FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

Strasbourg, SPIE Photonics Europe, Light Shaping Focus Session, 23.04.2018

A physical-optics based concept for geometric and diffractive light shaping

Frank Wyrowski, University of Jena, Applied Computational Optics

Research and Software Development: Physical Optics

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

Research and Software Development: Physical Optics

Wyrowski Photonics
Development of physical optics software VirtualLab Fusion

All examples shown in this talk were done with **VirtualLab Fusion** software.

Research and Software Development: Physical Optics

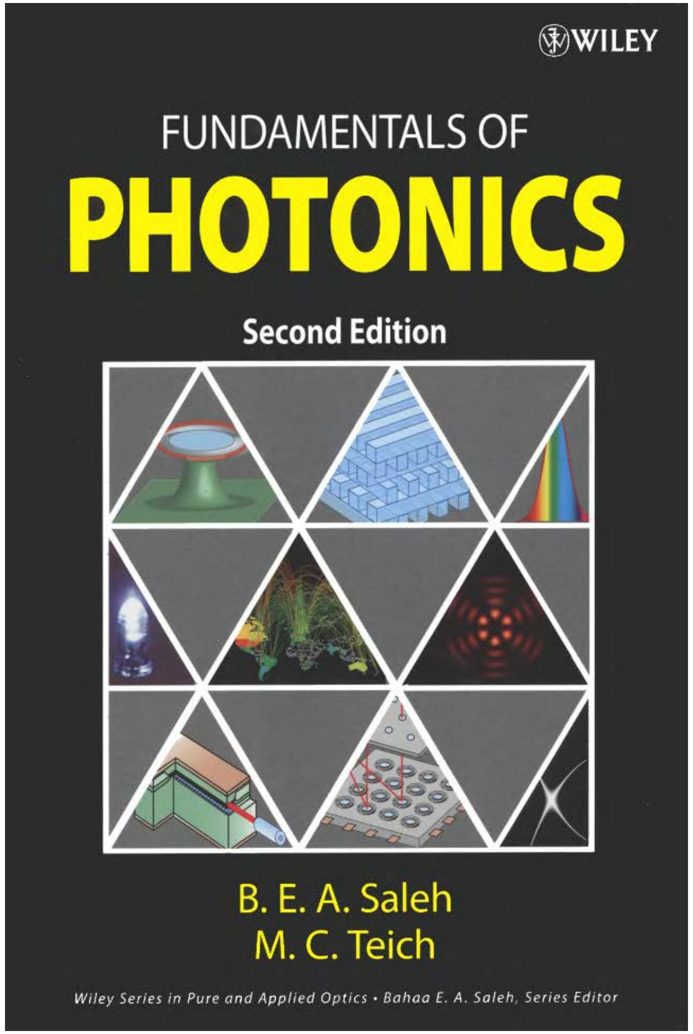
LightTrans

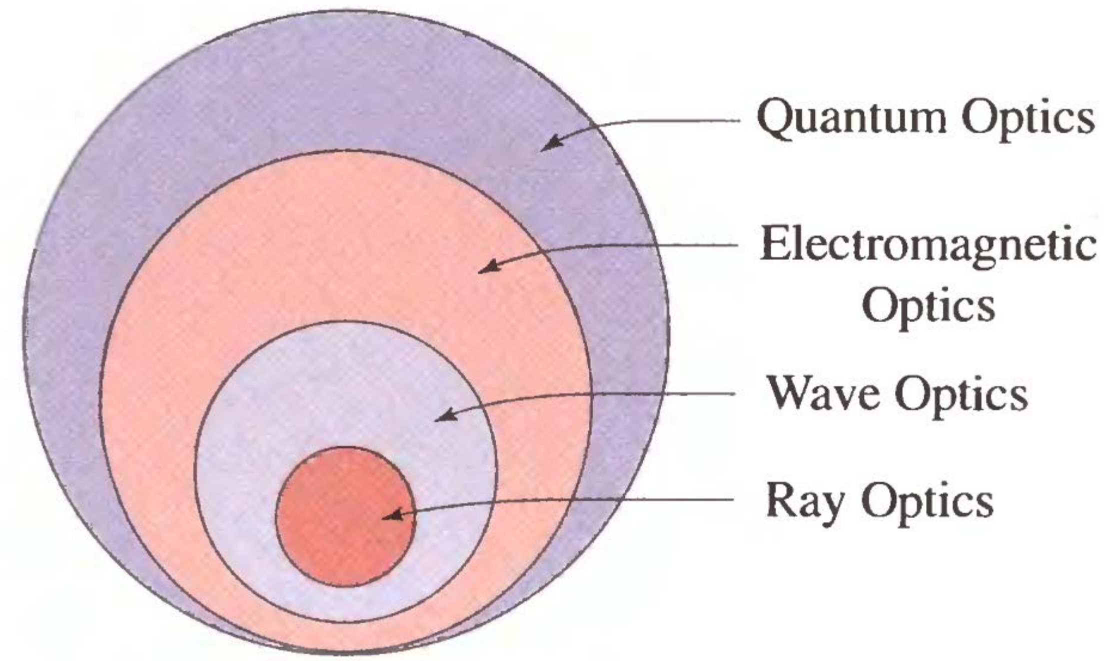
- Distribution of VirtualLab, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects

A physical-optics based concept for geometric and diffractive light shaping

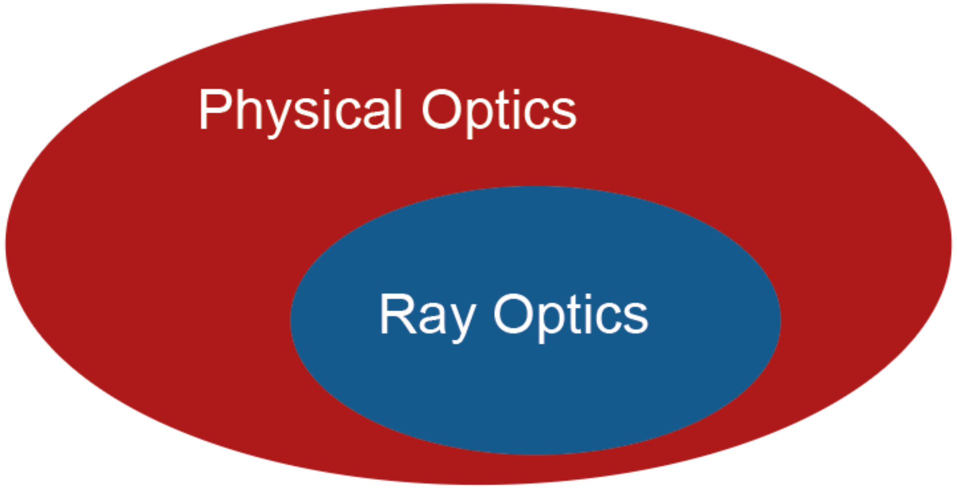
Diffractive and geometric branch of physical optics

Physical and Geometrical Optics: Traditional Understanding



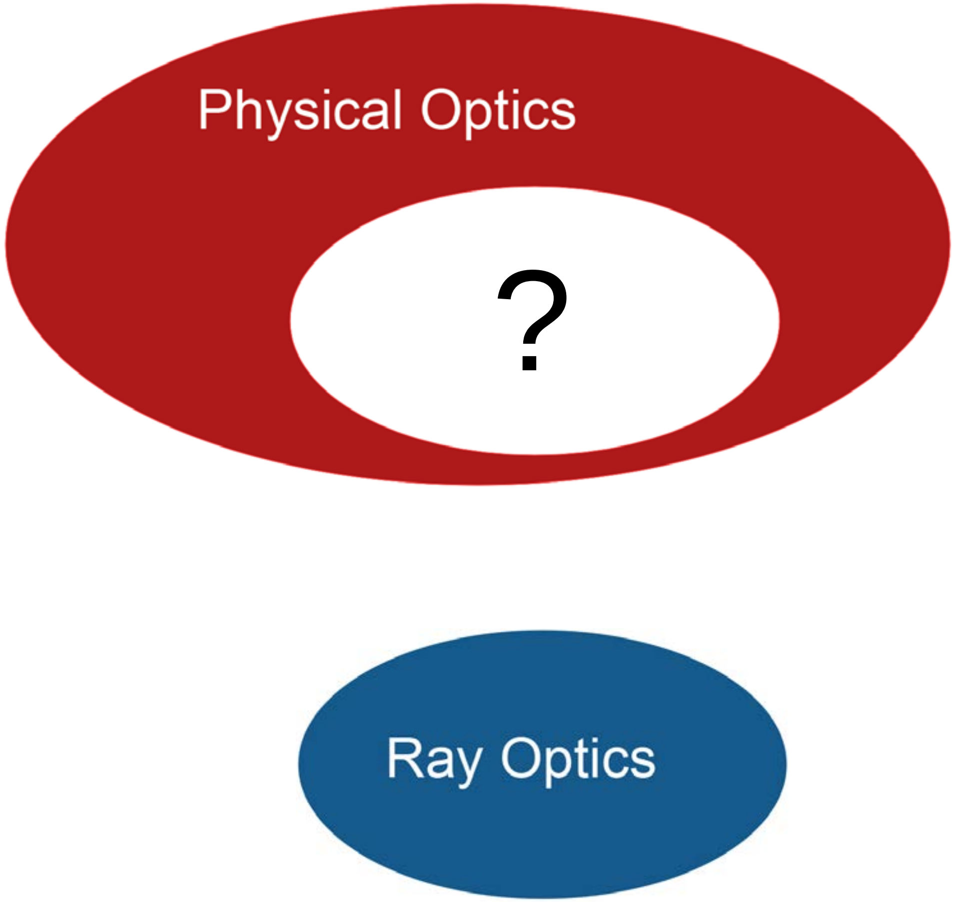


Physical and Geometrical Optics: Traditional Understanding



- 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 Fremat's principle which is mathematically expressed by ray equation.

