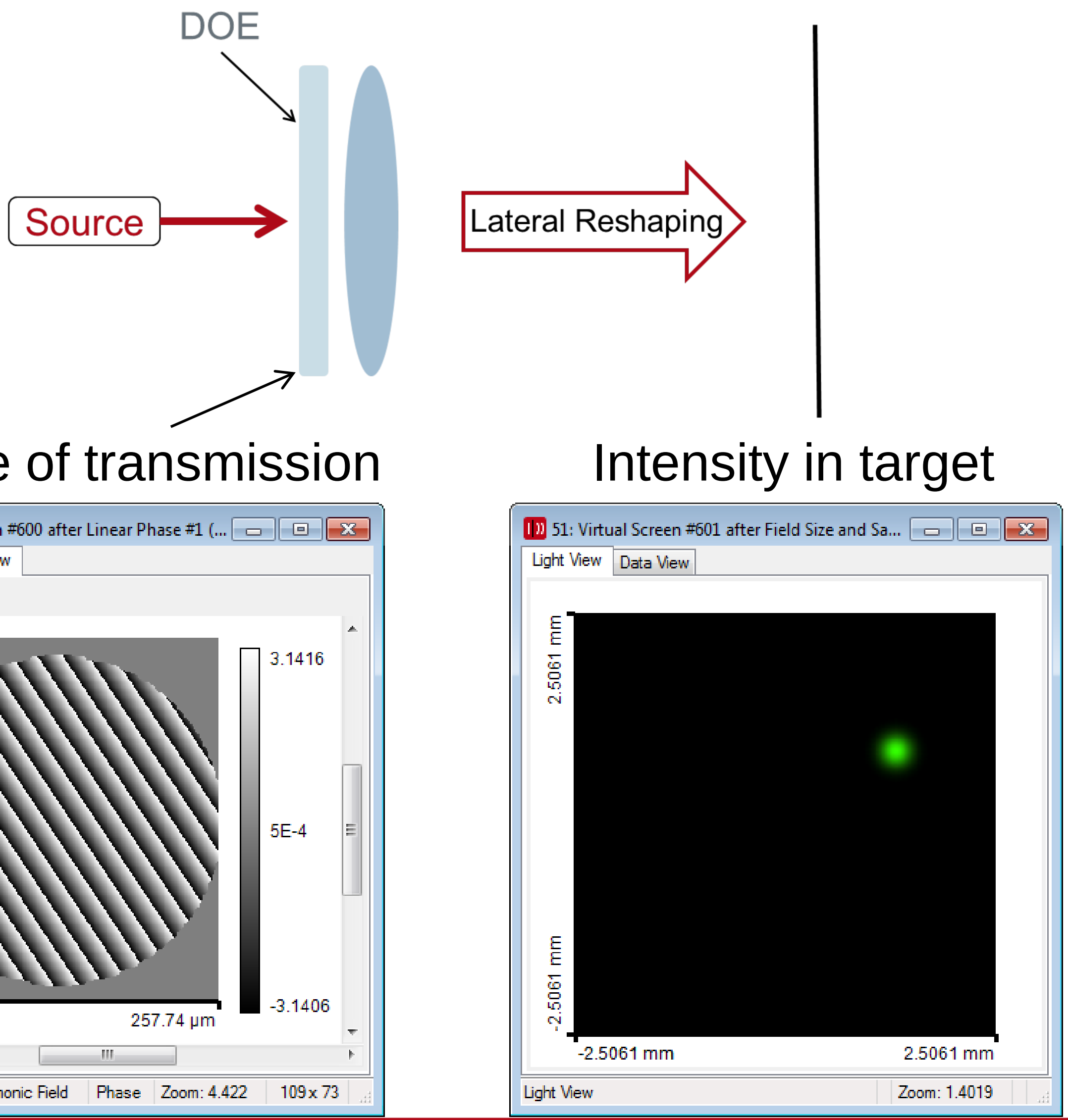


Illustration of Deflection

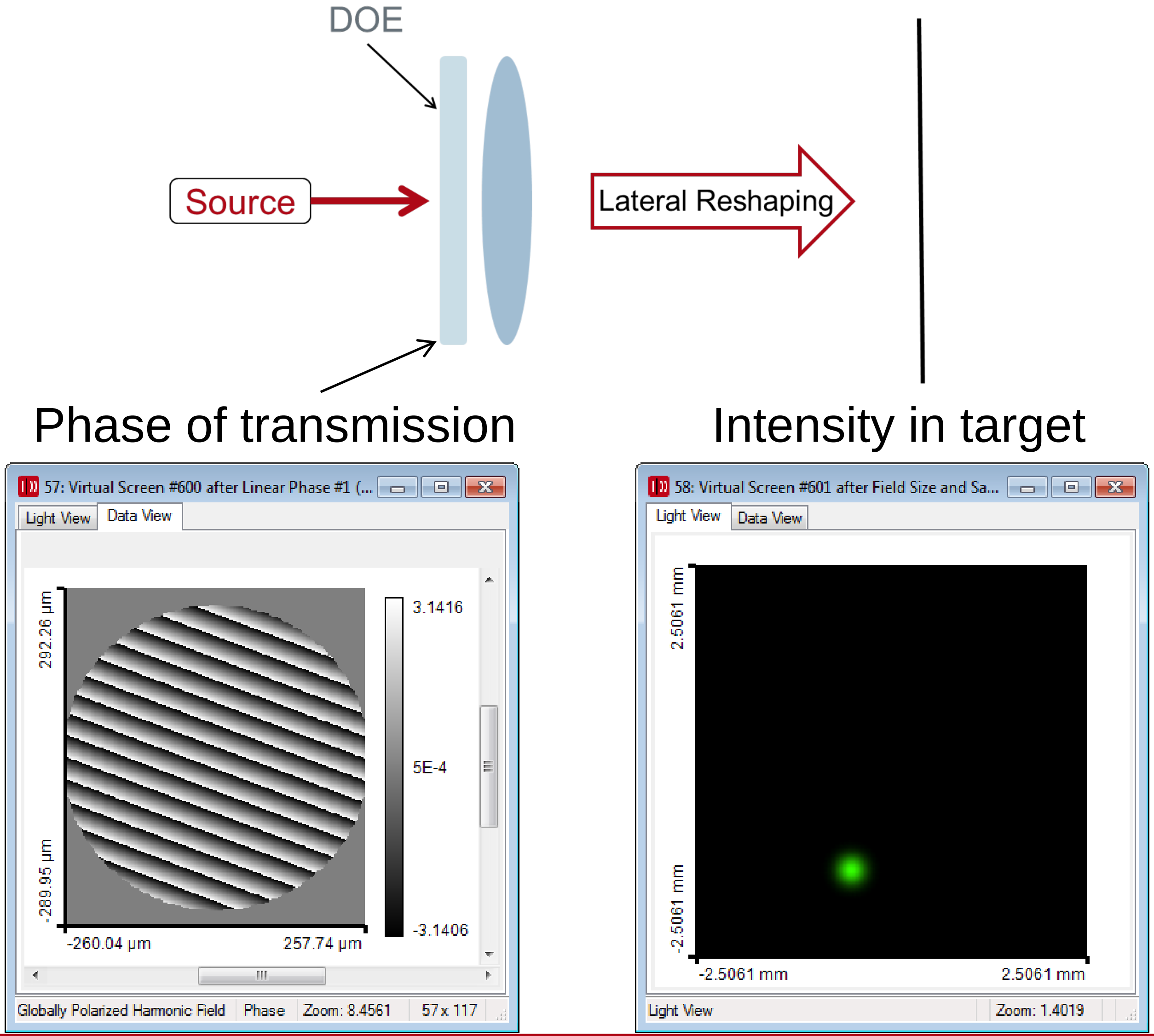
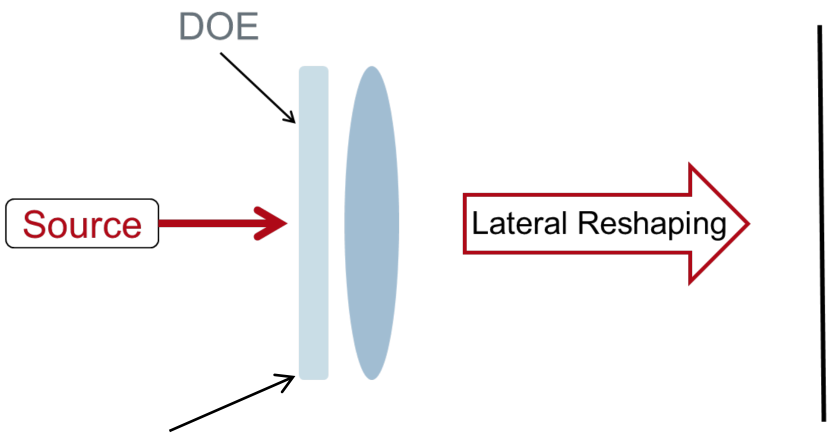
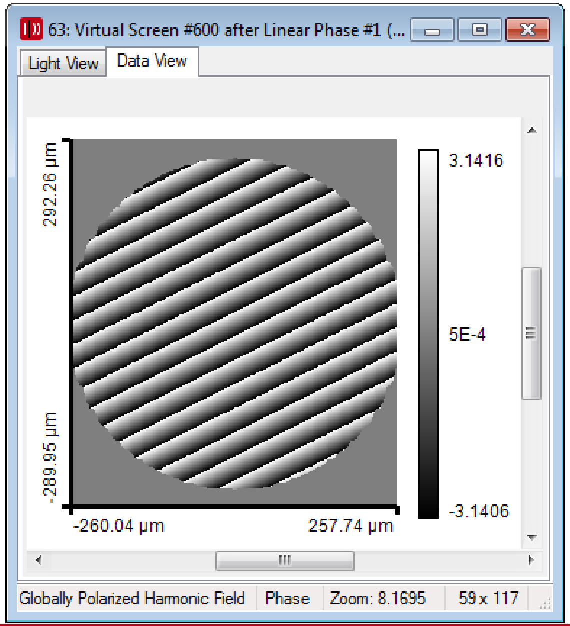


Illustration of Deflection



Phase of transmission



Intensity in target

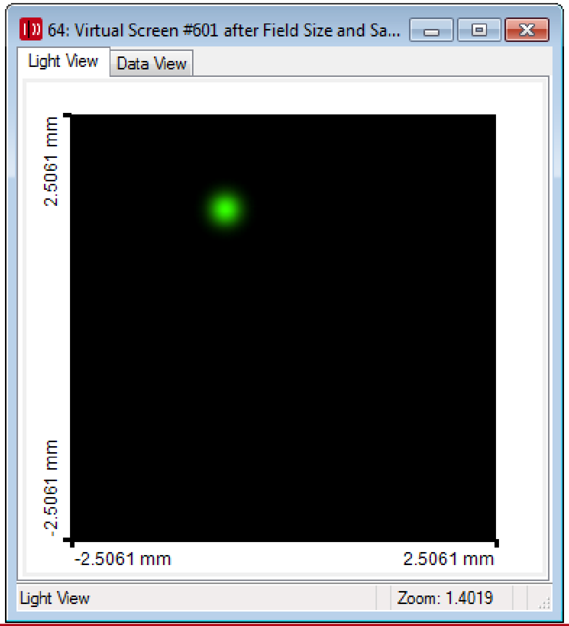
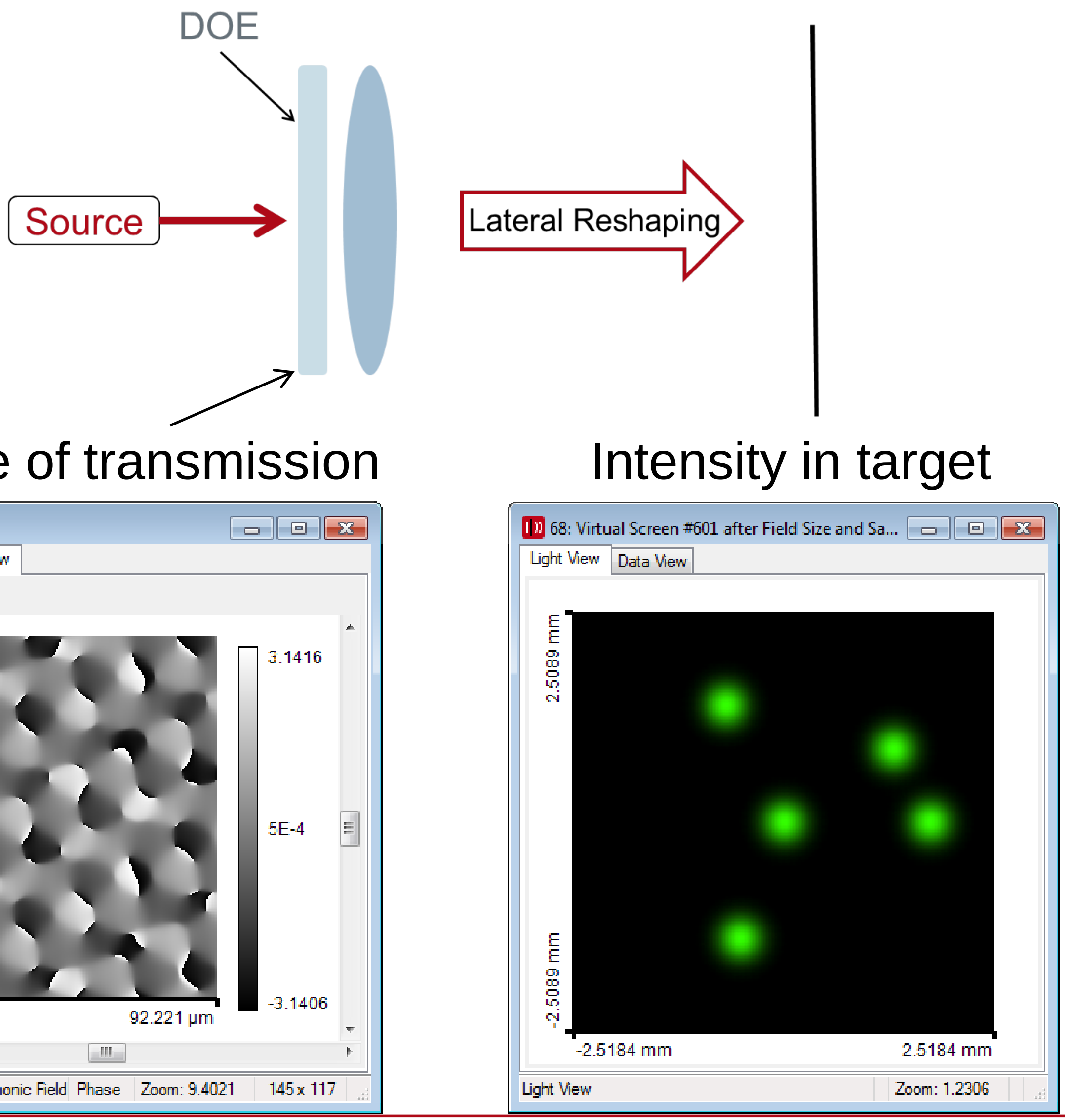
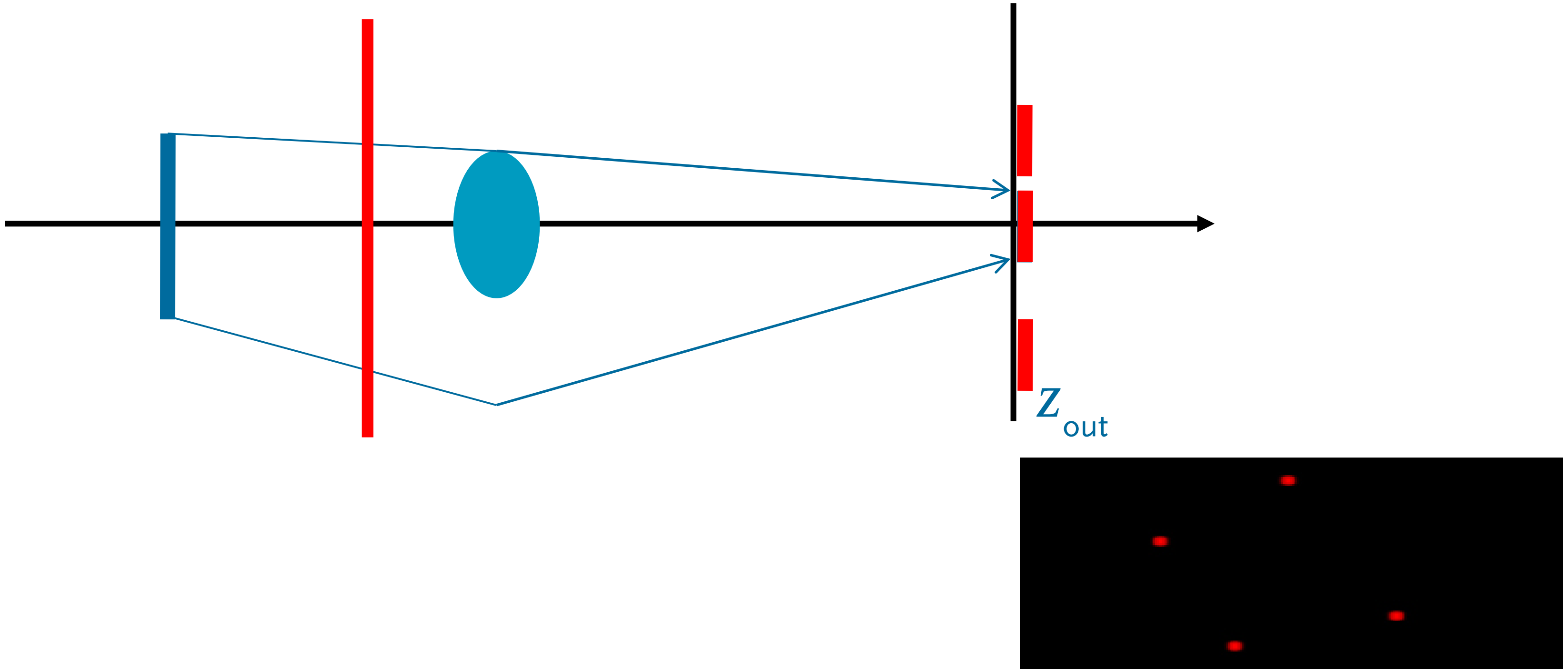


Illustration of Deflection: Sum



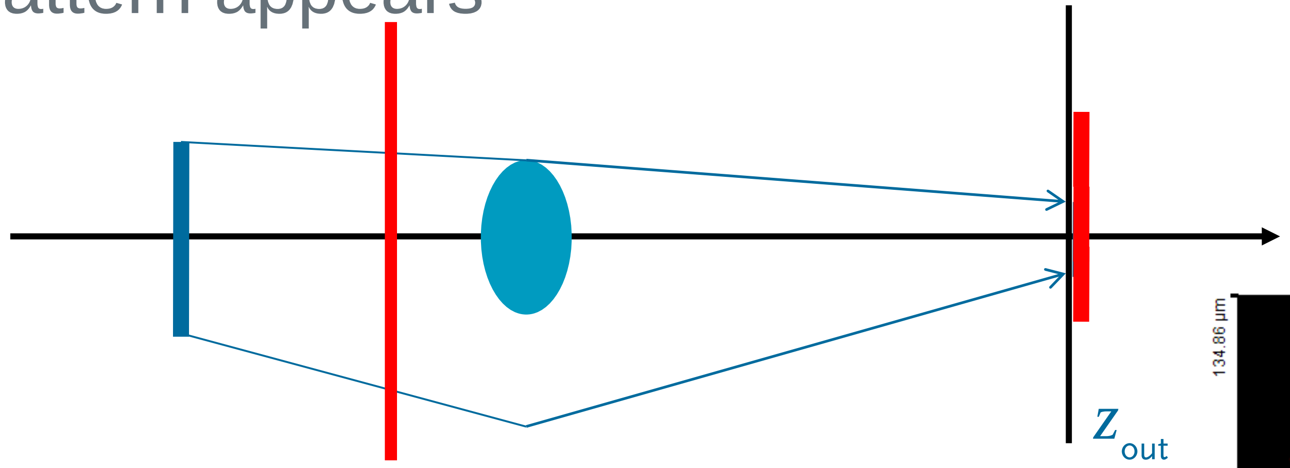
Basic Design Situations: Splitting

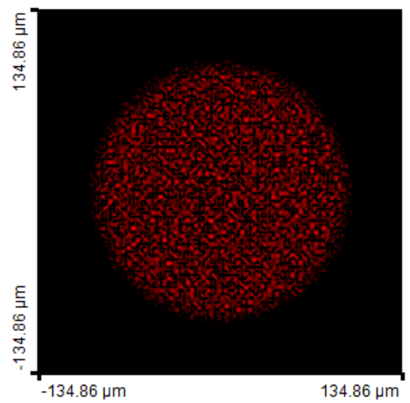
Diffractive Beam Splitting: Deflected output fields (beams) do not overlap



Basic Design Situations: Diffusing

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





Basic Design Situations: Diffusing

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

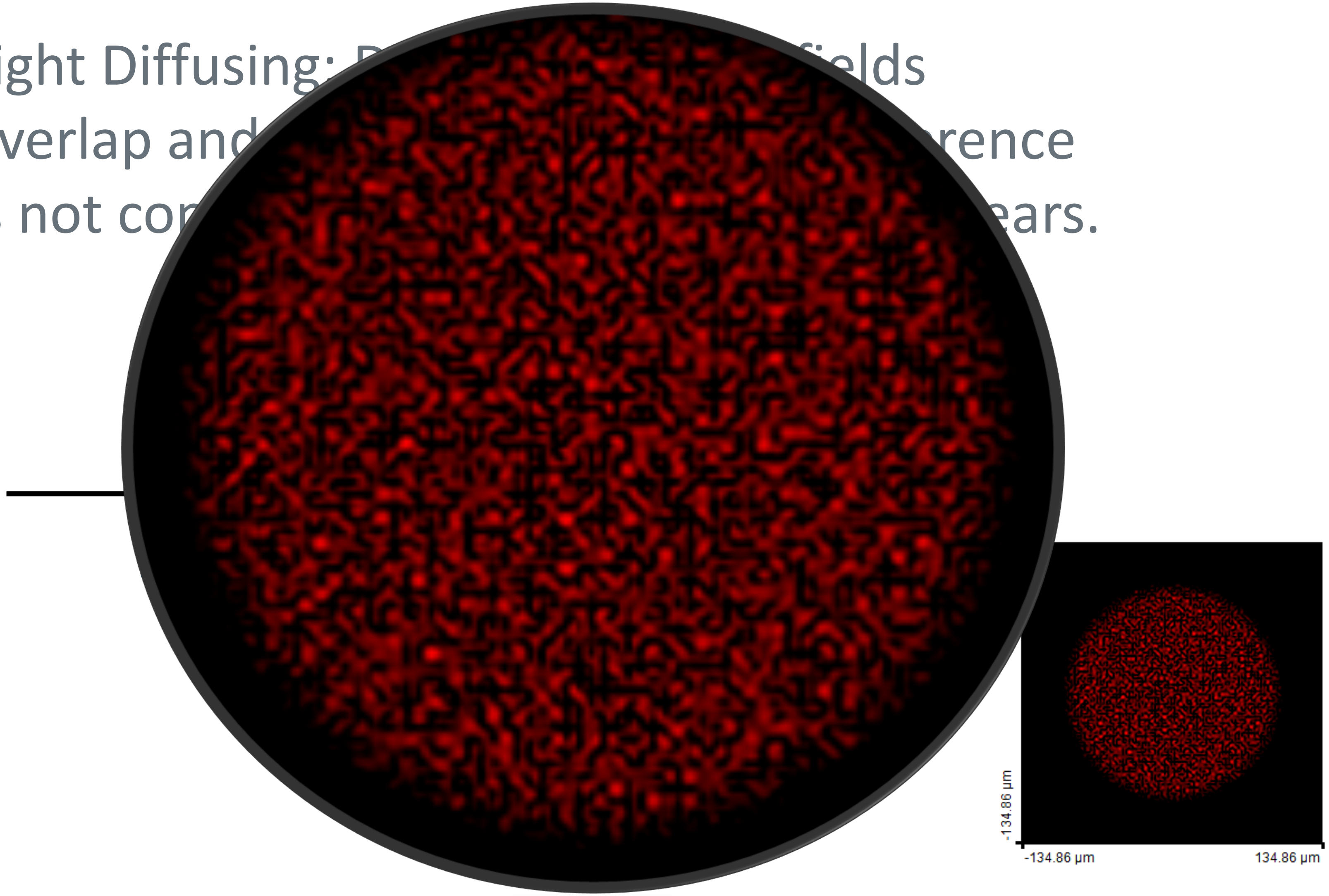


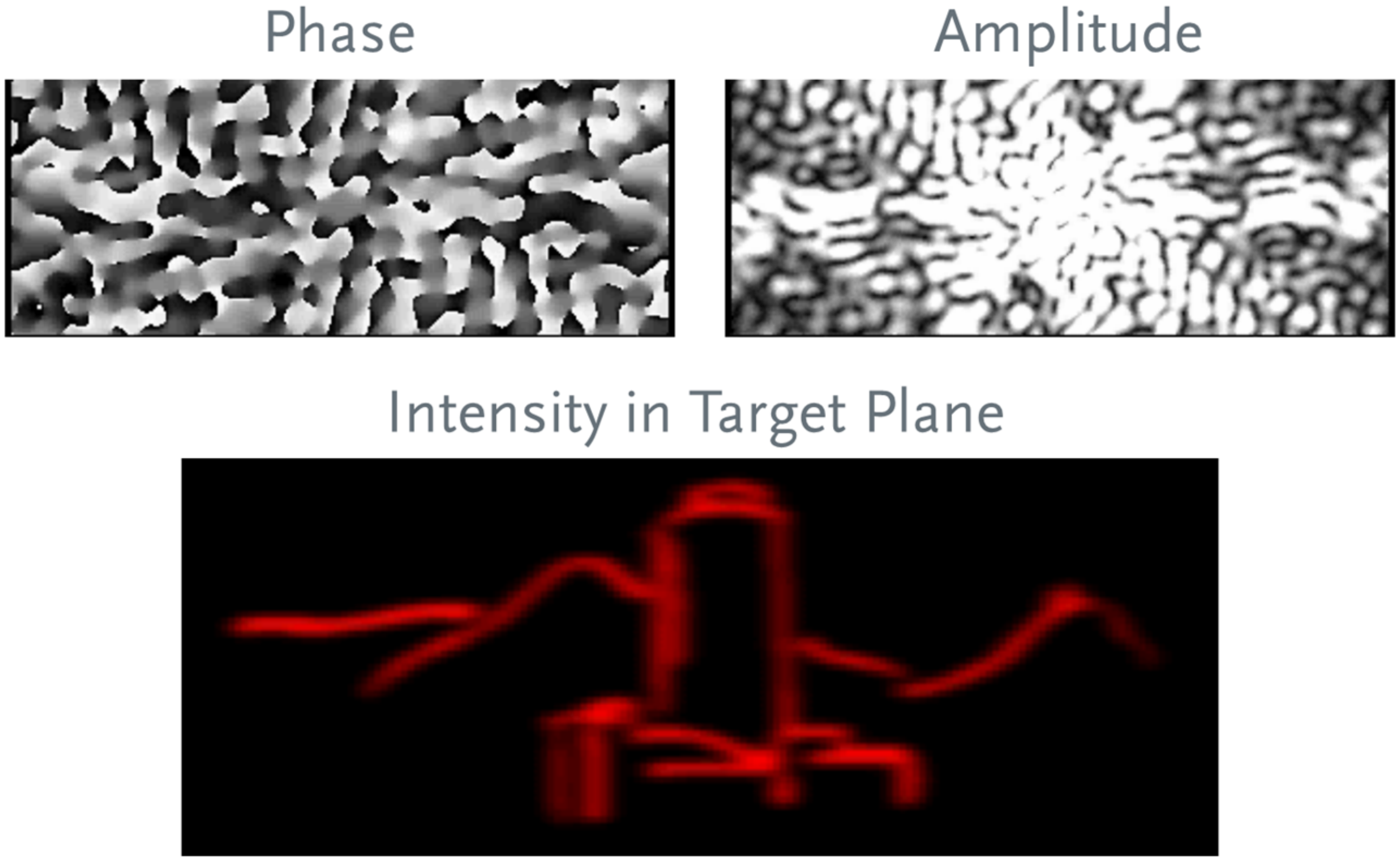
Illustration of Diffuser Concept

Phase

Amplitude

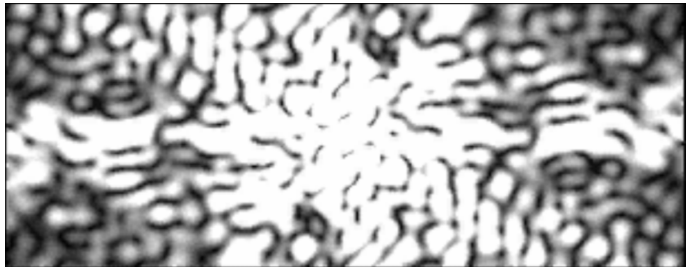
Intensity in Target Plane

Illustration of Diffuser Concept

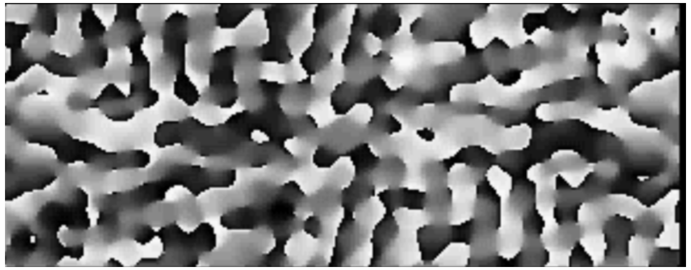


Light Diffusing

Amplitude

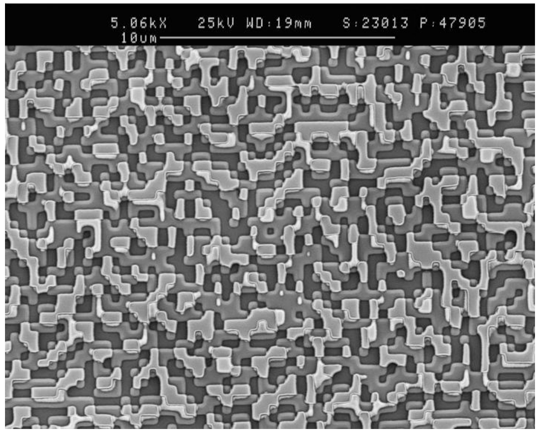


Phase



Advanced diffractive optics design techniques

Design technique (IFTA) implemented in VirtualLab™



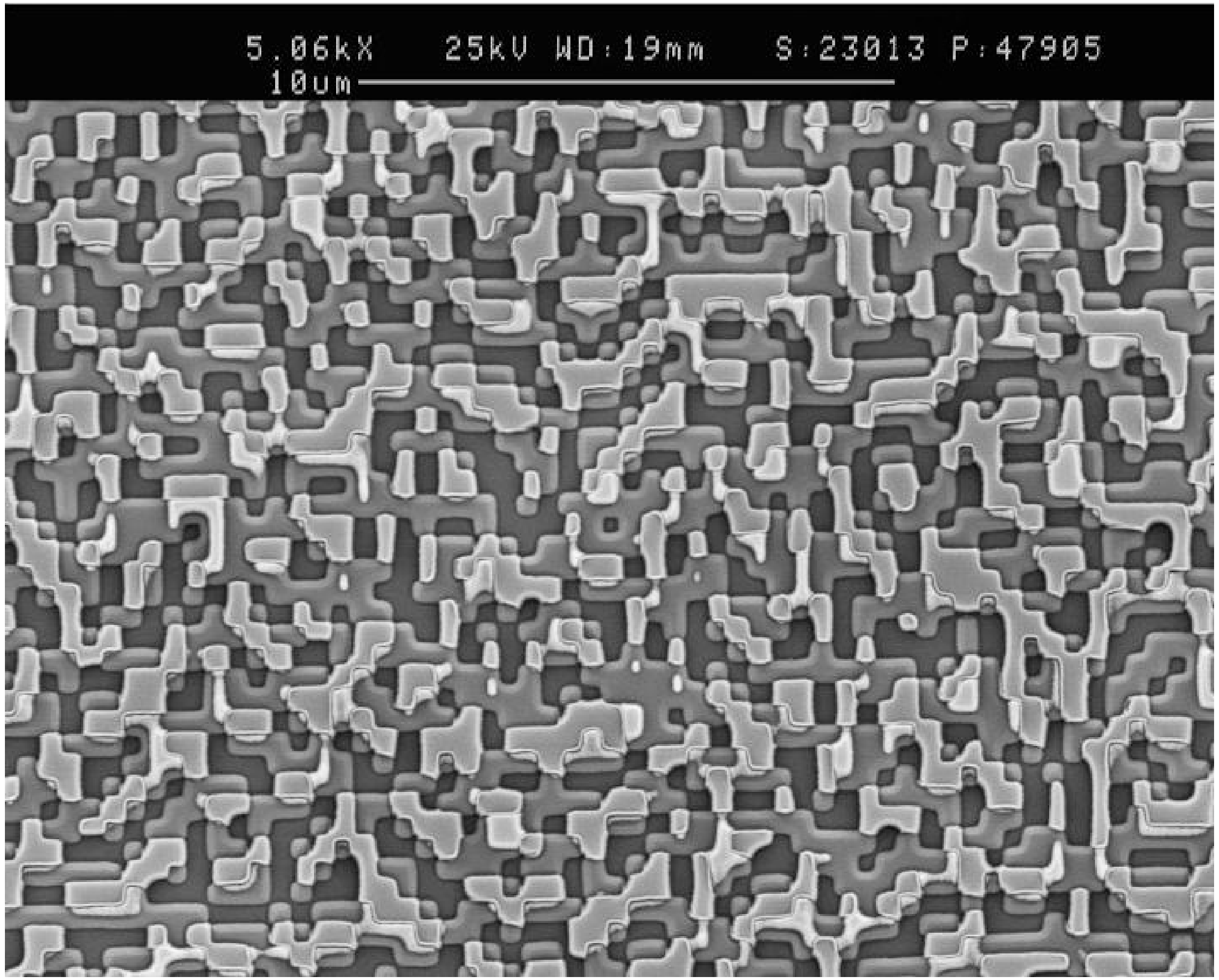
Micro-structured surface profile

Fabricated at IAP, University of Jena

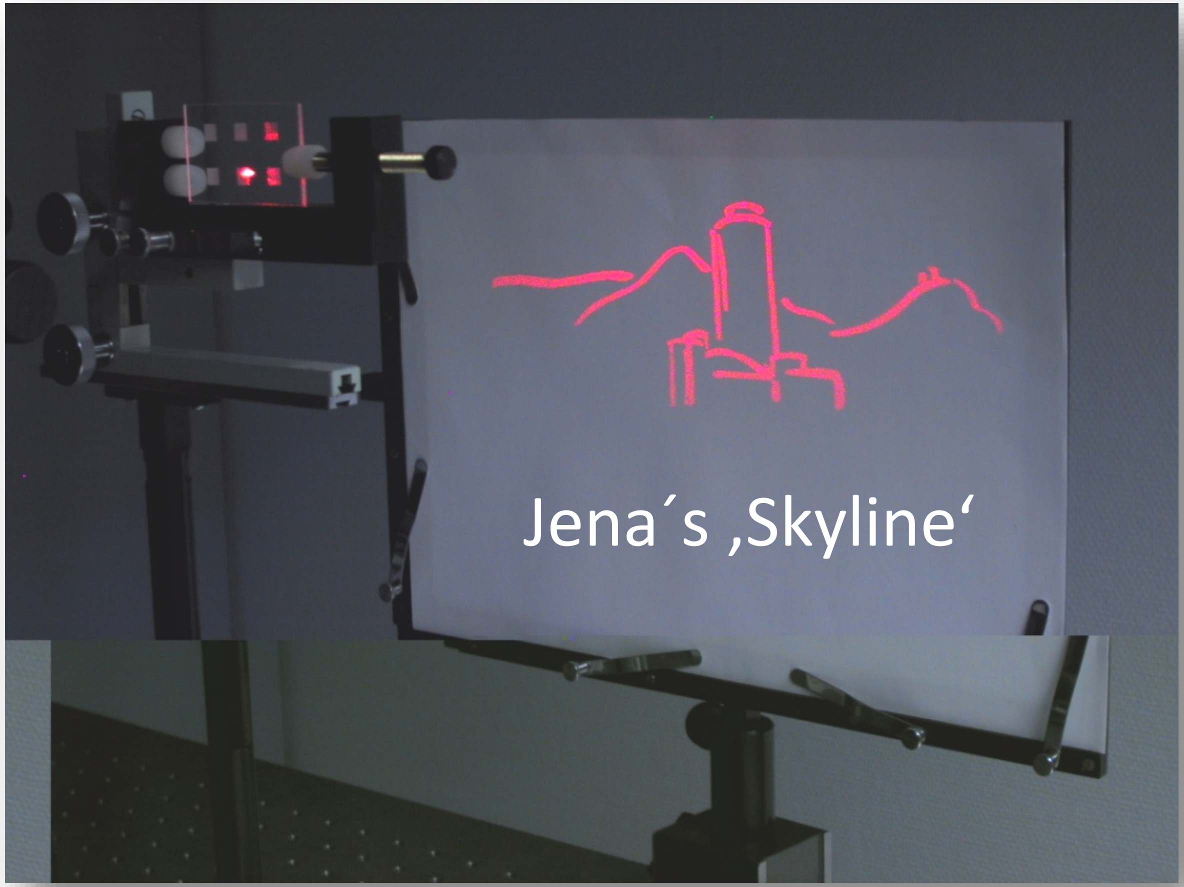
Feature Sizes of Element

Feature size
about 400 nm

4 height levels



Optical Experiment

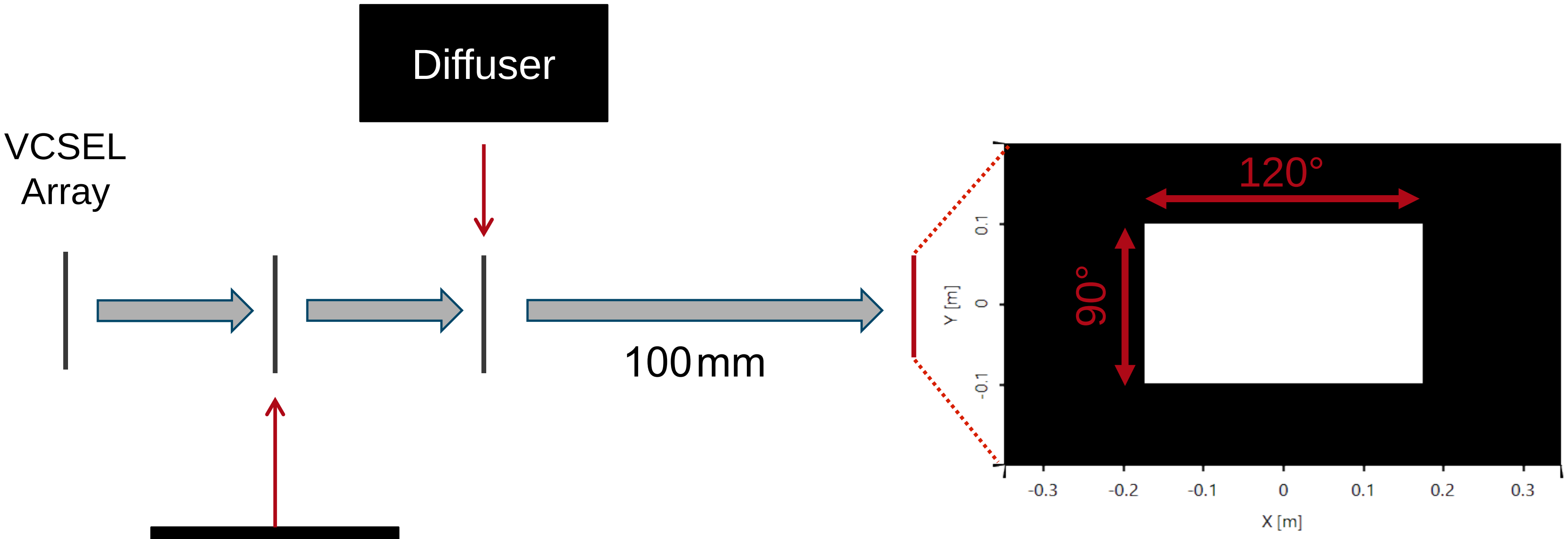


Show in VLF

h0.1

Shaping a VCSEL Array to an High-NA Top Hat Pattern

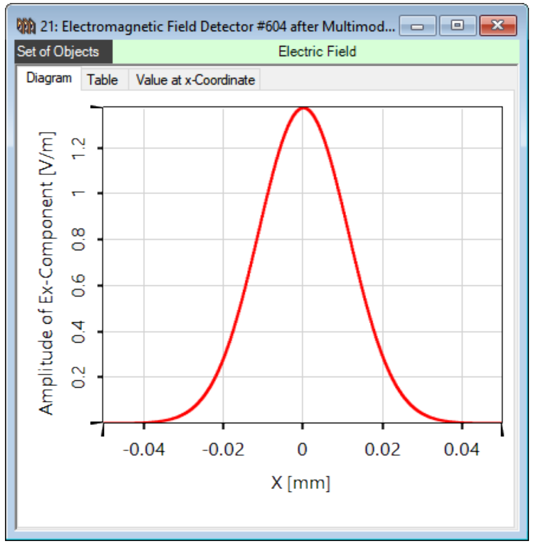
Abstract



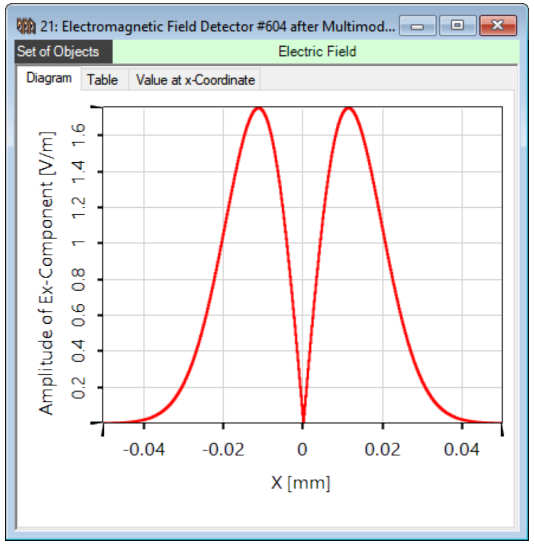
In the scope of this case study, the design of an optical diffuser is investigated to shape a specific VCSEL array to an high-NA top hat pattern.

Modeling a Single VCSEL

- The presented VCSEL source is a multimode source consisting of two superimposed Laguerre Gaussian modes, which are shown below.