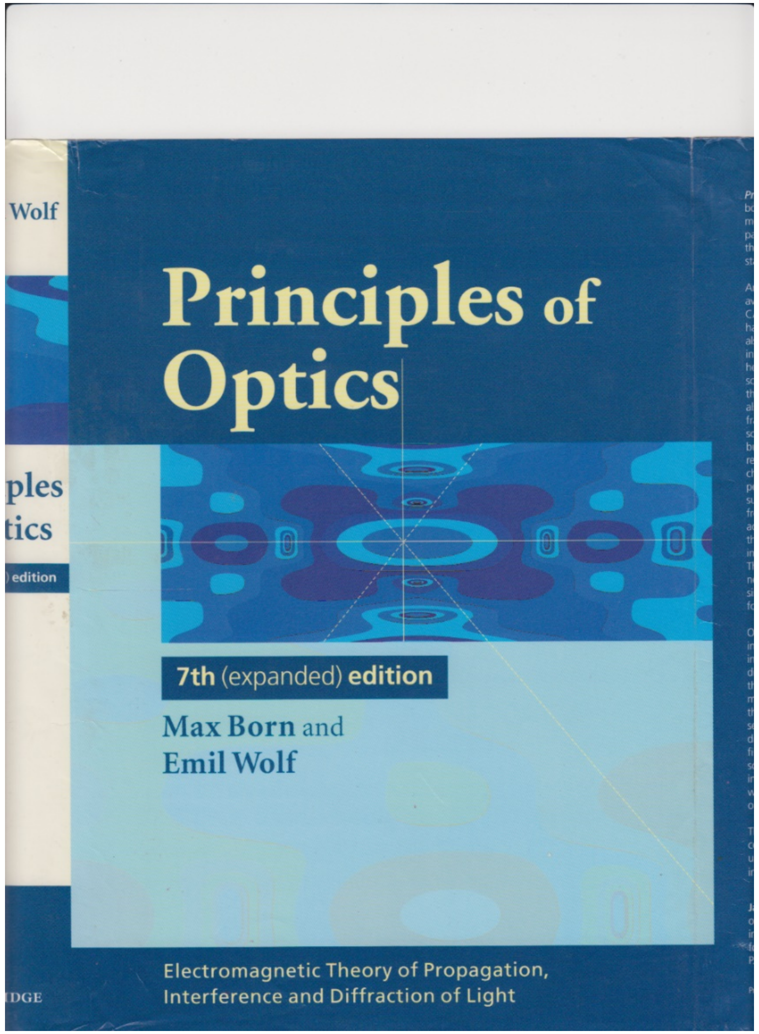
Physical and Geometrical Optics: Traditional Understanding

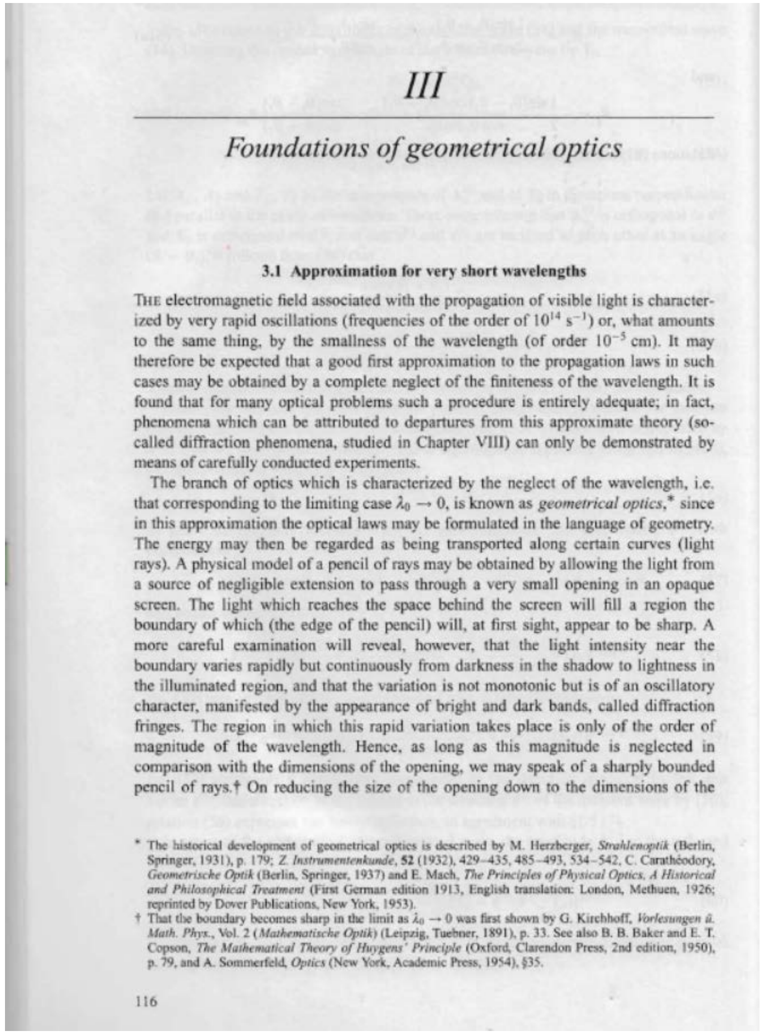


- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations.

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

Geometrical Optics of 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 $10^{14}\,\mathrm{s}^{-1}$) 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.

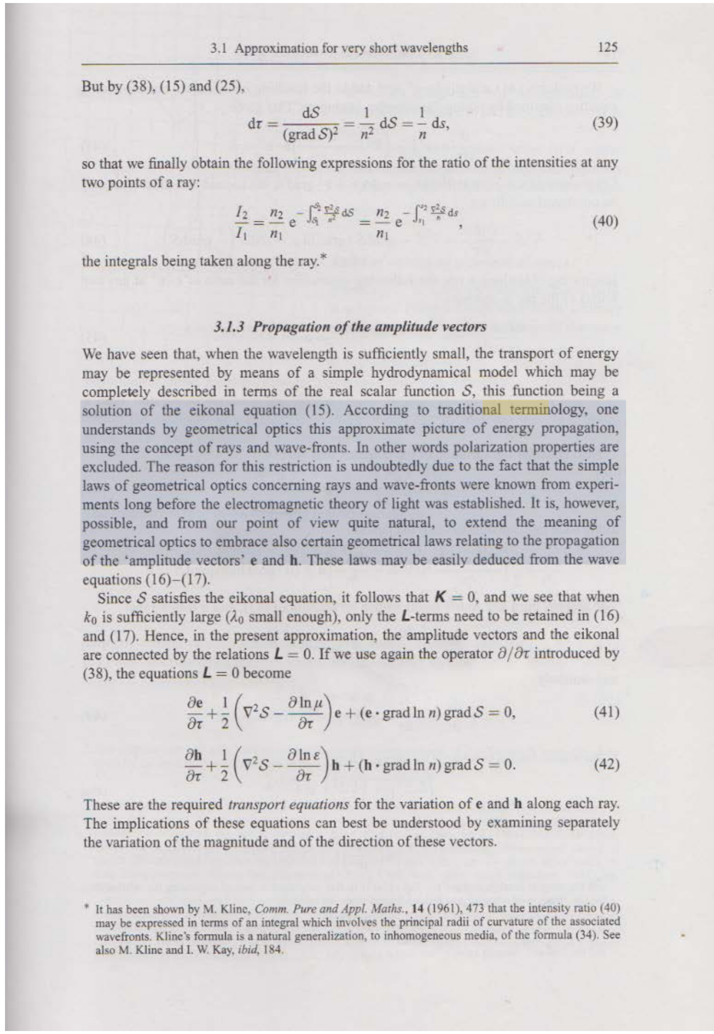
The branch of optics which is characterized by the neglect of the wavelength, i.e. that corresponding to the limiting case $\lambda_0 \to 0$, is known as *geometrical optics*,* since in this approximation the optical laws may be formulated in the language of geometry. The energy may then be regarded 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.

116

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

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

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

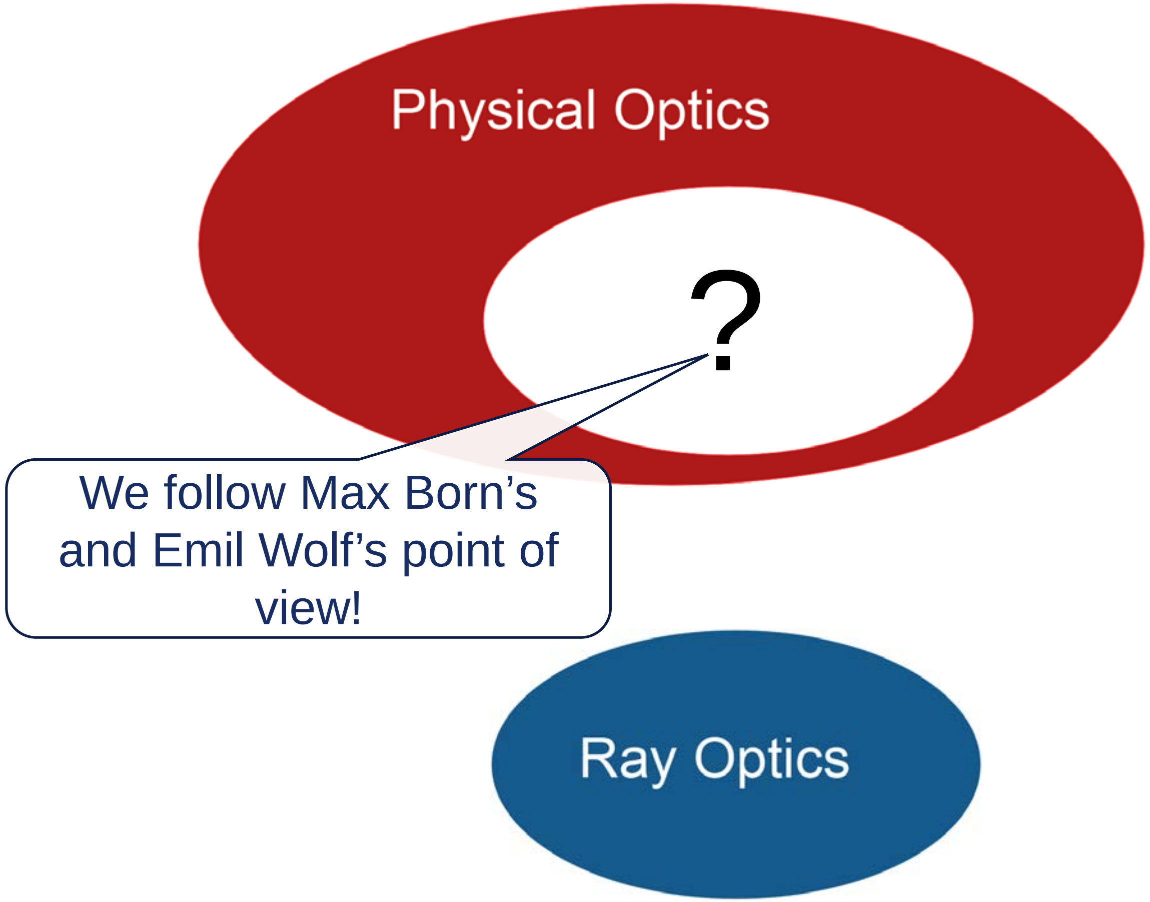
These are the required *transport equations* for the variation of **e** and **h** along each ray. The implications of these equations can best be understood by examining separately the variation of the magnitude and of the direction of these vectors.

* 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

- "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."

Physical and Geometrical Optics: Unified Theory

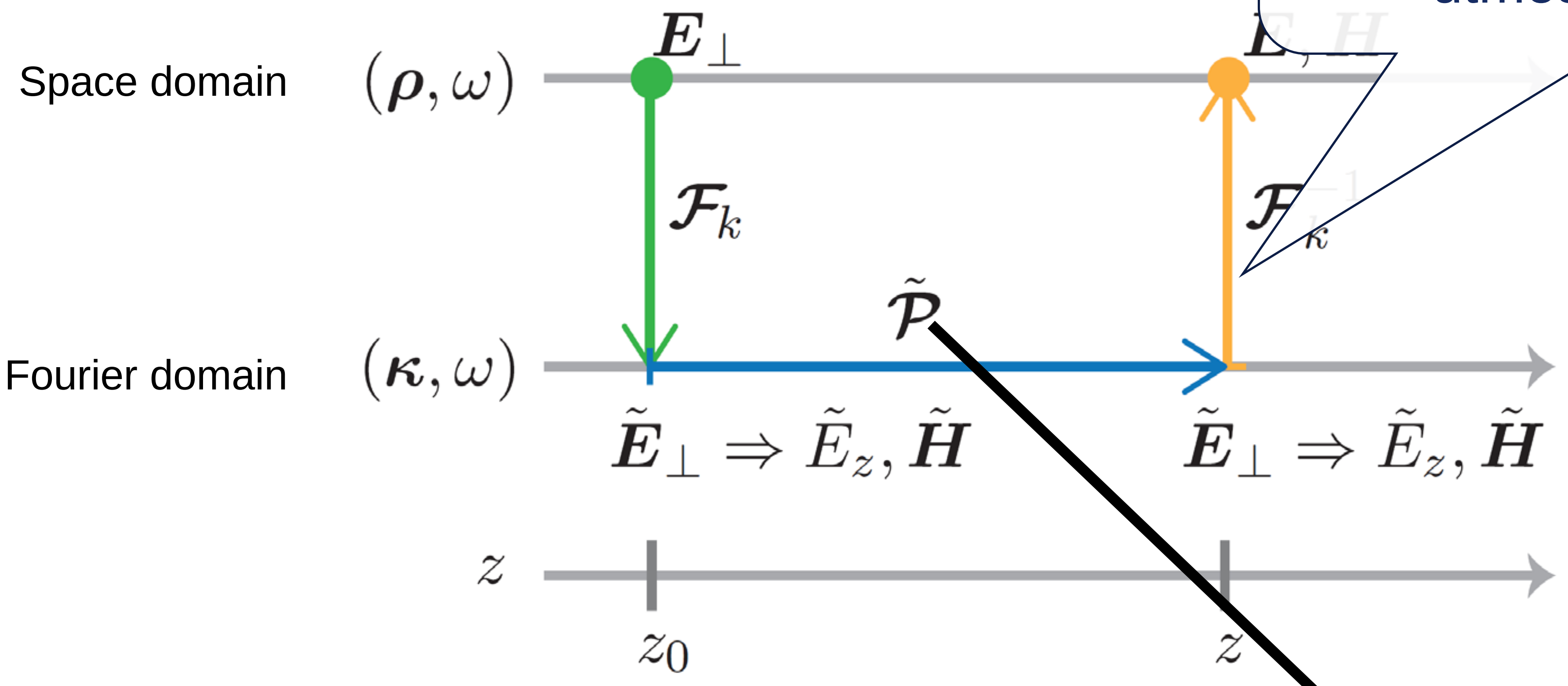


- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations.

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

Example: Free-Space Propagation

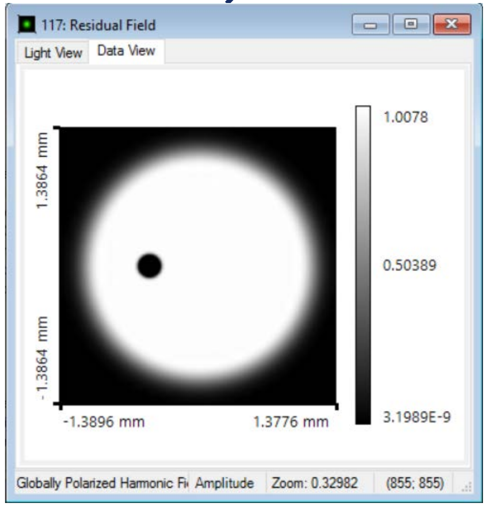
Characteristics of connection between both domains of utmost importance!

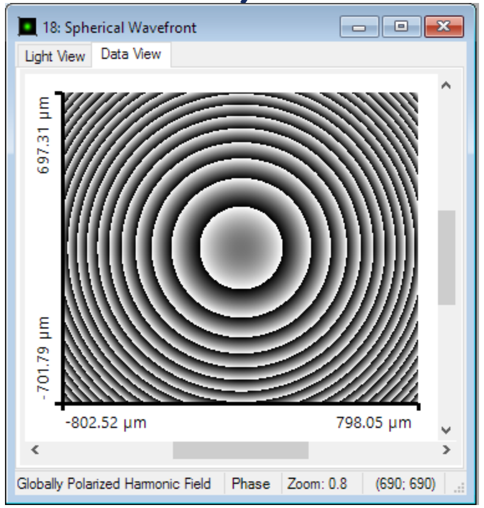


$$\boxed{V_\ell(\boldsymbol{\rho}, z) = \mathcal{F}_k^{-1}\left(\exp\left(\mathrm{i}\check{k}_z \Delta z\right)\left(\mathcal{F}_k V_\ell(\boldsymbol{\rho}, z_0)\right)\right)}$$