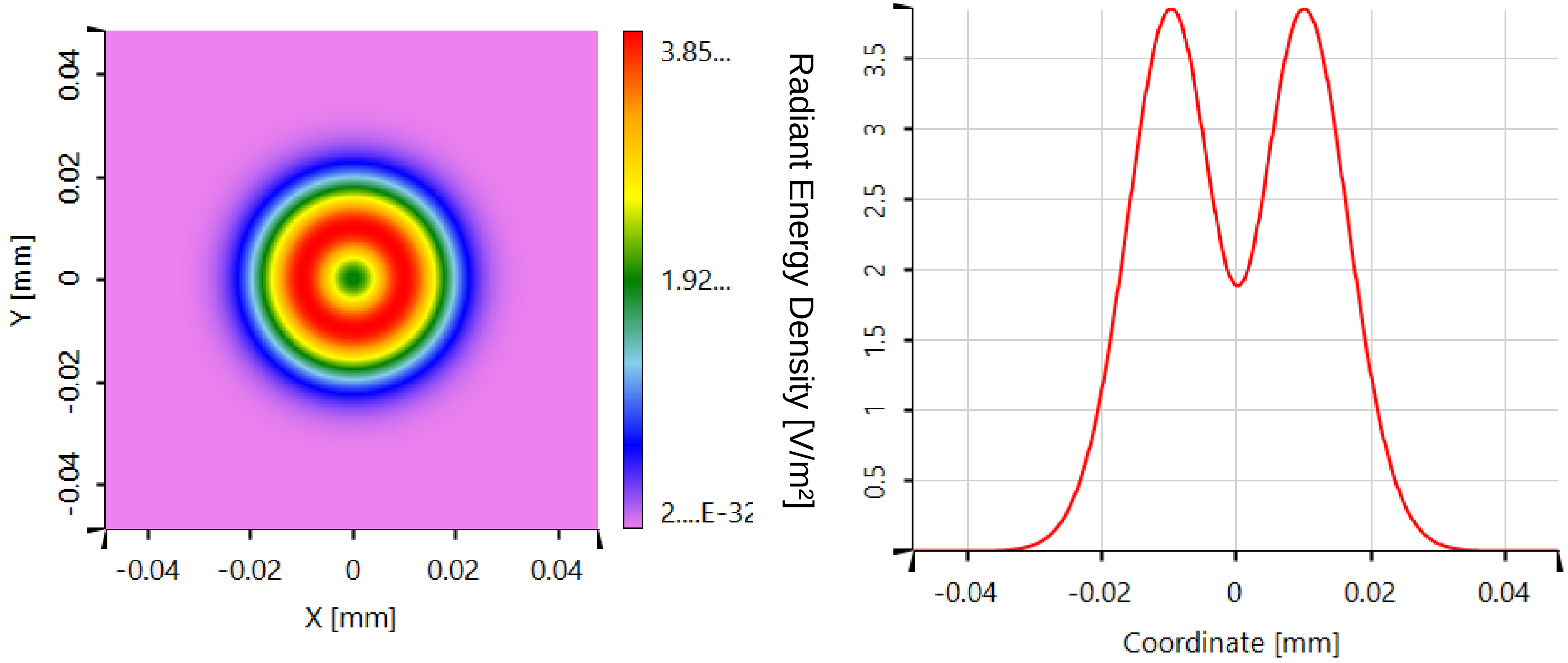
Laguerre Gaussian Mode 00 at 100 µm Distance with 18.14° Divergence (1/e²)



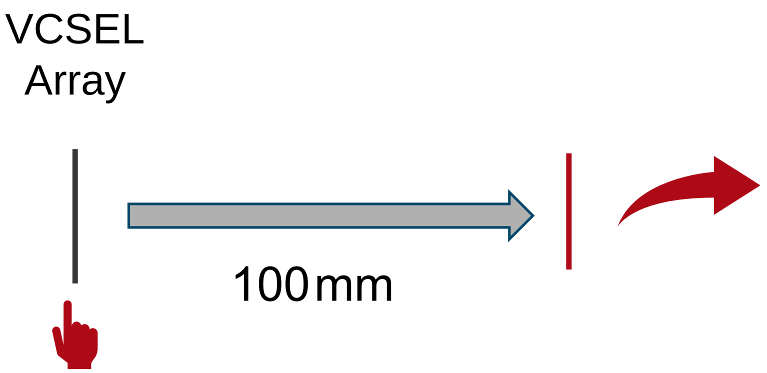
Laguerre Gaussian Mode 01 at 100 µm Distance with 25.67° Divergence (1/e²)

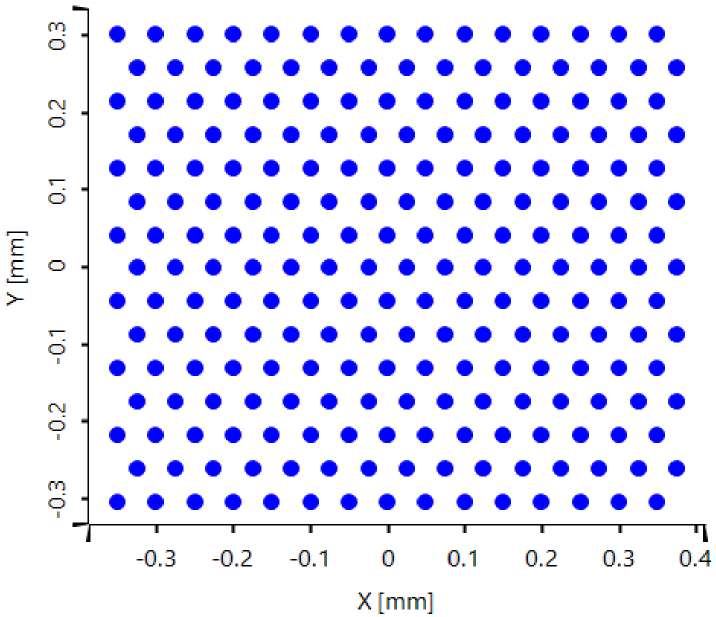
Modeling a Single VCSEL

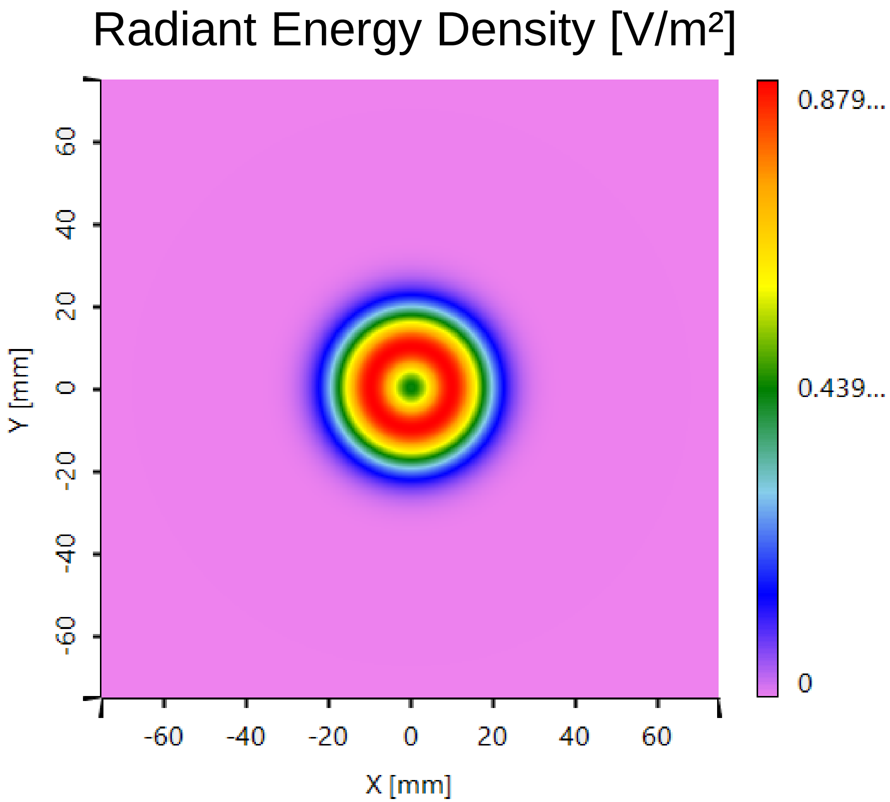
- The radiant energy density of a single VCSEL at a propagation distance of 100 μm is shown below.



Simulation of a VCSEL Array



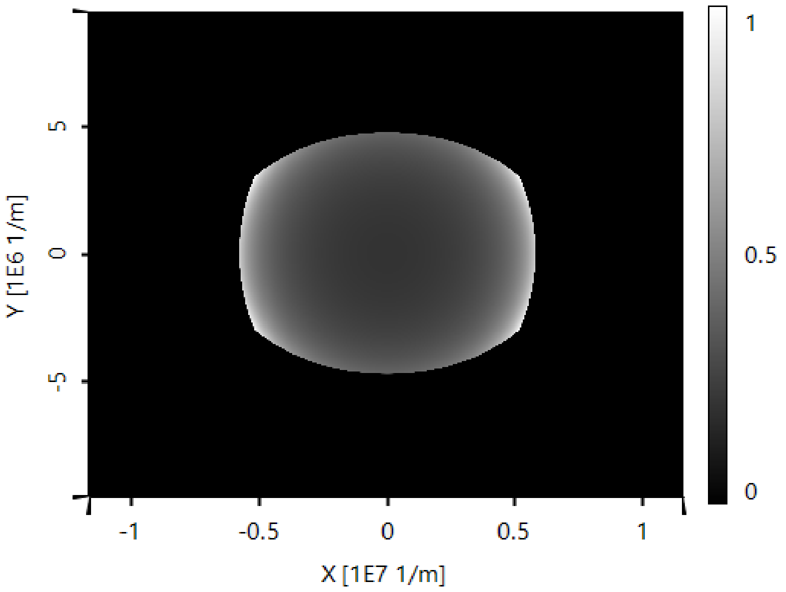




The VCSEL array consist of 15×15 VCSEL with a pitch of 50 µm×50 µm and an angle of 60° for the hexagonal grid.

Pattern Generation for the Diffuser Design

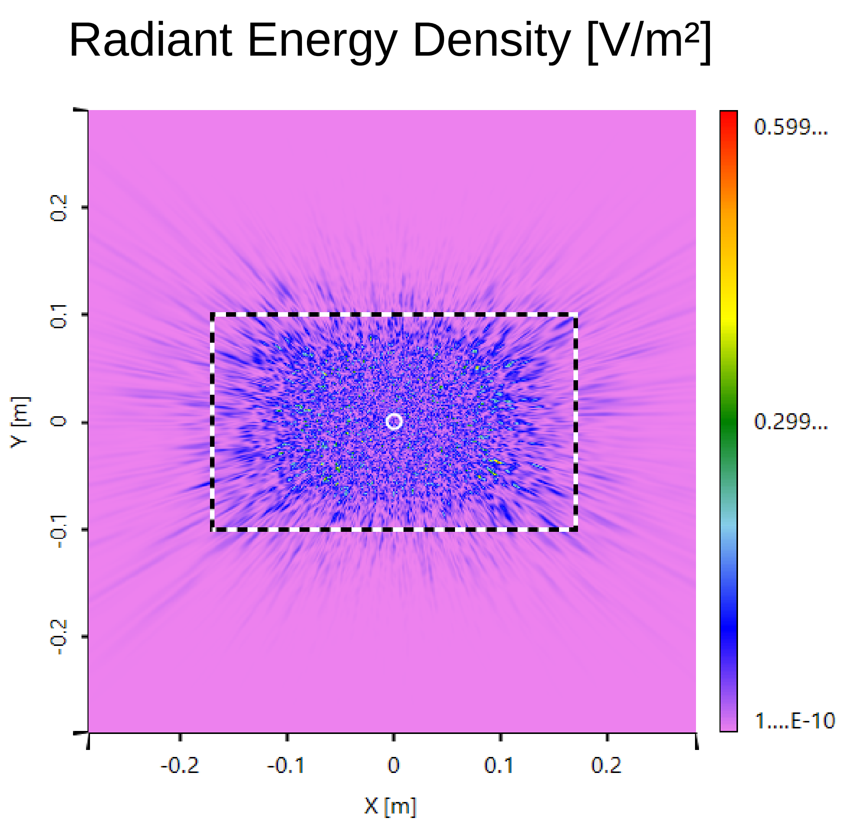
As a next step, an optical diffuser is designed using the IFTA algorithm. Therefore, the design target pattern is compensated regarding field pincushion distortion and radiant flux orthogonal to the detector plane.



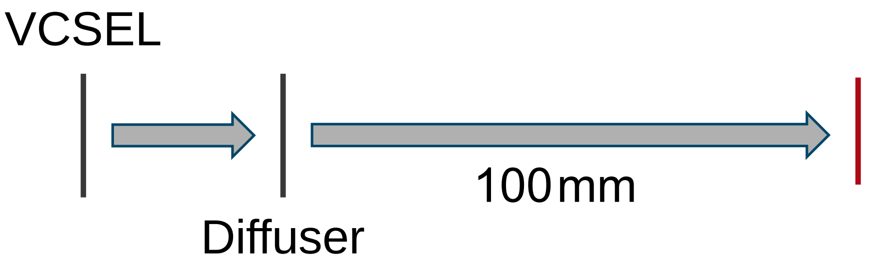
Compensated Design Target Pattern

Parameter	Value & Unit
Angular Size Design Pattern	120°×90°
Feature Size	270 nm×330 nm
Period	538.38 µm×538.56 µm
Operation Orders	1994×1632
Order Separation	0.1×0.1°
Number Phase Level	16

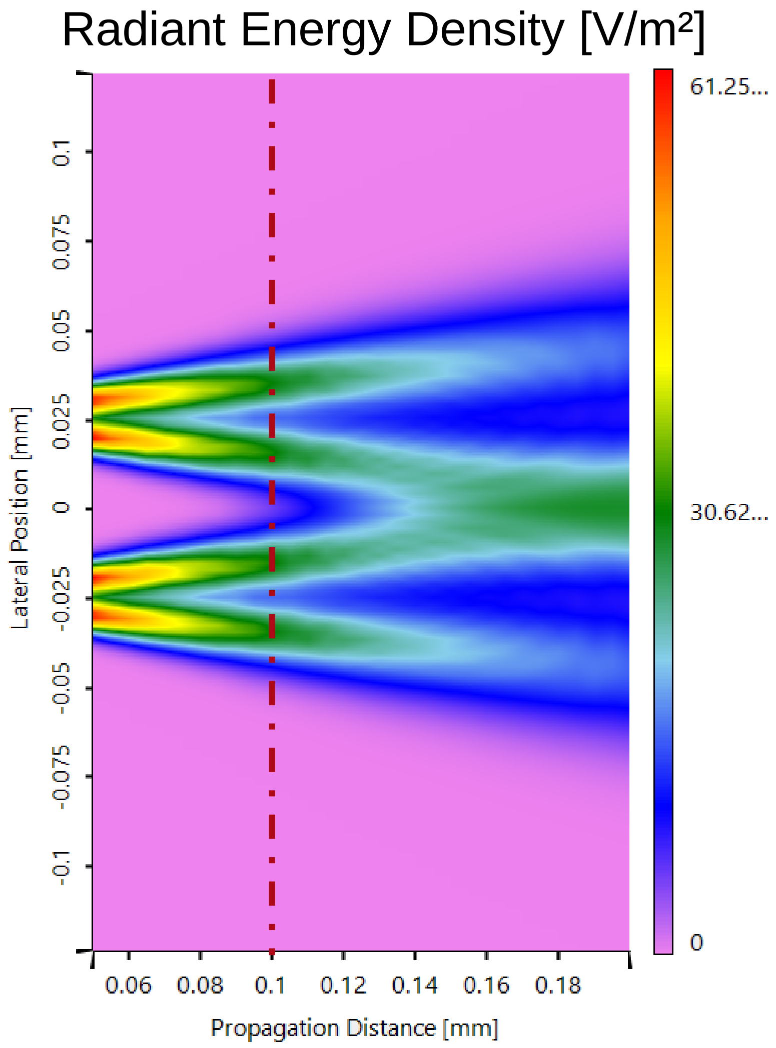
Simulation Result without Collimation



The radiant energy density of a single VCSEL propagating through the designed diffuser at the detector plane is shown on the left.

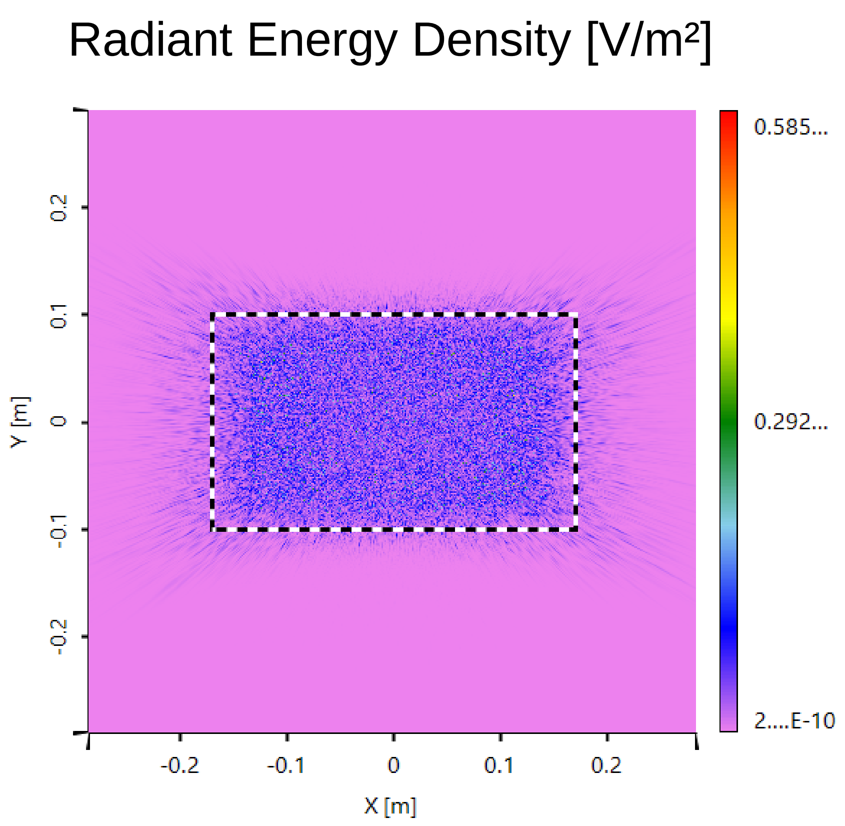


Finding the Plane of Collimation

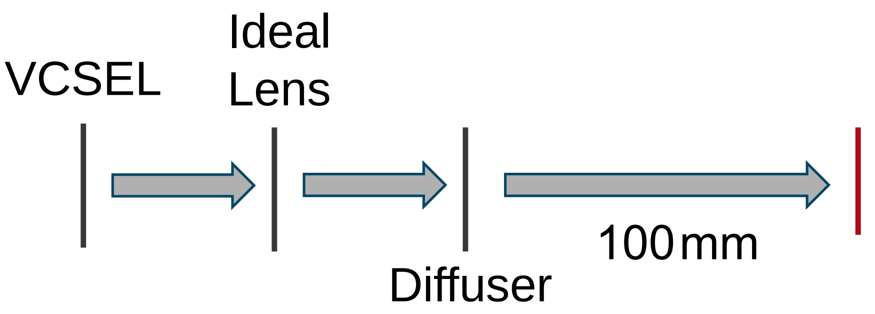


Each VCSEL is separated by a pitch of 50 µm. In order to collimate the beam of each VCSEL they must be separated first before a diffuser can shape the beam. Therefore, a plane is determined at a z-position of 100 µm, where the VCSELs are well separated before they overlap. There, e.g. a microlens array can be placed for collimation.

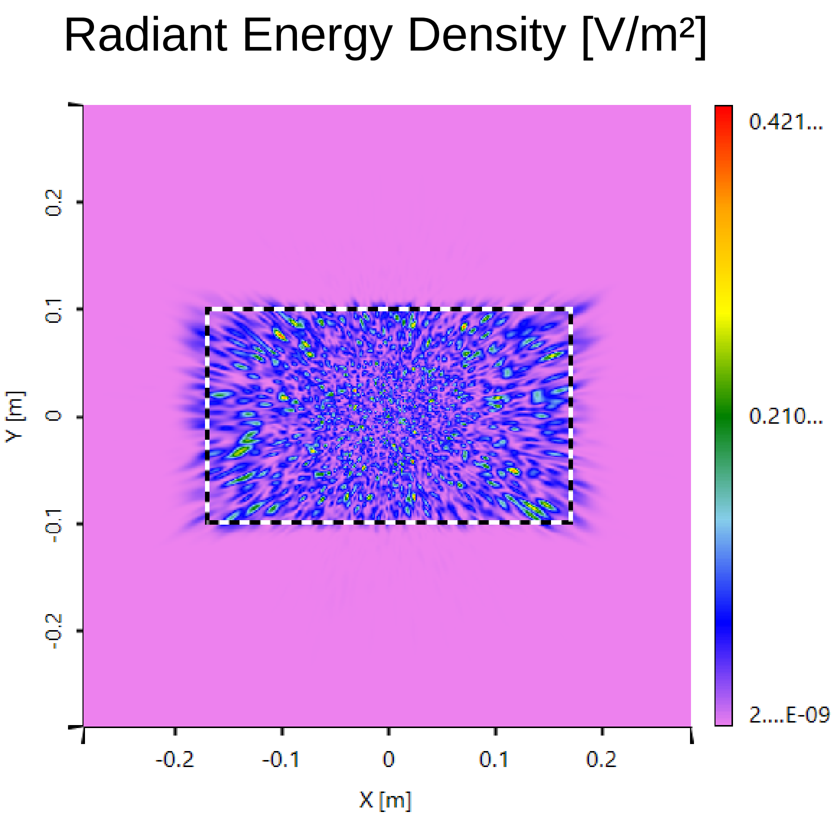
Simulation Result with Collimation (NA 0.12)



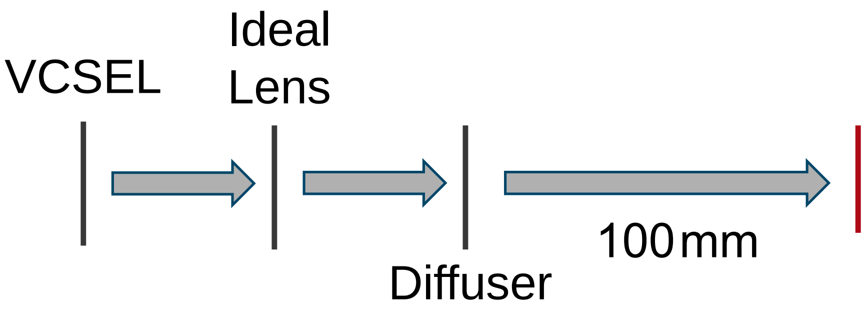
An ideal focal lens function with a focal length of 200 μm is used to collimate the beam of a VCSEL to a divergence of 8.91° (Mode 00). The result at the detector plane is shown on the left.



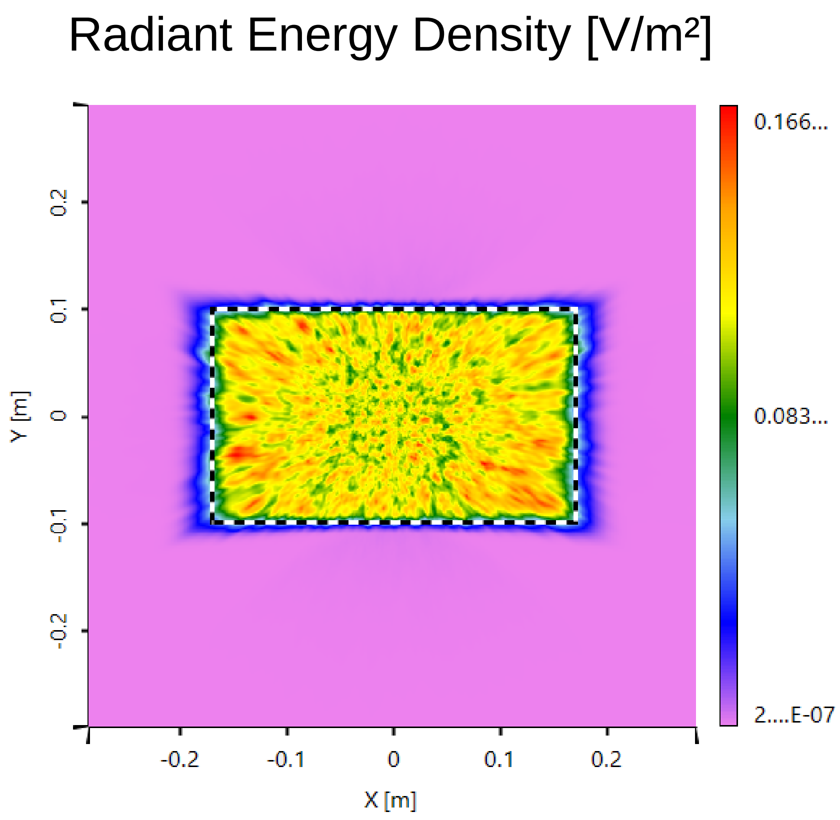
Simulation Result with Collimation (NA 0.24)



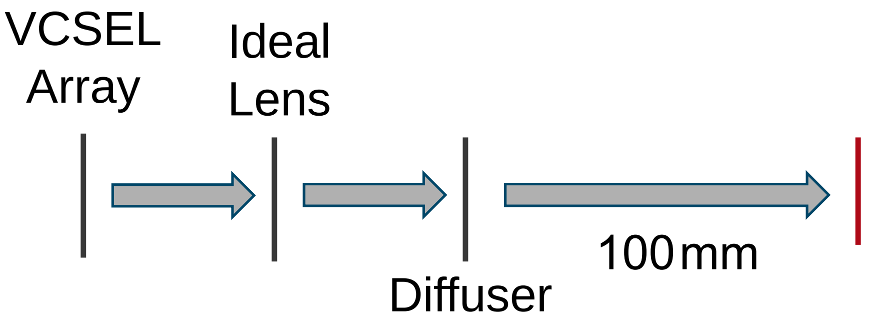
An ideal focal lens function with a focal length of 100 µm is used to collimate the beam of a VCSEL to a divergence of 2.34° (Mode 00). The result at the detector plane is shown on the left.



Simulation Result with Collimation (NA 0.24)



The detector result of the collimated 15×15 VCSEL array shaped by the designed diffuser is shown on the left.



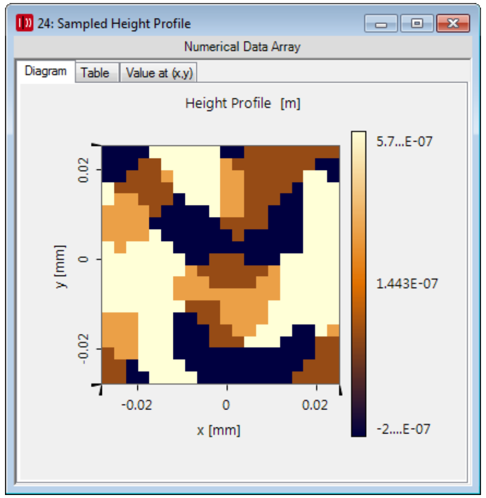
Micro Optical Component

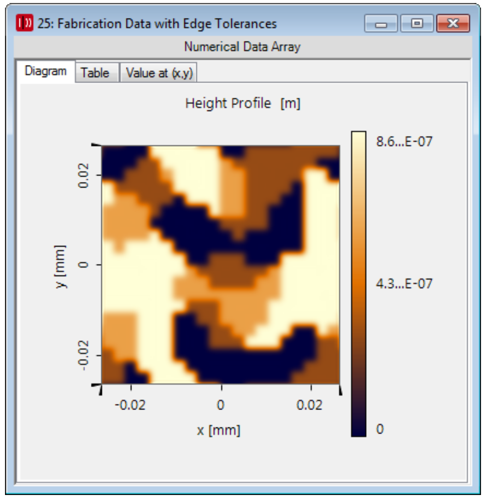
Modeling of Rounding of Pixels

Modeling of Rounding of Pixels

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

Example with Data from Scenario 23.01

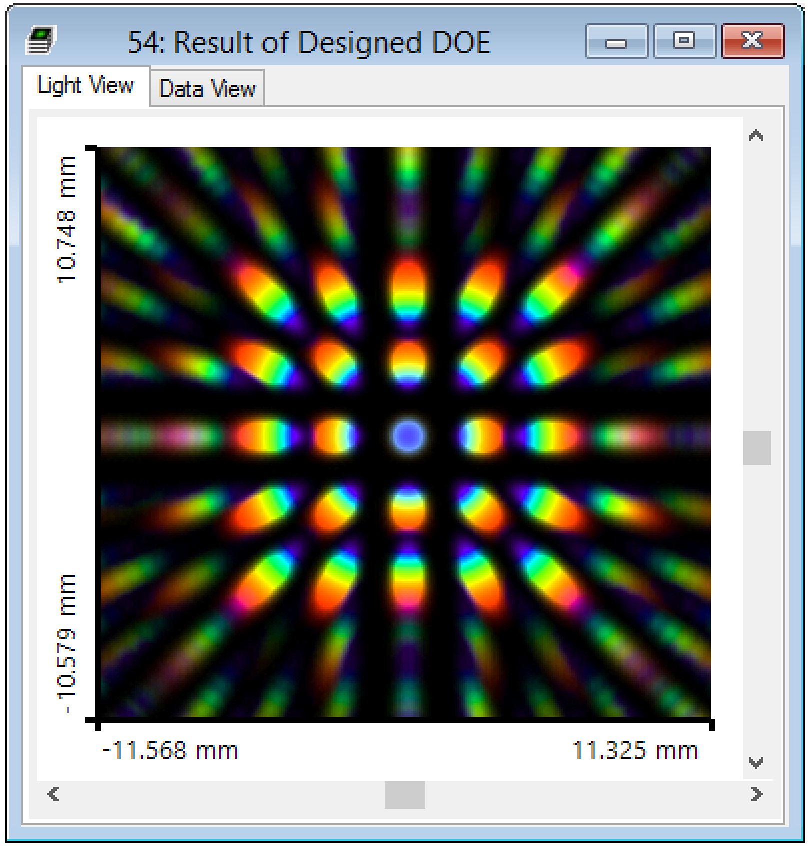




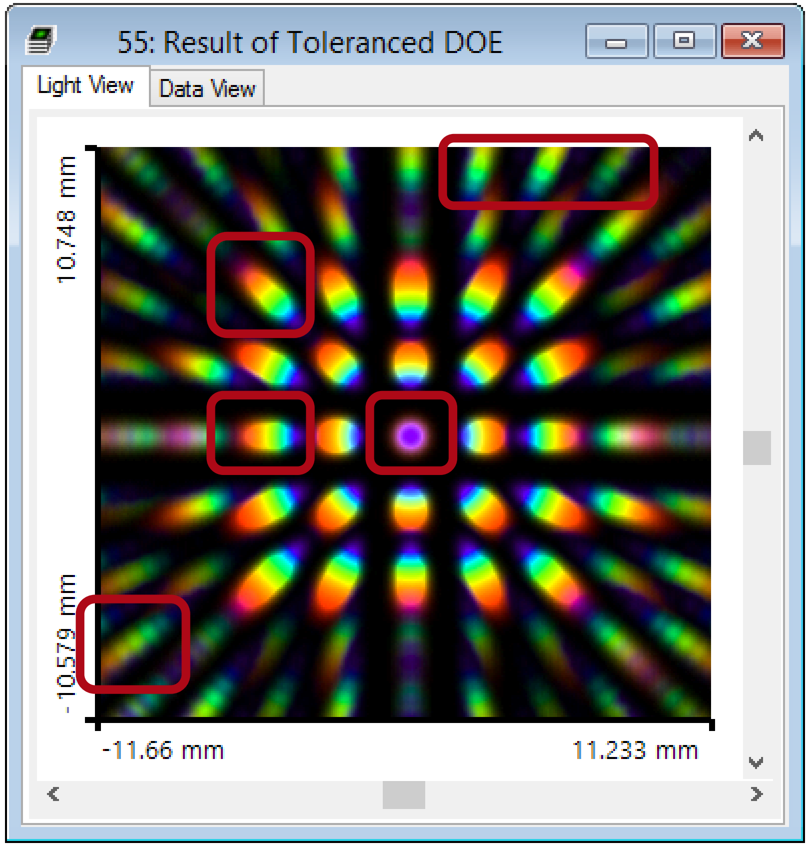
- VirtualLab Module **`Module_RoundedEdge_Tolerances.cs`** can be used to calculate from a perfect profile a profile with rounded edges.
- Calculation steps:
  - Get a *Data Array* with the perfect profile from the sampled interface.
  - Apply the module.
  - Set the *Data Array* with the modified profile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

Results with 4x Increased Brightness

Simulation Result of Designed DOE



Simulation Result of DOE with Rounded Edges

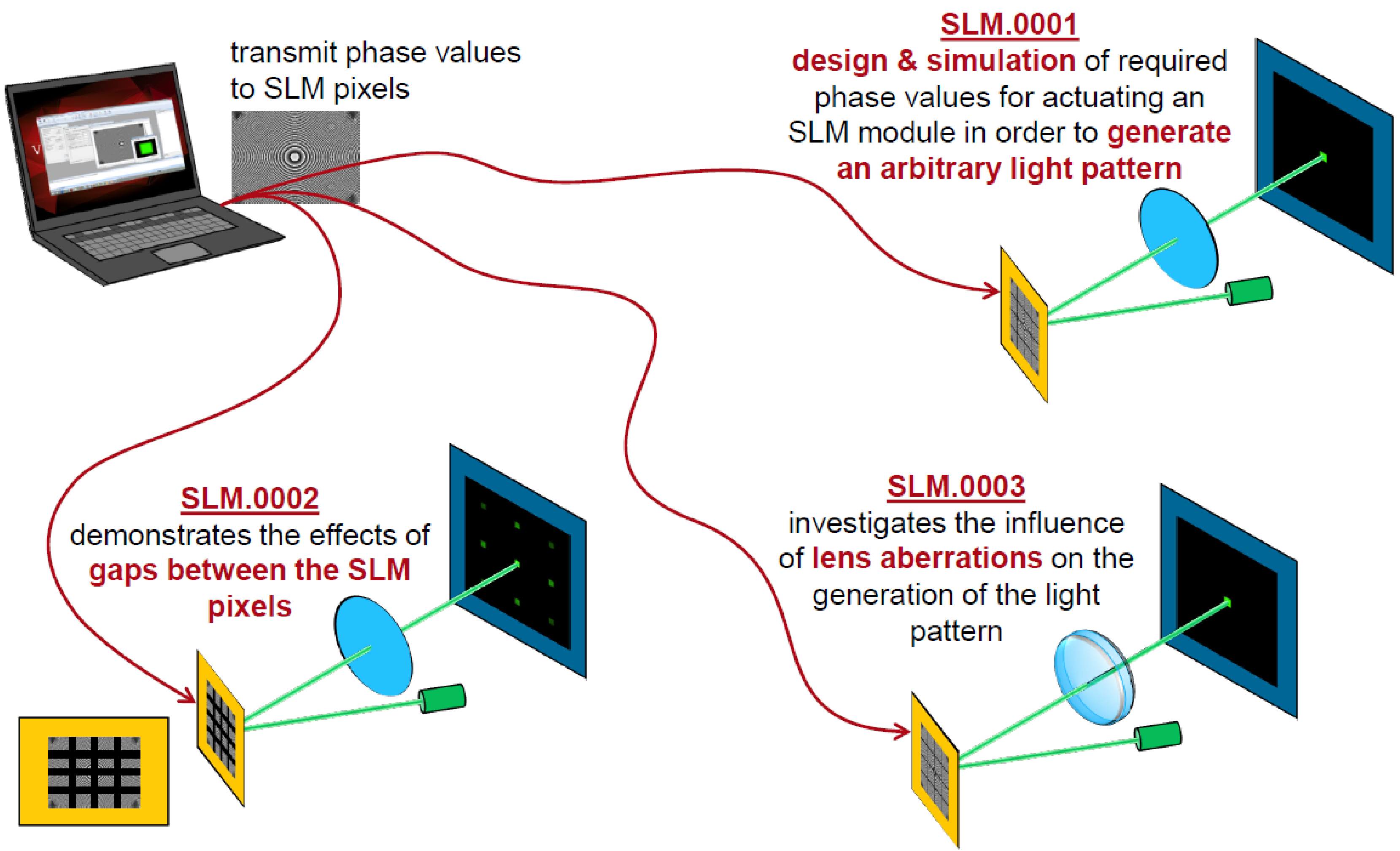


Comments on Diffuser Technology

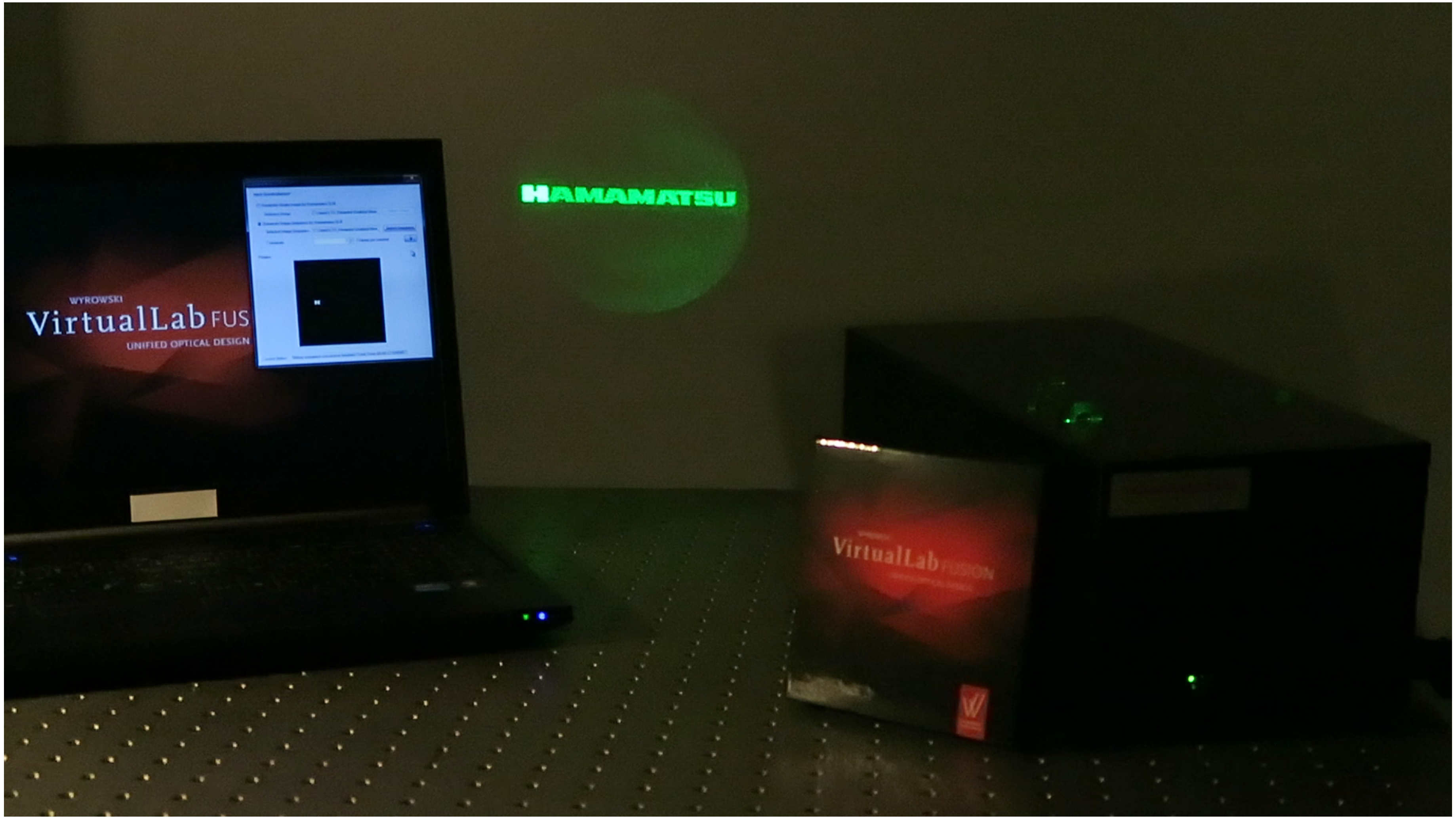
- Very flexible in light pattern generation
- Robust against adjustment problems
- Coherent light leads to speckle pattern
- Size of speckle features can be adjusted by focusing system
- Diffusers work for partially coherent beams
- Partially coherent beams smooth the speckle pattern; effect can be simulated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

Laser Show China

Spatial Light Modulator



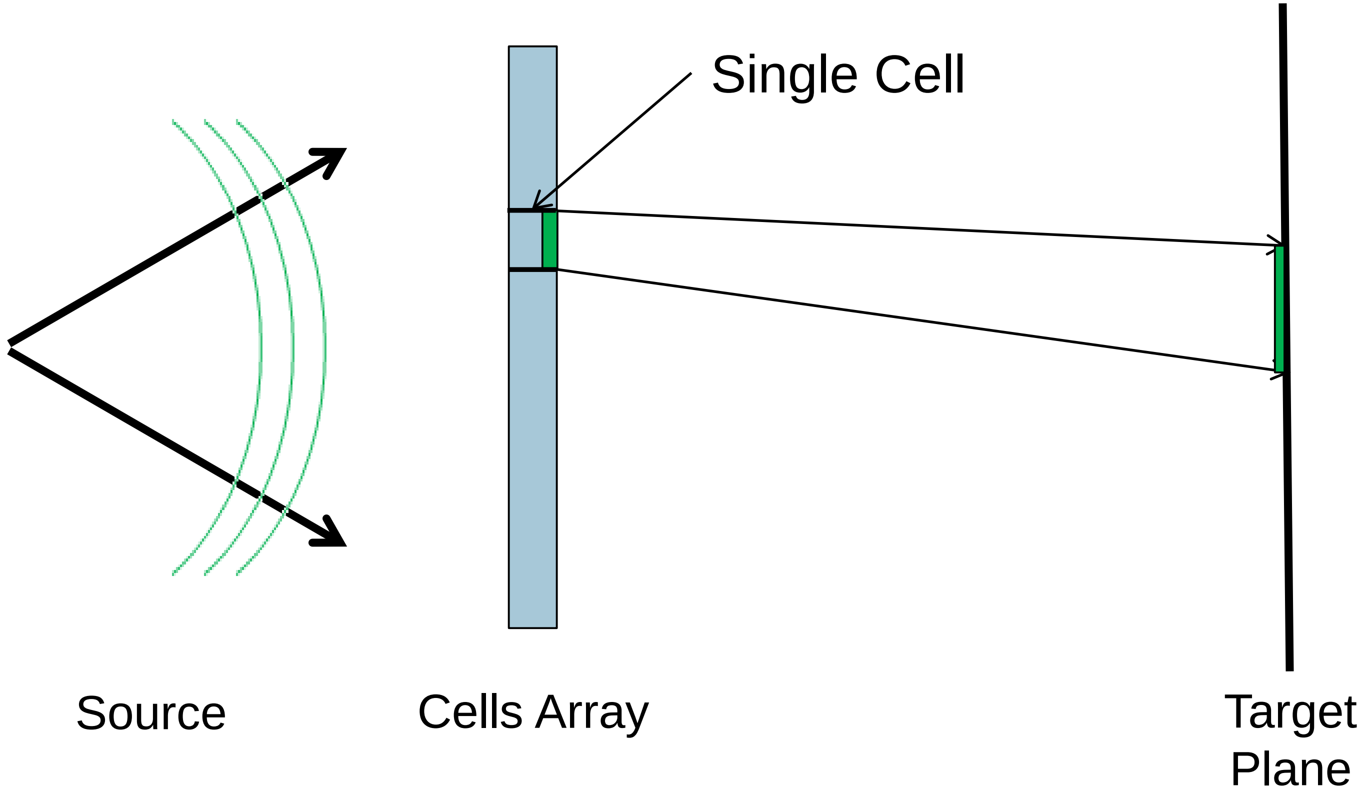
Spatial Light Modulator



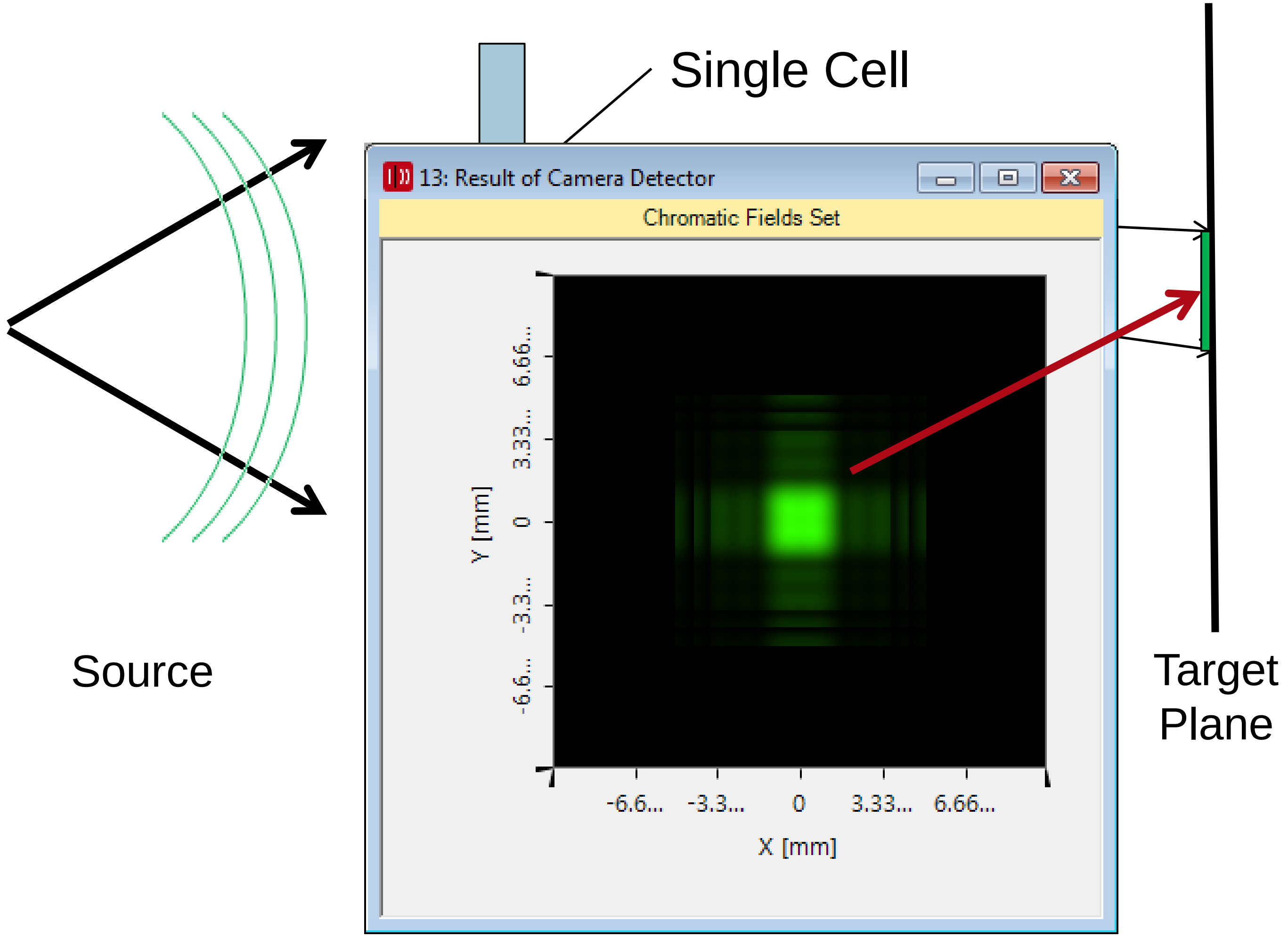
Light shaping by multichannel concept

Diffractive and refractive optical elements

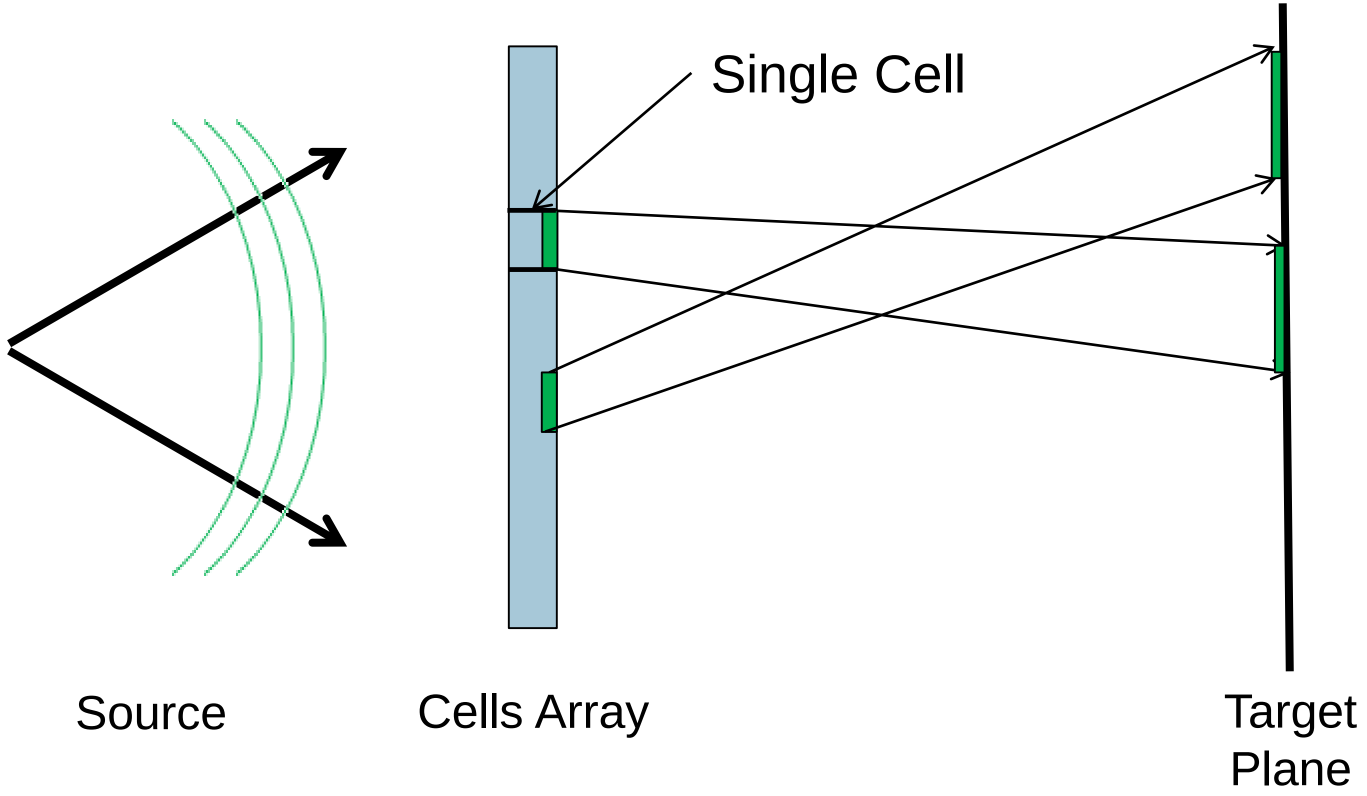
Light Deflection by Cells Arrays



Light Deflection by Cells Arrays

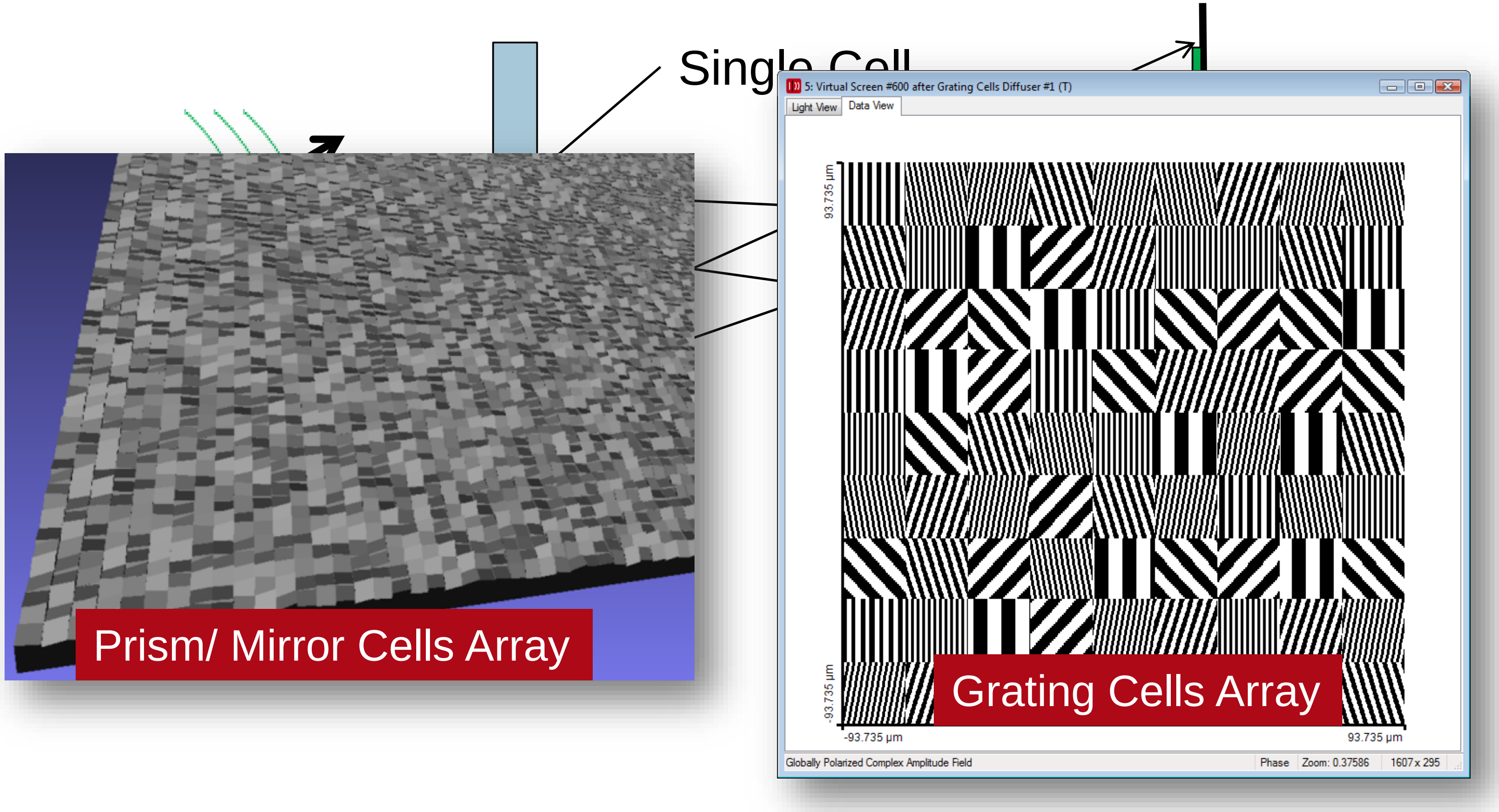


Light Deflection by Cells Arrays

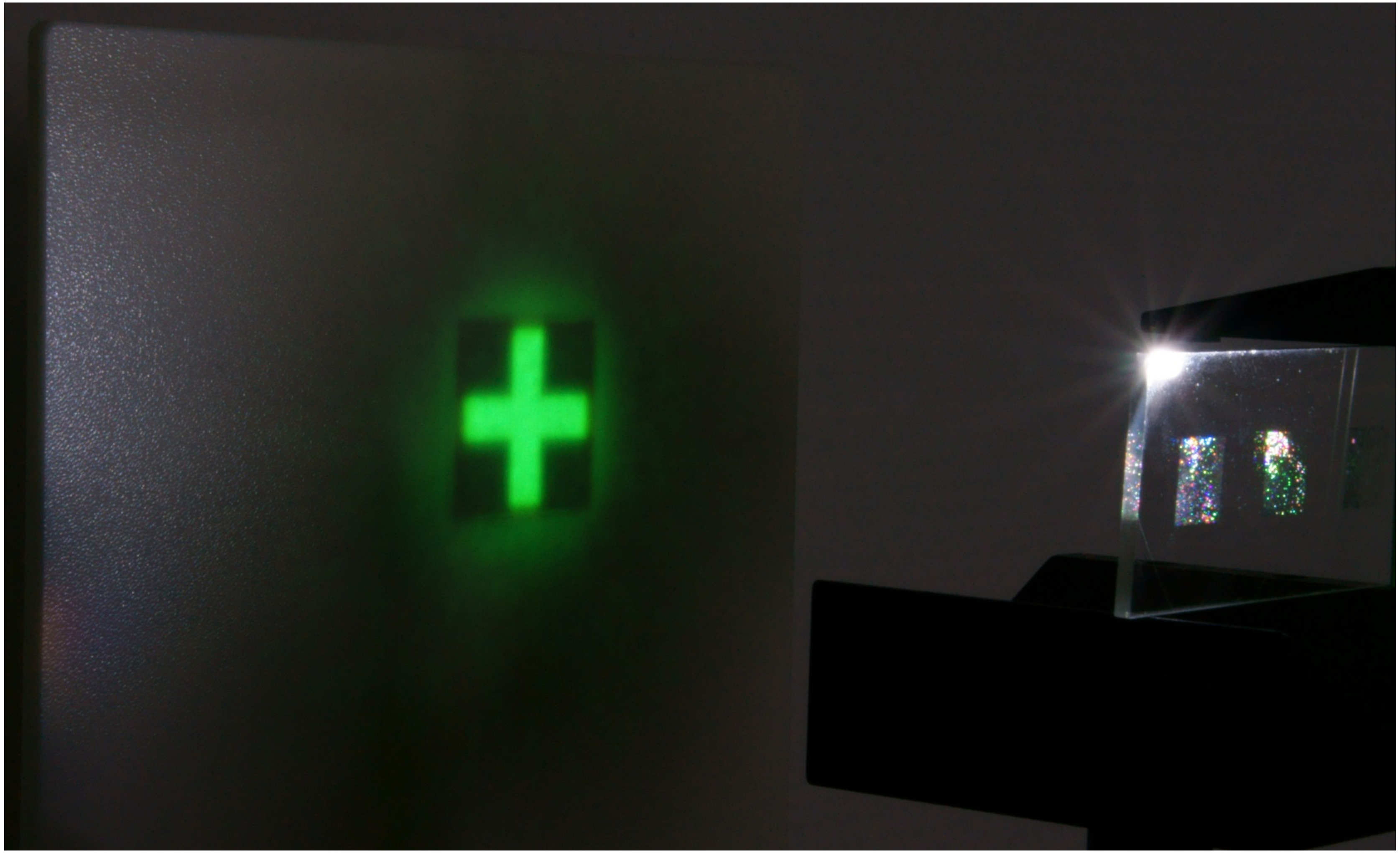


Cells Arrays are used typically for generation of binary light patterns

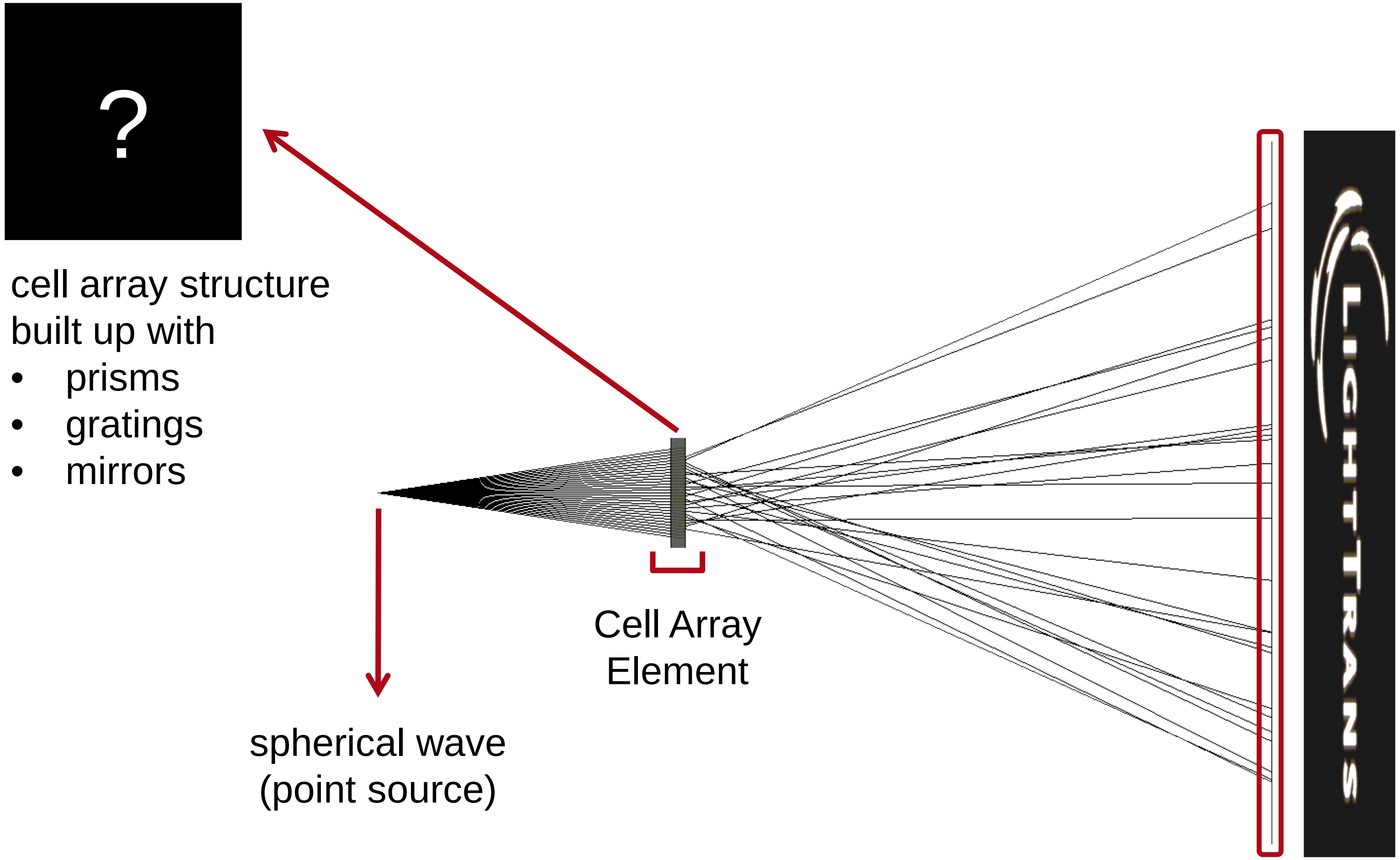
Light Deflection by Cells Arrays



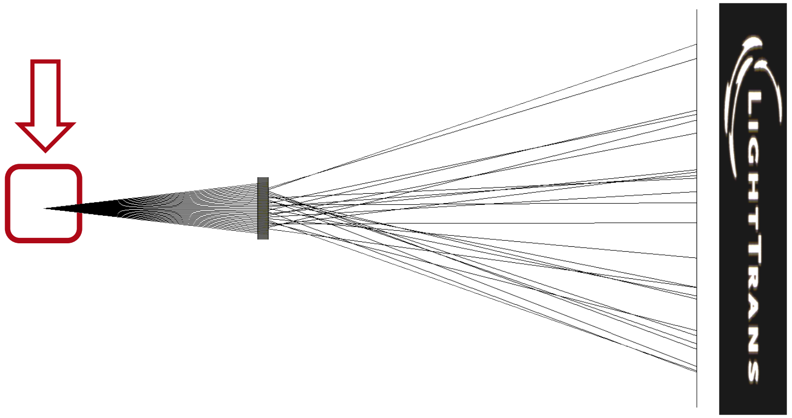
GCA - Green LED (Distinct Spot Overlap)



Task/System Illustration

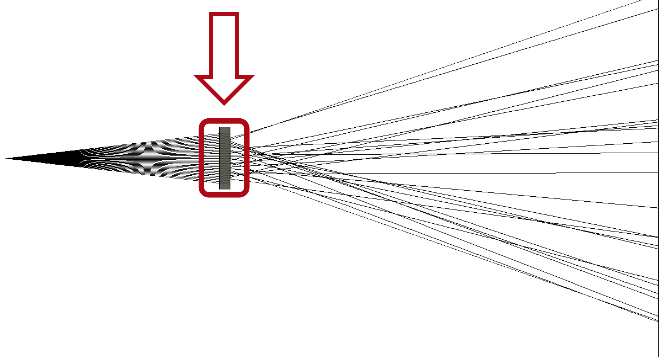


Specification: Light Source



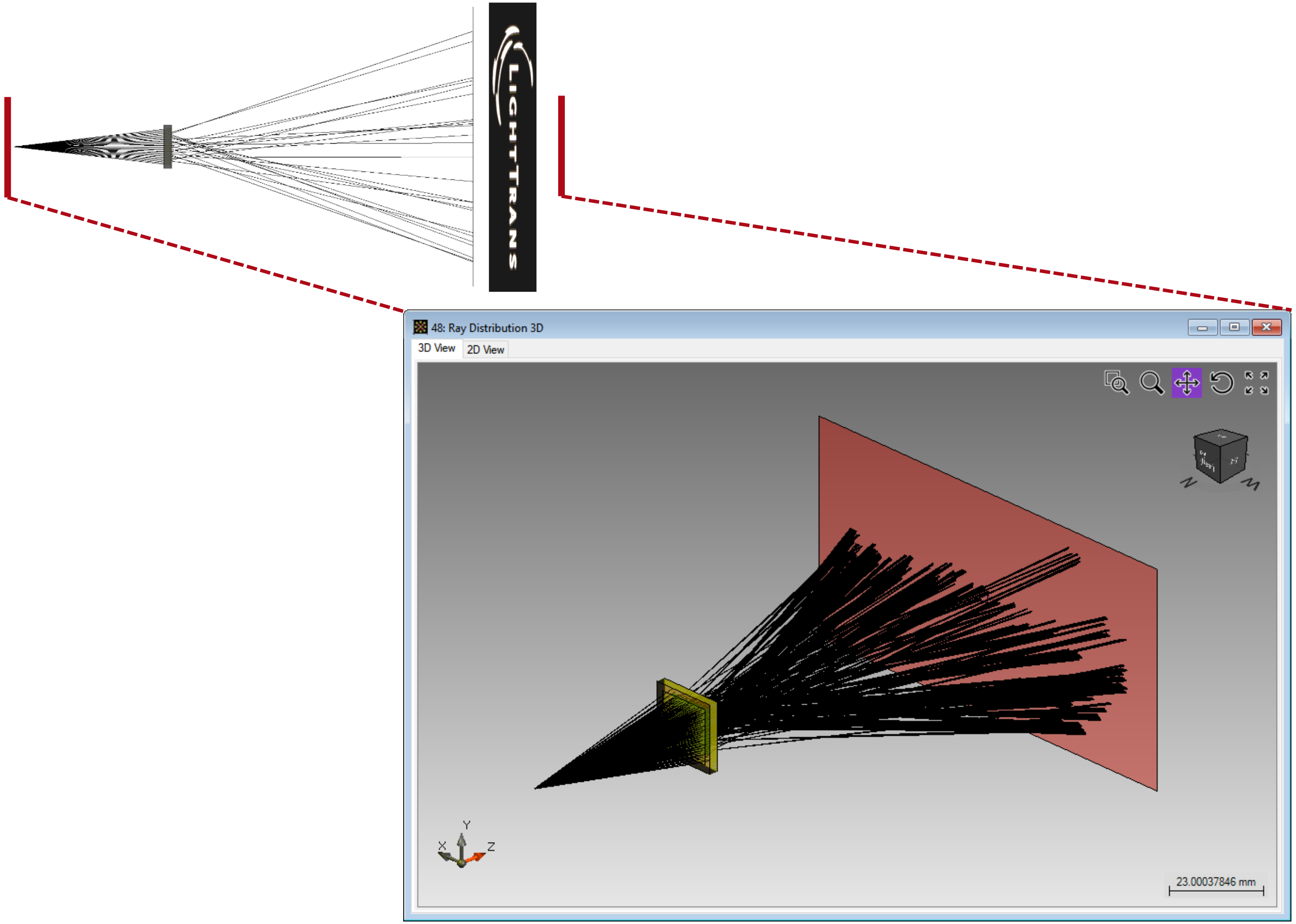
Parameter	Description / Value & Unit
type	RGB LED
emitter size	100x100 µm
wavelength	(473, 532, 635) nm
polarization	right circularly polarized light
number of lateral modes	3x3
Total number of lateral and spectral modes	27

Specification: Cell Array

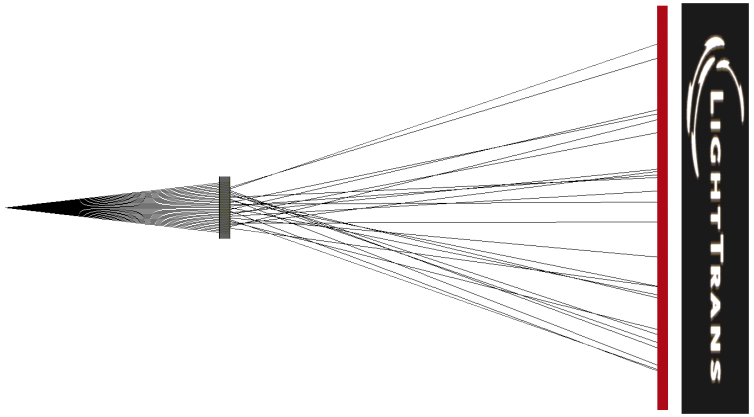


Parameter	Value & Unit
number of cells	100x100
cell size	125x125µm
array aperture	12.5x12.5mm

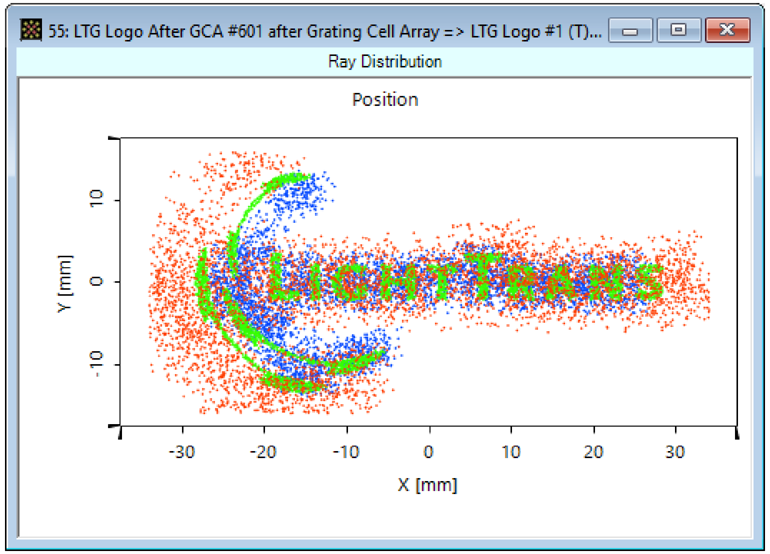
Results: 3D System Ray Tracing



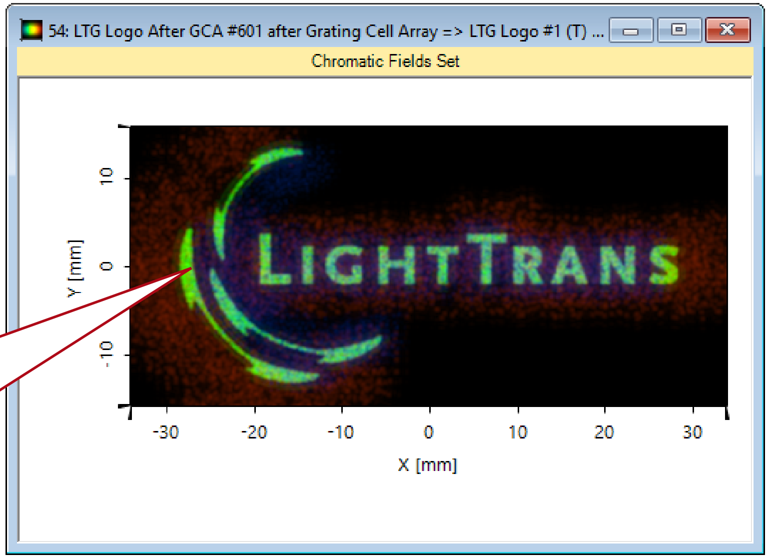
Results: Grating Cells Array



spot diagram

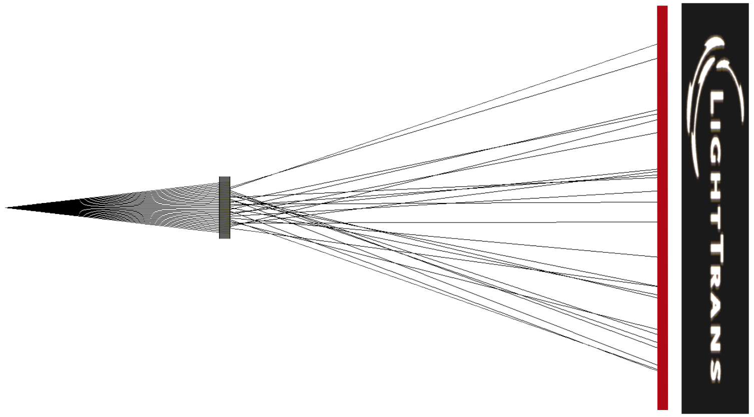


y pattern
olor view)

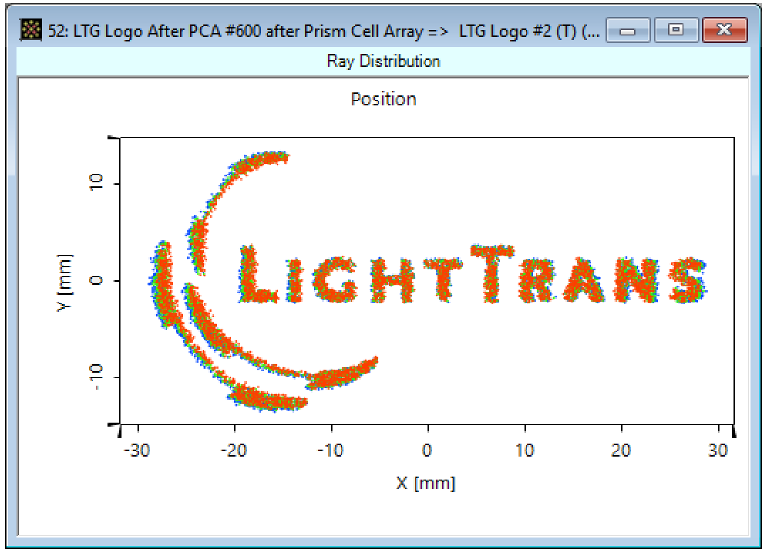


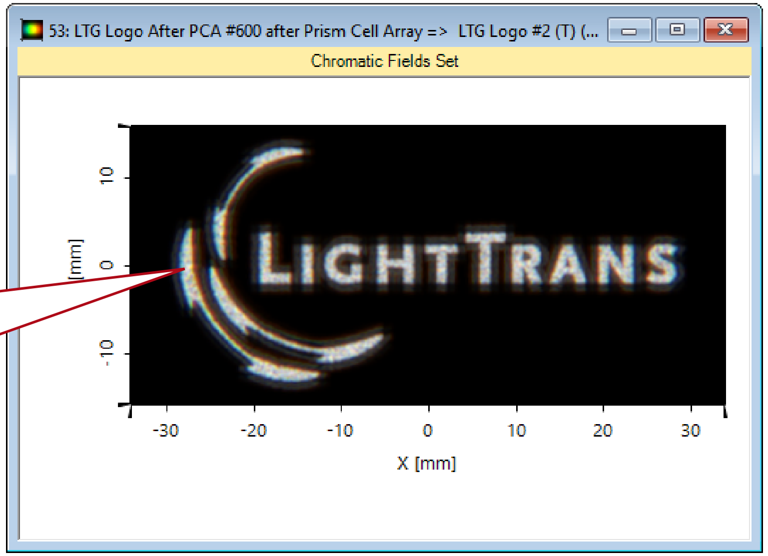
for grating cells array strong dispersion effects occur

Results: Prism Cells Array



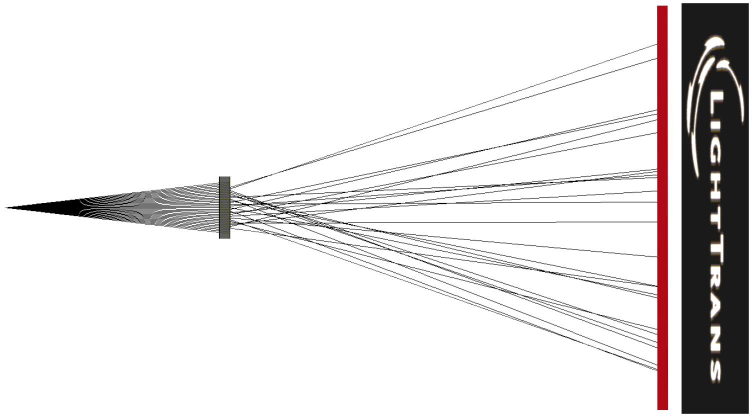
spot diagram



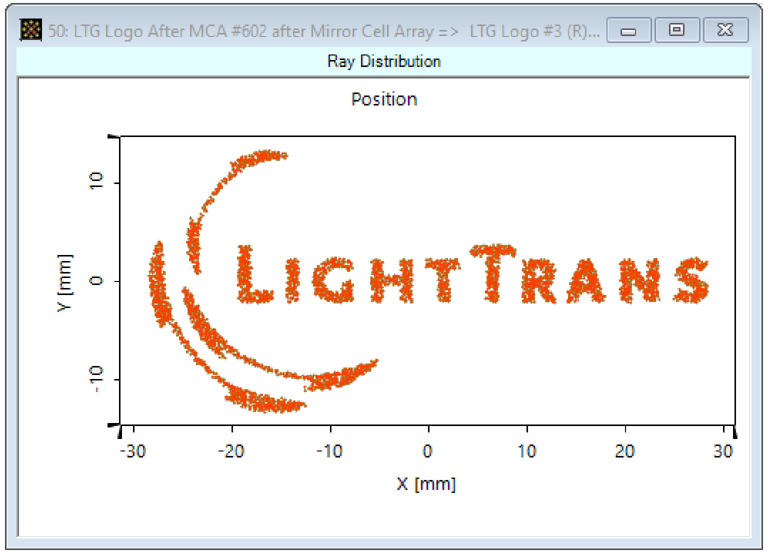


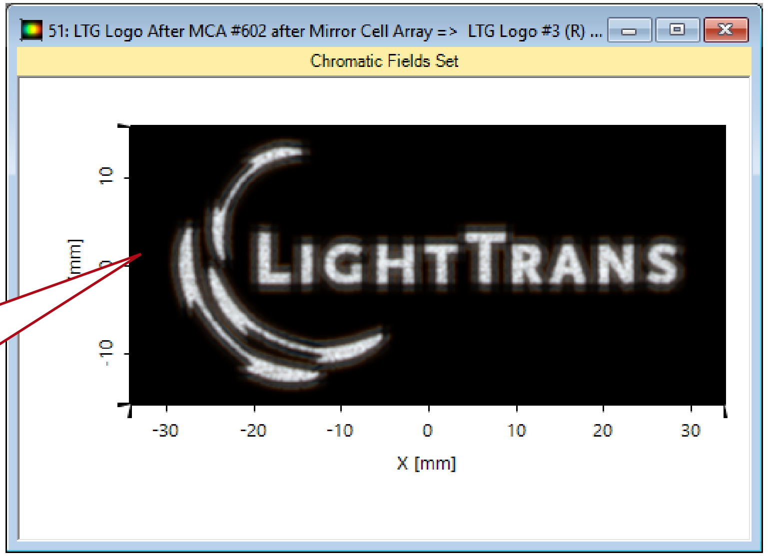
the dispersion is significantly reduced by using prisms

Results: Mirror Cells Array



spot diagram

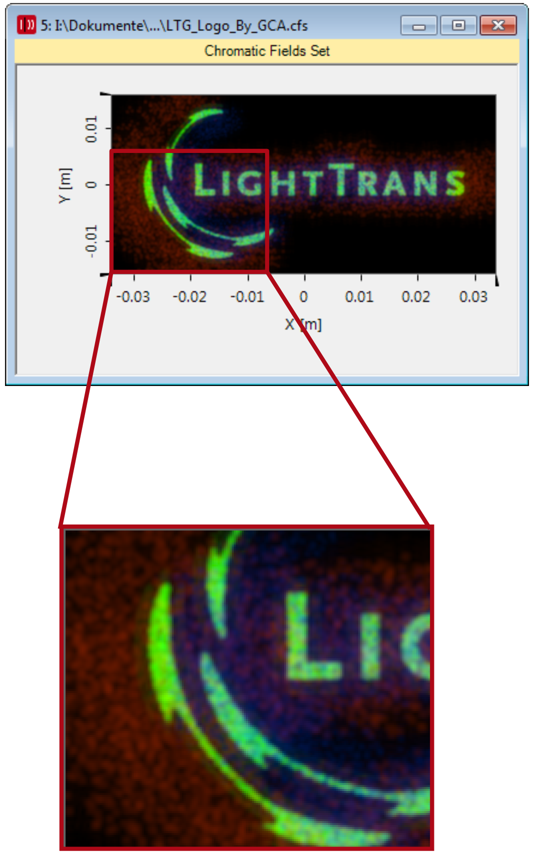




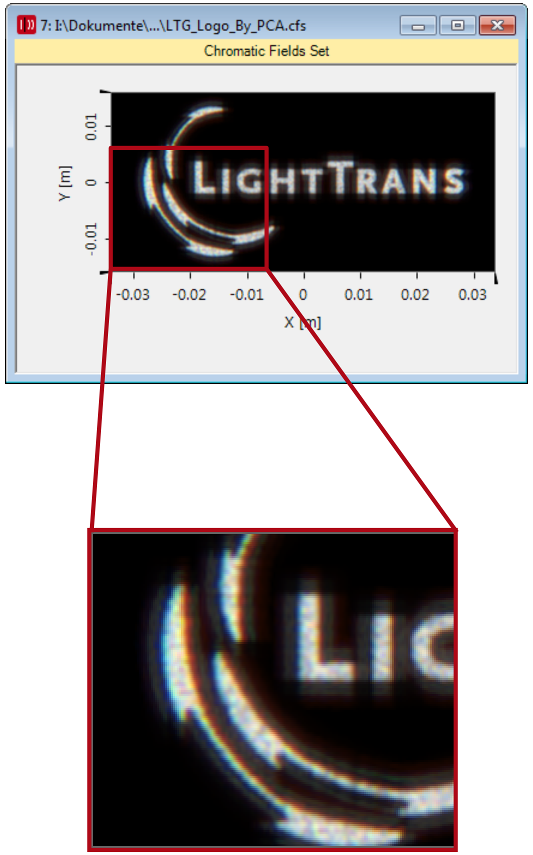
due to reflective approach no dispersion effects occur