Example Spherical Field with Stop

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

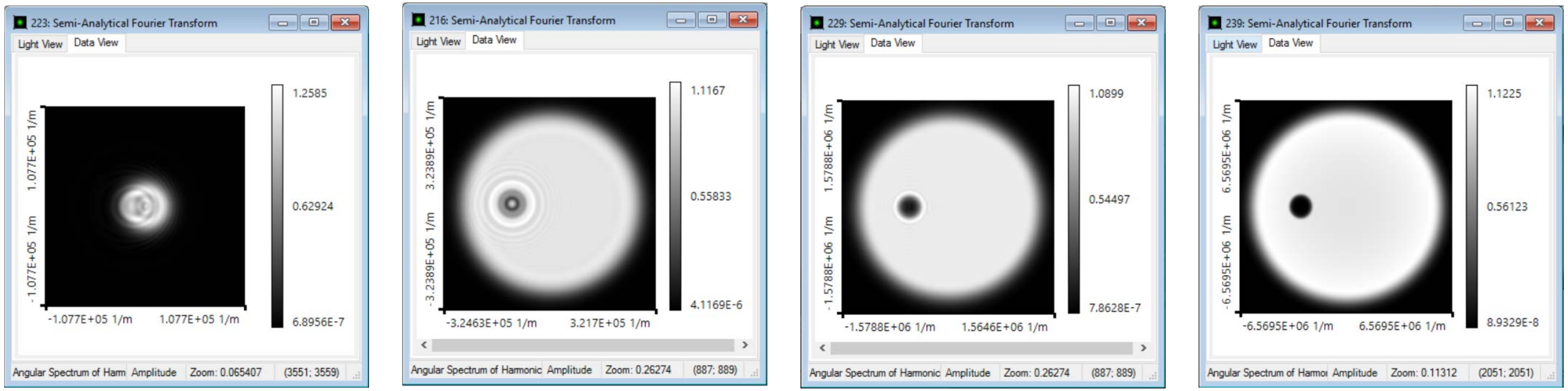




Results of Fourier Transform

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

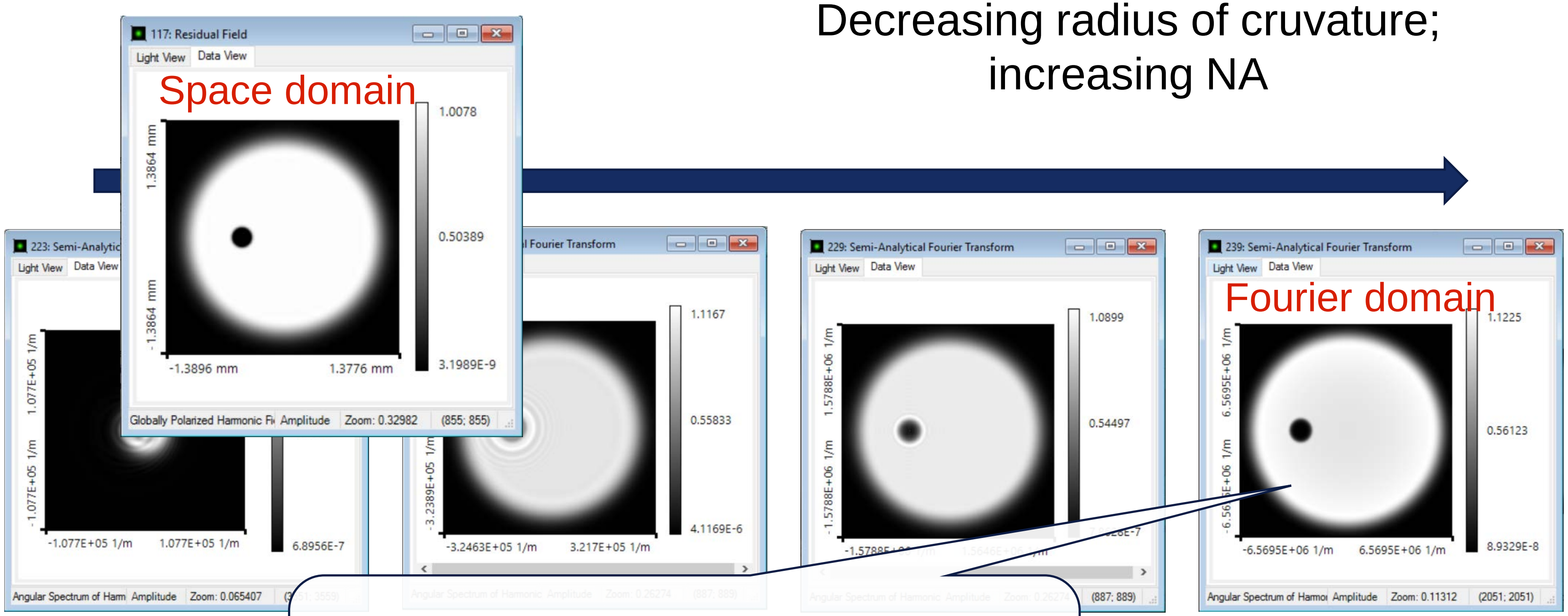
Decreasing radius of cruvature;
increasing NA



Results of Fourier Transform

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

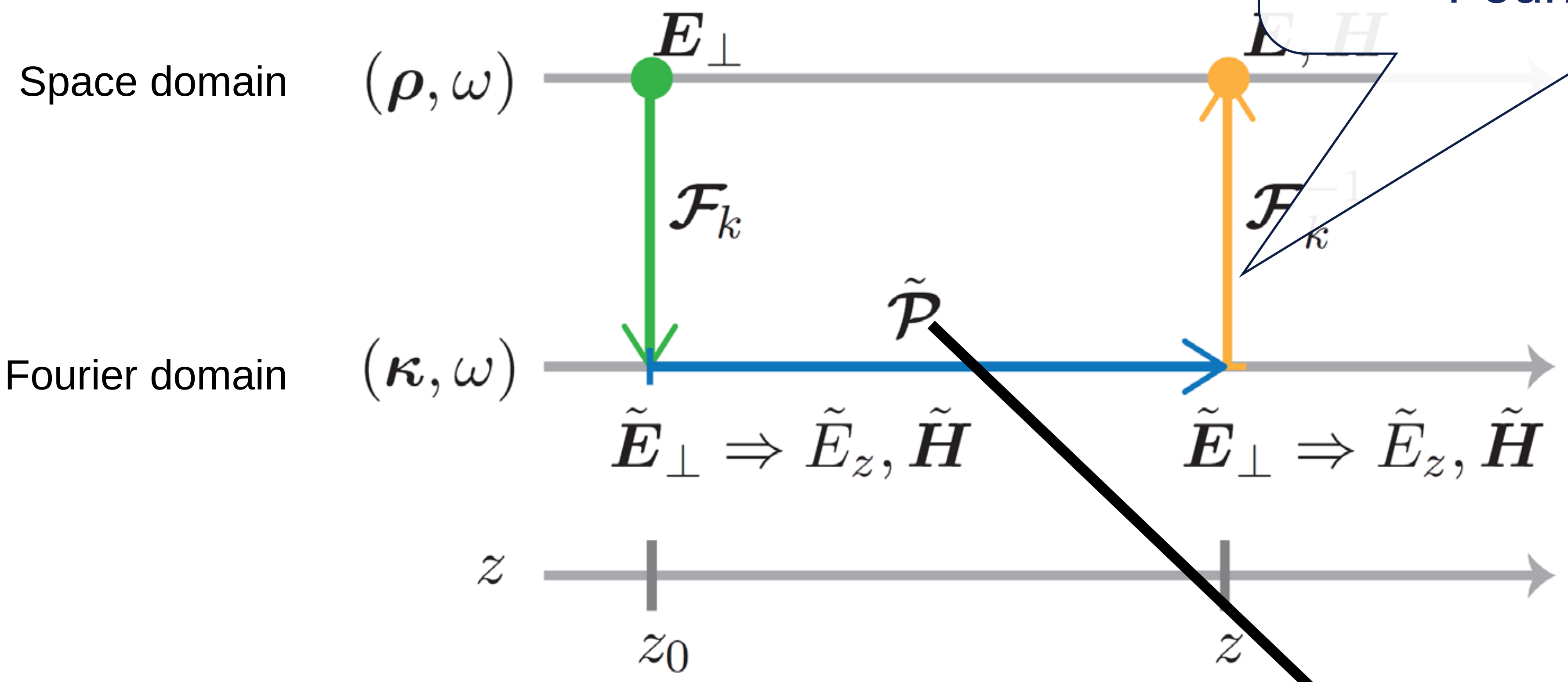
Decreasing radius of cruvature;
increasing NA



Mapping between both
domains: geometric field zone

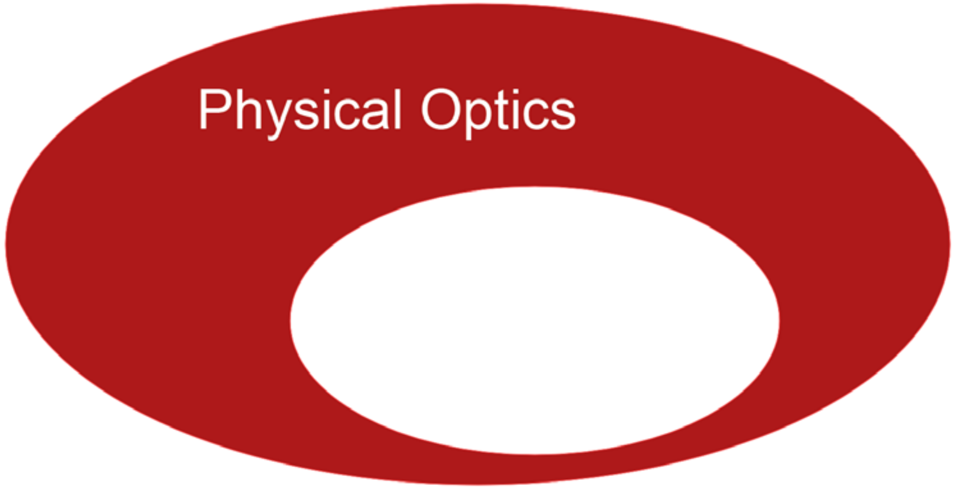
Example: Free-Space Propagation

Mapping in geometric field zone expressed by geometric Fourier transform!



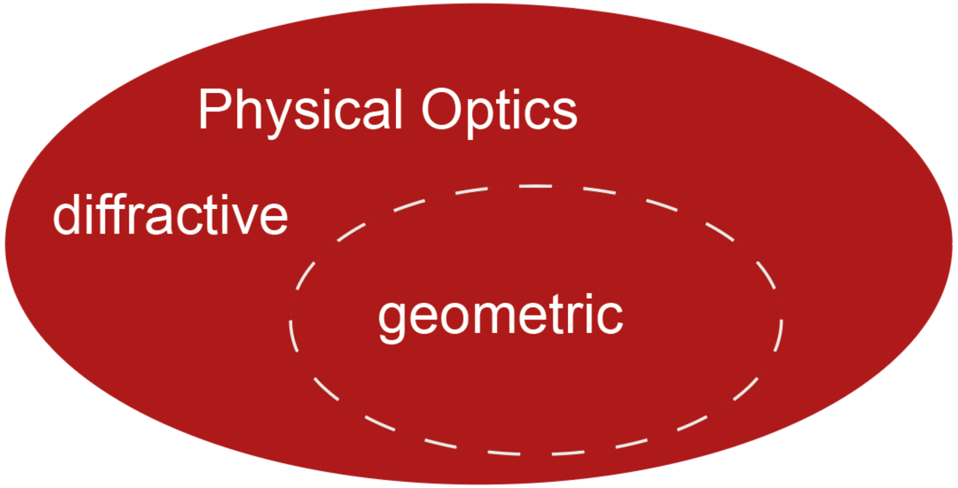
$$V_\ell(\boldsymbol{\rho}, z) = \mathcal{F}_k^{-1}\left(\exp\left(\mathrm{i}\check{k}_z \Delta z\right)\left(\mathcal{F}_k V_\ell(\boldsymbol{\rho}, z_0)\right)\right)$$