White Light Simulation

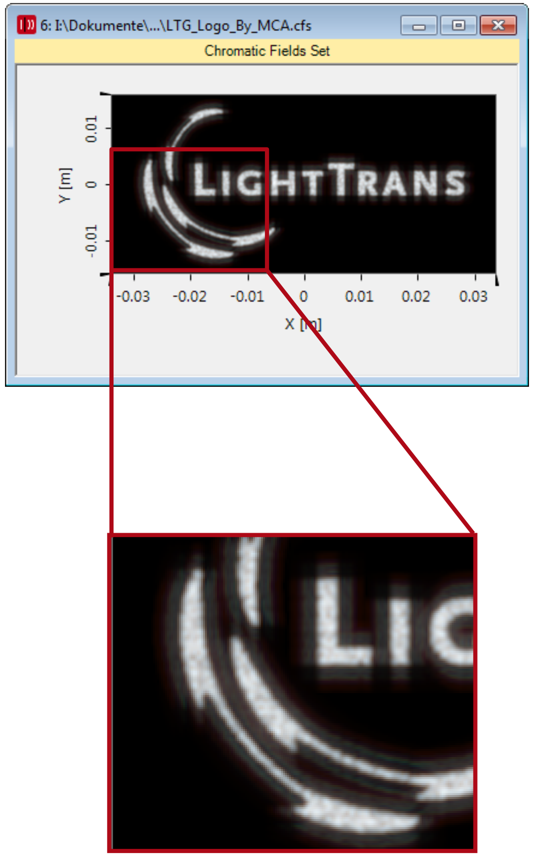
Intensity
Grating Cells Array



Intensity
Prism Cells Array



Intensity
Mirror Cells Array

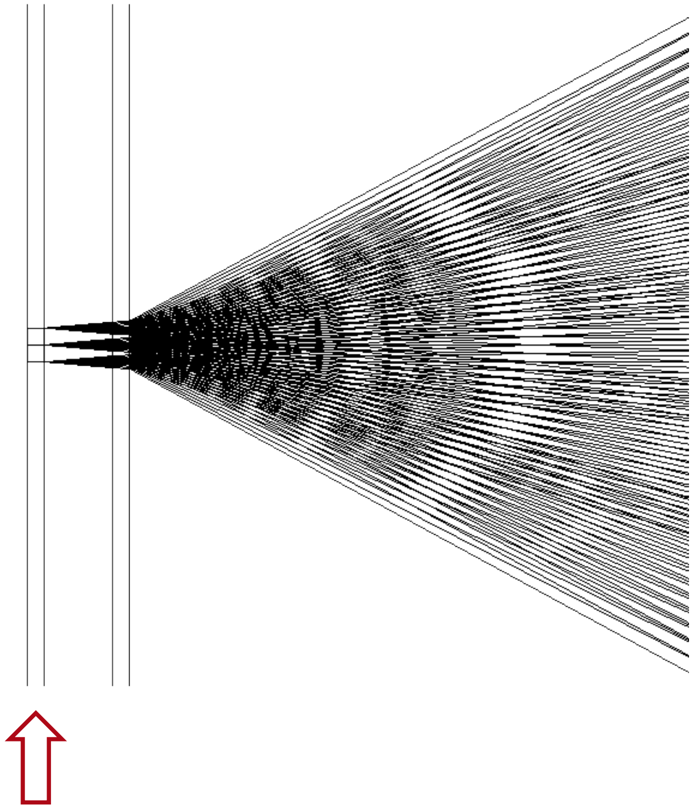


Virtual And Mixed Reality > Pattern Generation

High-NA Pattern Generation Using Two Beam Splitter Elements

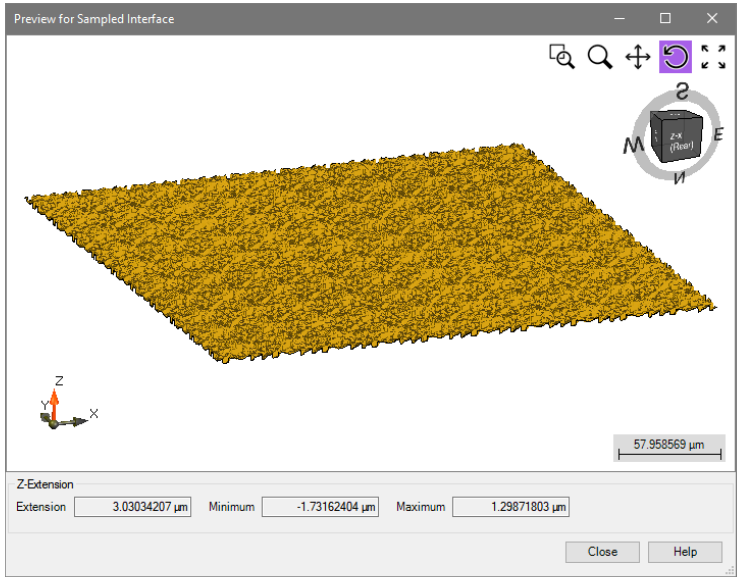
LightTrans International UG

Specification: First Beam Splitter



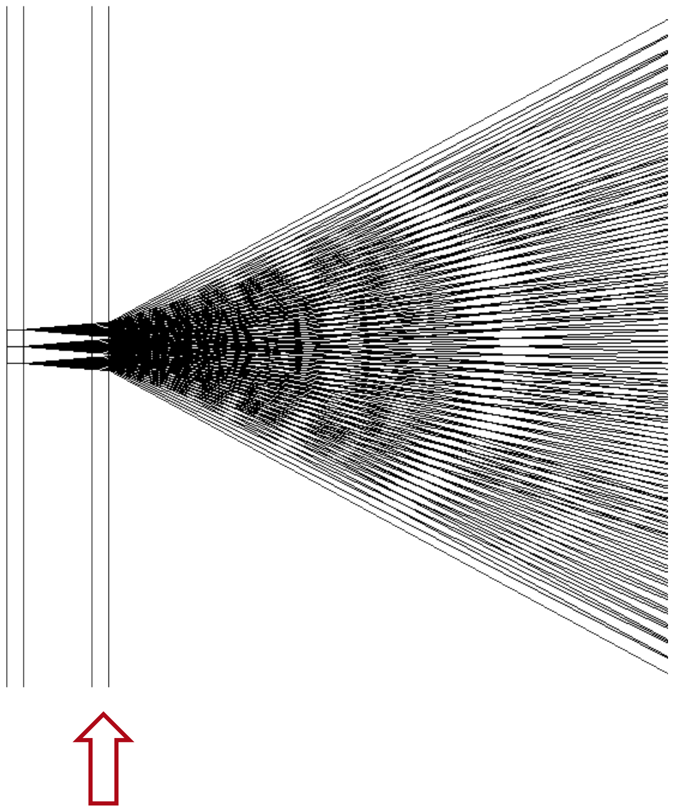
paraxial beam splitter

Parameter	Value & Unit
number of orders	11x11
order separation	1x1°
period	30.35x30.35 µm
pixel size	690x690 nm
discrete height levels	8
material	fused silica



surface profile

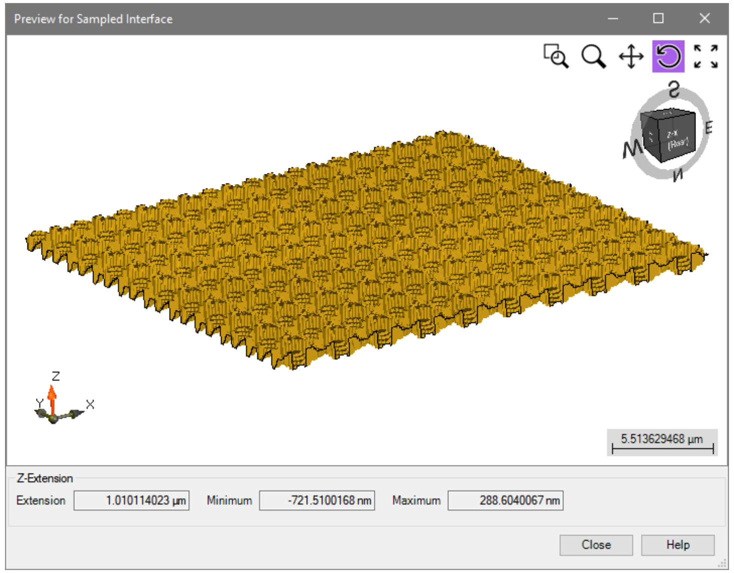
Specification: Second Beam Splitter



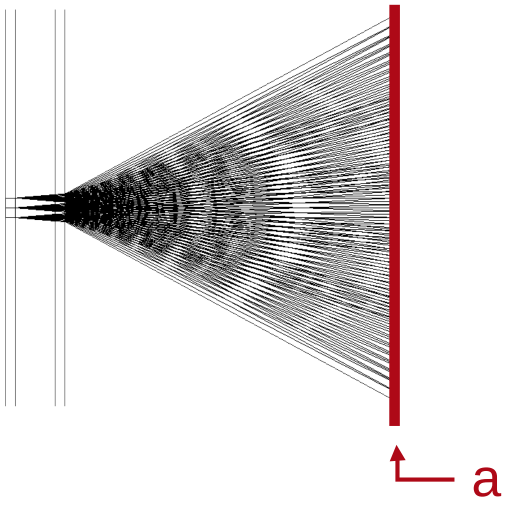
high-NA beam splitter

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

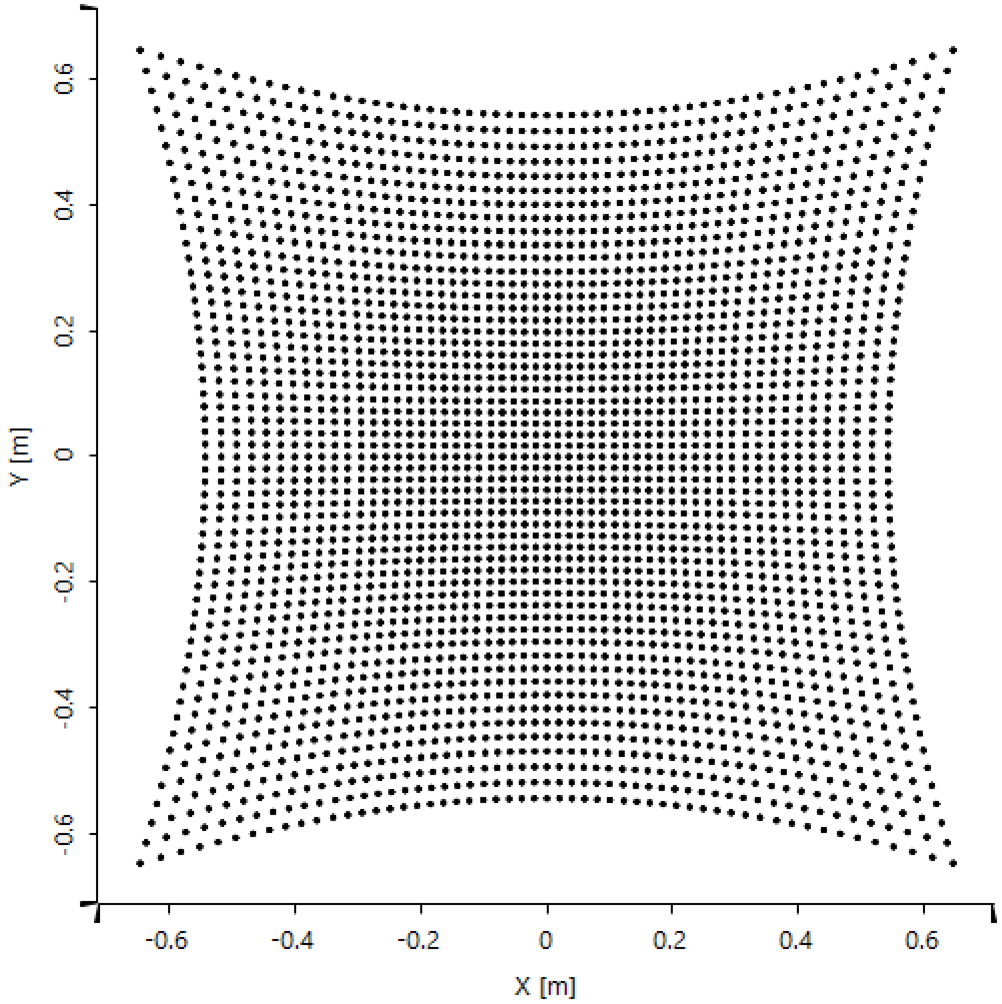
surface profile



Results: Spot Diagram

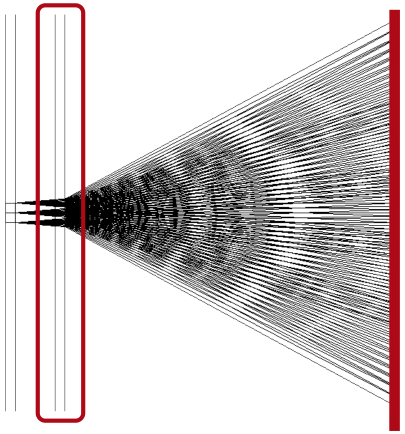


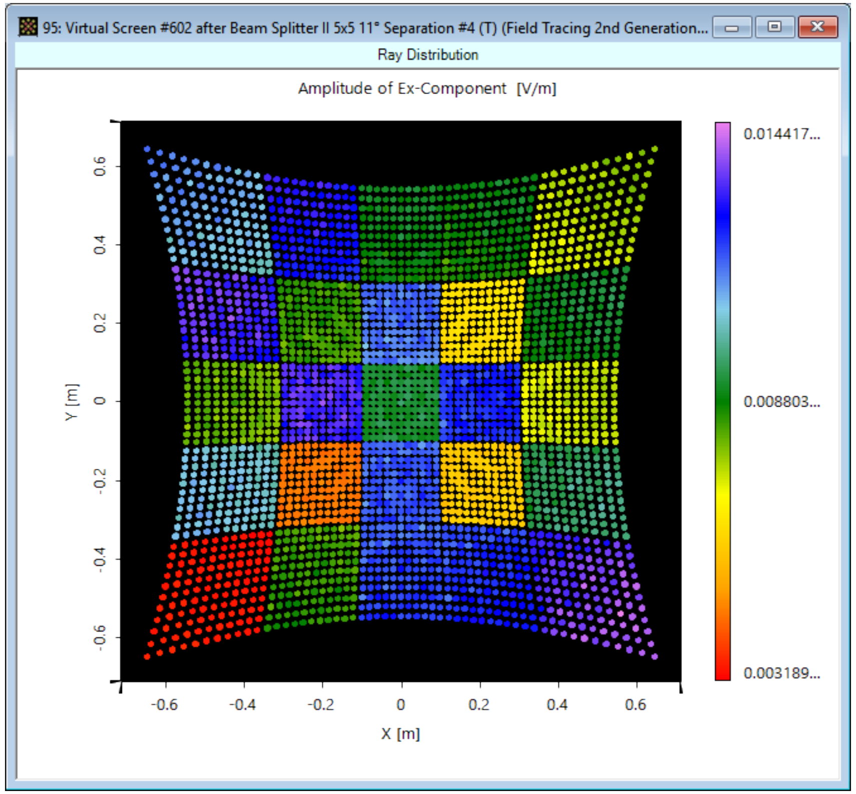
combination of both beam splitter generate **55x55 order** with **55x55° full opening spread**



spot diagram

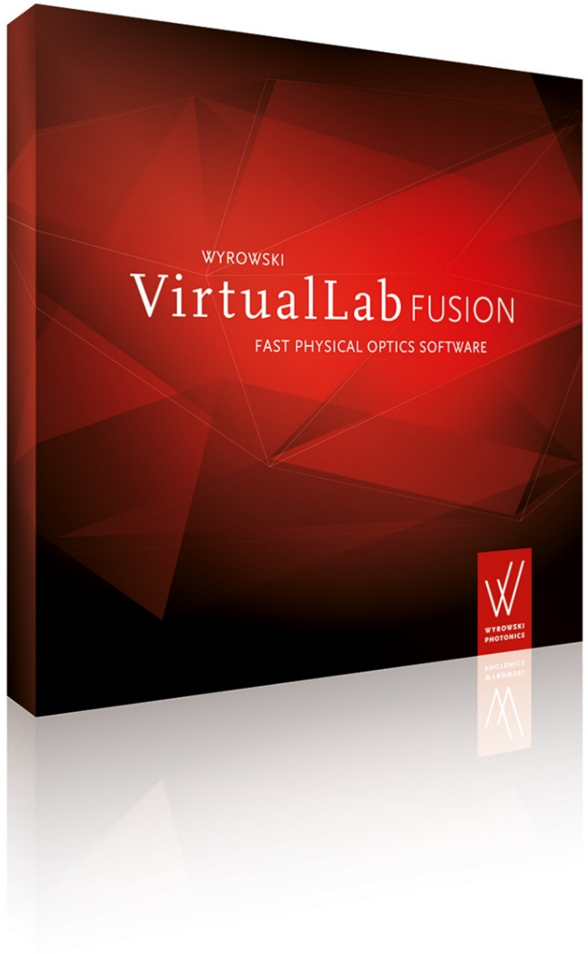
Results: Output Evaluation





Light Shaping Concepts

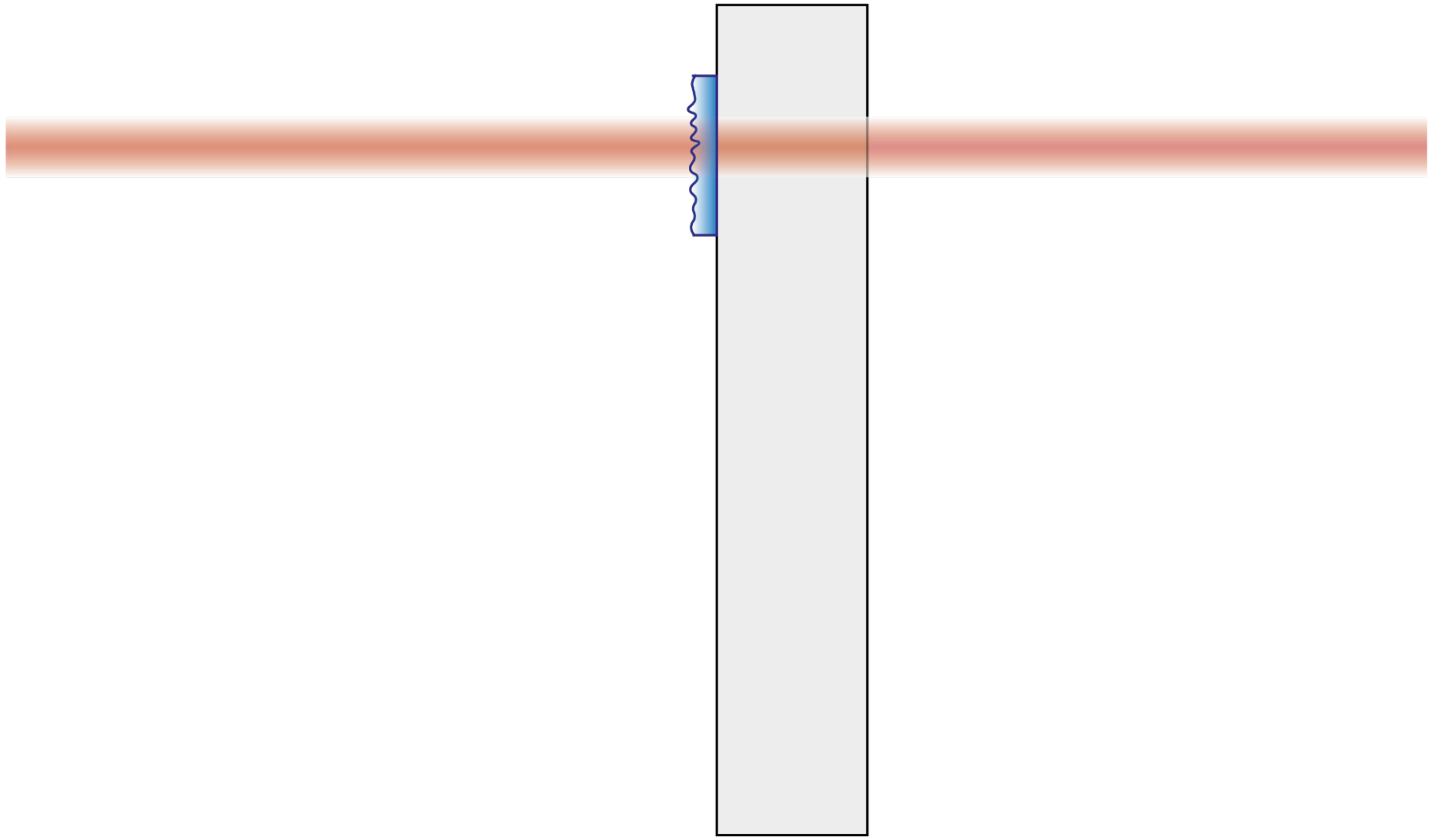
- Tailored aberrations
- Stored scanning process
- Multichannel concept: Single Deflection
- Multichannel concept: General



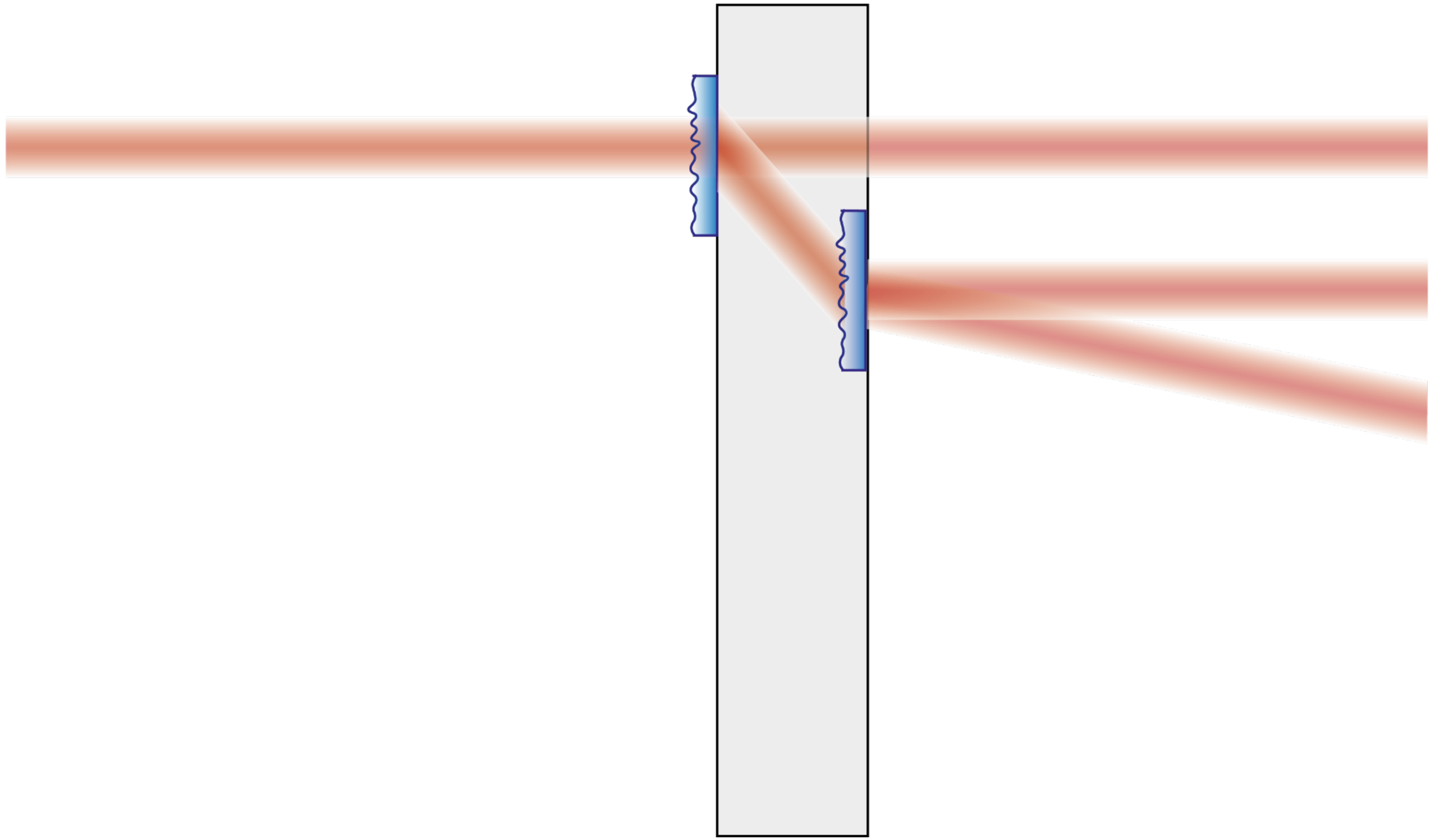
Final part

NED

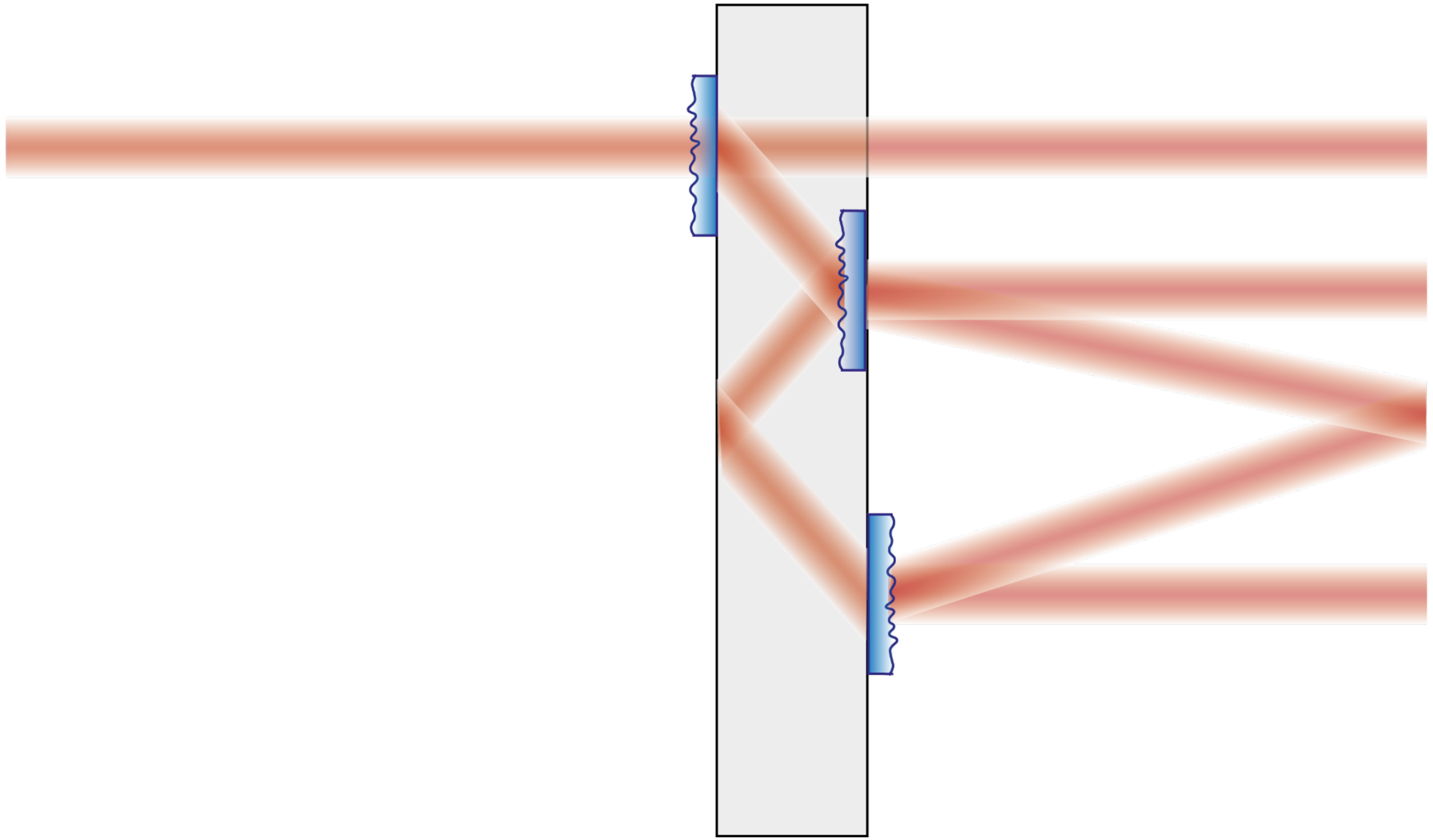
Diffractive Optics



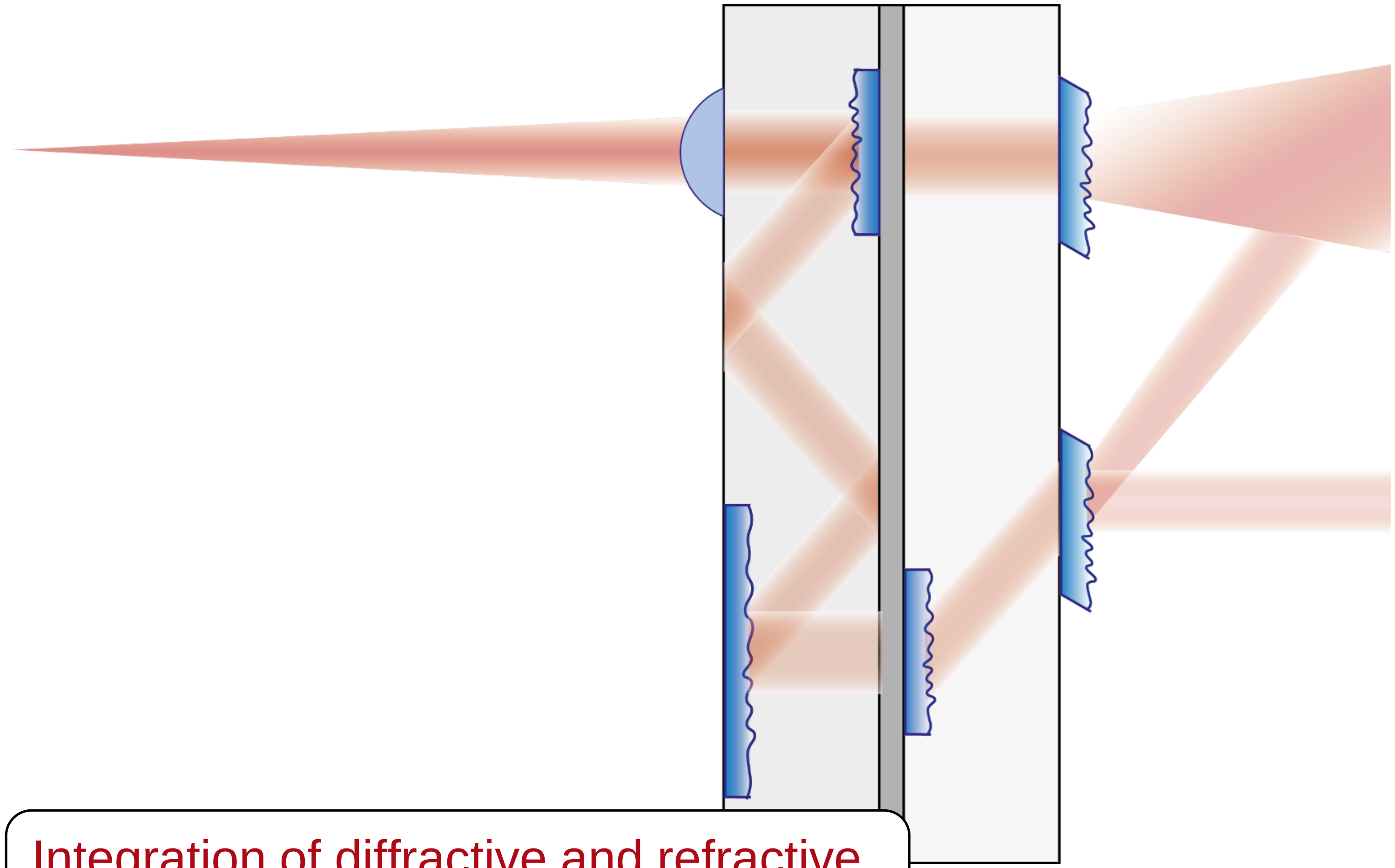
Diffractive Optics



Diffractive Optics

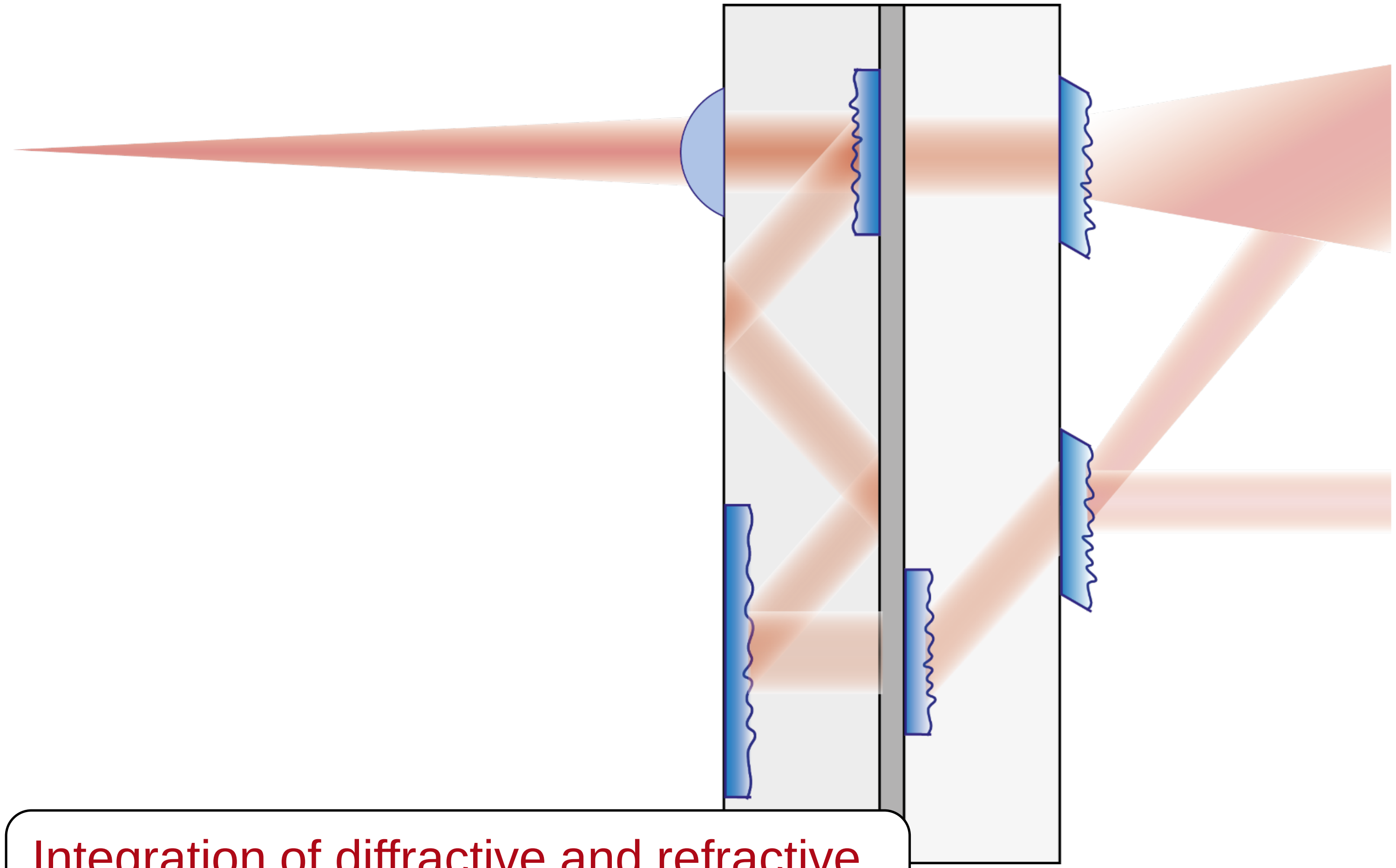


Diffractive Optics



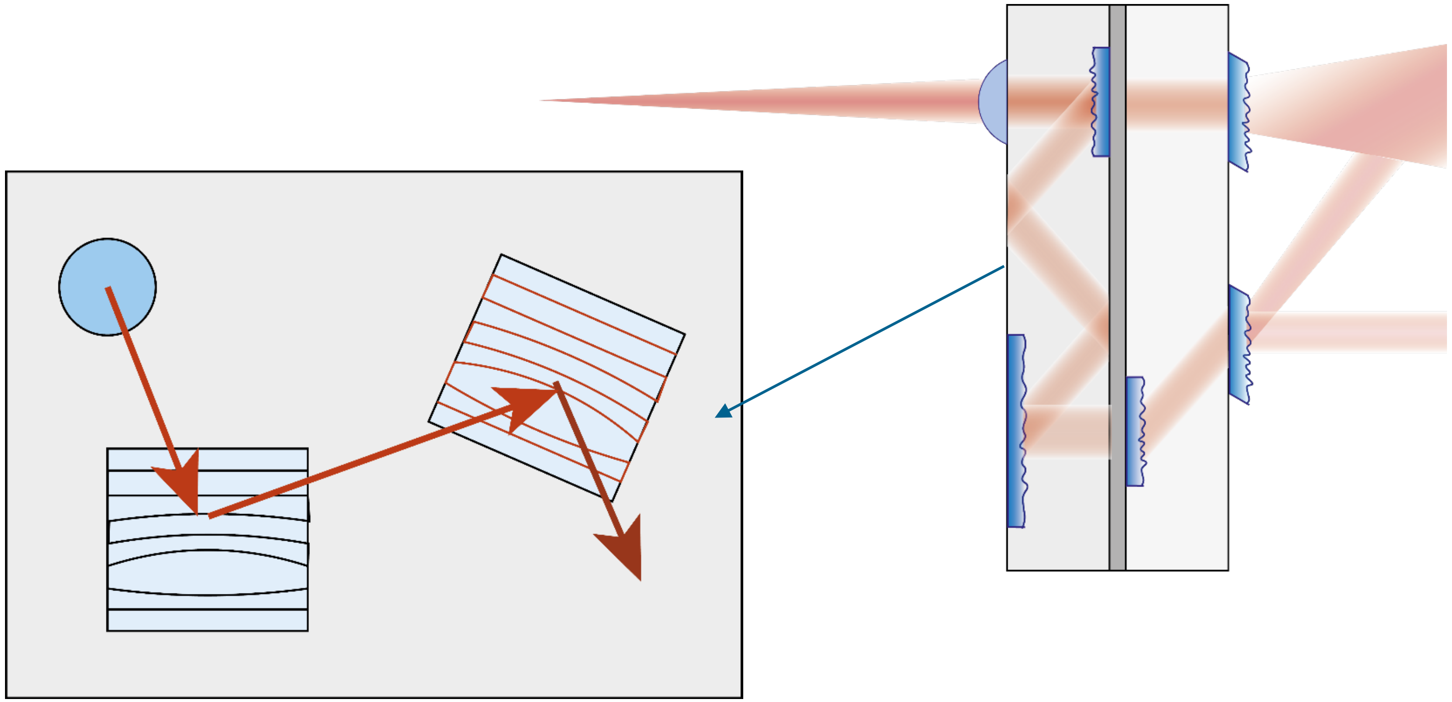
Integration of diffractive and refractive elements: micro-optical system

Integrated Diffractive Optics



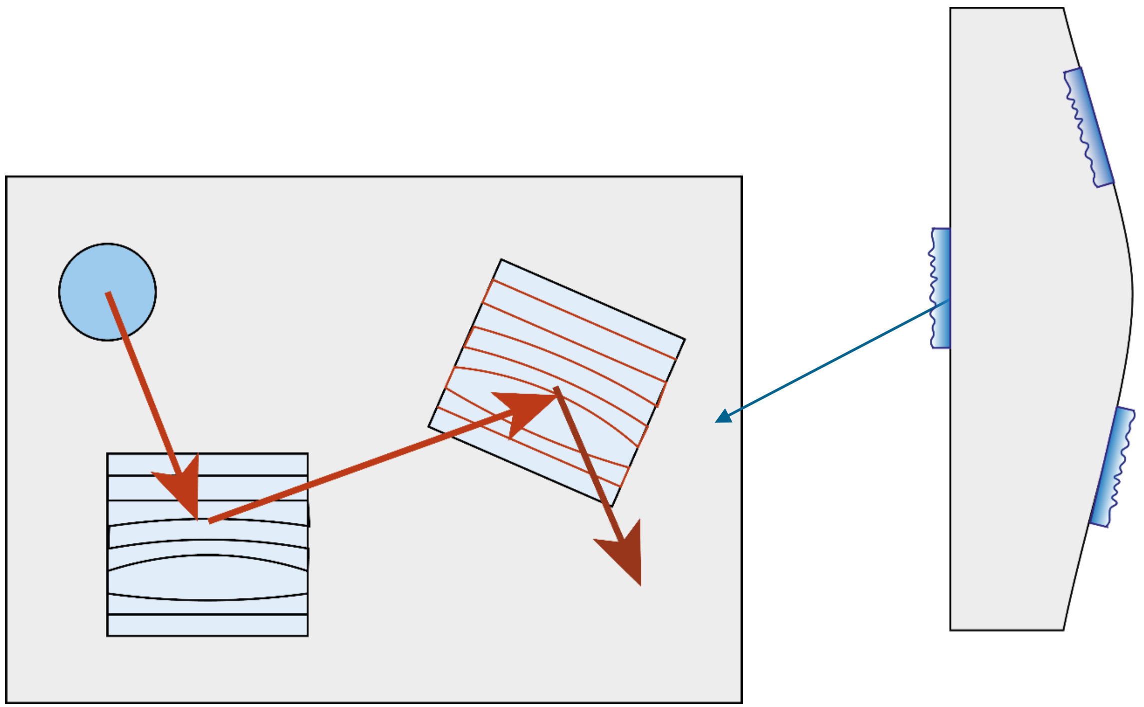
Integration of diffractive and refractive elements: micro-optical system

Integrated Diffractive Optics



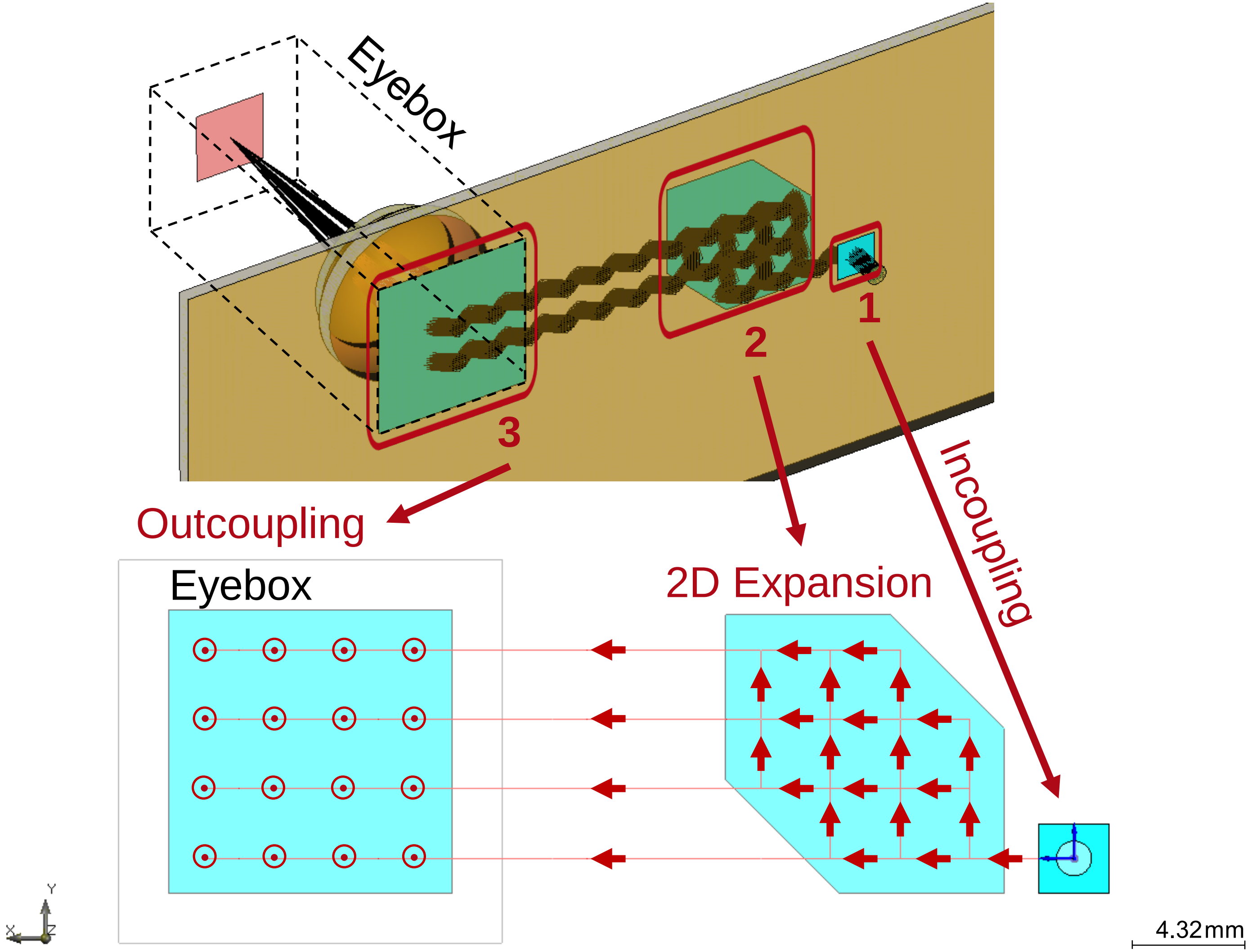
Integration of diffractive and refractive elements: micro-optical system

Integrated Diffractive Optics

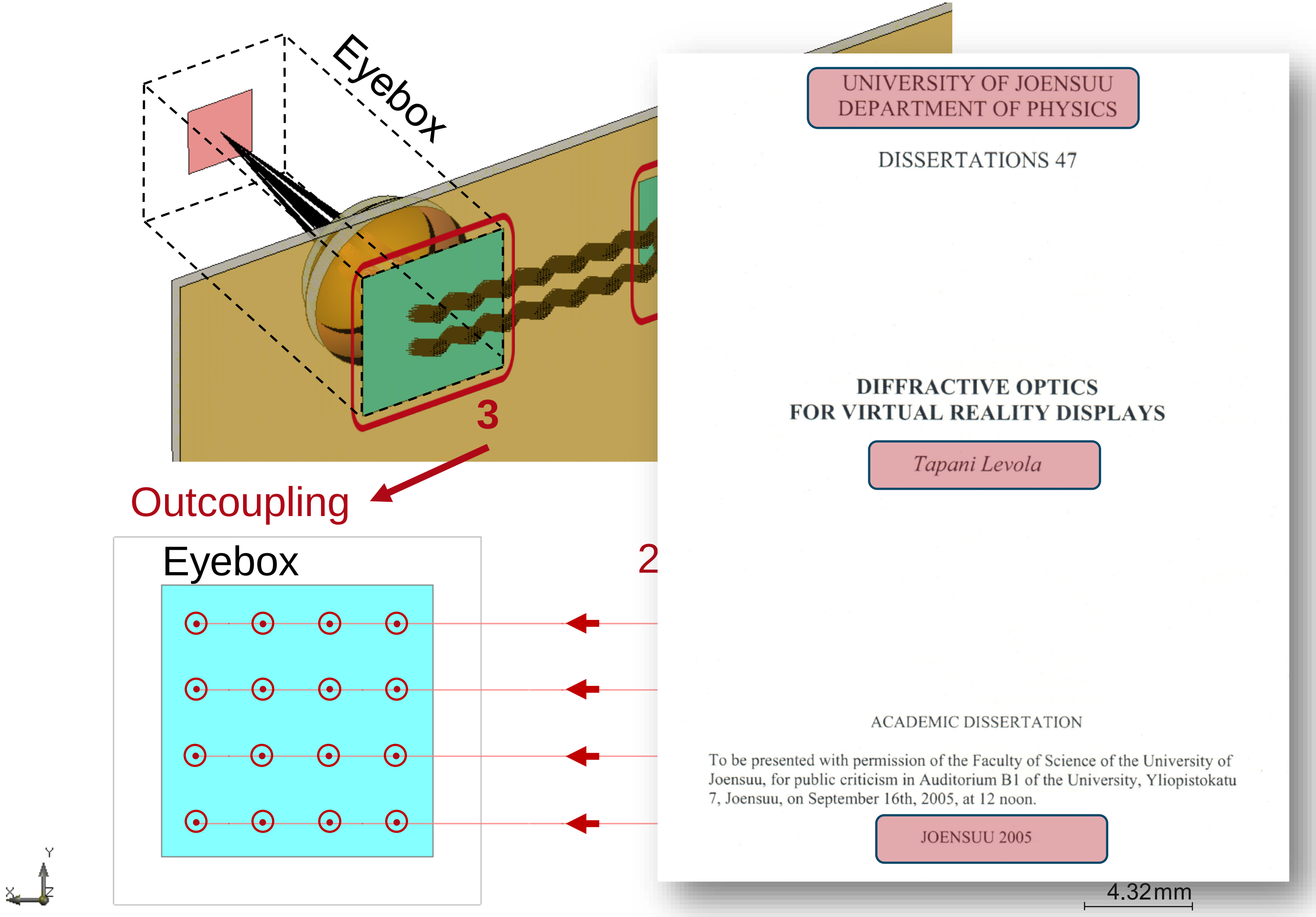


Integration of diffractive and refractive elements: micro-optical system

Integrated Diffractive Optics for Mixed Reality



Integrated Diffractive Optics for Mixed Reality



Virtual and Mixed Reality: Imaging Systems

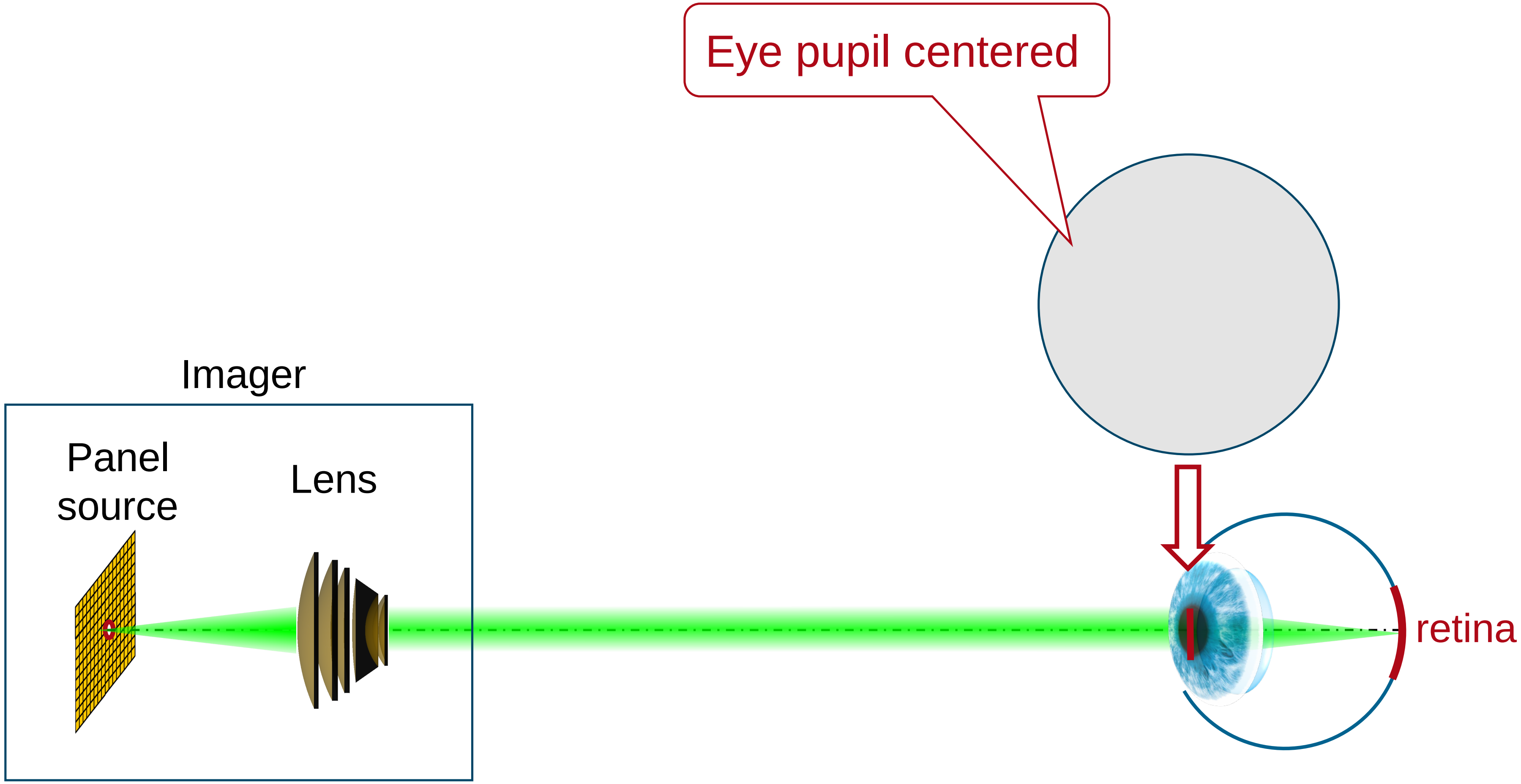


- VR/MR glasses are sophisticated imaging devices.
- Development of VR/MR glasses demands advanced modeling and design of imaging systems.
- What are the special challenges in the modeling?

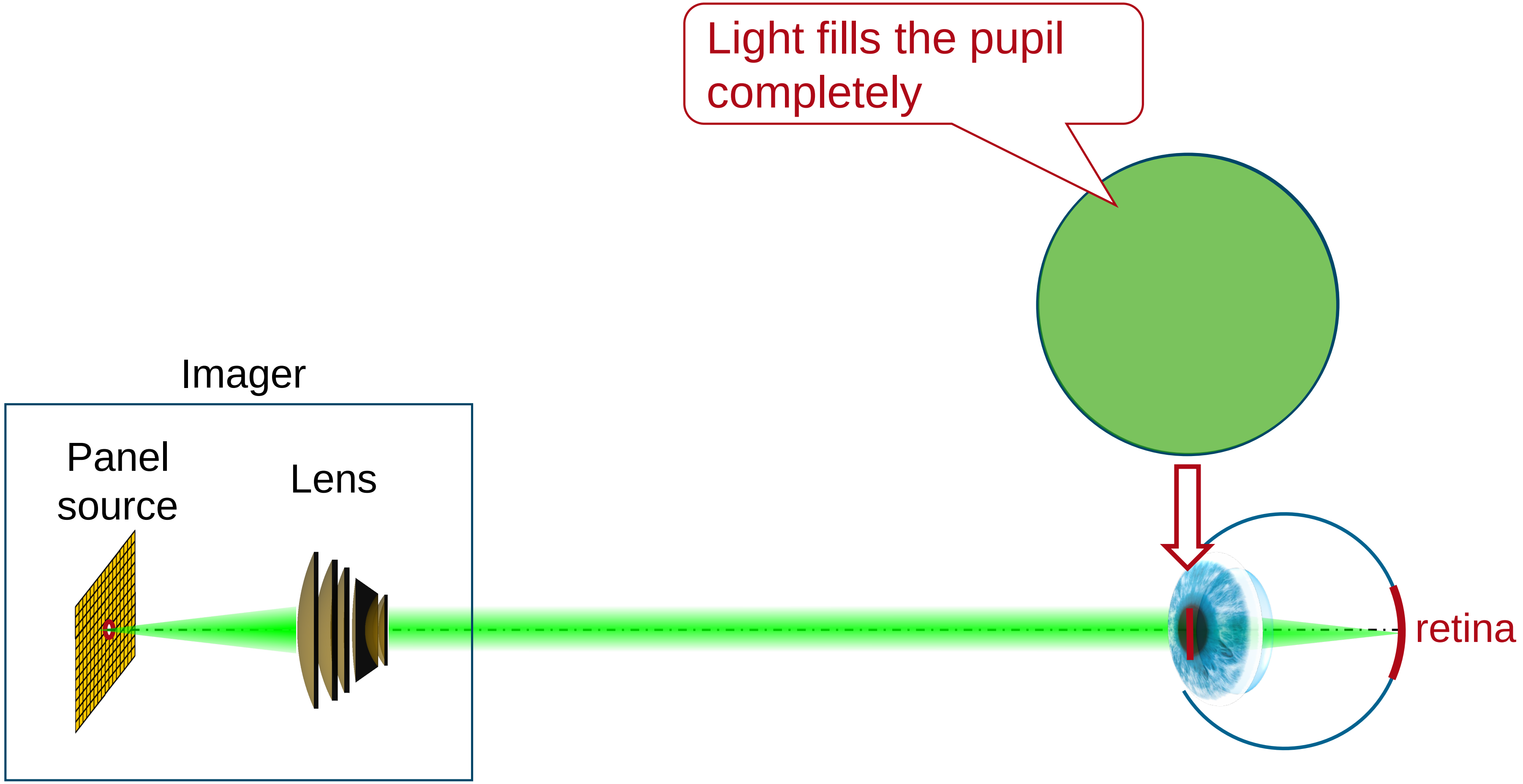
Typical Imaging Quality Criteria

- Modeling of imaging quality criteria like
  - ➢ Wavefront error
  - ➢ PSF/MTF
- Criteria dependent on image point position on micro display: FOV

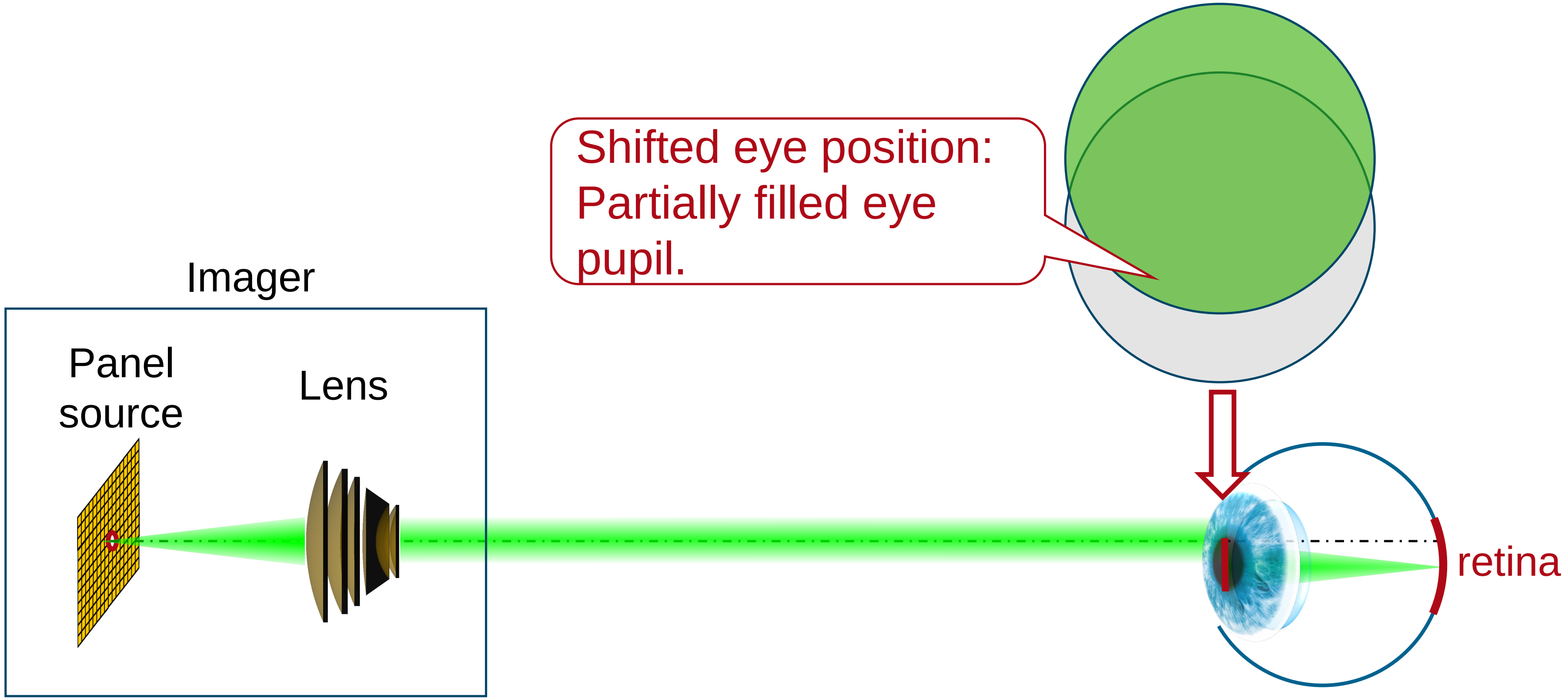
PSF Calculation: Partially Filled Pupil



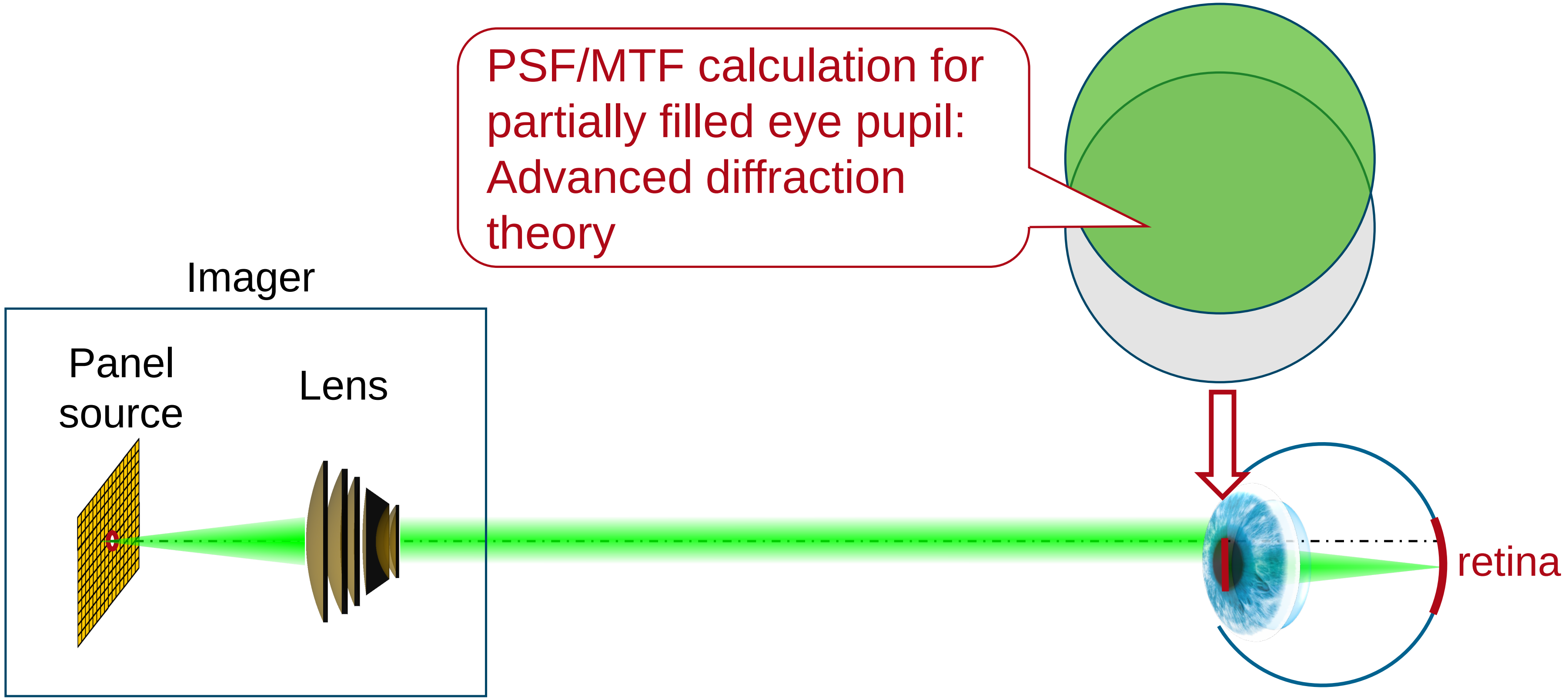
PSF Calculation: Partially Filled Pupil



PSF Calculation: Partially Filled Pupil



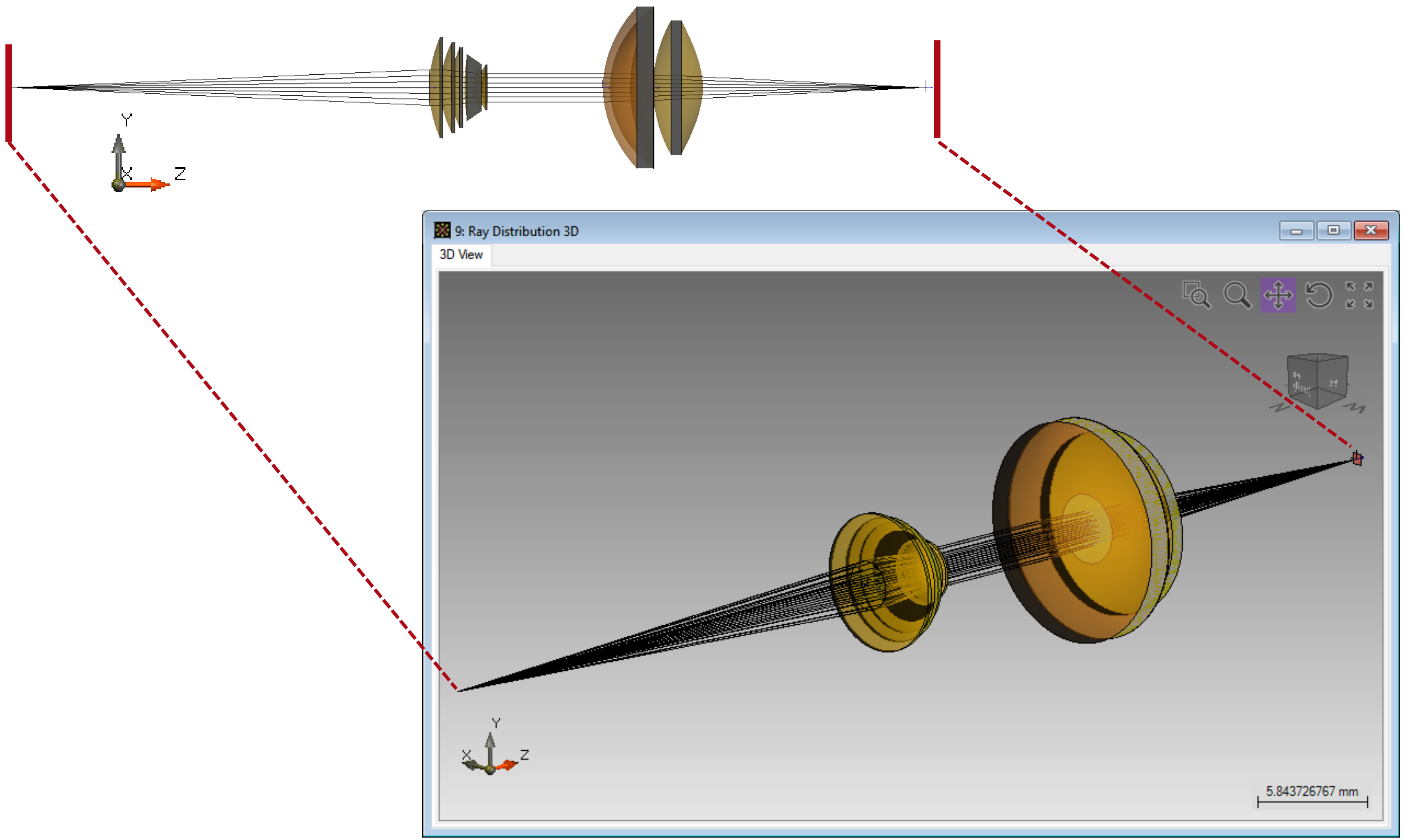
PSF Calculation: Partially Filled Pupil



Challenges in Modeling of VR/MR

- PSF/MTF calculation for partially filled exit pupils

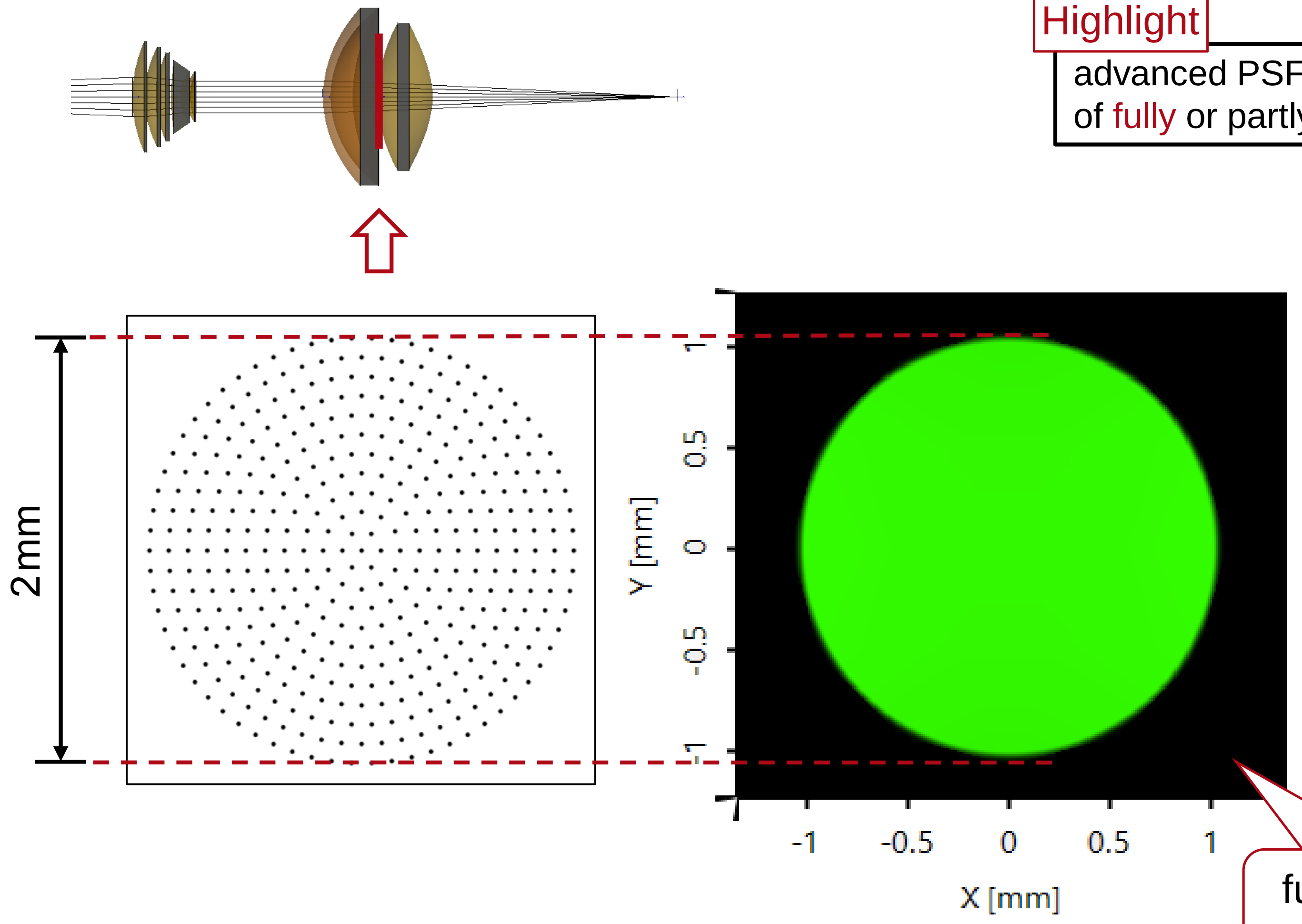
Results: 3D System Ray Tracing



Results: Illumination of Pupil

Highlight

advanced PSF and MTF evaluation of fully or partly illuminated apertures



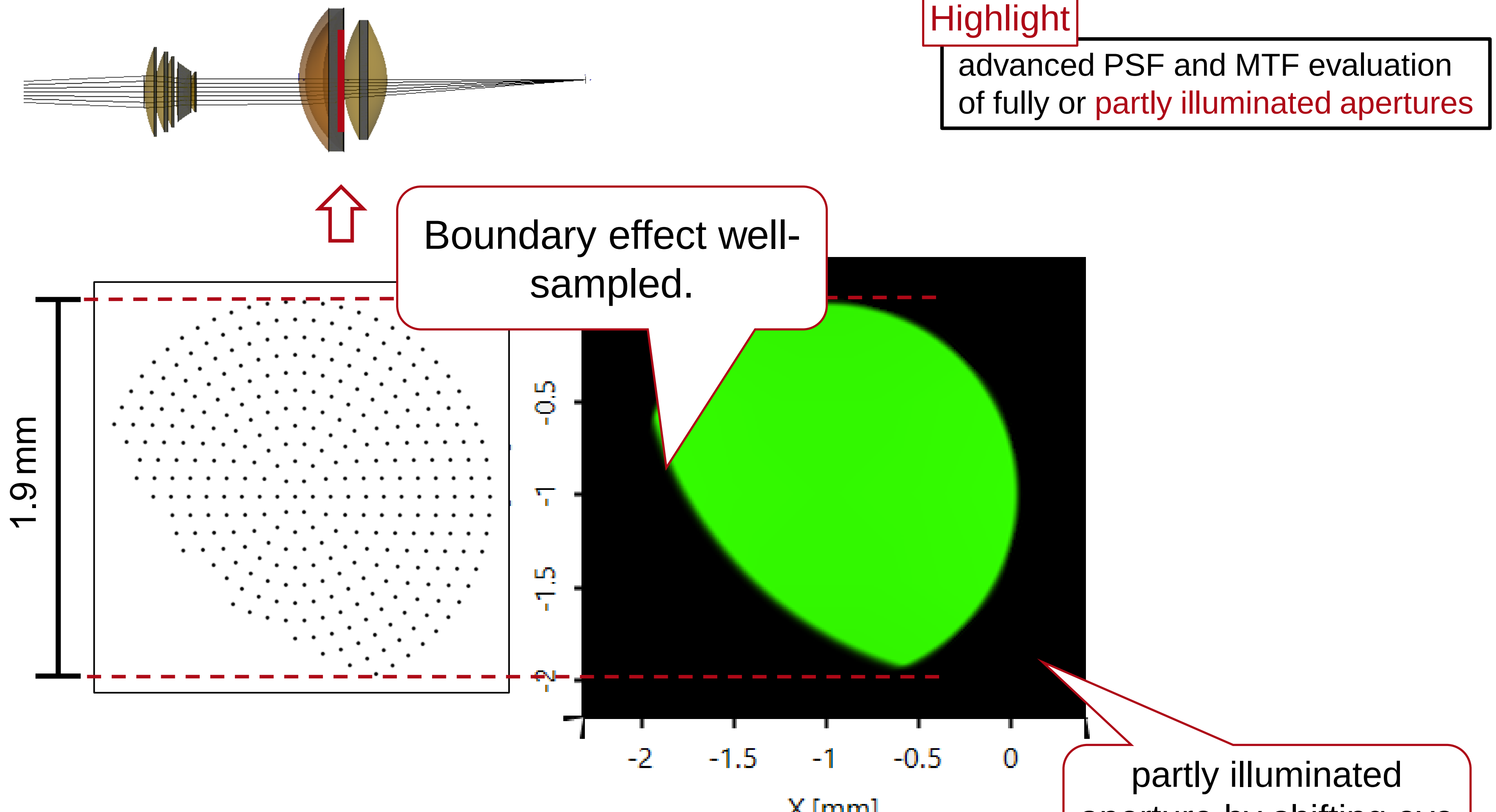
fully illuminated aperture

dot diagram of ray positions **intensity**

Results: Illumination of Pupil

Highlight

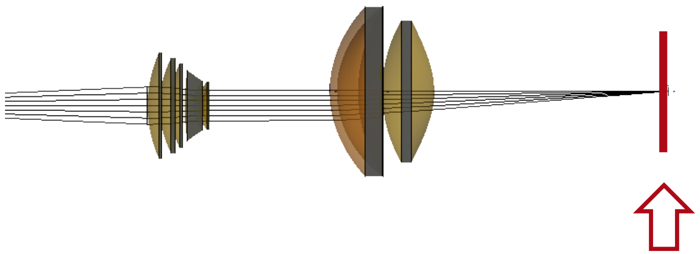
advanced PSF and MTF evaluation of fully or partly illuminated apertures



dot diagram of ray positions

intensity

Results: PSF & MTF



Highlight

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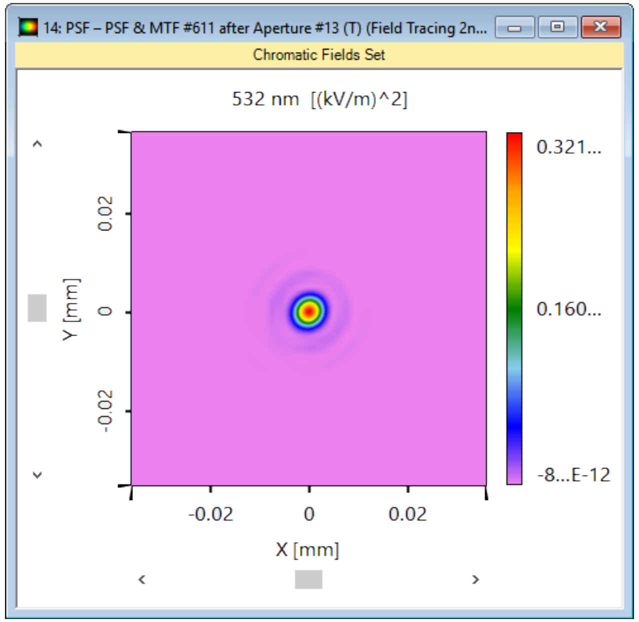
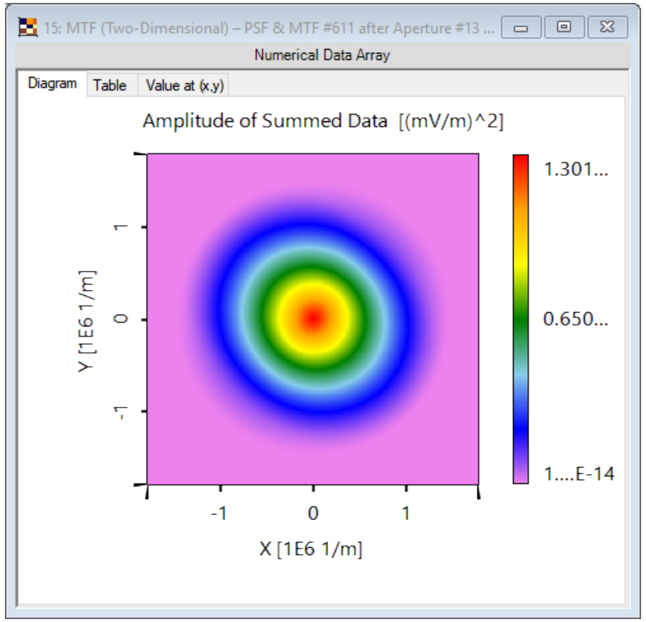


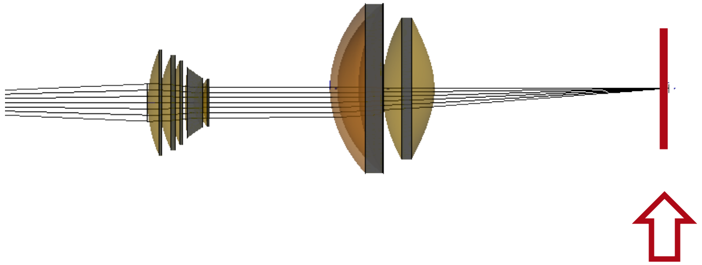
PSF



2D MTF

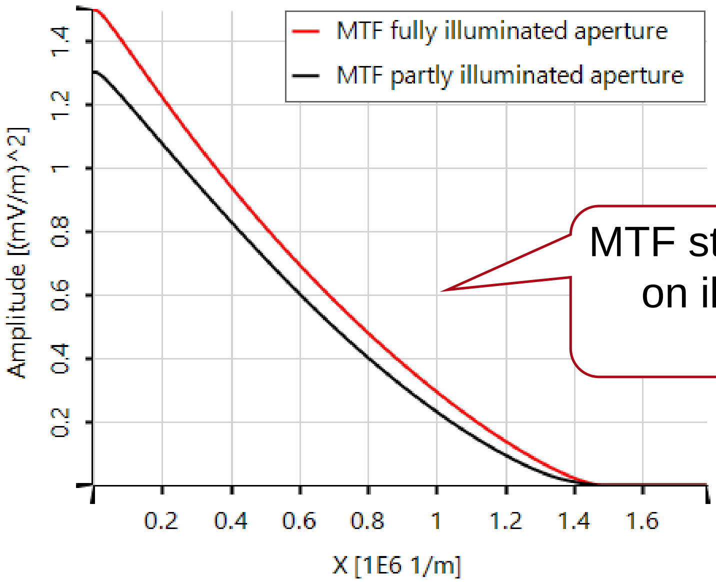
Simulation Time ~ few seconds

Results: PSF & MTF – Comparison



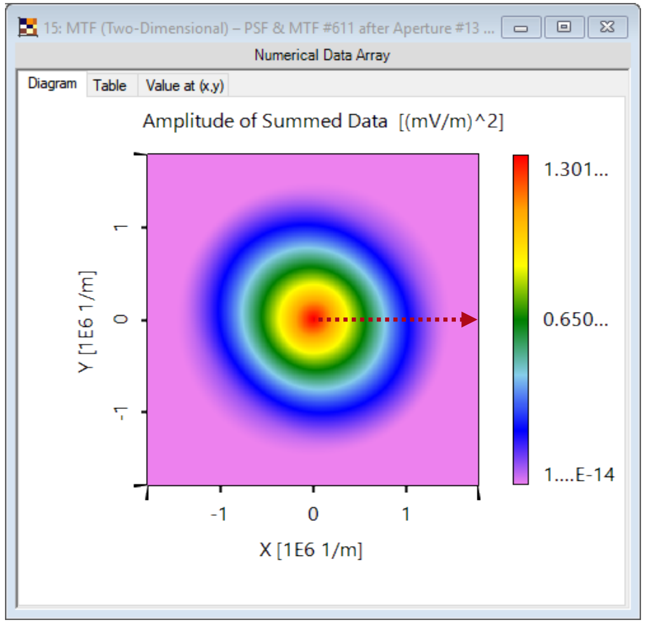
Highlight

advanced PSF and MTF evaluation of fully or partly illuminated apertures



MTF strongly depends on illumination of aperture

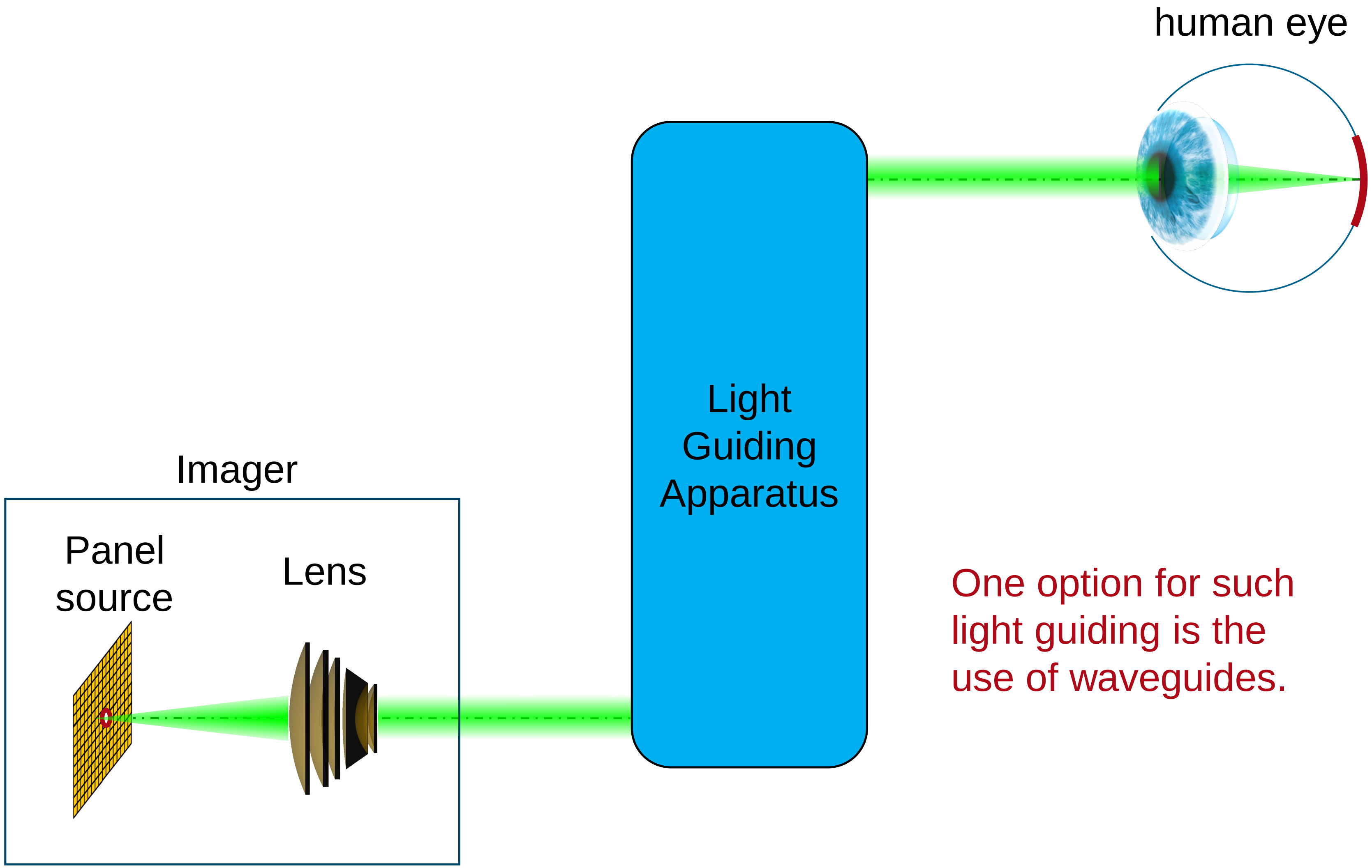
MTF profile line



2D MTF
(from system with partly illuminated aperture)

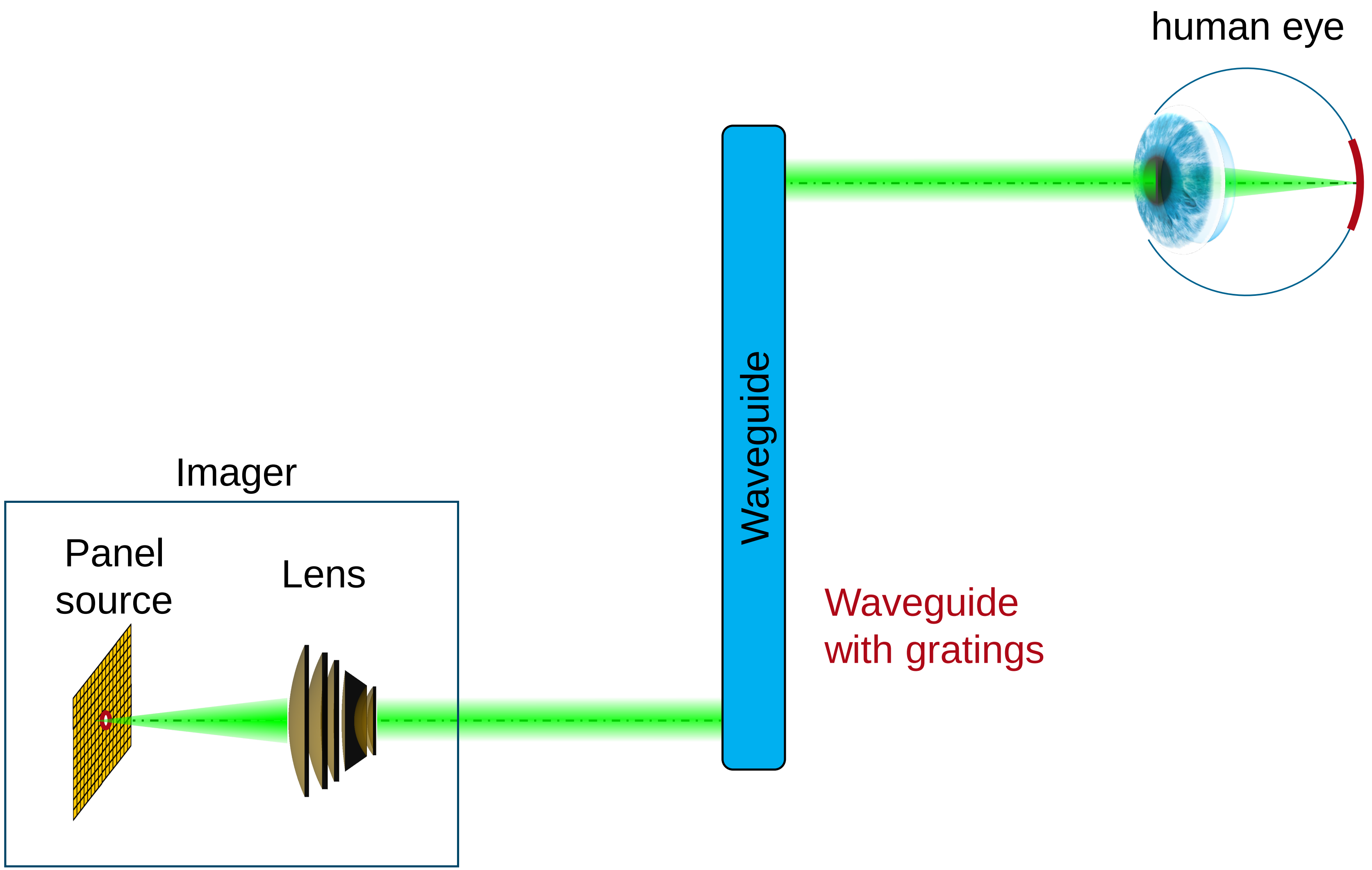
Spatial Guiding of Imaging Channel

Spatial Guiding of Imaging Channel

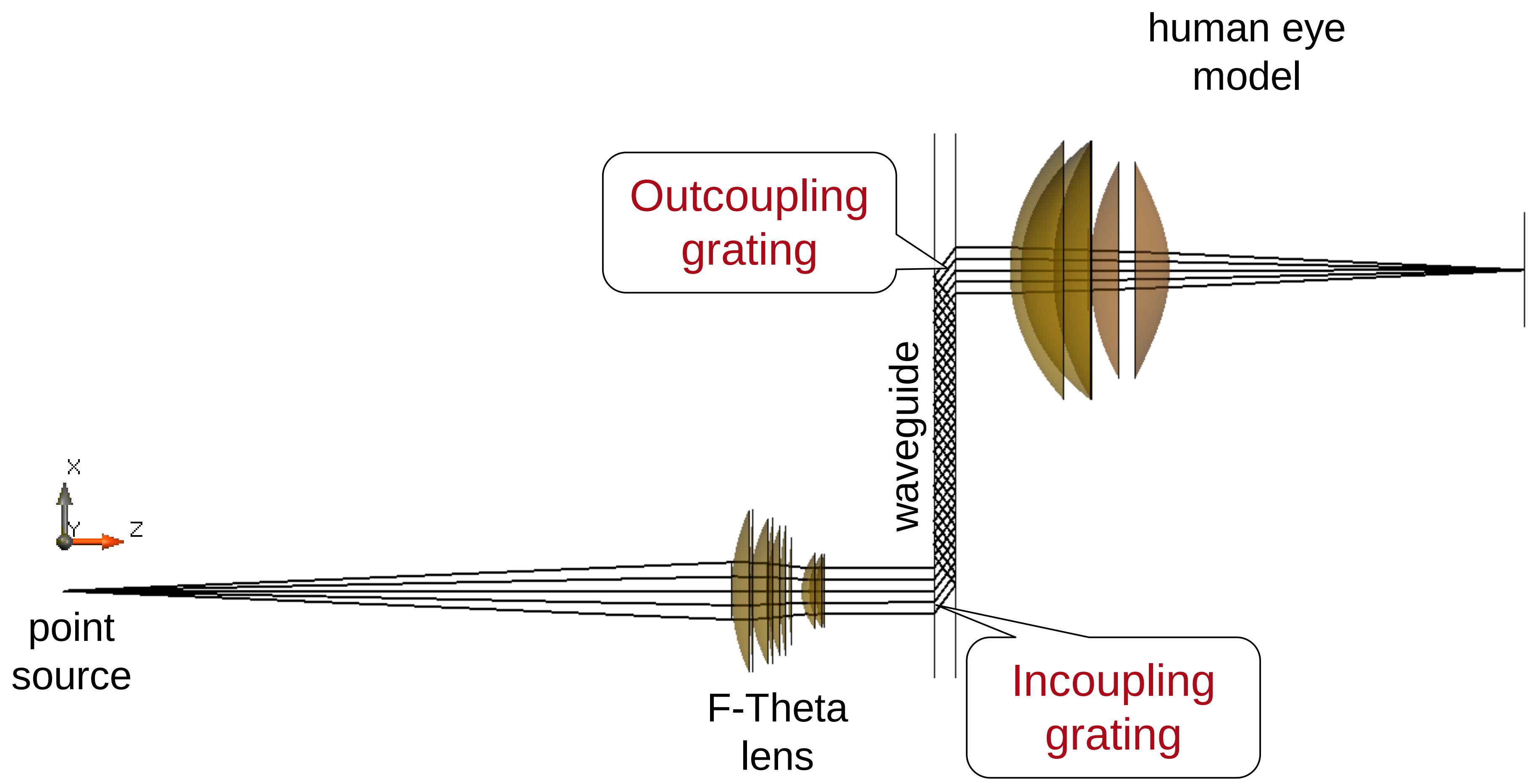


One option for such light guiding is the use of waveguides.