Physical and Geometrical Optics: Unified Theory



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

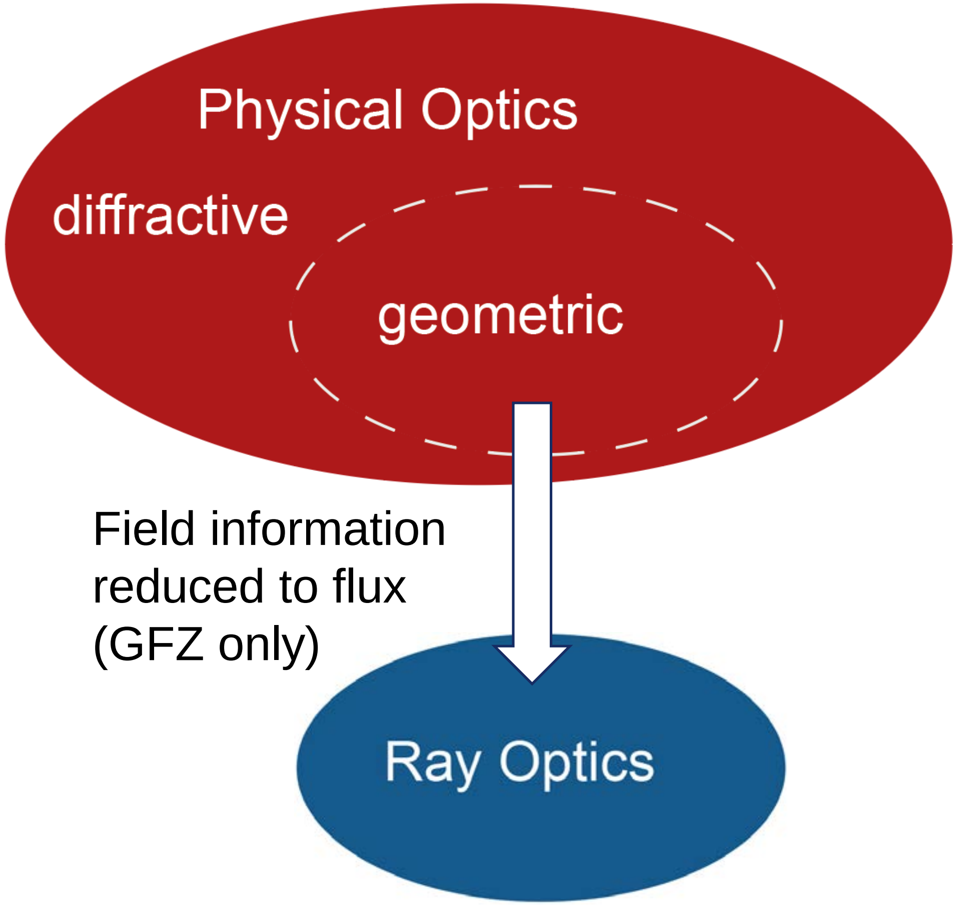
Physical and Geometrical Optics: Unified Theory



- In the **geometric zone** of a field the geometric Fourier transform is valid for a predefined accuracy level.
- **That can be interpreted as the decomposition of a field into local plane waves!**

- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations
  - Transition between diffractive/geometric branch fully specified and controlled by validity of geometric FT
  - Diffractive and geometric field zones

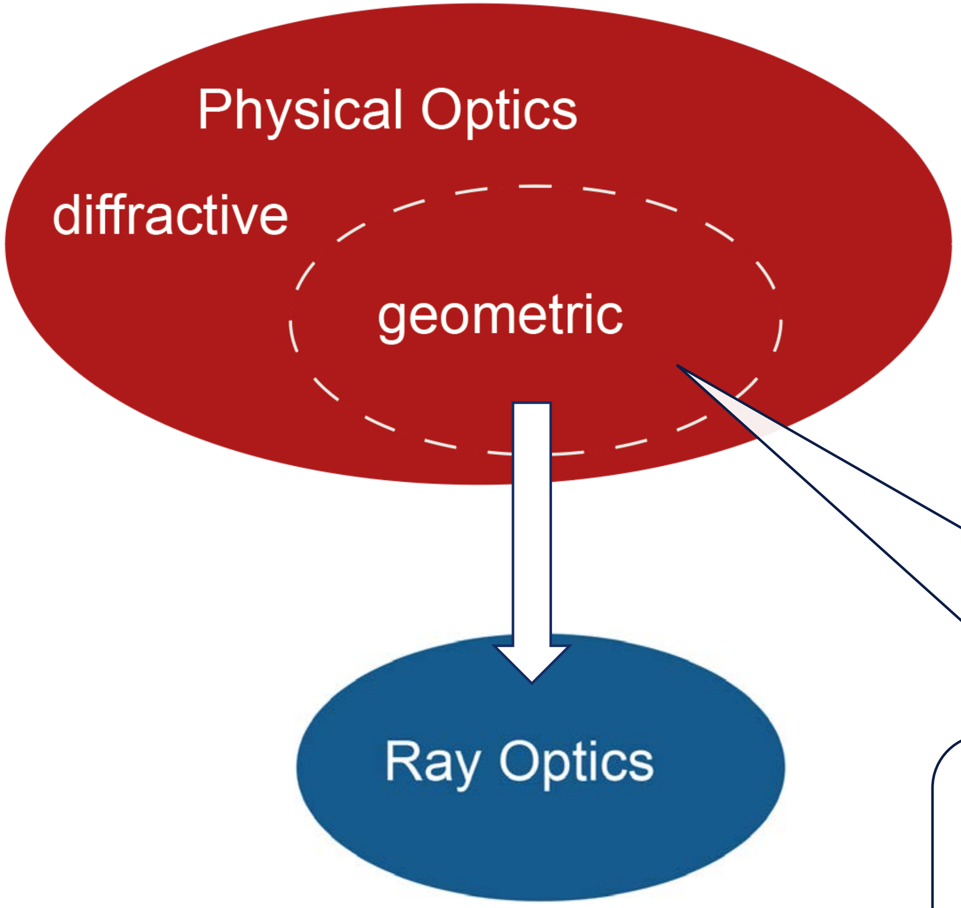
Physical and Geometrical Optics: Unified Theory



- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations
  - Transition between diffractive/geometric branch fully specified and controlled by validity of geometric FT
  - Diffractive and geometric field zones

- Geometrical/ray optics:
  - Light is represented by mathematical rays (with energy flux) which

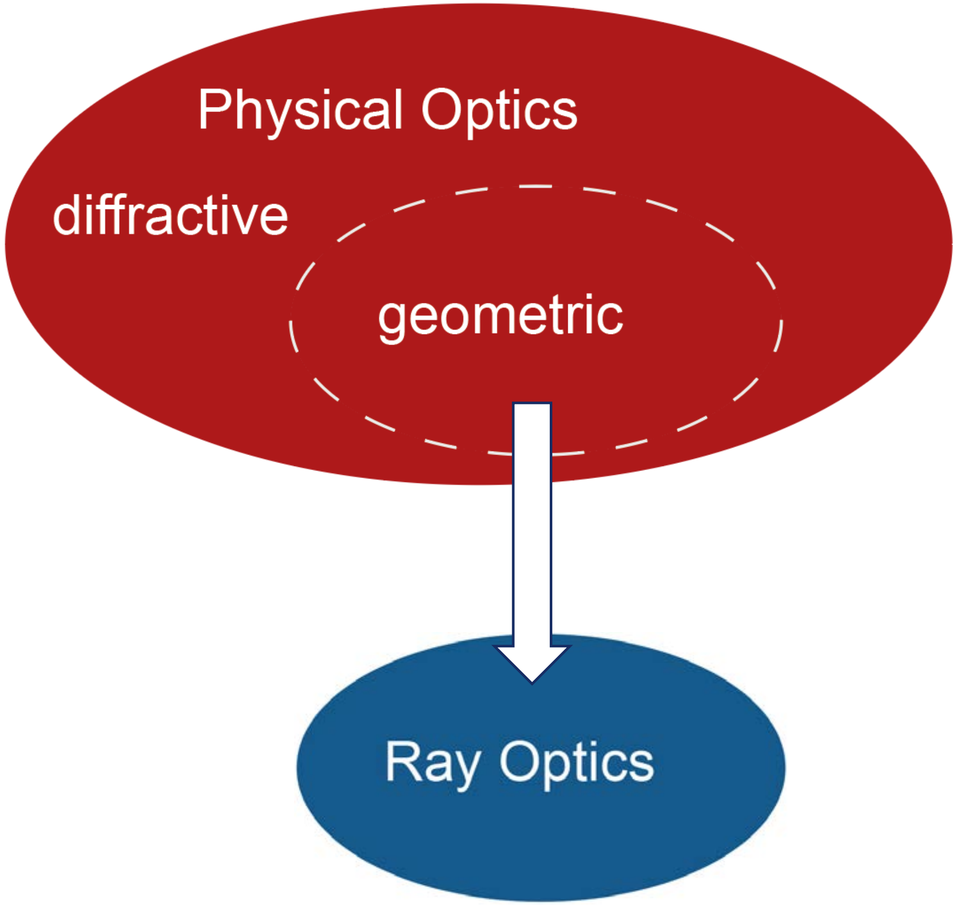
Physical and Geometrical Optics: Unified Theory



- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations
  - Transition between diffractive/geometric branch fully specified and controlled by validity of geometric FT
  - Diffractive and geometric field zones

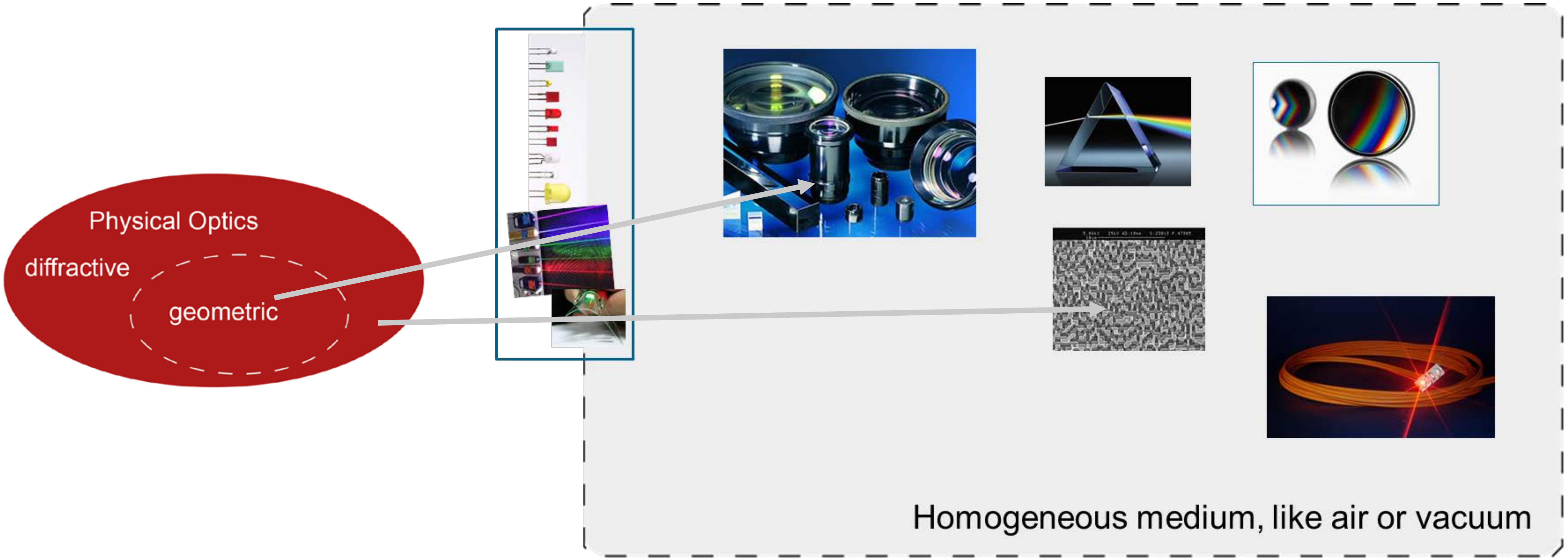
Physical optics in geometric zones is as fast as ray tracing (with potential to be faster)!