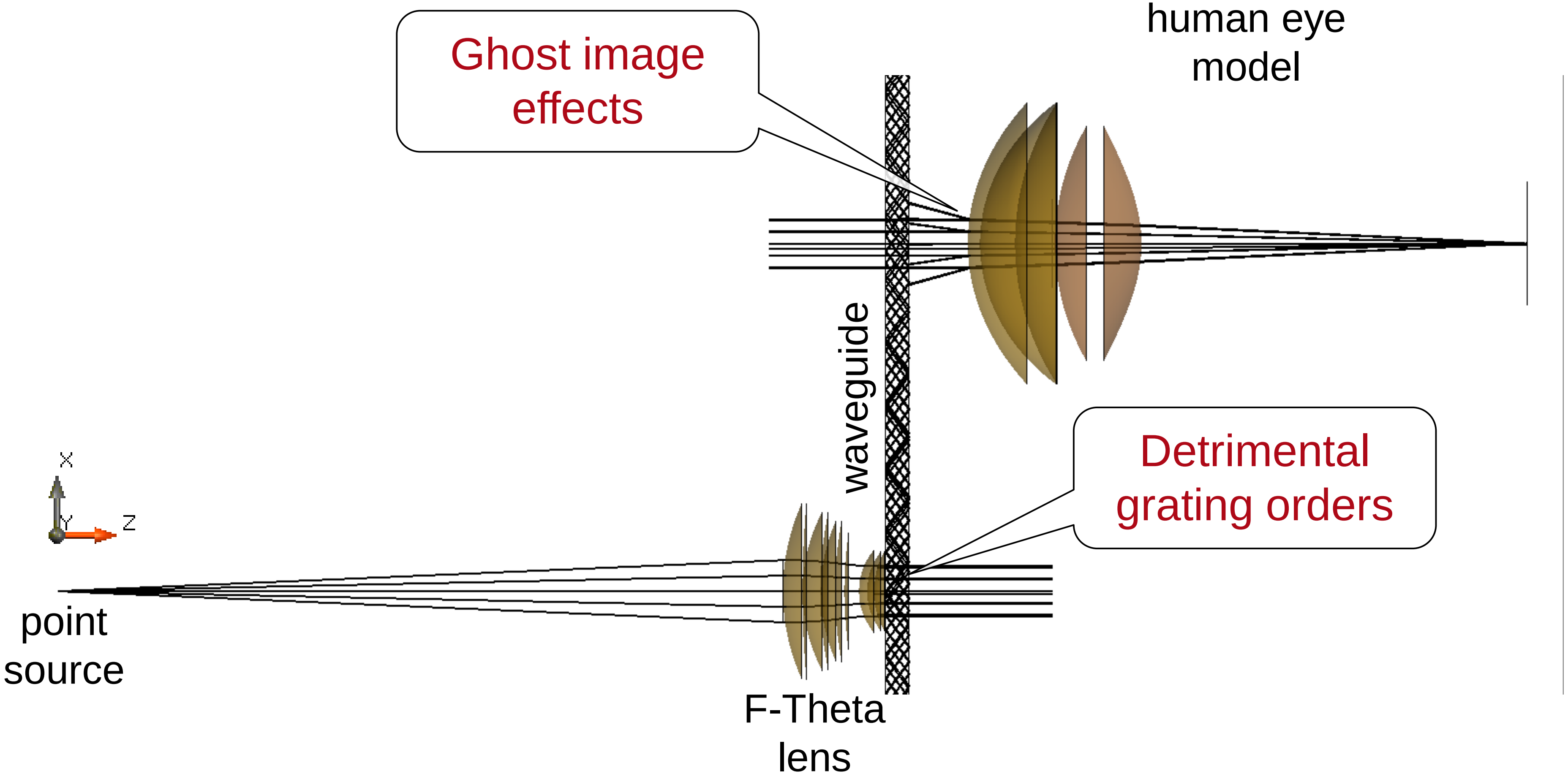
Spatial Guiding of Imaging Channel



Gratings, Detrimental Orders and Ghost Images



Gratings, Detrimental Orders and Ghost Images



Challenges in Modeling of VR/MR

- PSF/MTF calculation for partially filled exit pupils
- Non-sequential modeling of imaging channels

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- PSF/MTF calculation for partially filled exit pupils
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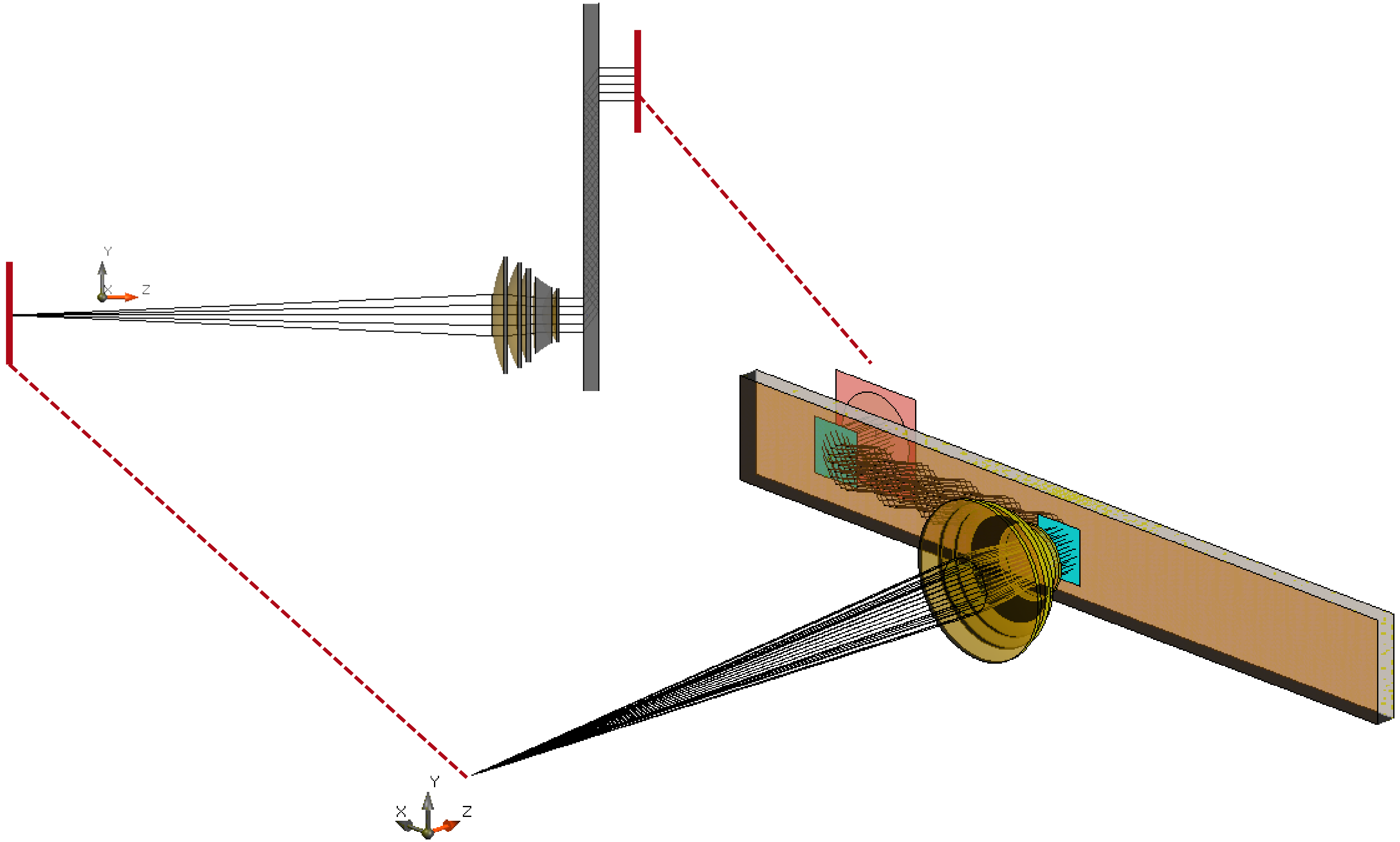
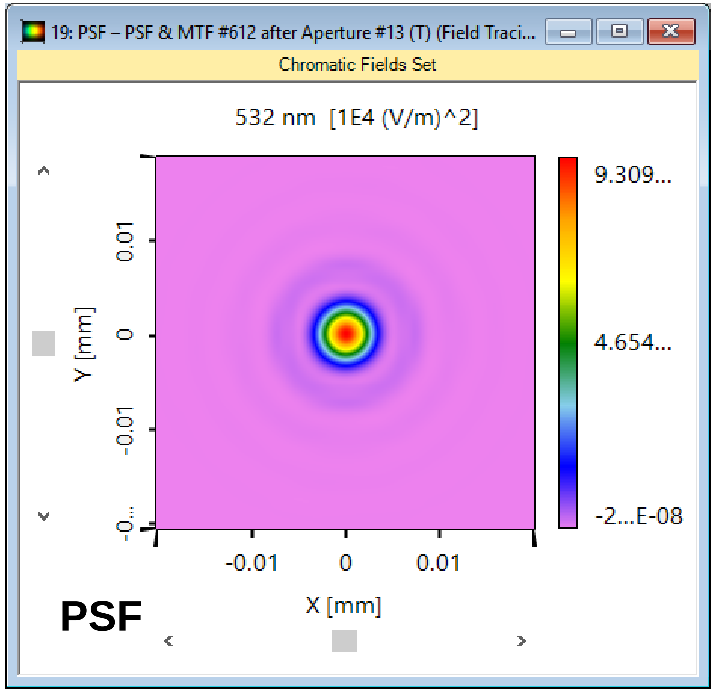
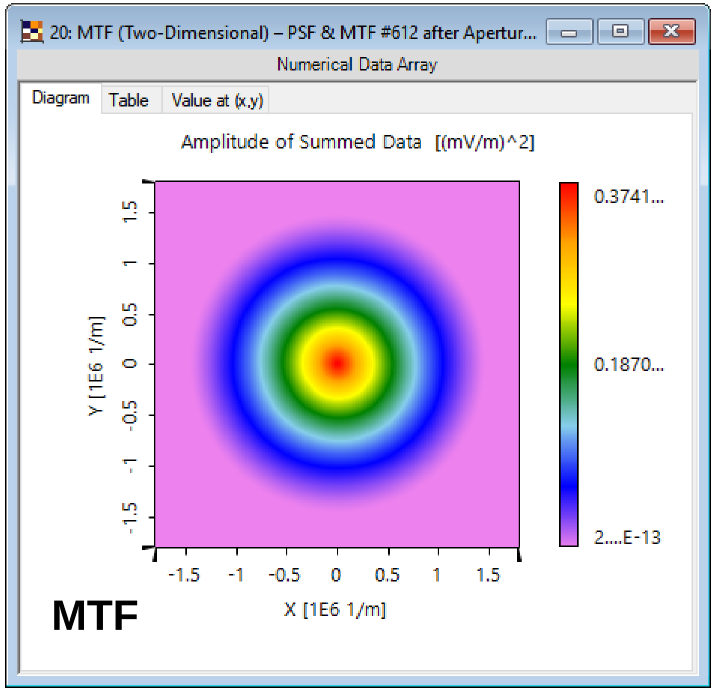
- Imaging channels with gratings
  - Non-sequential lightpath analysis including polarization dependent evaluation of grating effects
  - Inclusion of higher orders and straylight

Result: 3D Ray Tracing



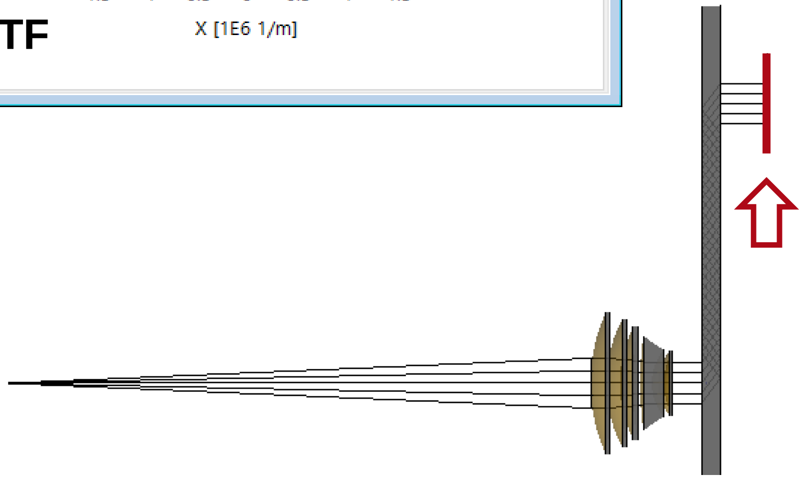
Result: 2D PSF & 2D MTF



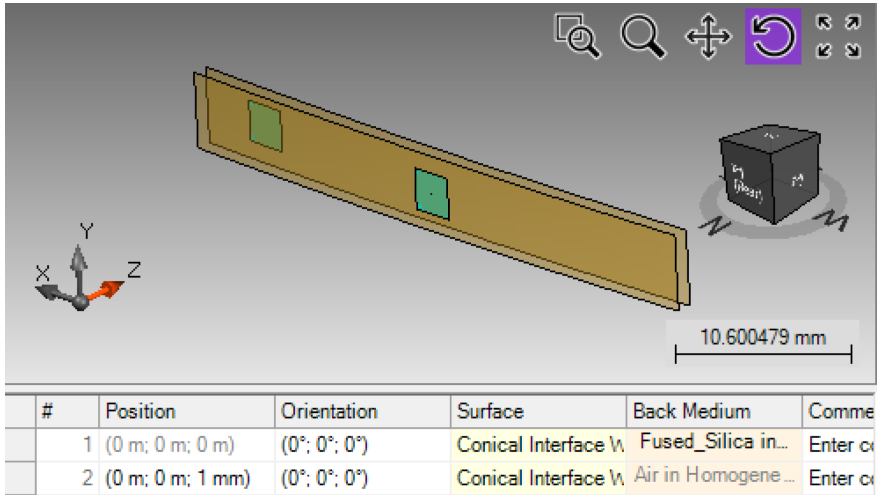


Highlights

- non-sequential analysis of propagation in the waveguide
- regard of wavefront aberrations for PSF and MTF calculation



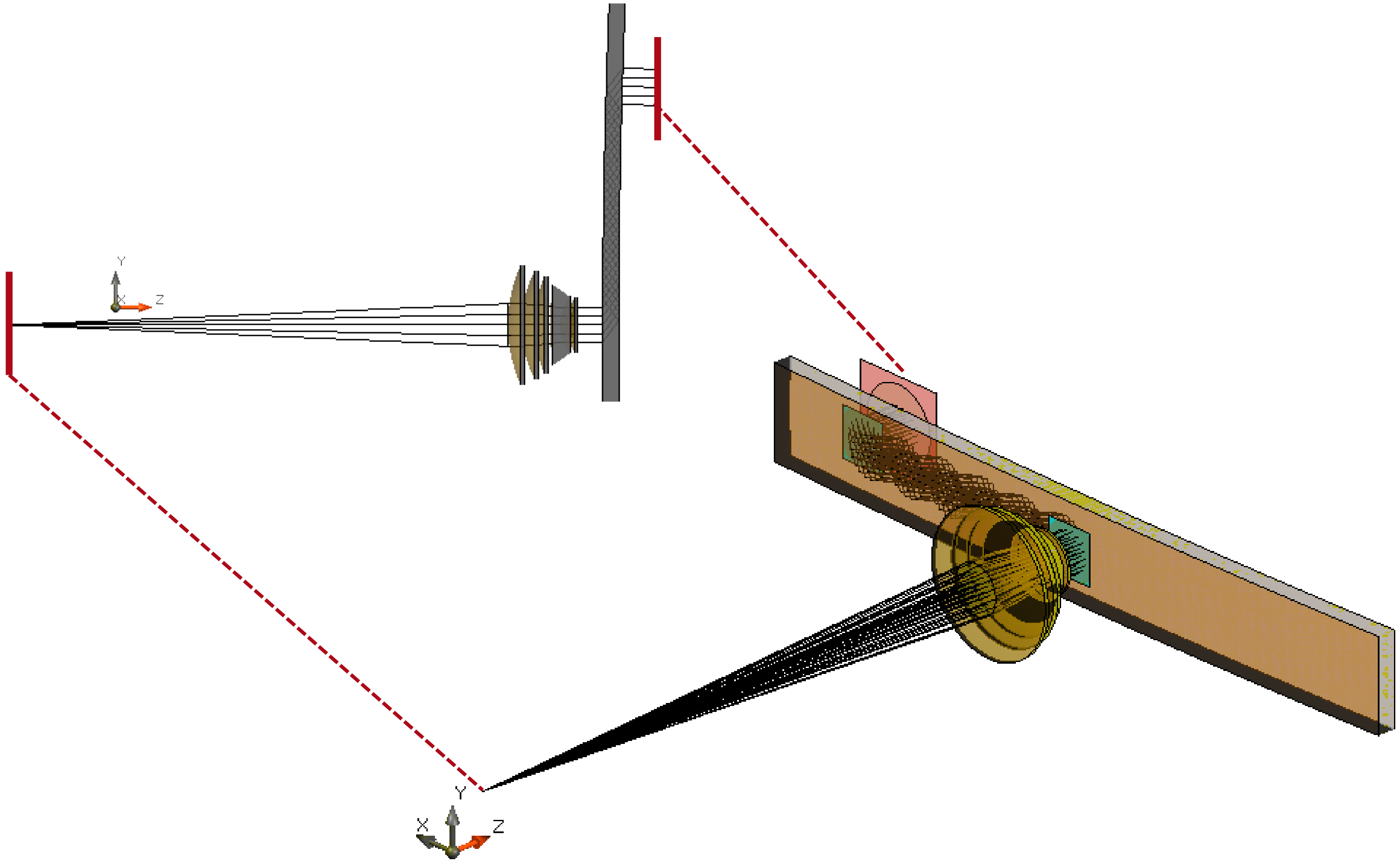
Simulation of Waveguide with Curved Surfaces



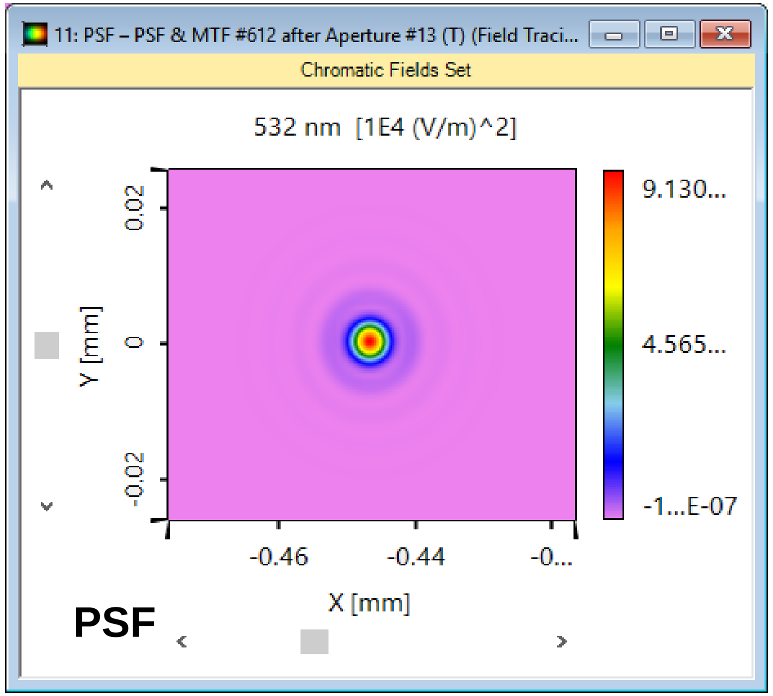
Parameter	Value & Unit
type surface(s)	conical
radius of curvature	500 mm
size of surface(s)	40 x 5 mm
total profile height	6.2500391 µm

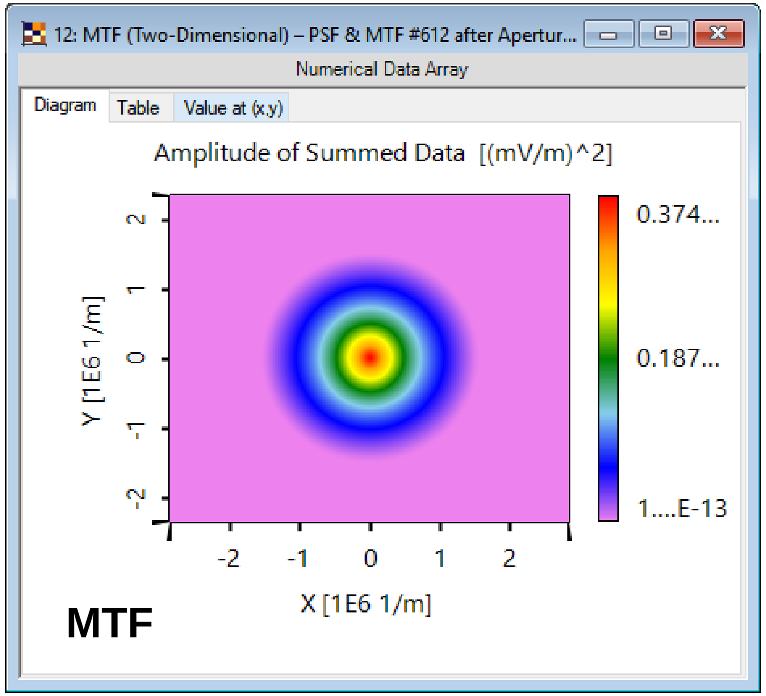
- For waveguide applications it is very important to investigate the effect of surface deformations.
- Therefore we introduce curved surfaces instead of planar surfaces to describe the waveguide stack.

Result: 3D Ray Tracing



Result: 2D PSF & 2D MTF for Curved Surfaces





Highlights

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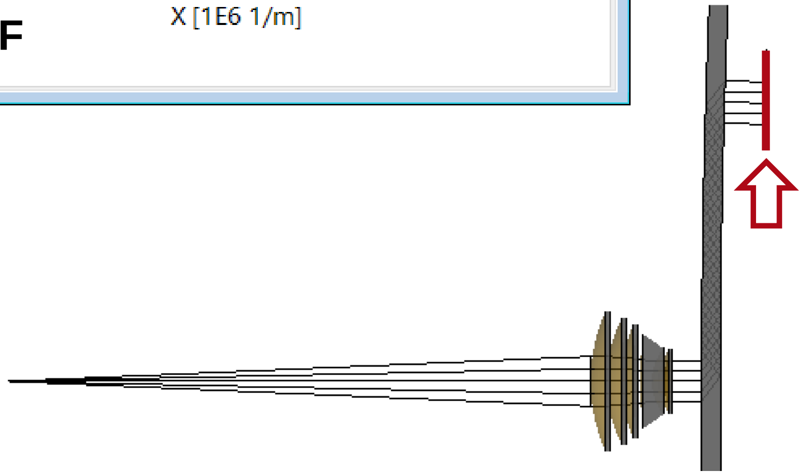
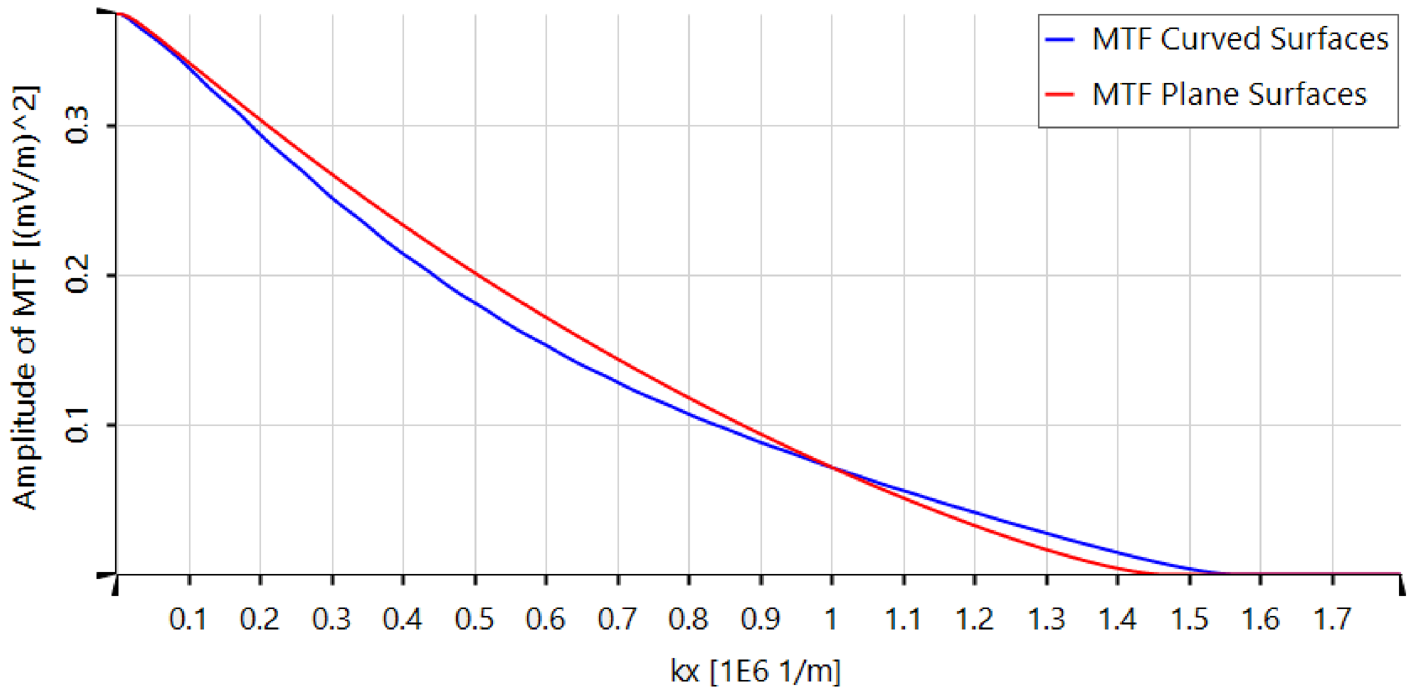


Result: 1D MTF Curved vs. Planar



Highlights

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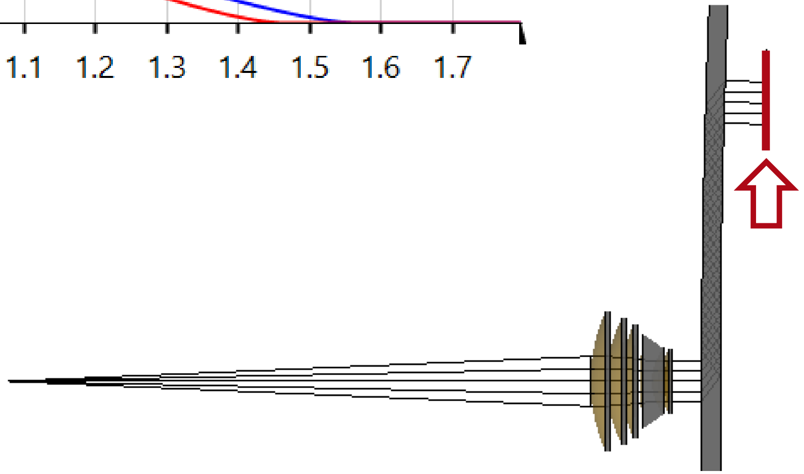
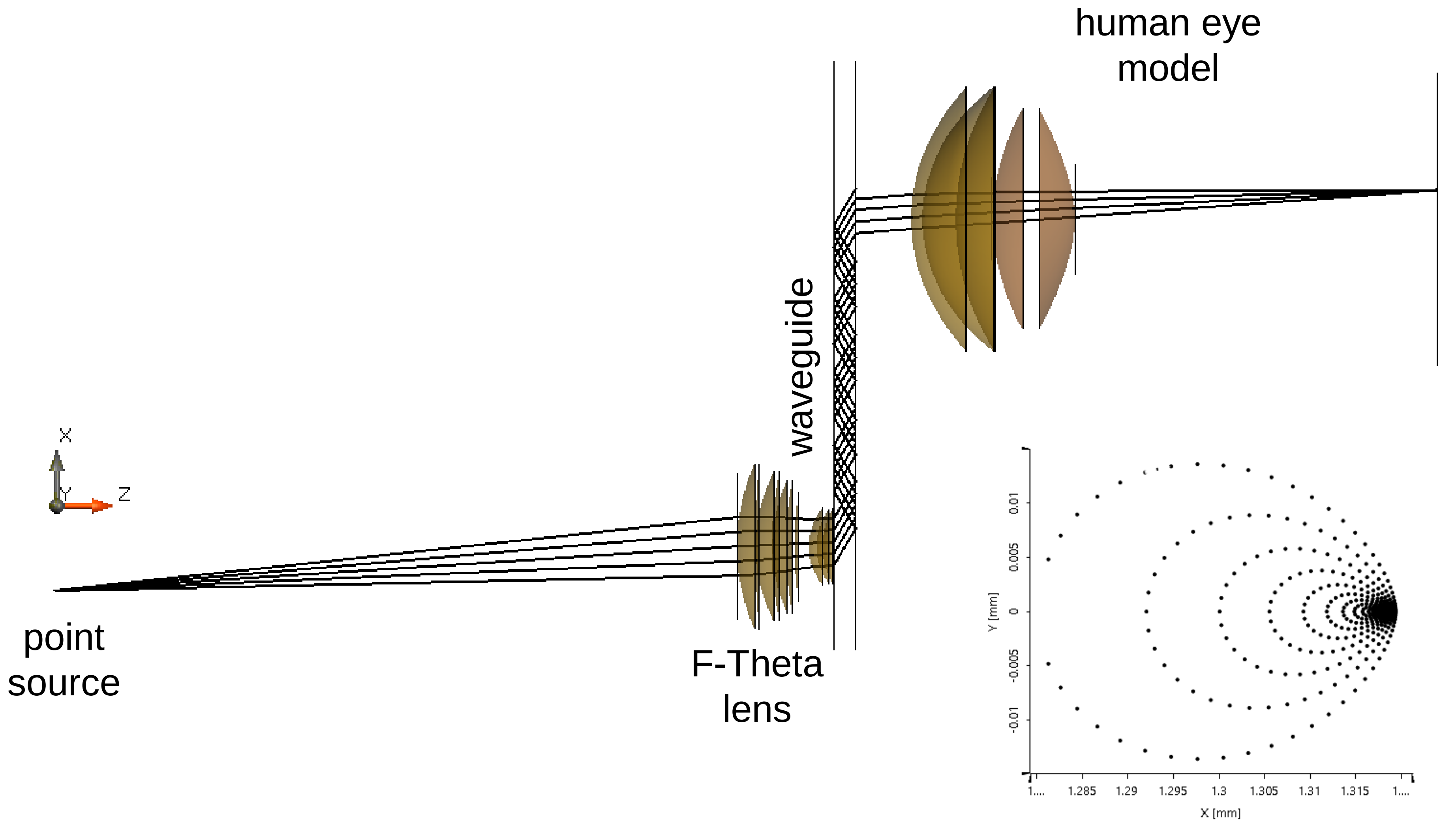
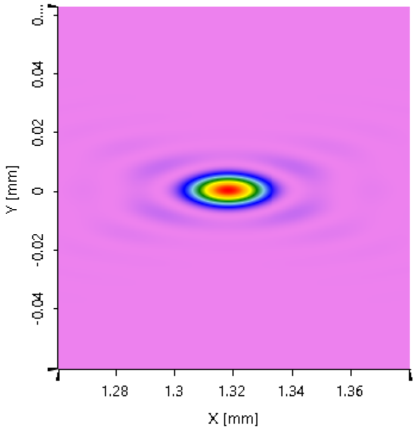


Evaluation of FOV Effects

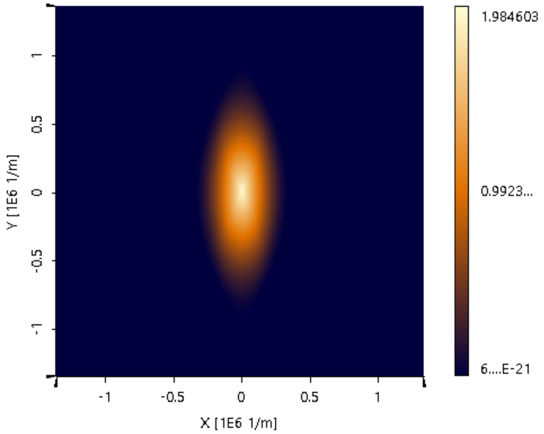


Evaluation in FOV Effects

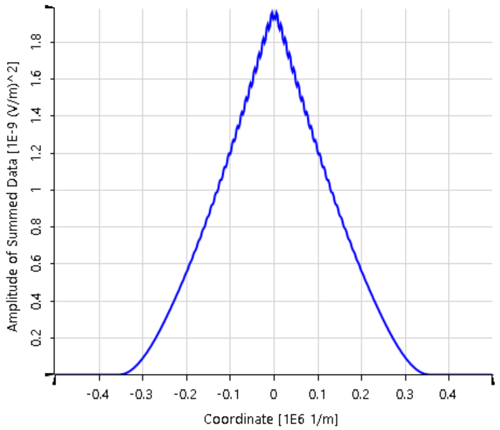
PSF
(Squared Amplitudes)

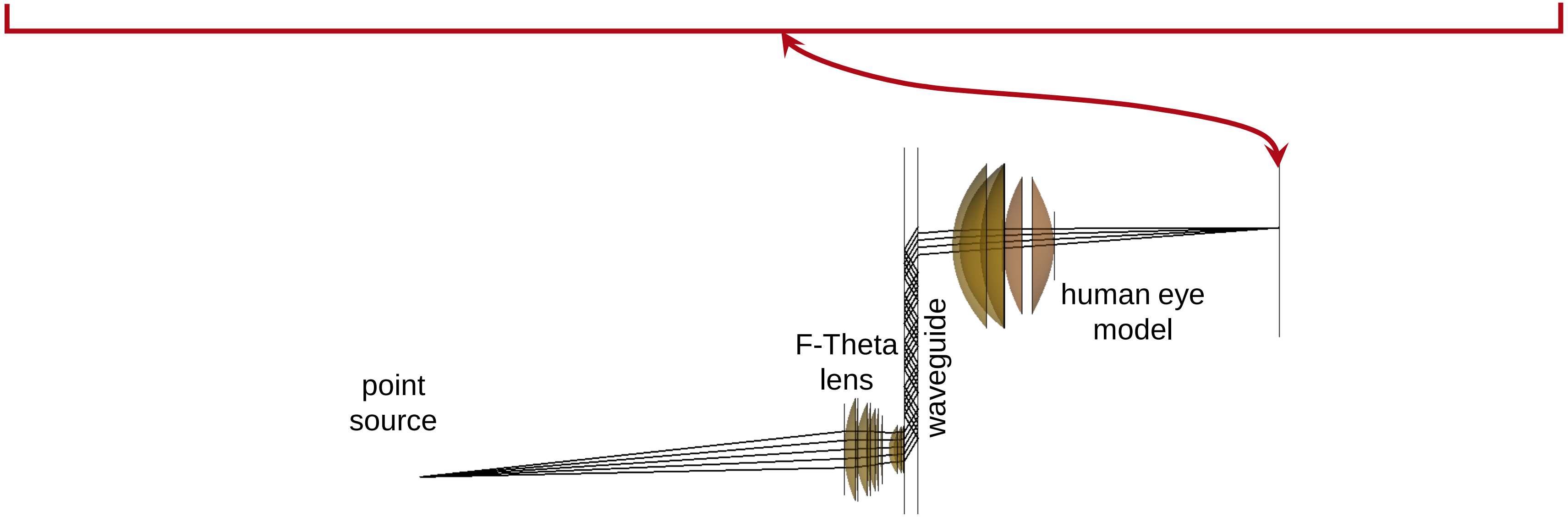


2D MTF



1D MTF (along X)





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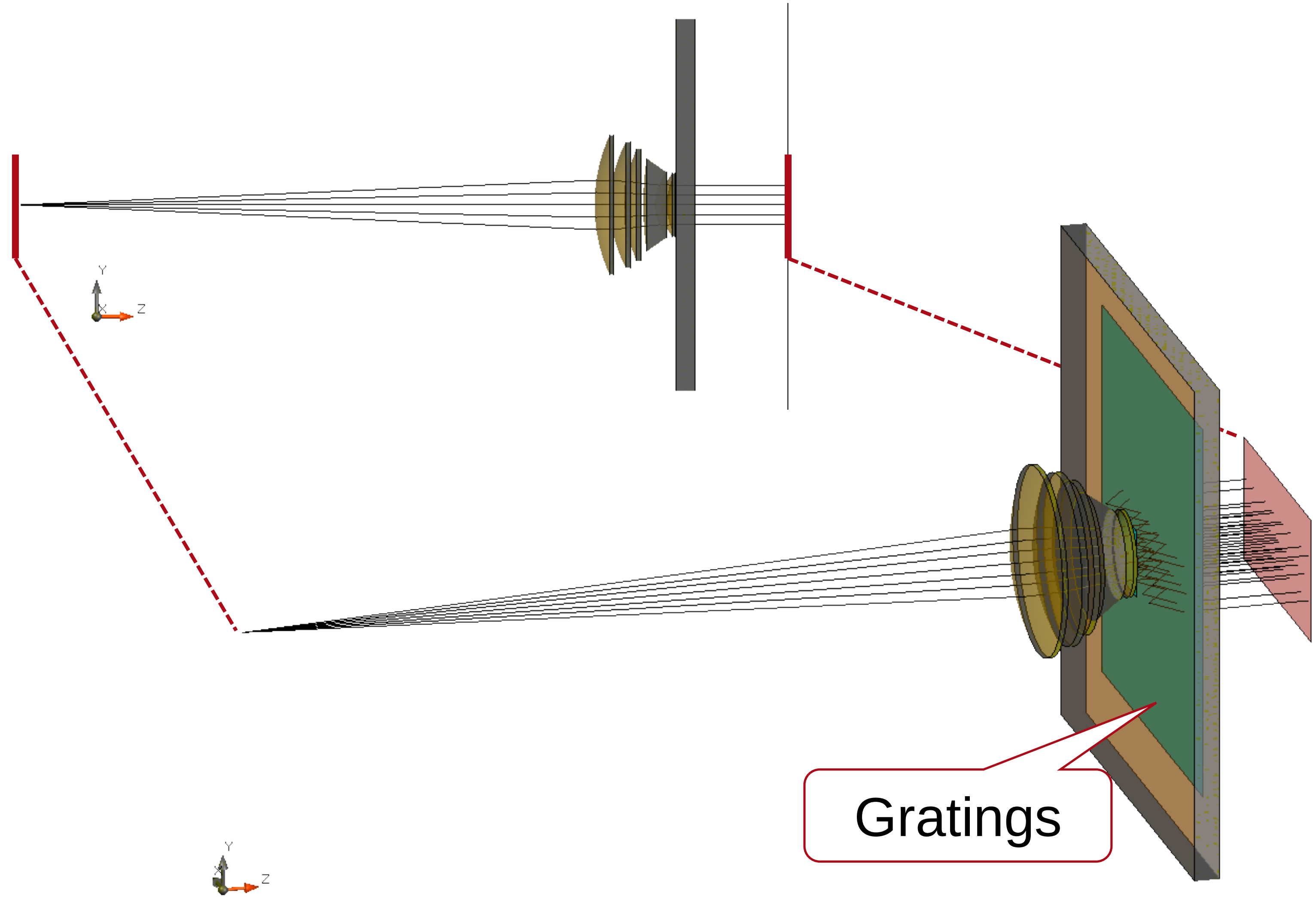
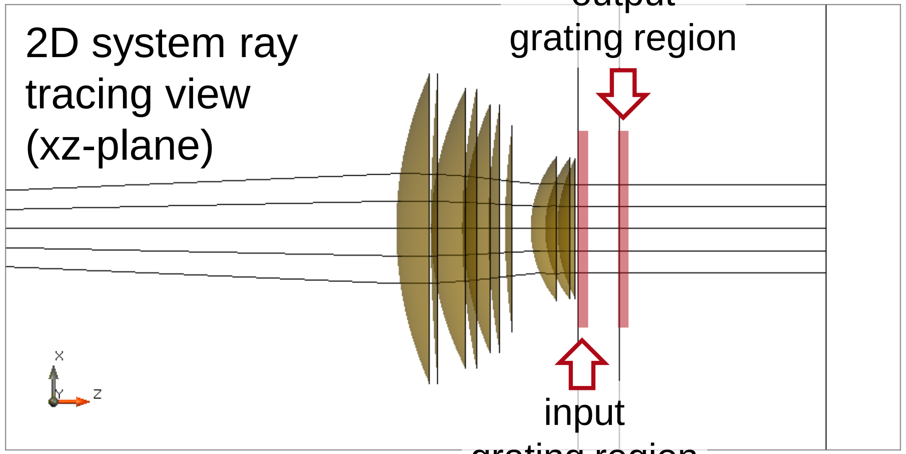
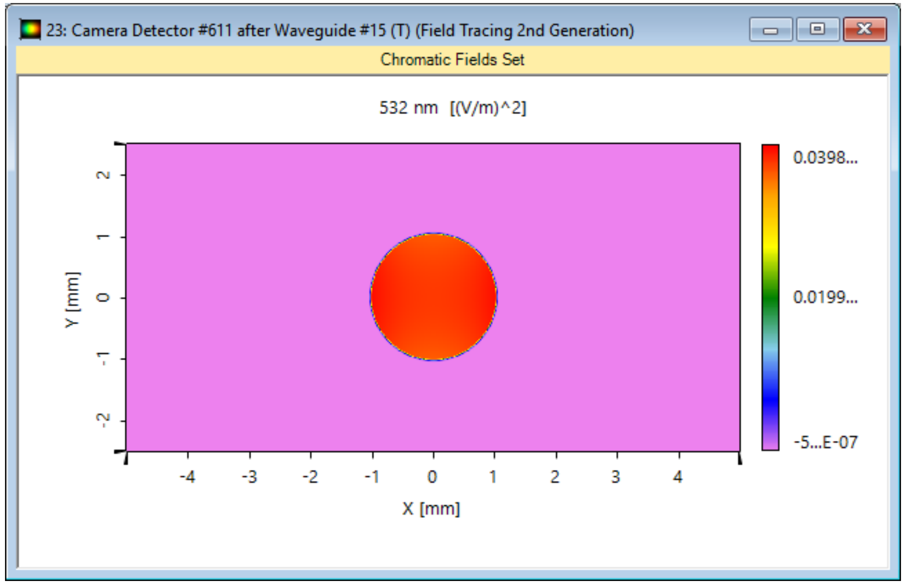
Results: 3D System Ray Tracing



Result I: Only 0th Non-Reflected Orders





Highlights

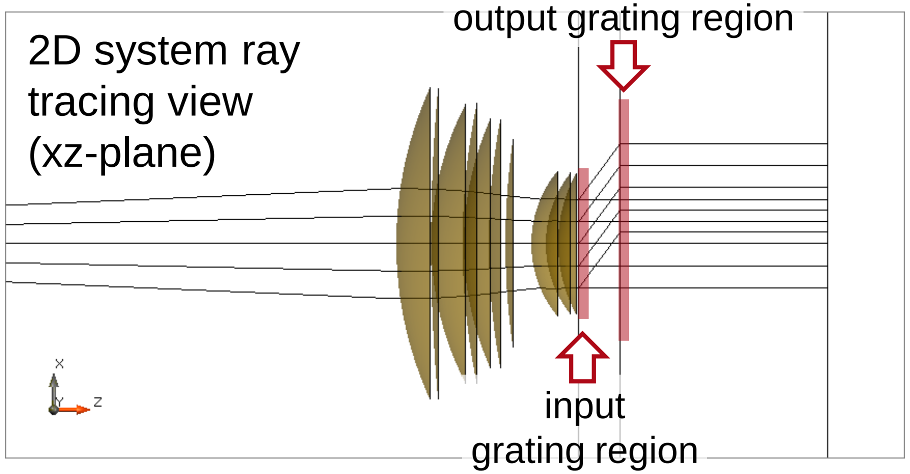
tailored light guiding within a waveguide using surface gratings

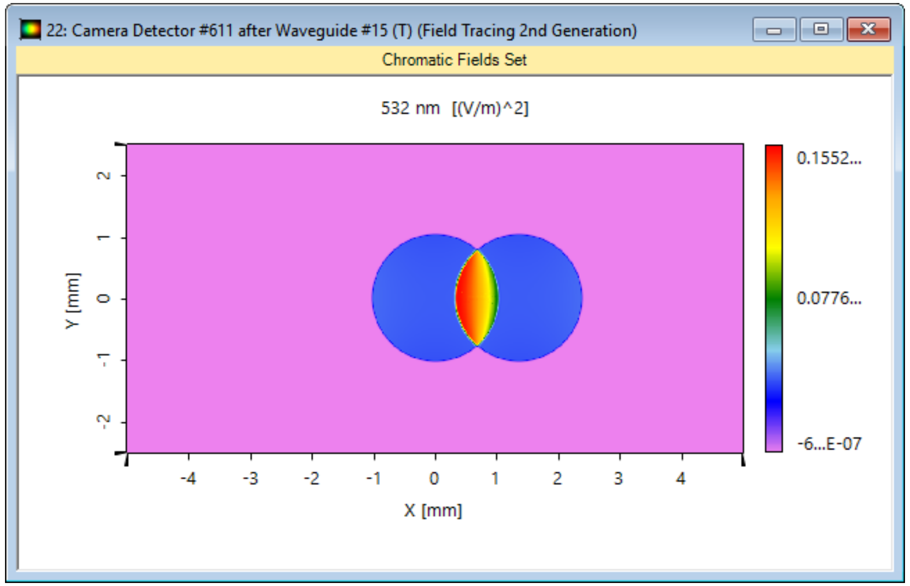
Region	Channel	Order	Efficiency
input	forward	T0	20 %
output	forward	T0	20 %

individual specification option for simulated diffraction order for each region

intensity pattern (inverse rainbow colors) with modulation due to polarization effects from lens surfaces

Result II: Plus +1st Non-Reflected Orders





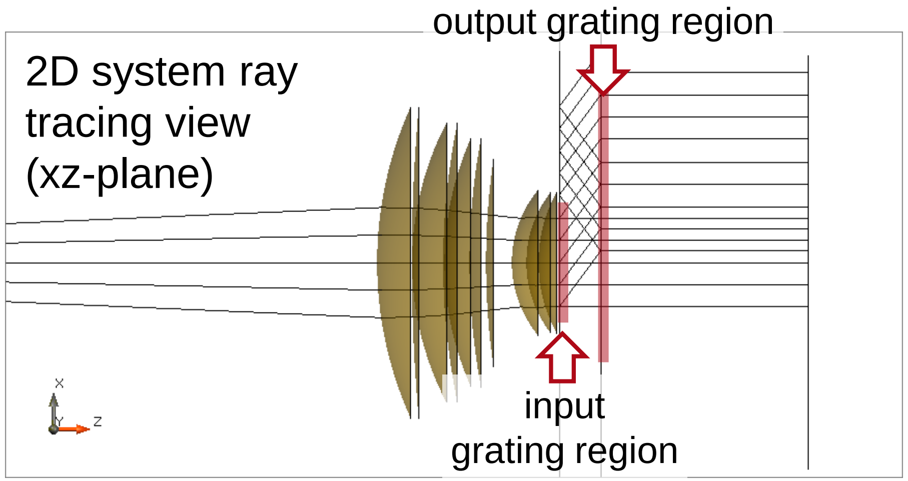
Highlights

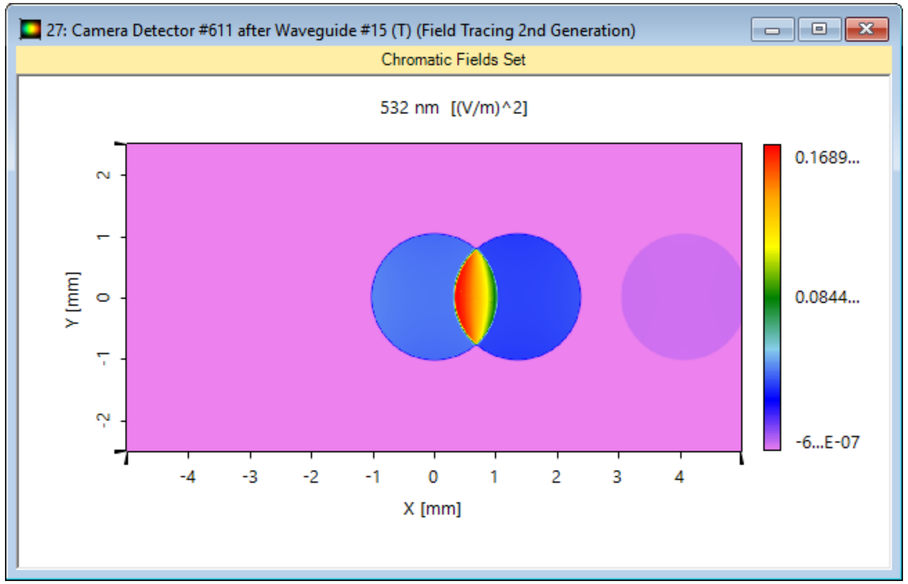
tailored light guiding within a waveguide using surface gratings

Region	Channel	Order	Efficiency
input	forward	T0	20%
input	forward	T+1	20%
output	forward	T0	20%
output	forward	T-1	20%

intensity pattern (inverse rainbow colors)
different order modes are summed coherently

Result III: Plus Back Reflections





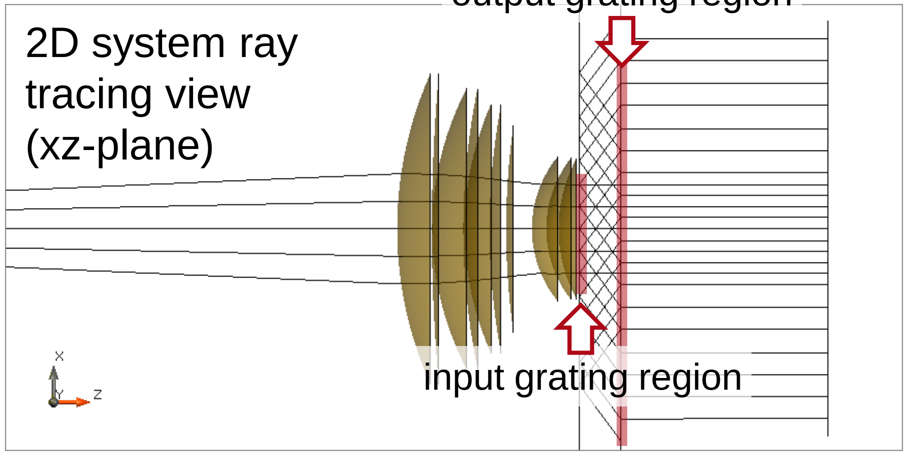
Highlights

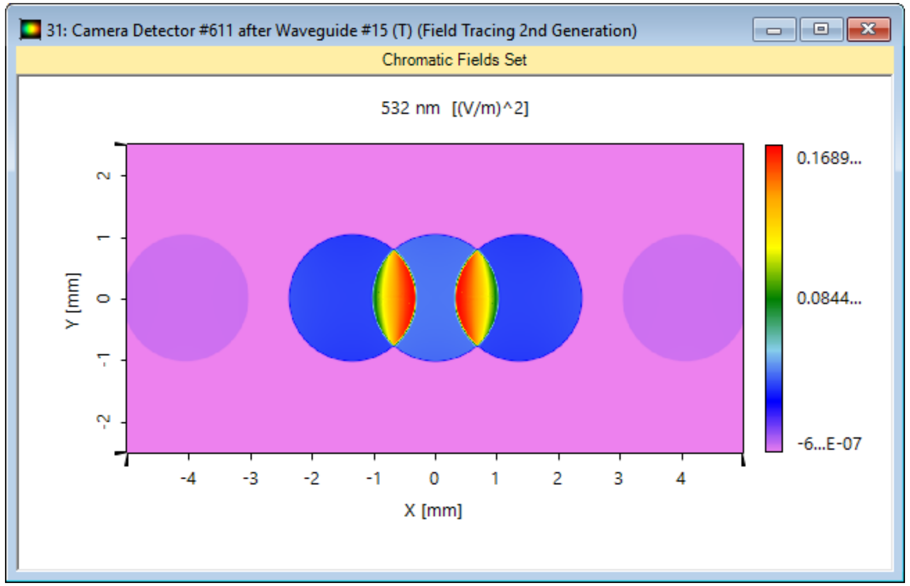
tailored light guiding within a waveguide using surface gratings

Region	Channel	Order	Efficiency
input	forward	T0	20%
input	forward	T+1	20%
input	backward	R0	10%
output	forward	T0	20%
output	forward	R0	10%
output	forward	T-1	20%

intensity pattern (inverse rainbow colors) with multiple reflected light modes

Result IV: Further Multi-Reflected Orders





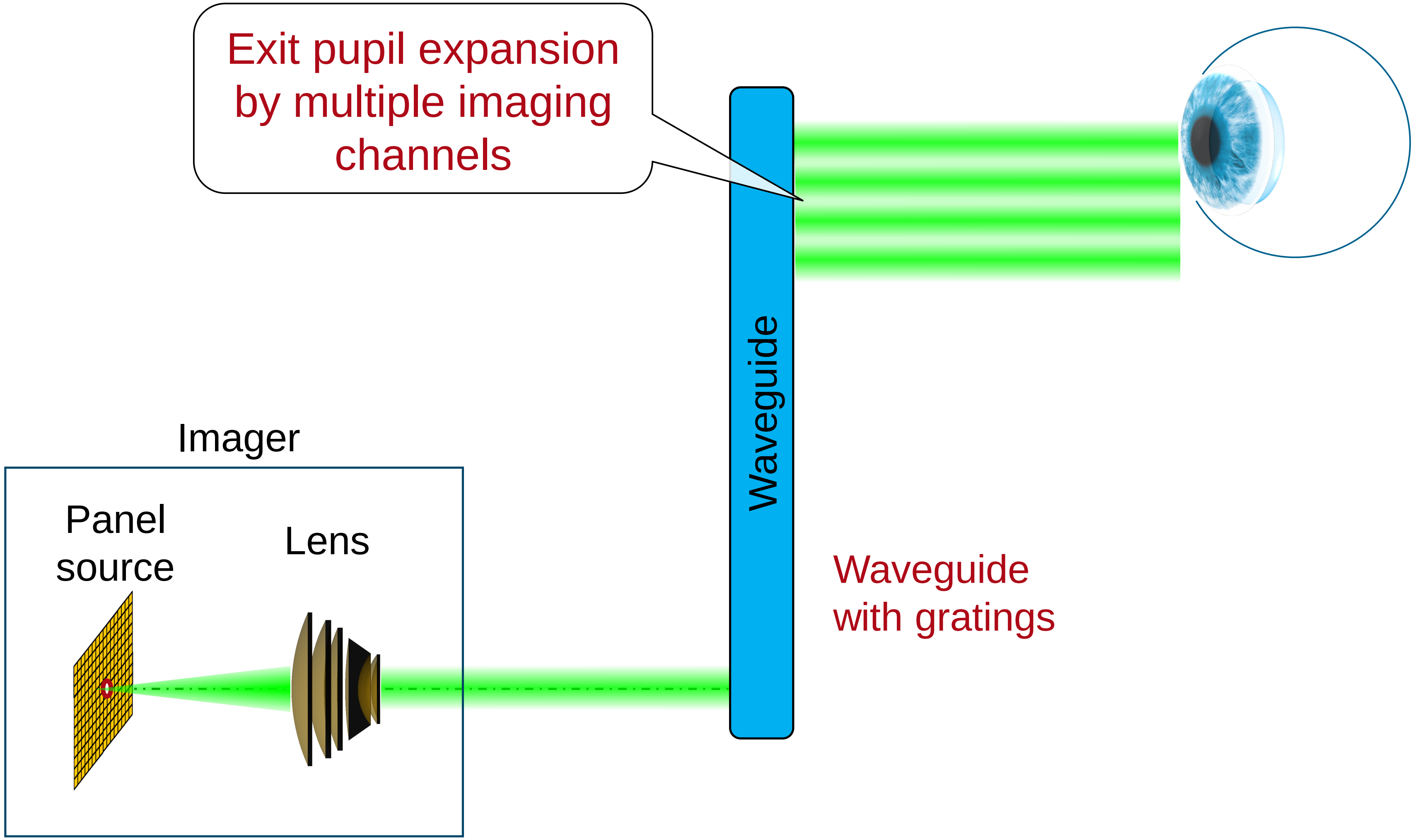
Highlights

tailored light guiding within a waveguide using surface gratings

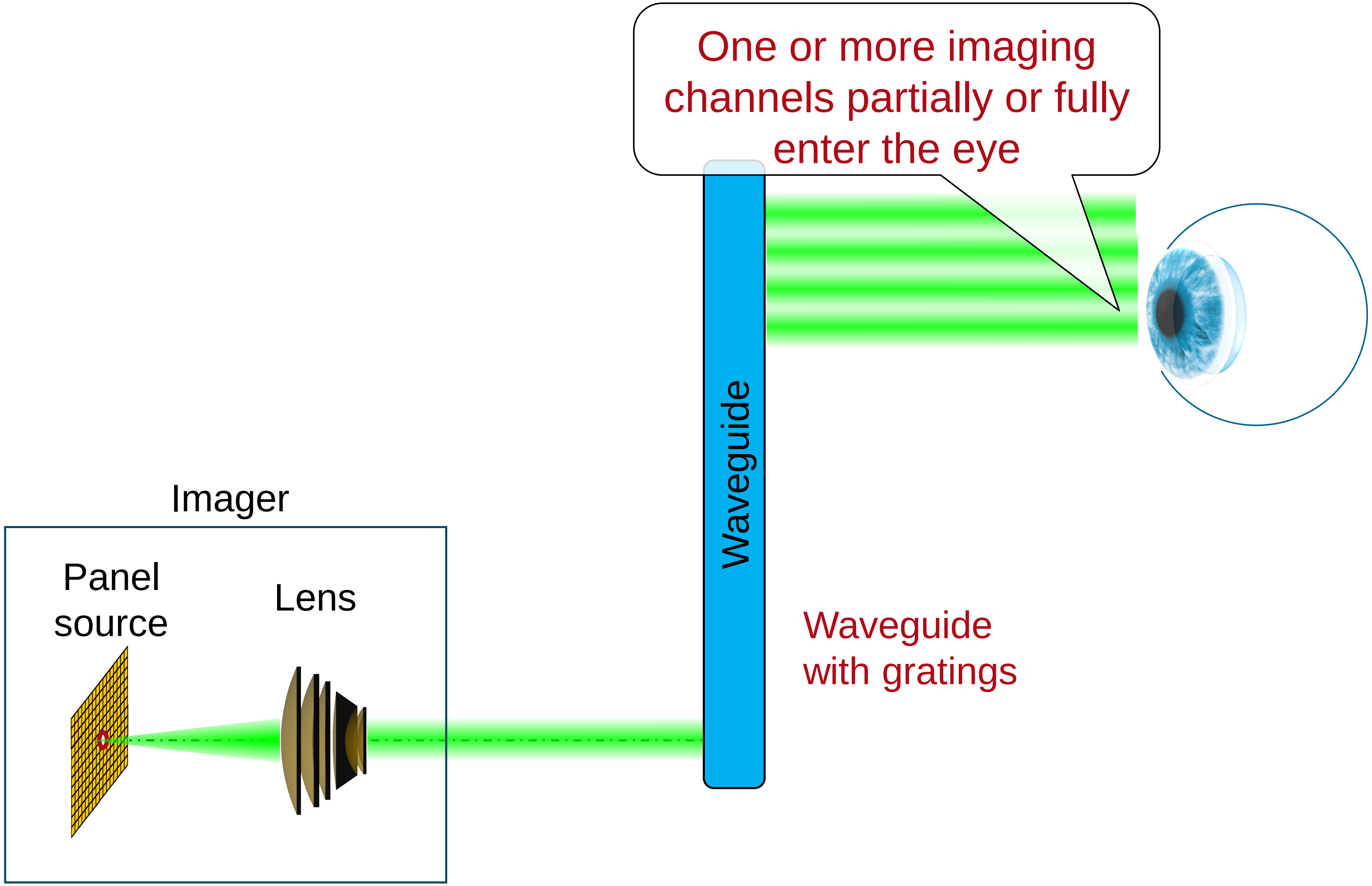
Region	Channel	Order	Efficiency
input	forward	T0	20%
input	forward	T+1	20%
input	forward	T-1	20%
input	backward	R0	10%
output	forward	T0	20%
output	forward	R0	10%
output	forward	T+1	20%
output	forward	T-1	20%

intensity pattern (inverse rainbow colors) with further multiple reflected light modes

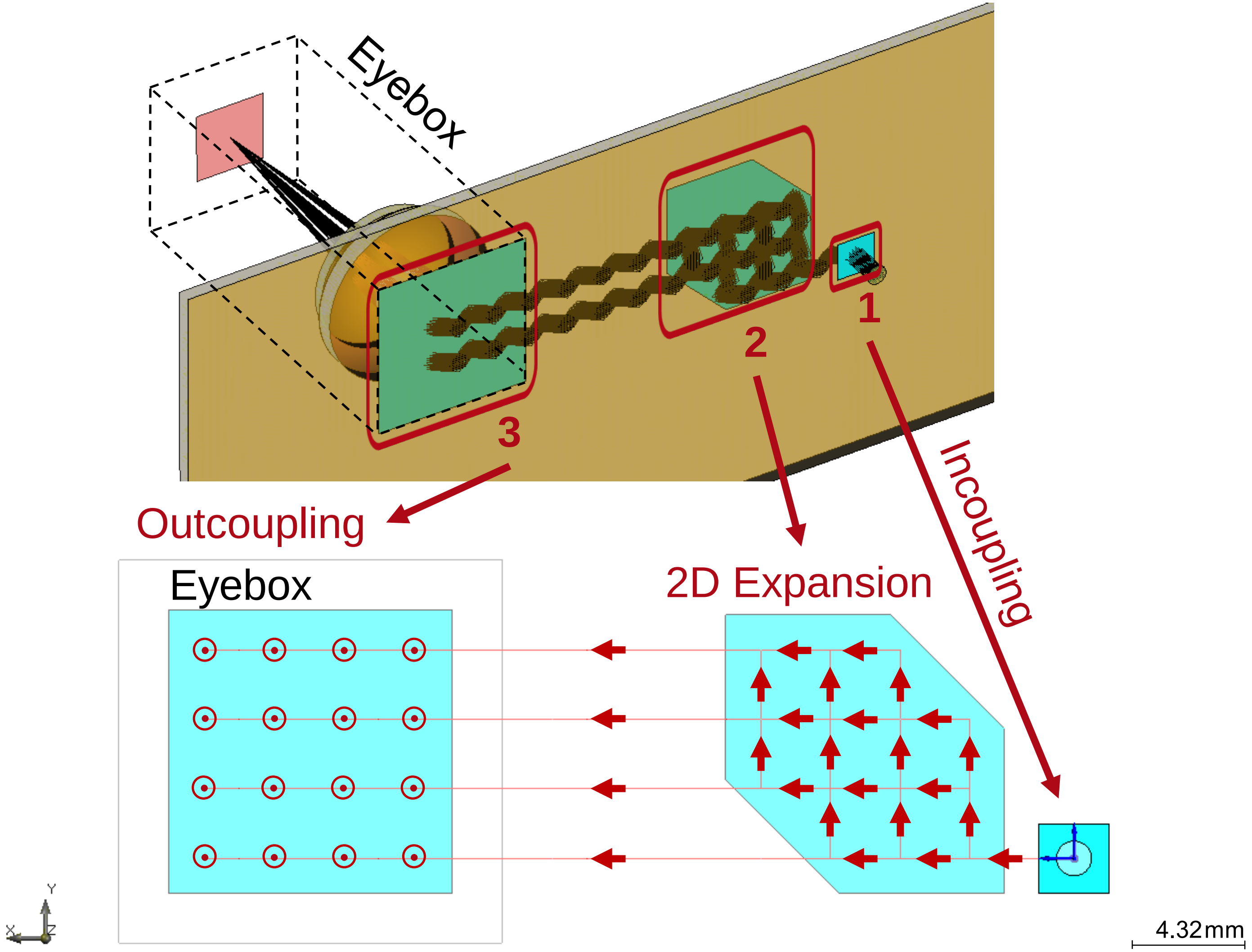
Exit Pupil Expansion



Exit Pupil Expansion



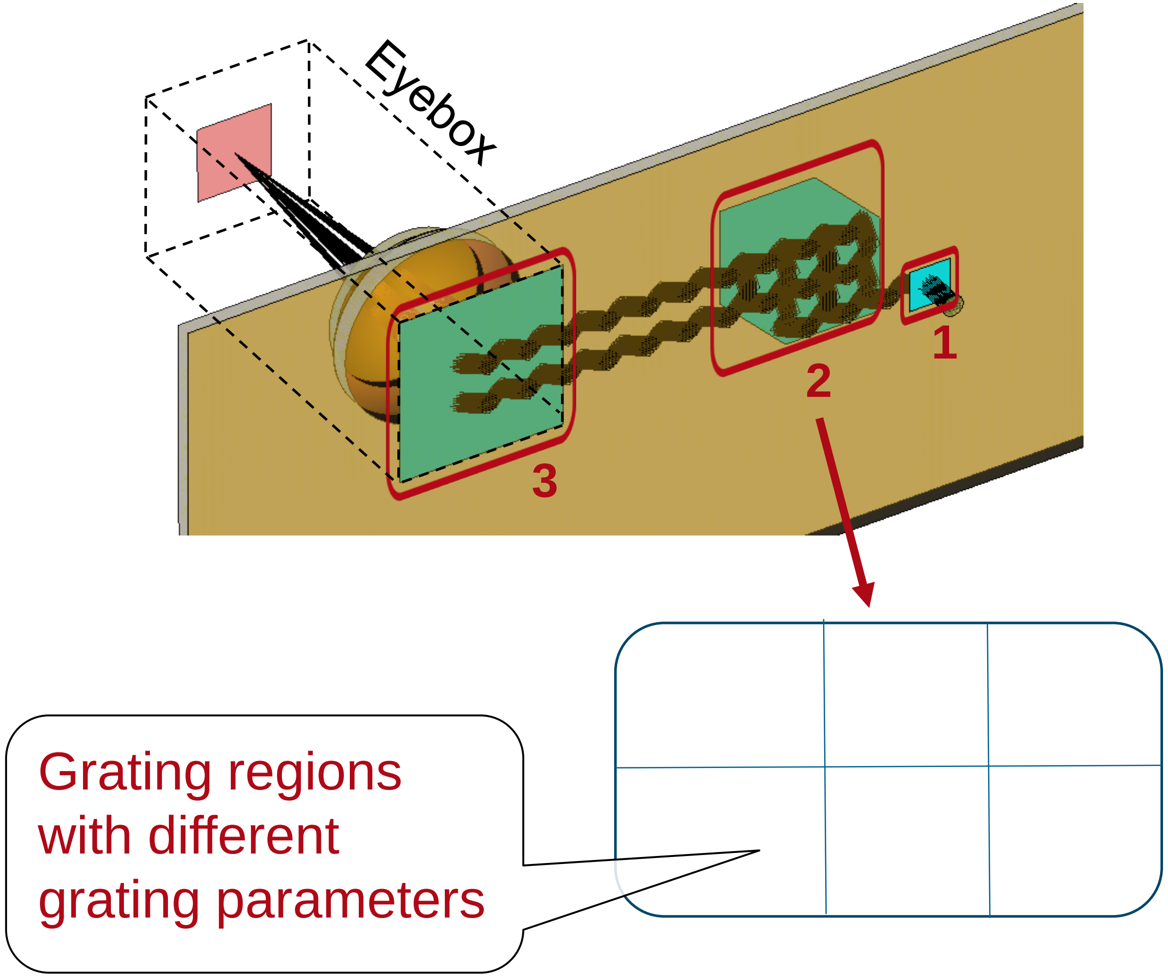
2D Exit Pupil Expansion (Levola)



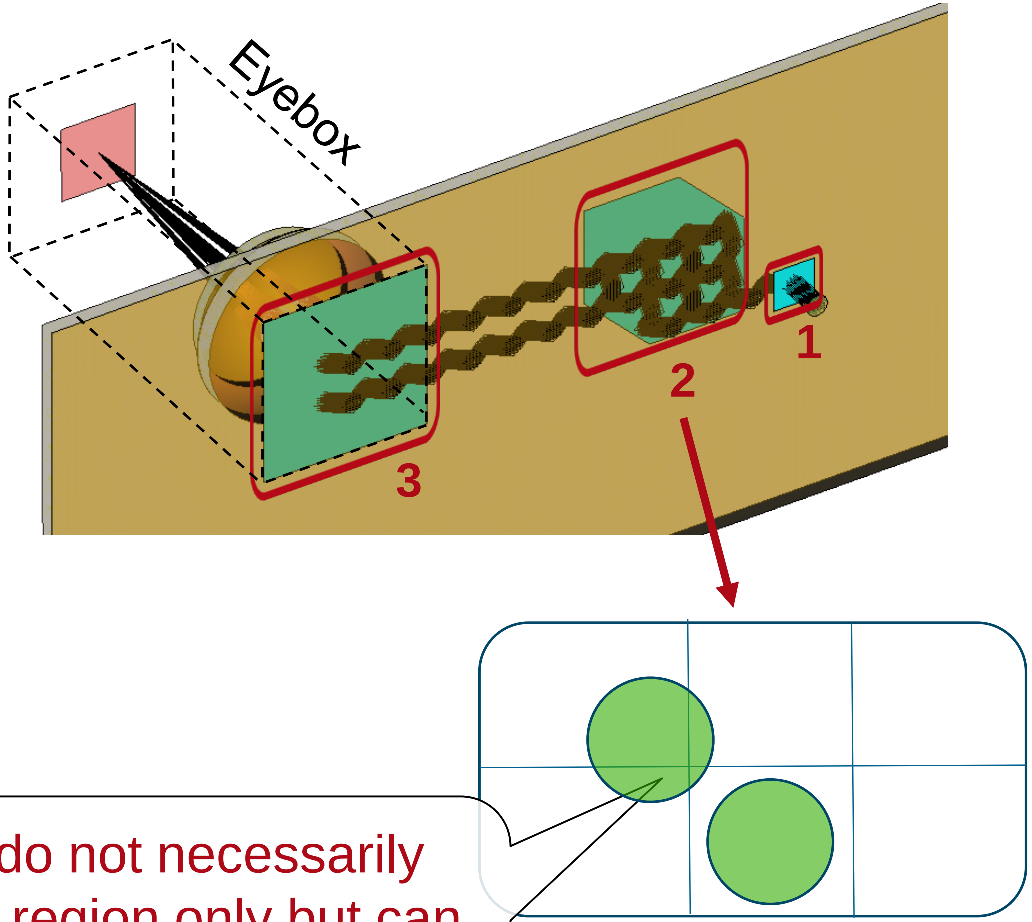
Challenges in Modeling of VR/MR

- PSF/MTF calculation for partially filled exit pupils
- Non-sequential modeling of imaging channels
- Imaging channels with gratings
  - Non-sequential lightpath analysis including polarization dependent evaluation of grating effects
  - Inclusion of higher orders and straylight
- Multichannel imaging system
  - Evaluation of channel distribution in eyebox

Modulated Grating Regions



Aperture Effects at Region Boundaries

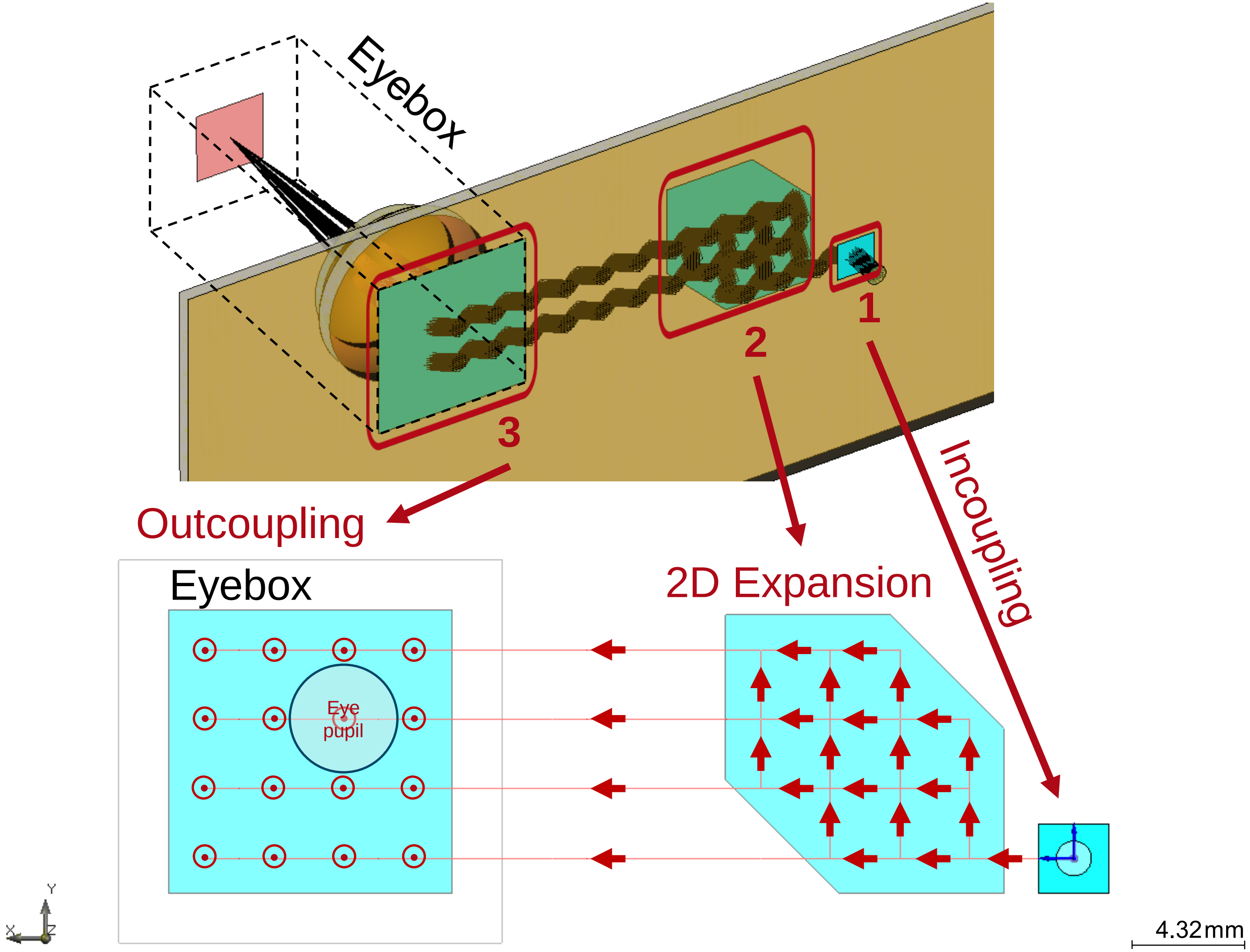


Fields do not necessarily hit one region only but can be split at region boundaries.

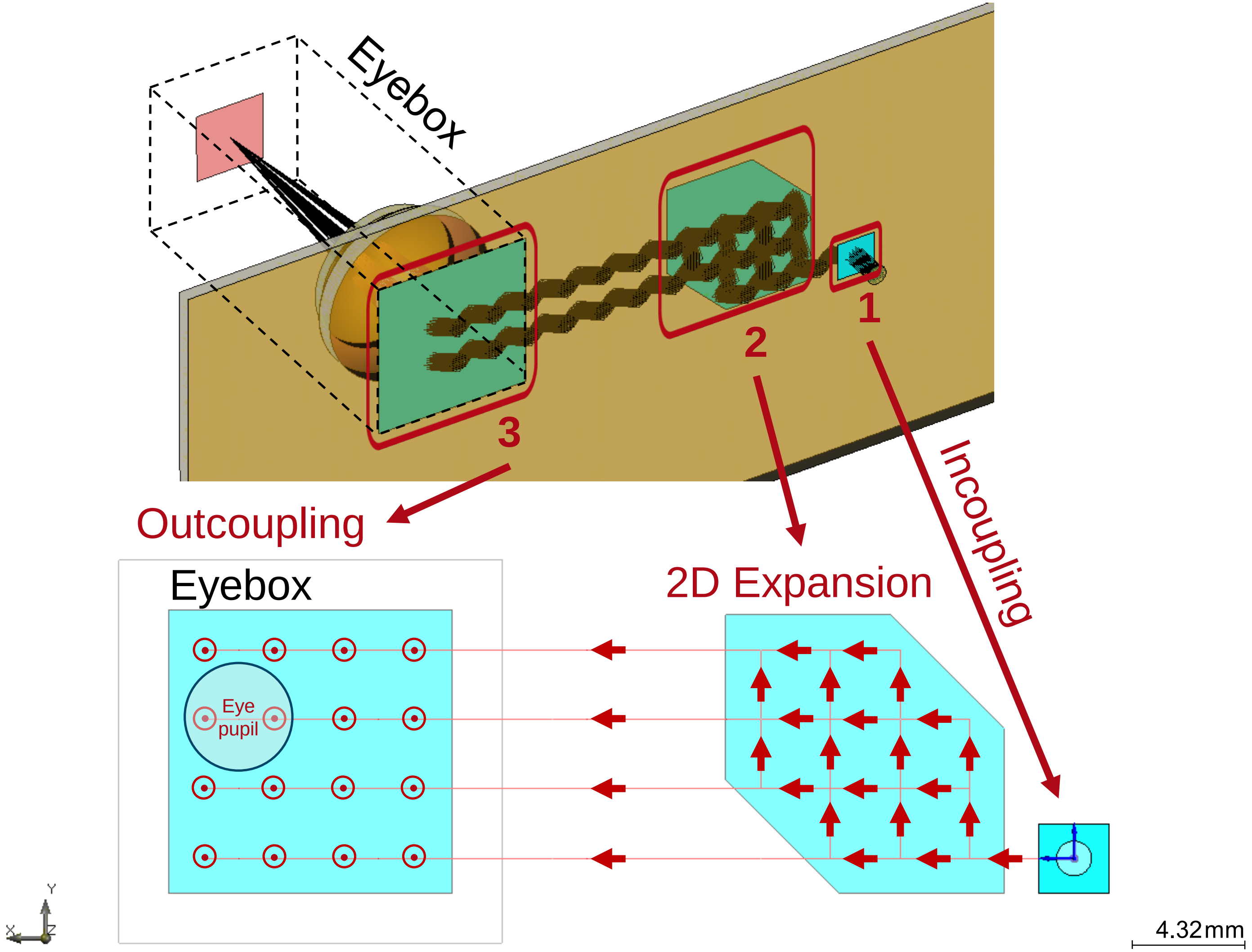
Challenges in Modeling of VR/MR

- PSF/MTF calculation for partially filled exit pupils
- Non-sequential modeling of imaging channels
- Imaging channels with gratings
  - Non-sequential lightpath analysis including polarization dependent evaluation of grating effects
  - Inclusion of higher orders and straylight
- Multichannel imaging system
  - Evaluation of channel distribution in eyebox
  - Multiple aperture effects along lightpath of each channel

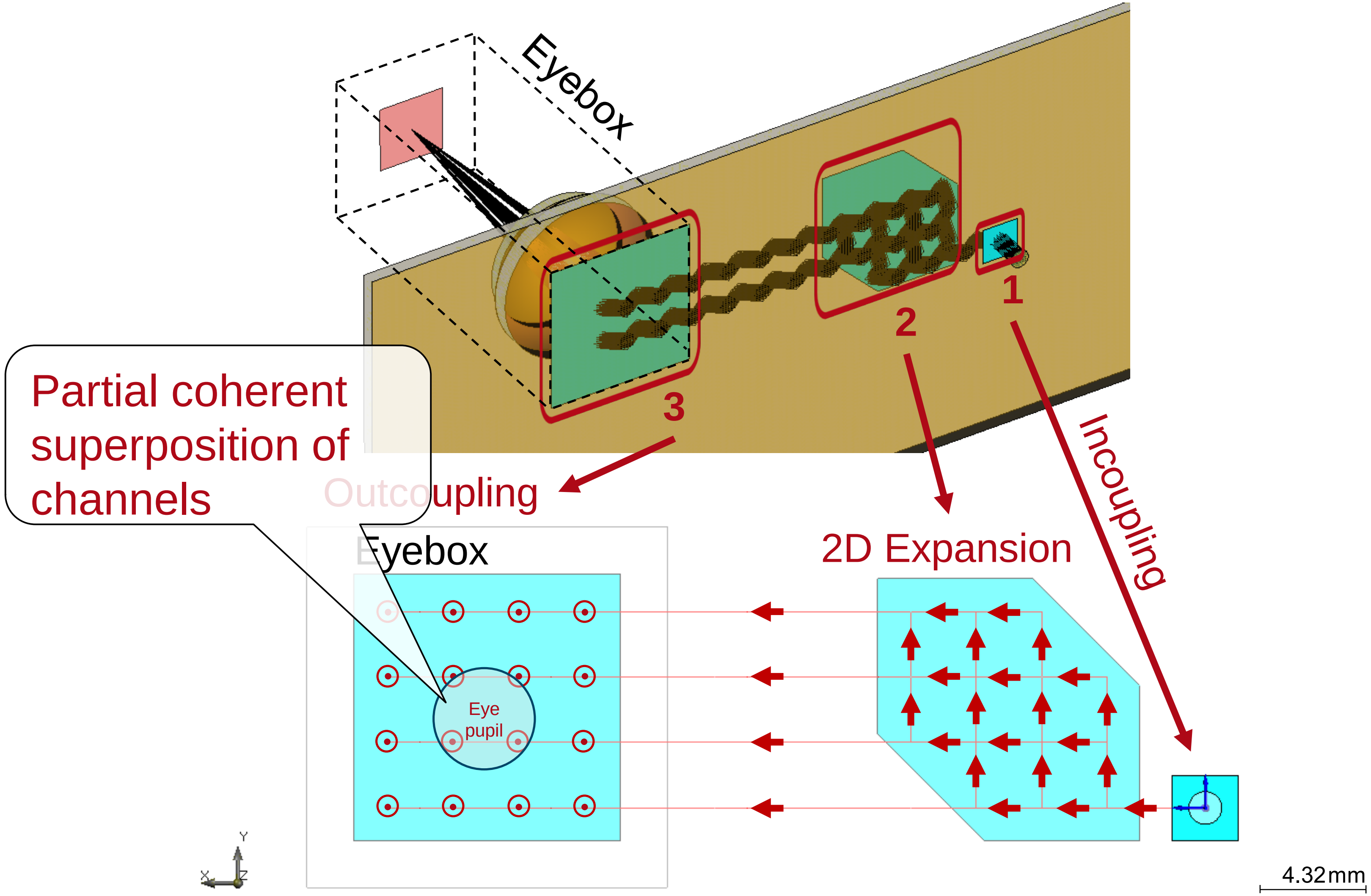
Multiple Channels in Eye Pupil



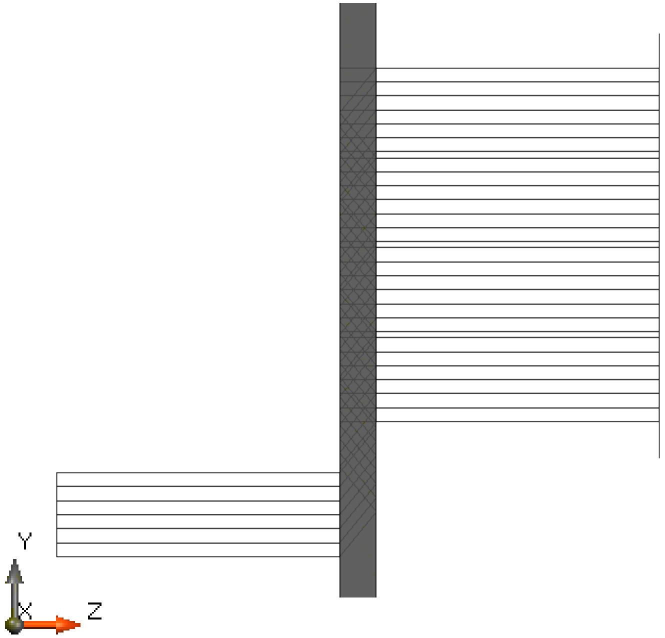
Multiple Channels in Eye Pupil

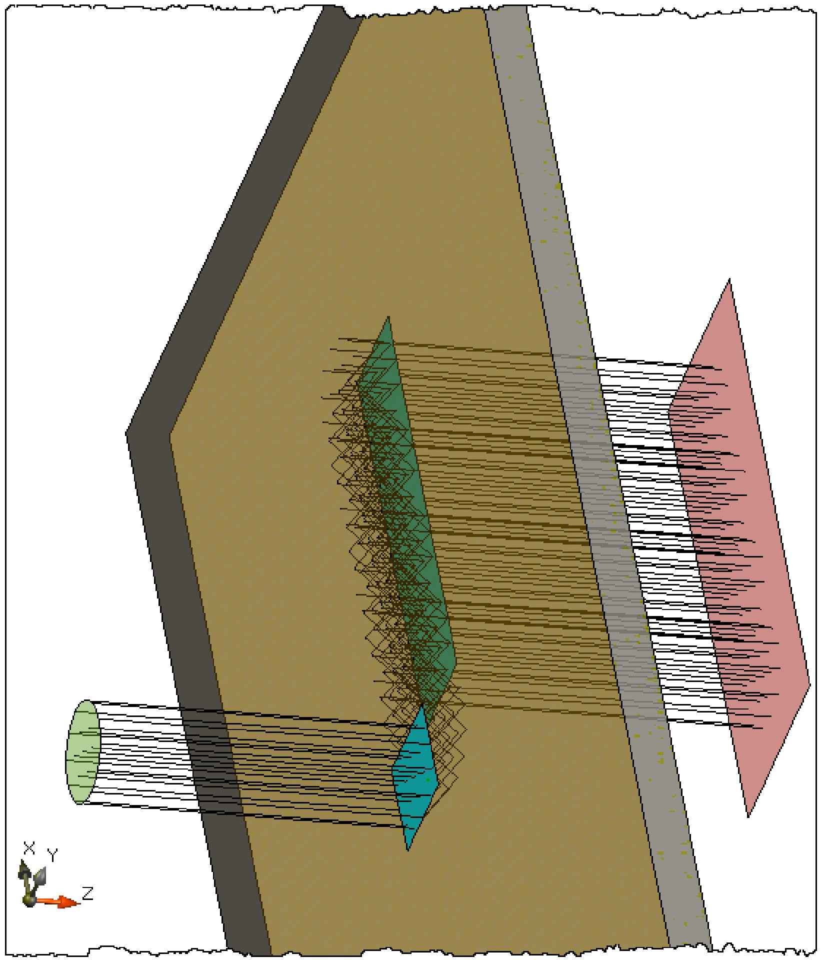


Multiple Channels in Eye Pupil

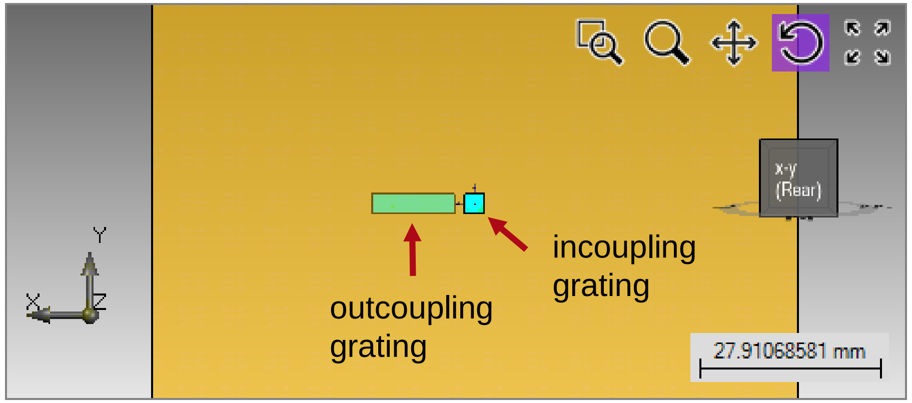


Results: 3D System Ray Tracing

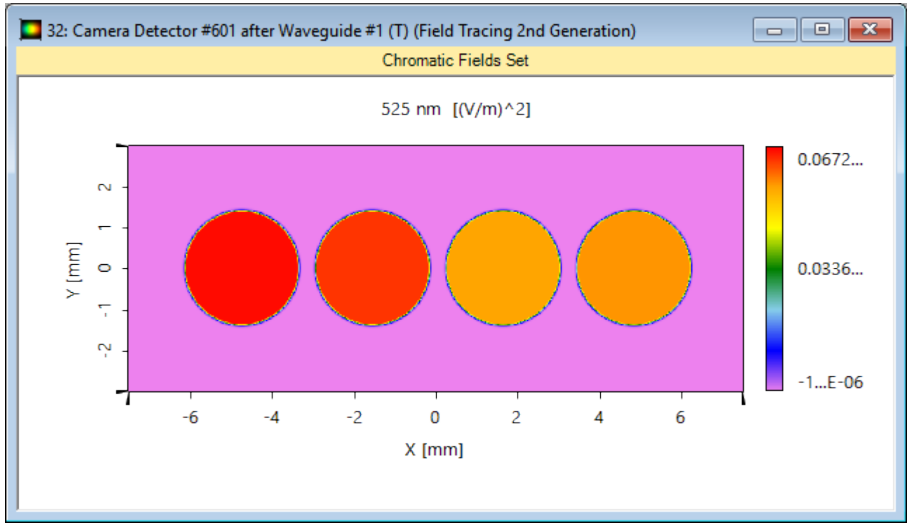




Results: One Outcoupling Grating



intensity pattern (false color view)