Physical and Geometrical Optics: Unified Theory

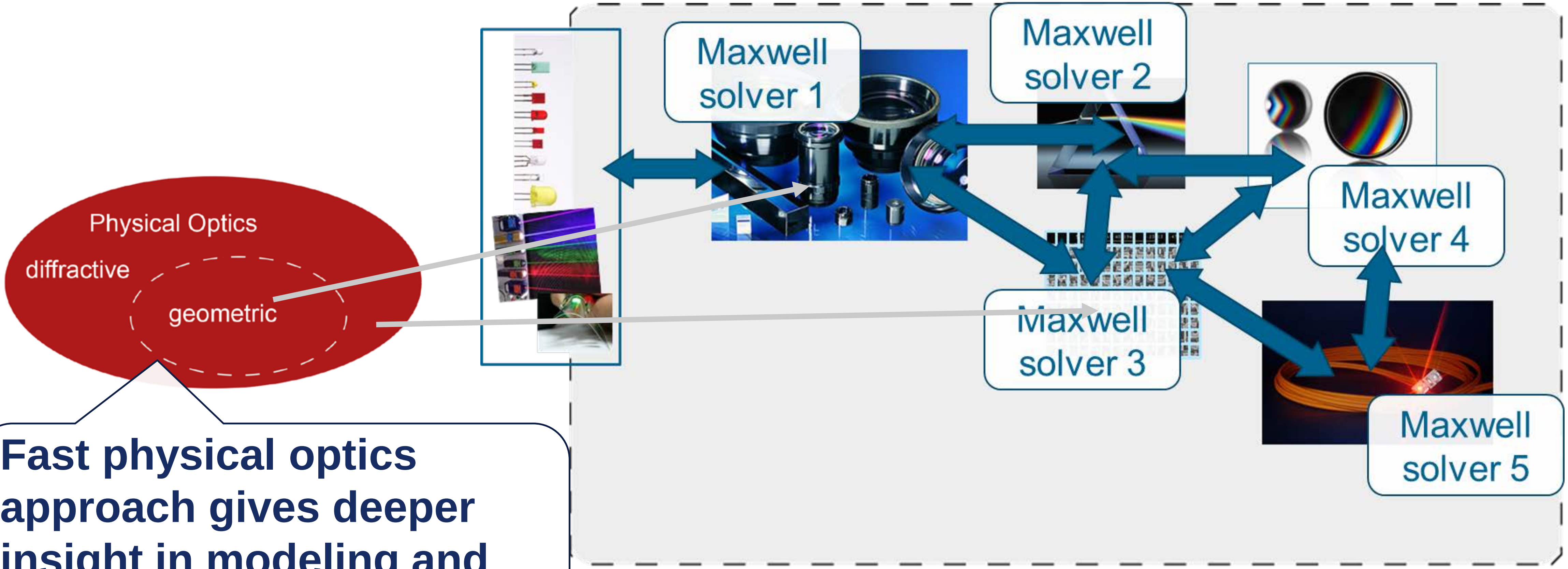


- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell's equations
  - Transition between diffractive/geometric branch fully specified and controlled by validity of geometric FT
  - Diffractive and geometric field zones
- VirtualLab deals with the transitions between diffractive and geometric branch of physical optics automatically (steady development).

Physical Optics Modeling: Regional Maxwell’s Solver

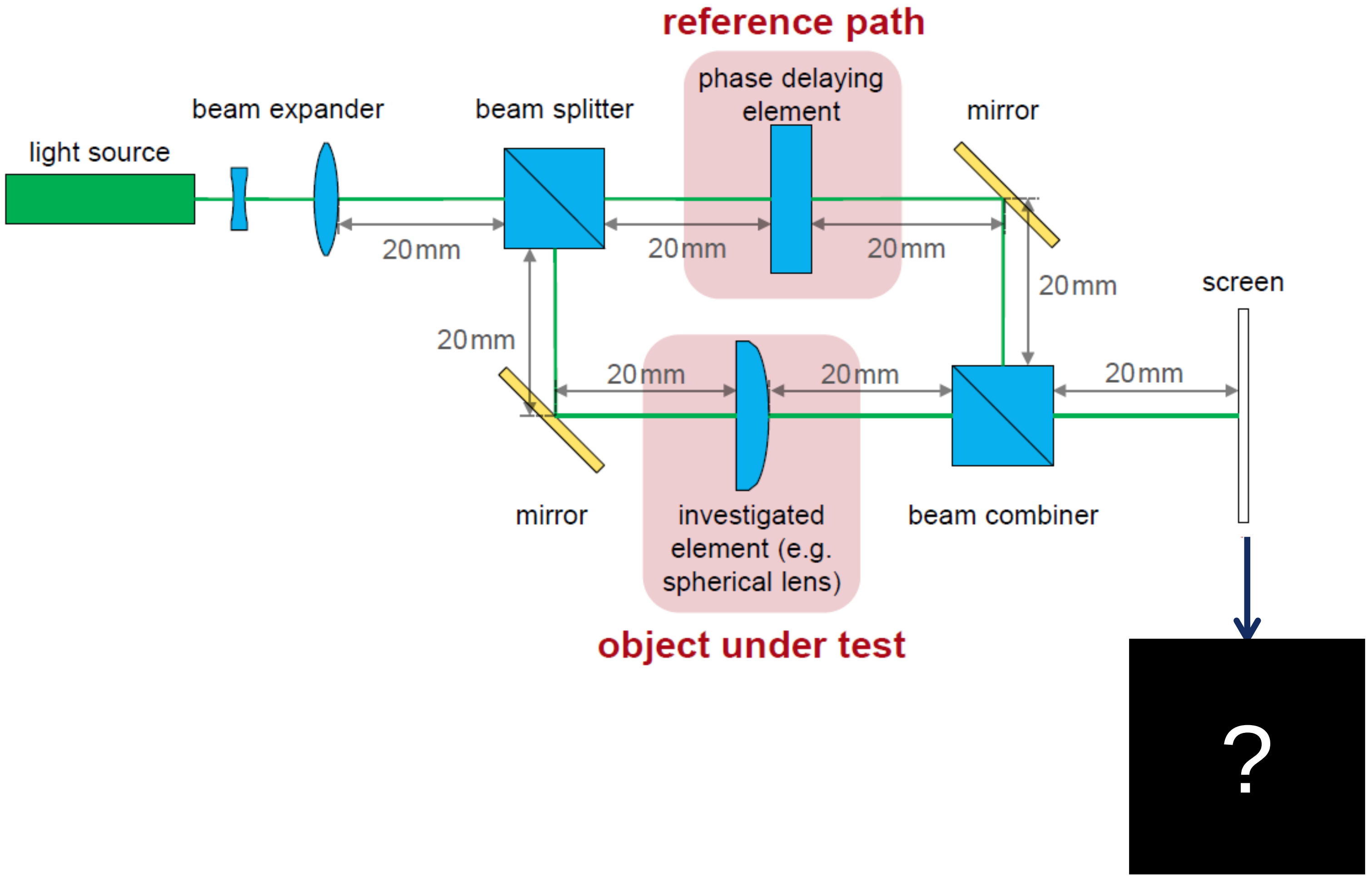


Physical Optics Modeling: Non-sequential Solver Connection



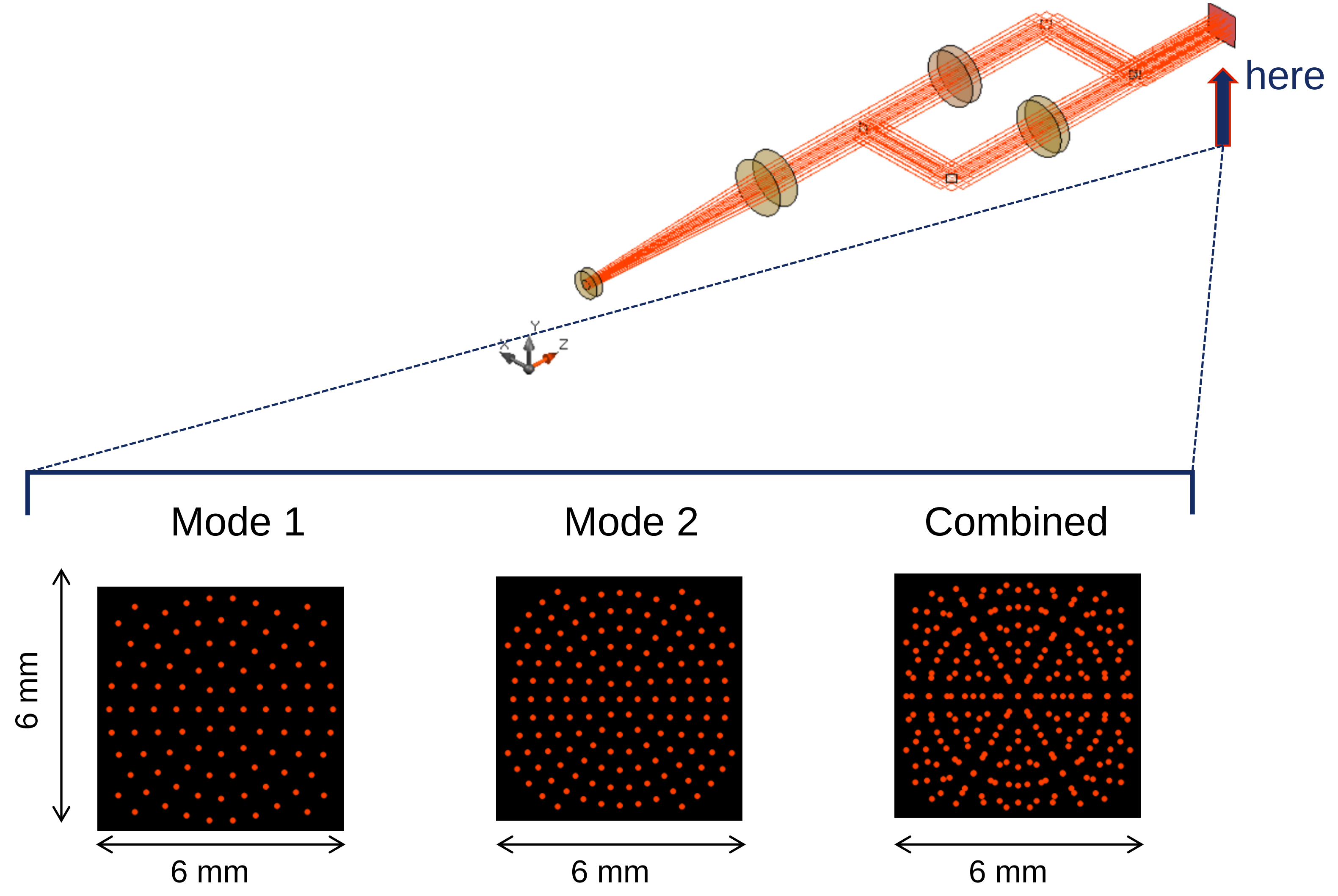
Fast physical optics approach gives deeper insight in modeling and more flexibility in design!