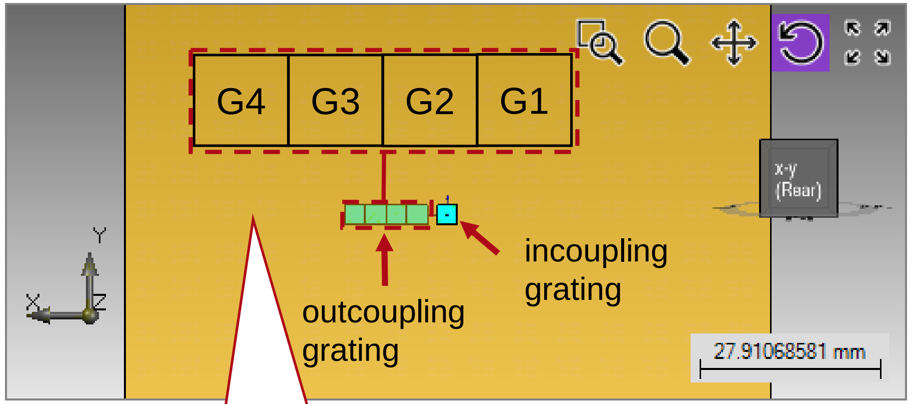


Highlights

- waveguide simulations including rigorously calculated efficiencies of sub-wavelength grating structures

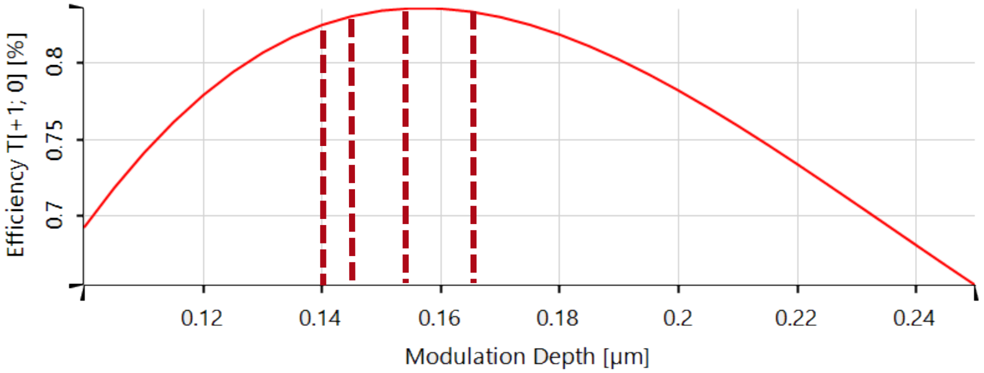
Grating Parameter	Value & Unit
type	sawtooth grating
period	395 nm
height	140 nm

Results: Four Optimized Outcoupling Gratings



segmentation of outcoupling grating

different grating depths of each segment for optimized efficiencies

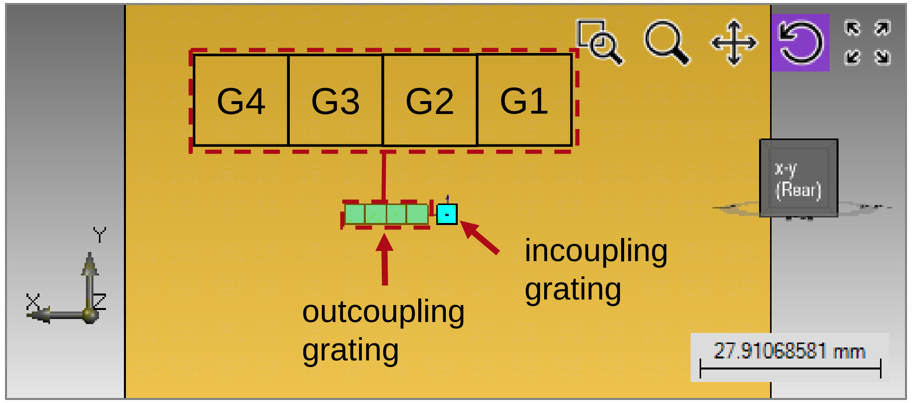


Highlights

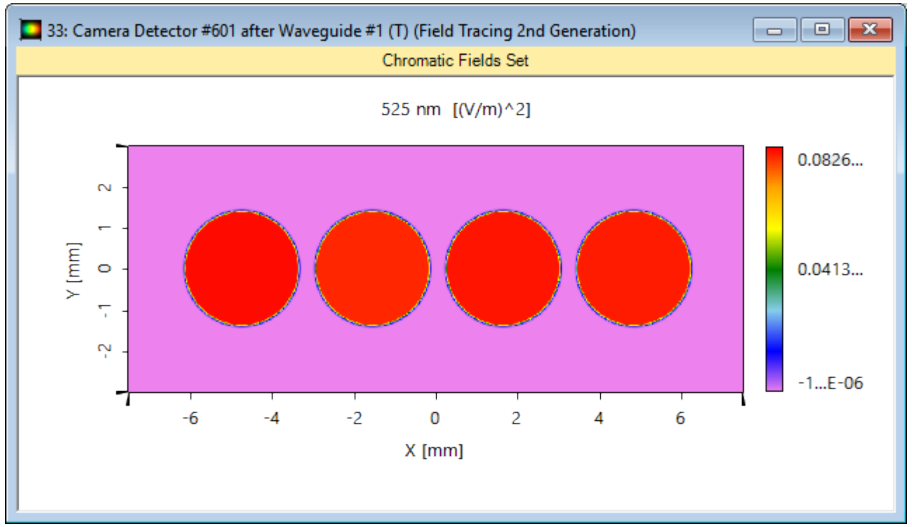
- waveguide simulations including rigorously calculated efficiencies of sub-wavelength grating structures
- specification & optimization of multiple grating regions for tailored output generation

Grating Parameter	Value & Unit
type	sawtooth grating
period	395 nm
depth G1	140 nm
depth G2	145 nm
depth G3	155 nm
depth G4	165 nm

Results: Optimized Output Uniformity



intensity pattern (false color view)



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Challenges in Modeling of VR/MR

- PSF/MTF calculation for partially filled exit pupils
- Non-sequential modeling of imaging channels
- Imaging channels with gratings
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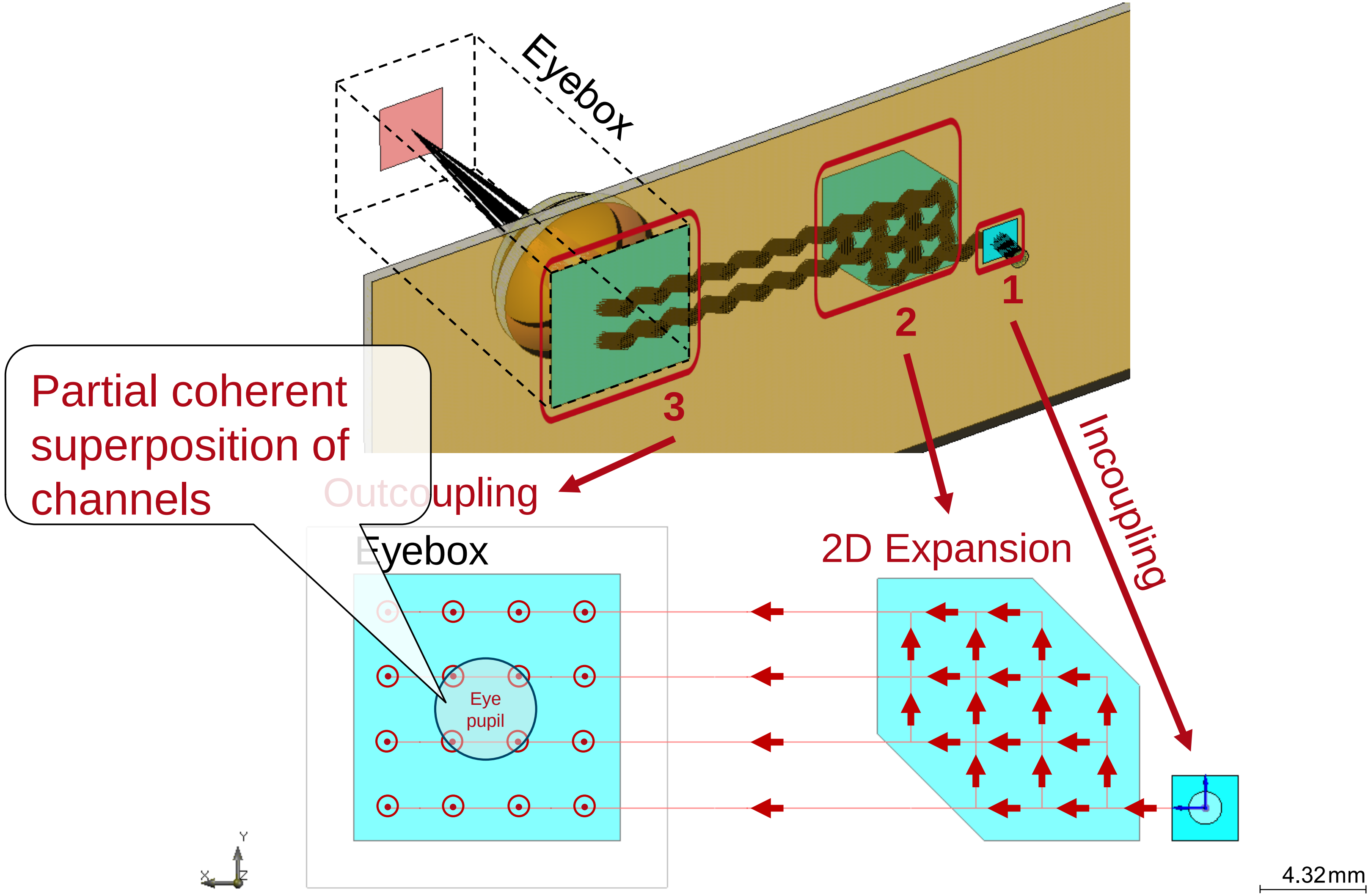
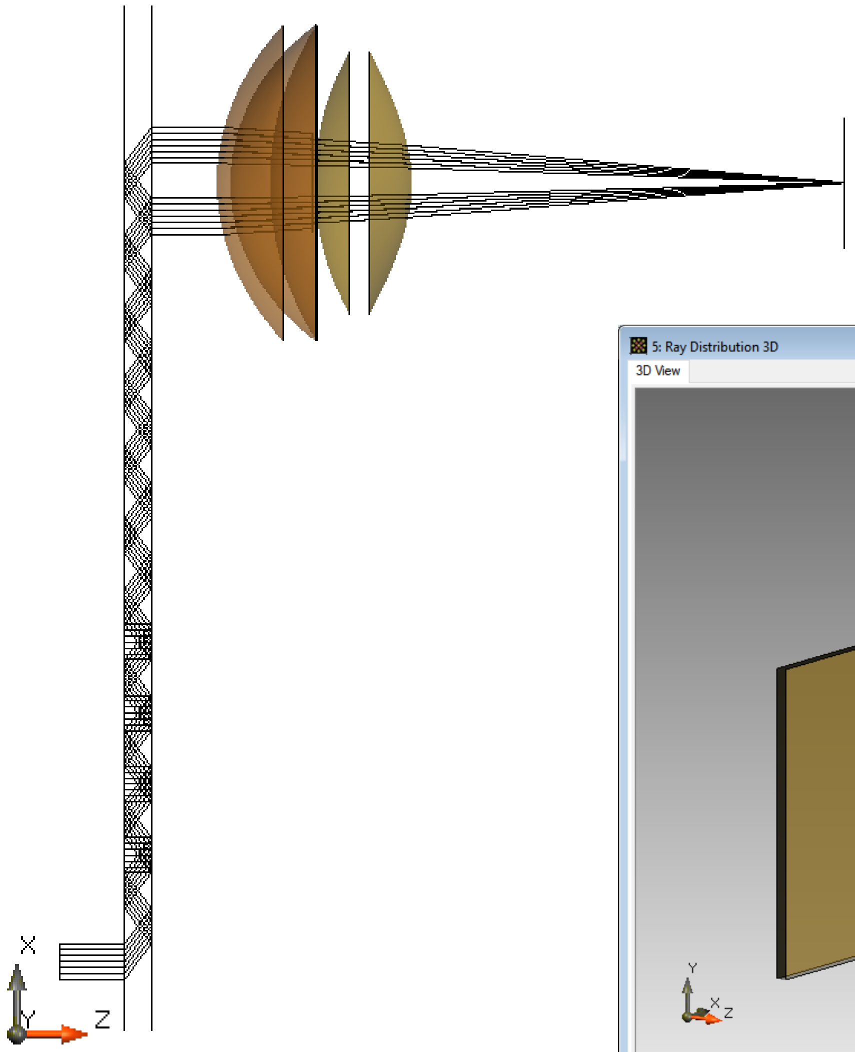
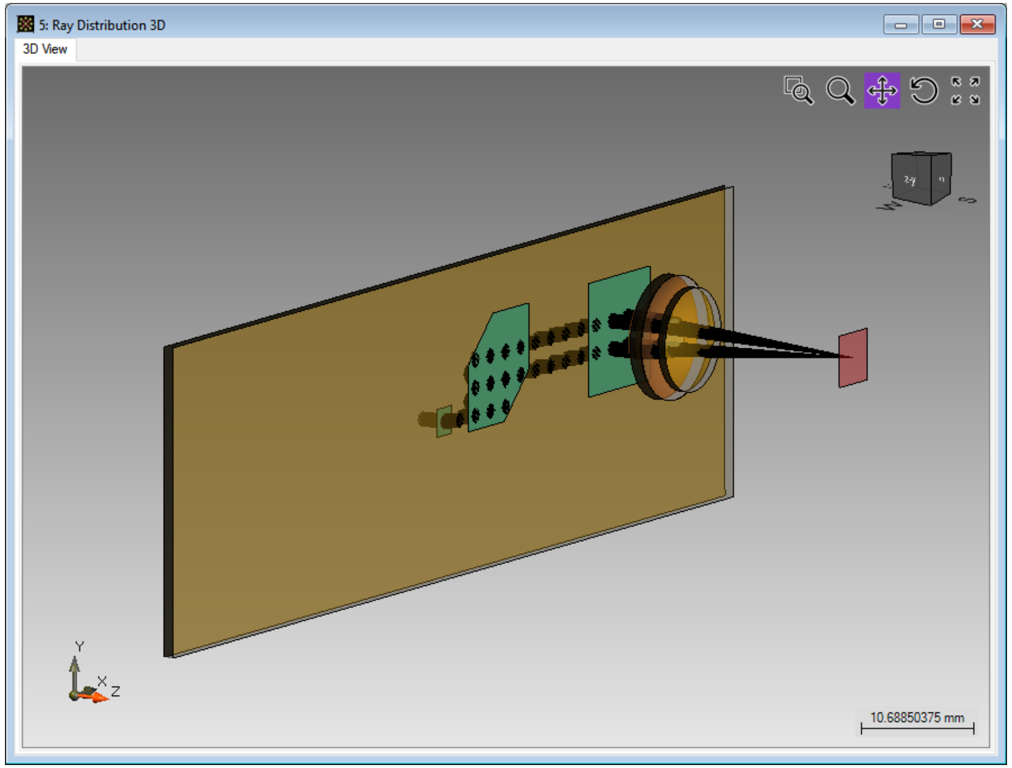
  - Inclusion of higher orders and straylight
- Multichannel imaging system
  - Evaluation of channel distribution in eyebox
  - Multiple aperture effects along lightpath of each channel
  - Partially coherent superposition of channels for PSF/MTF calculation

Multiple Channels in Eye Pupil

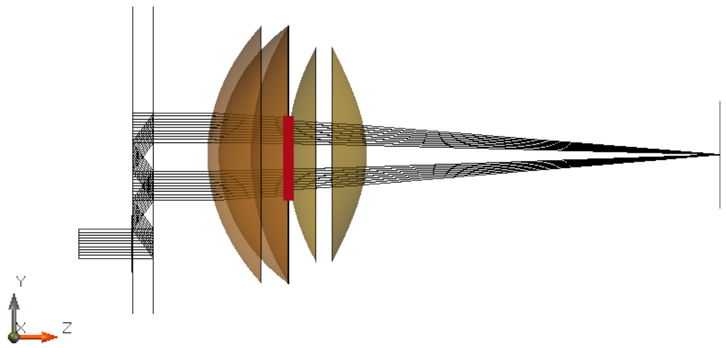


3D Ray Tracing Analyzer





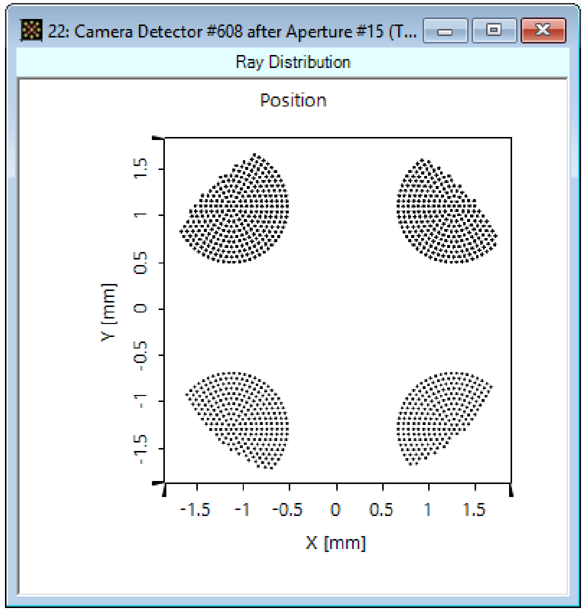
Result: Spots & Intensity at Pupil



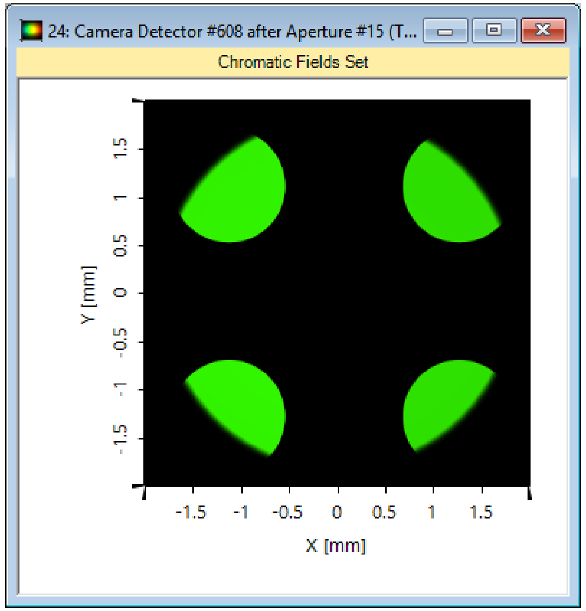
Highlights

- non-sequential ray and field tracing analysis of waveguide optics
- definition of arbitrary in- and outcoupling regions at the waveguide containing ideal or real grating surfaces

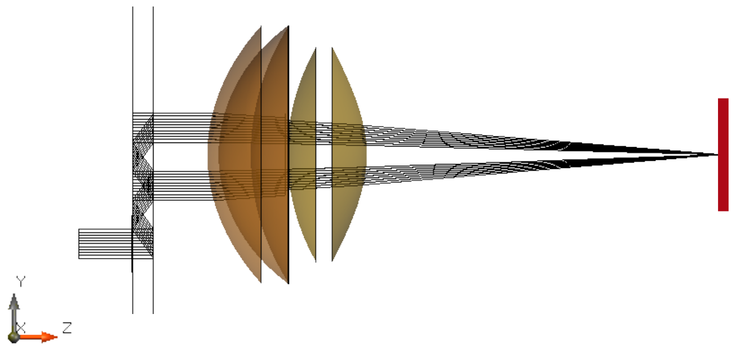
ray tracing spot diagram



intensity
(real color view)



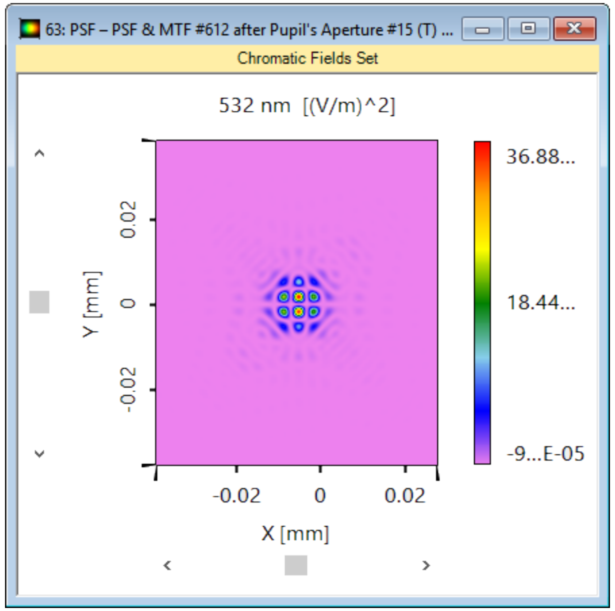
Result: PSF at Retina



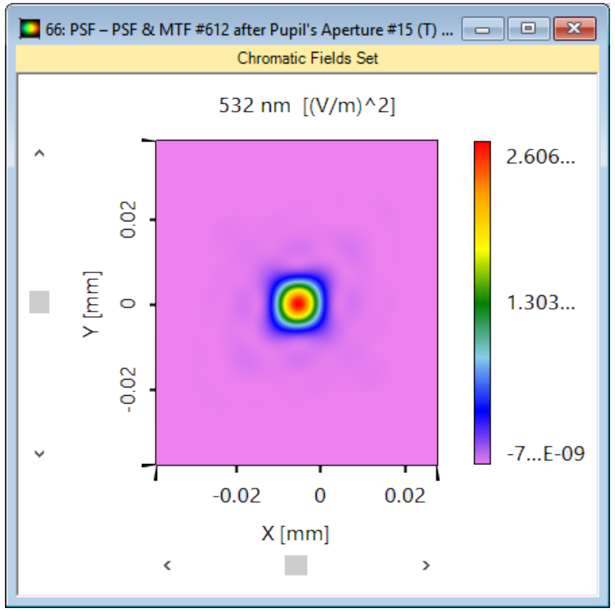
Highlights

- non-sequential ray and field tracing analysis of waveguide optics including **coherence**, polarization and energy effects
- calculation of **PSF** and MTF of arbitrary shaped and illuminated apertures

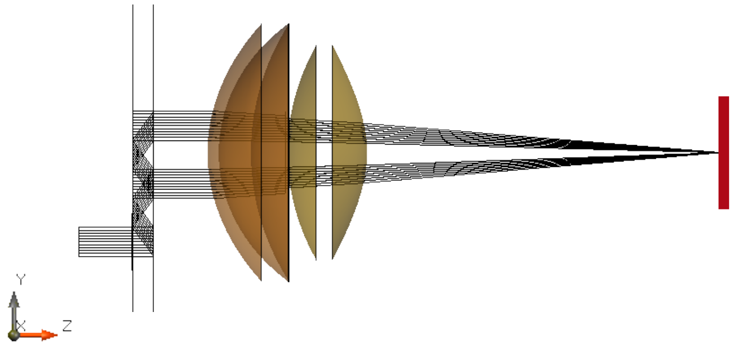
PSF coherent



PSF incoherent



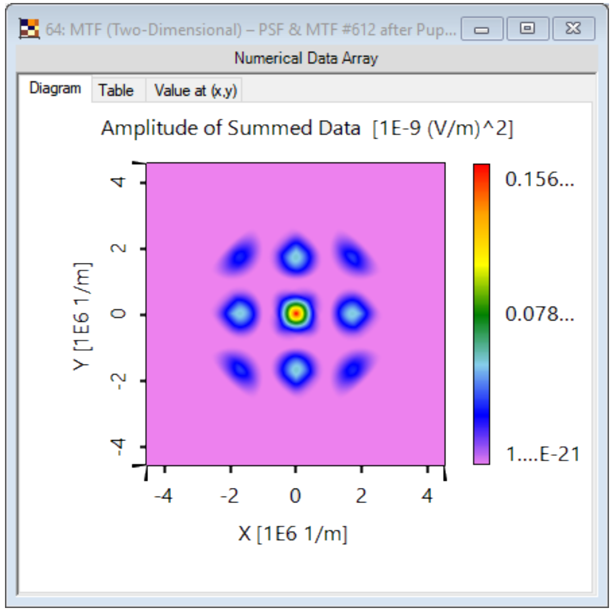
Result: MTF at Retina



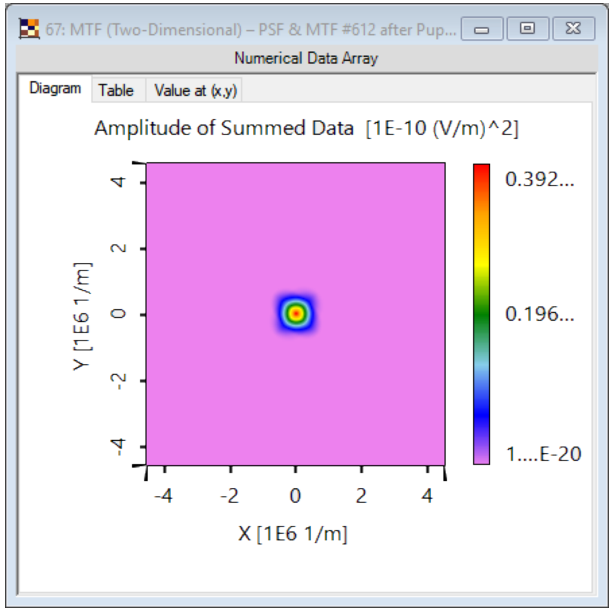
Highlights

- non-sequential ray and field tracing analysis of waveguide optics including coherence, polarization and energy effects
- calculation of PSF and MTF of arbitrary shaped and illuminated apertures

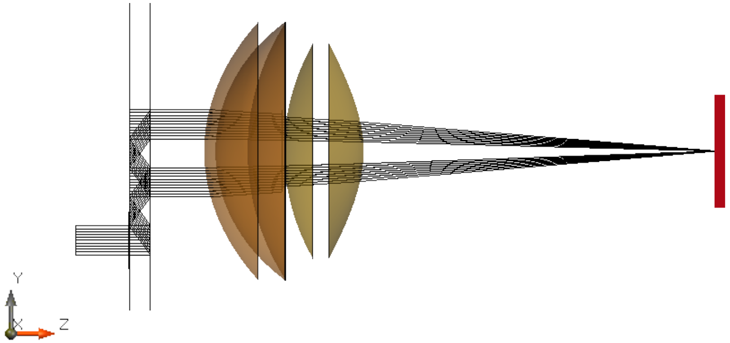
MTF coherent



MTF incoherent



Result: MTF at Retina



Highlights

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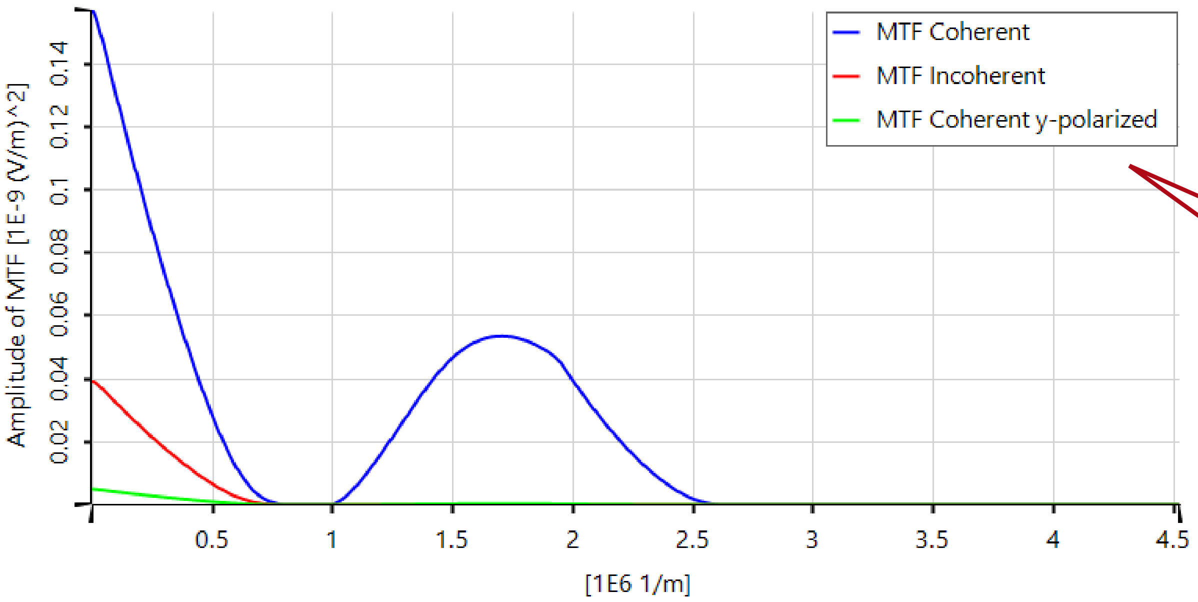
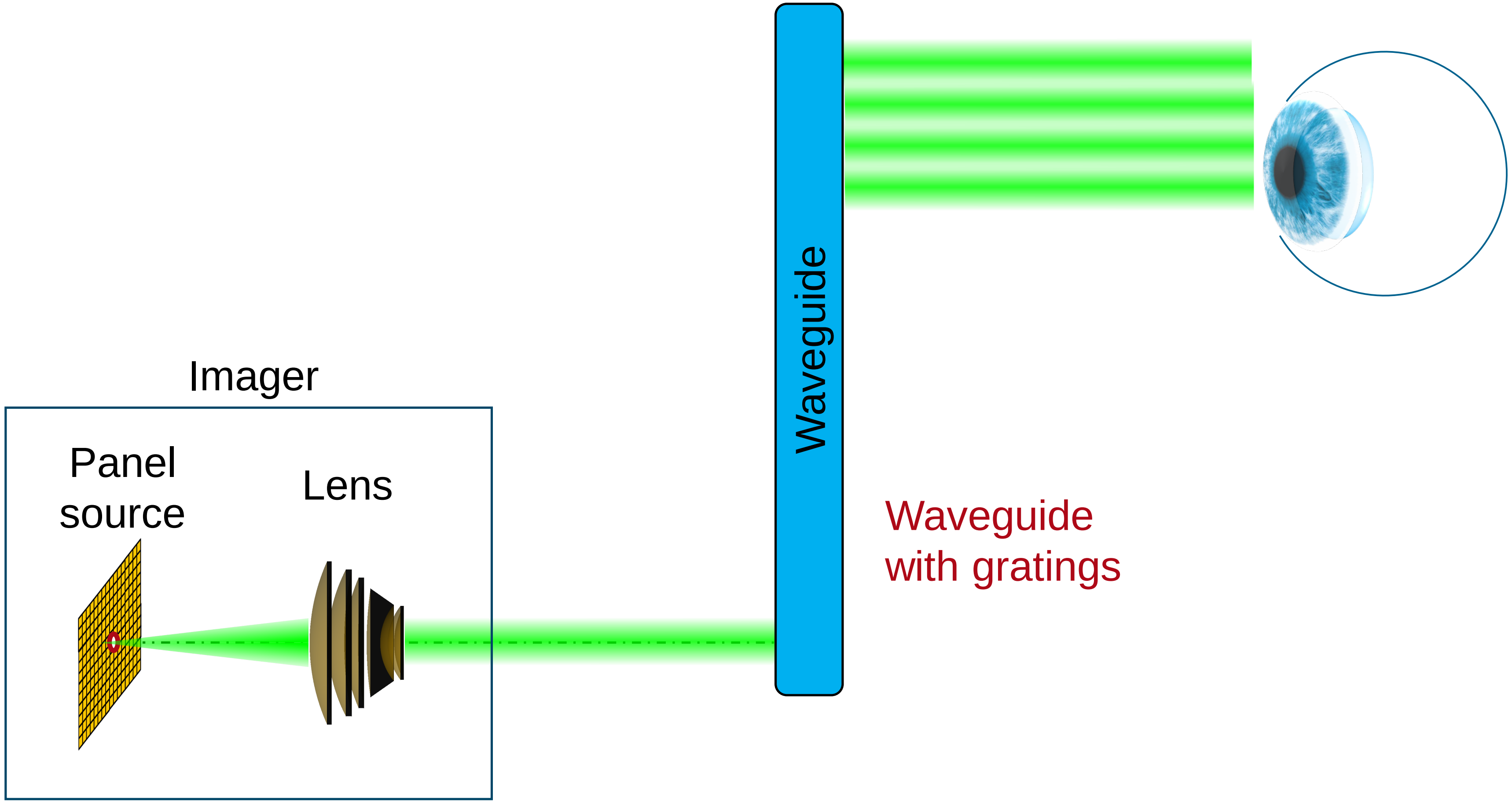
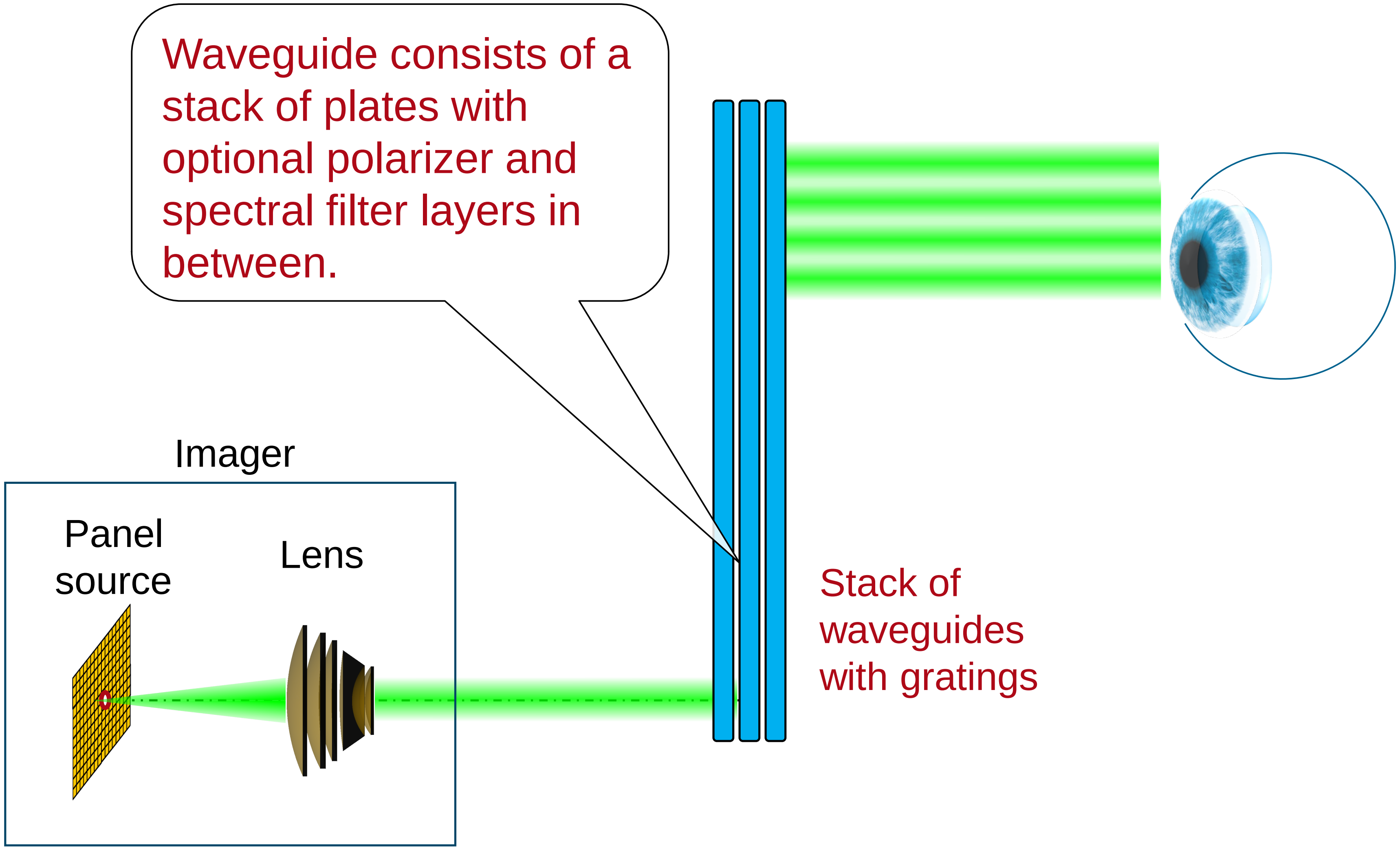


MTF strongly dependent on coherence and polarization effects

Waveguide Stack



Waveguide Stack



Challenges in Modeling of VR/MR

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- Multilayer stack with spectral filter and polarization layers

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→ Modeling must be based on non-sequential physical optics to provide access to all merit functions and to ensure accurate modeling results.

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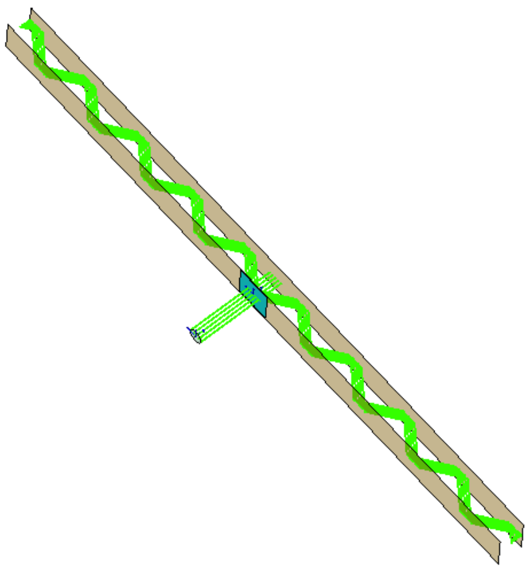
→ The non-sequential physical optics modeling must be **fast** to enable practical work.

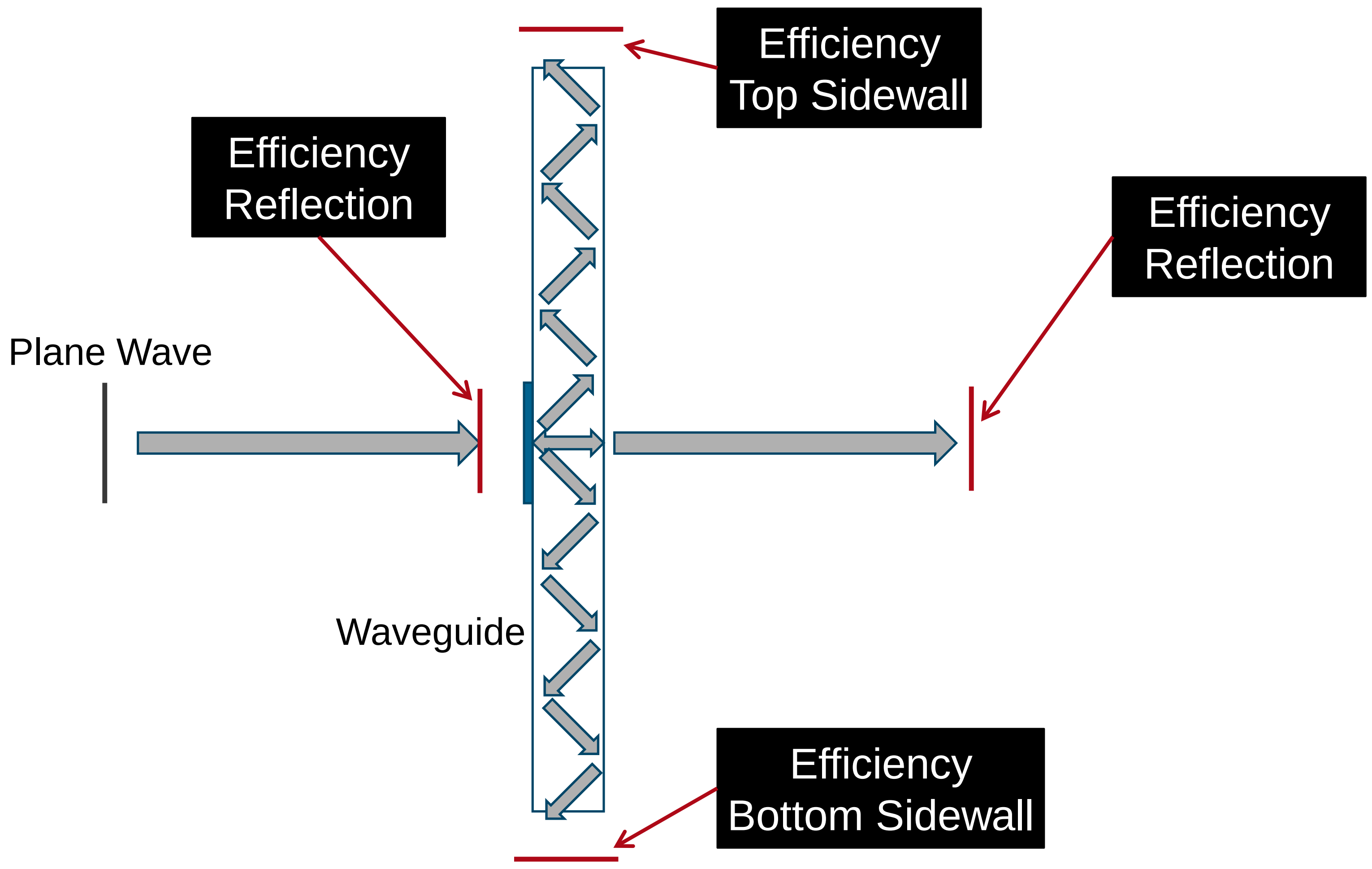
Efficiency Calculation in Optical Systems

Abstract

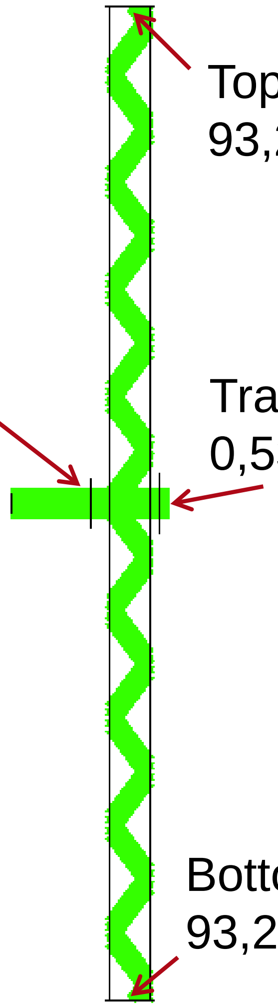
- In modern optical system design it is always important to evaluate the efficiency of the system.
- If the efficiency in the detector signals is significantly smaller than 100% it is also important for the optical engineer to understand where the rest of the light is going to.
- VirtualLab allow the automatic evaluation of the efficiency of an optical system.



Modeling Task: Waveguiding without Outcoupling



Simulation Results



Detector	Efficiency
Transmission	0,53691%
Reflection	4,4525%
Top Sidewall	93,206%
Bottom Sidewall	1,7849%
Total	**99,981%**

Efficiency is calculated by building the ratio between the source flux and the flux at the detector.

Summation of all detector signal gives the efficiency of the complete system.

Some Info

- Webpages:
  - Applied Computational Optics Group (http://www.applied-computational-optics.org)
  - Wyrowski Photonics UG (www.wyrowski-photonics.com).
  - LightTrans (http://www.lighttrans.com/)