Task/System Illustration

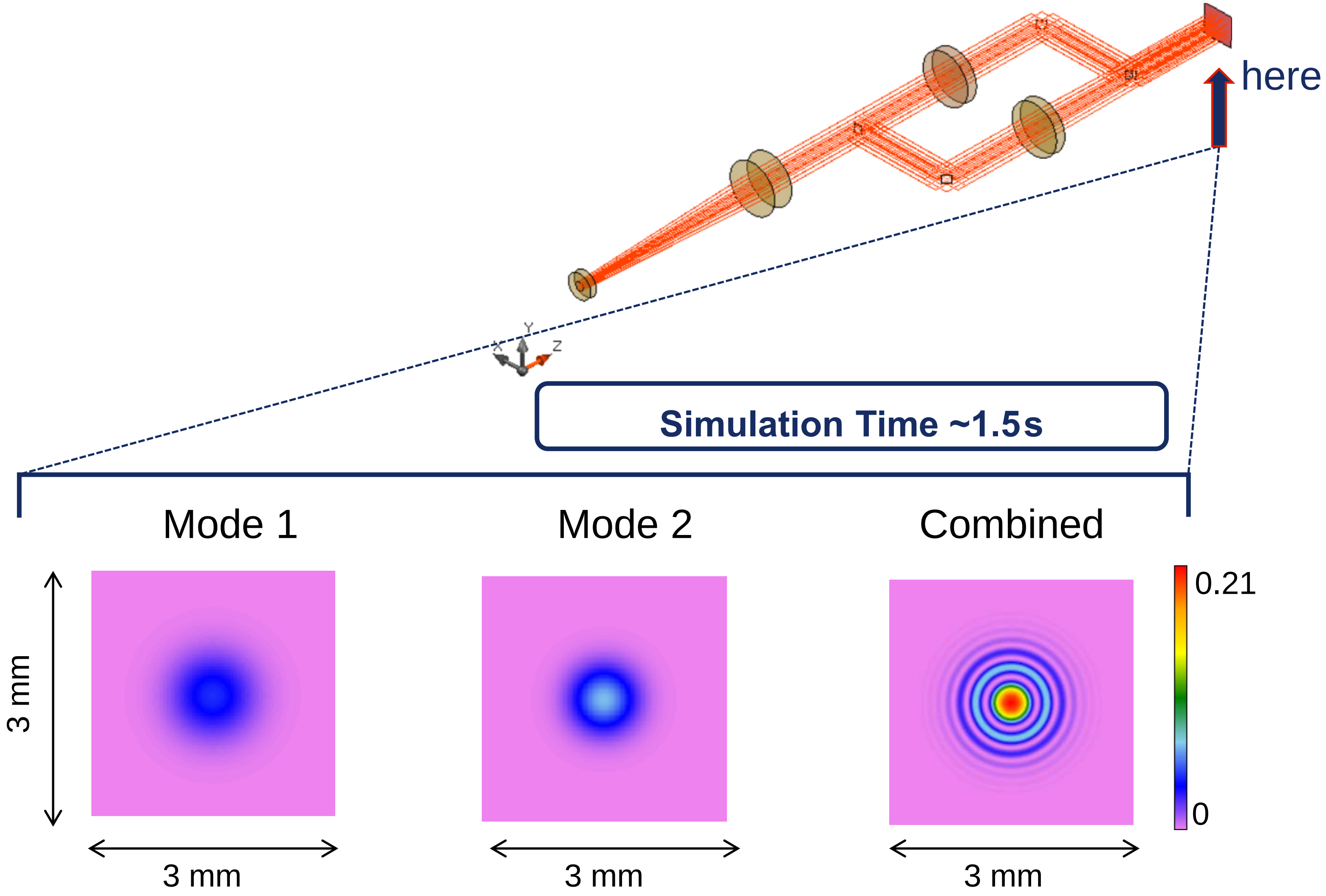


Intensity of the interference pattern

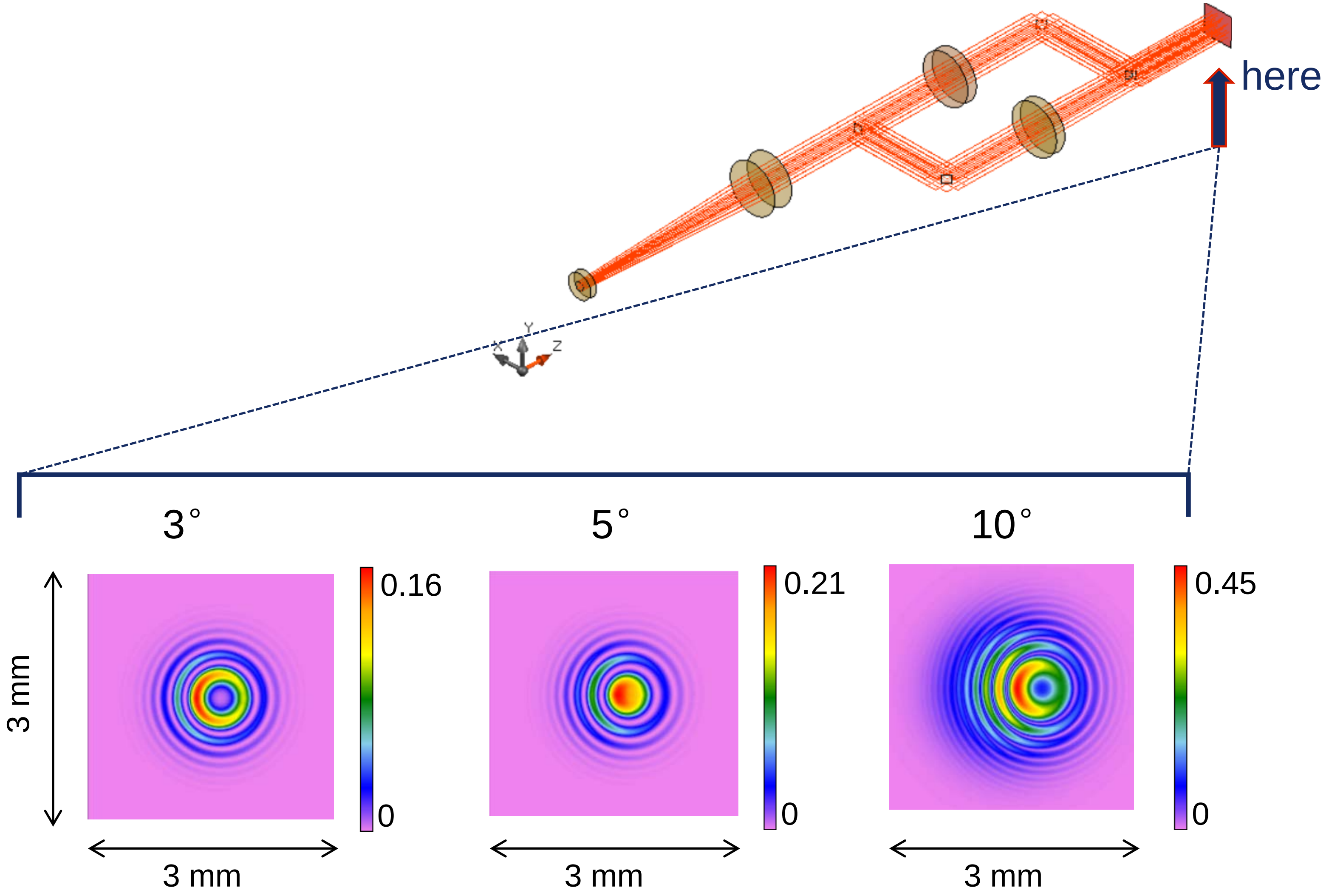
Results: Ray Dot Diagram at Detector



Results: Field at Detector

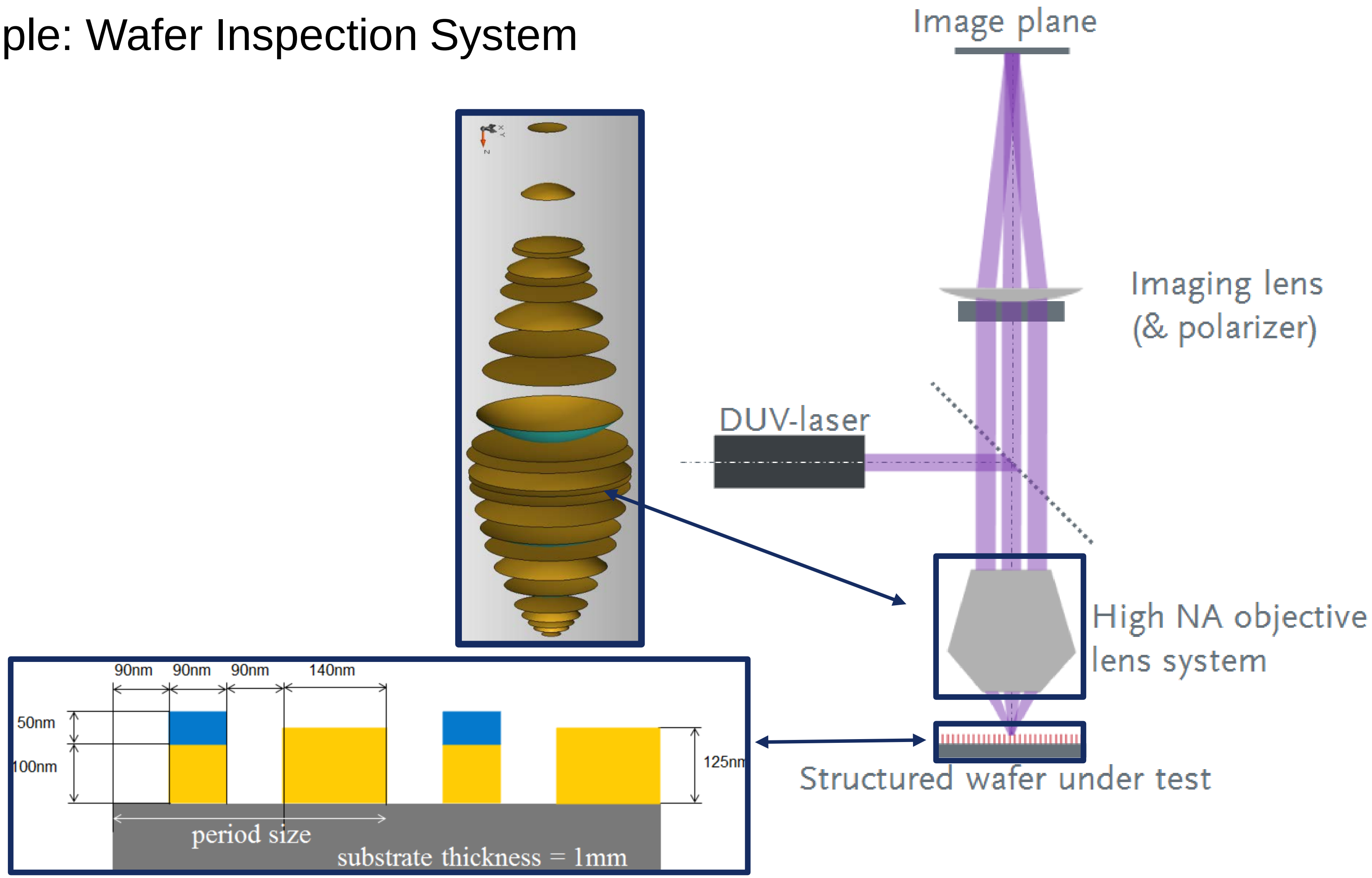


Results: Field Tracing with Tilt of the Object

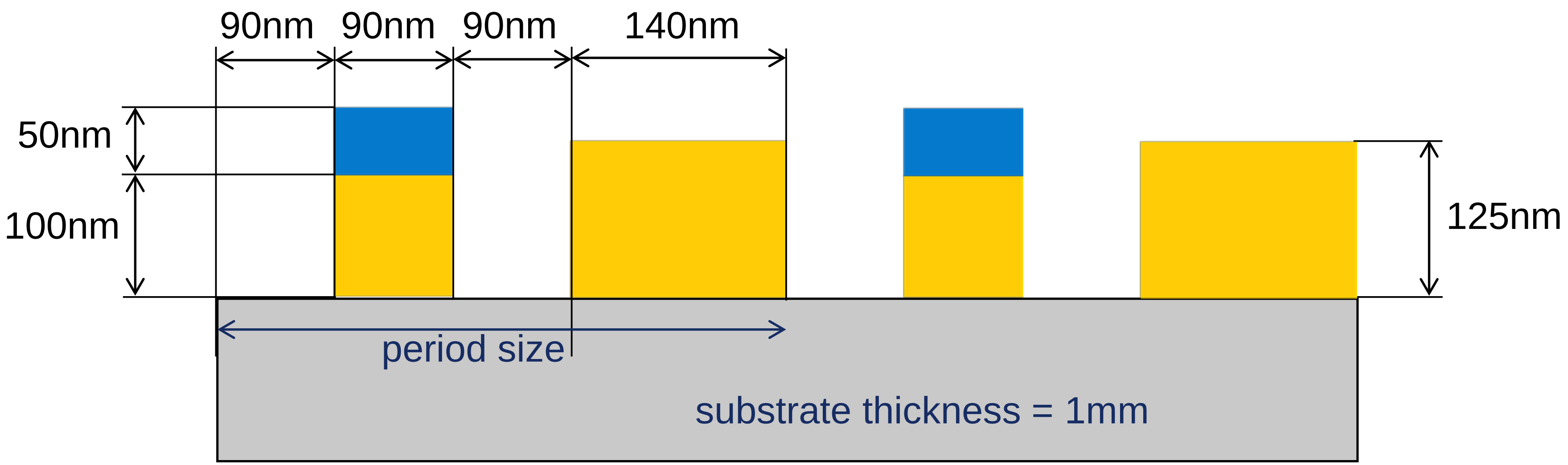


Example of Multi-Scale Optical System

Example: Wafer Inspection System

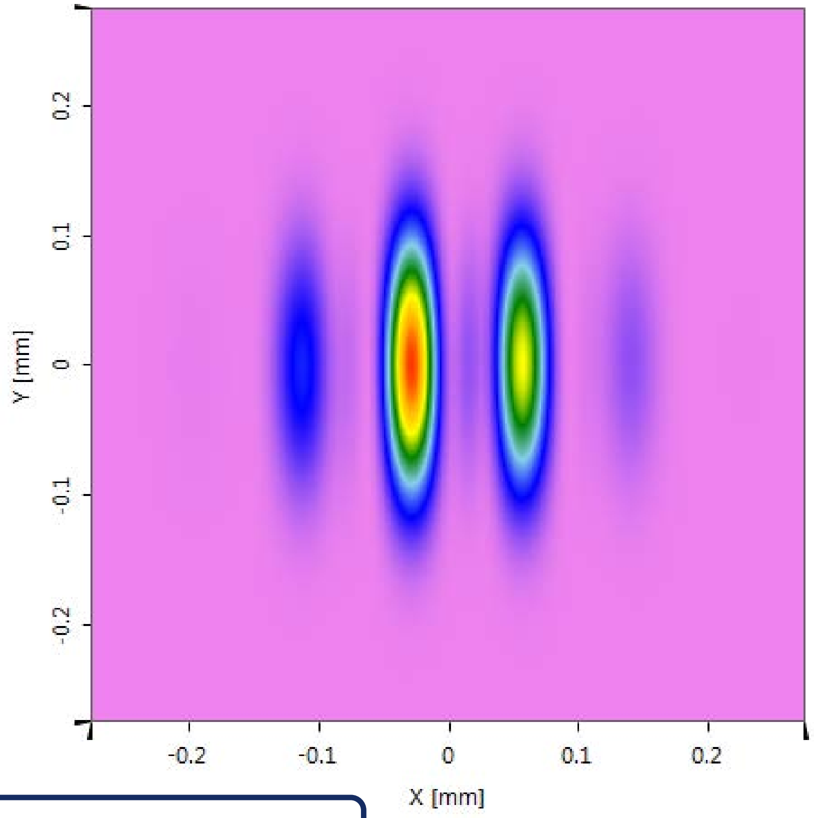


Base Grating Structure

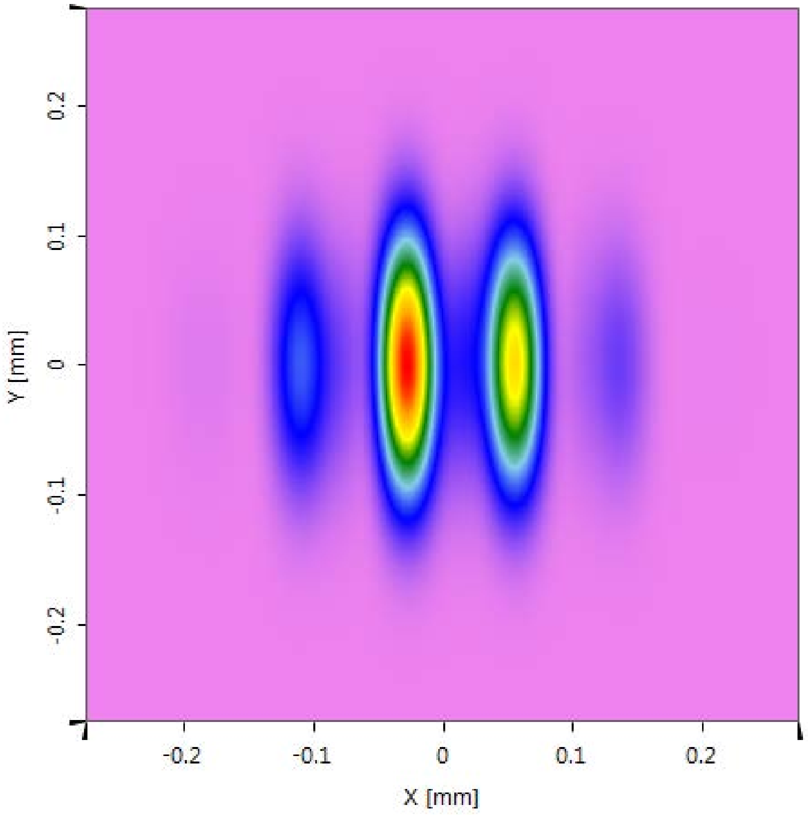


Base Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

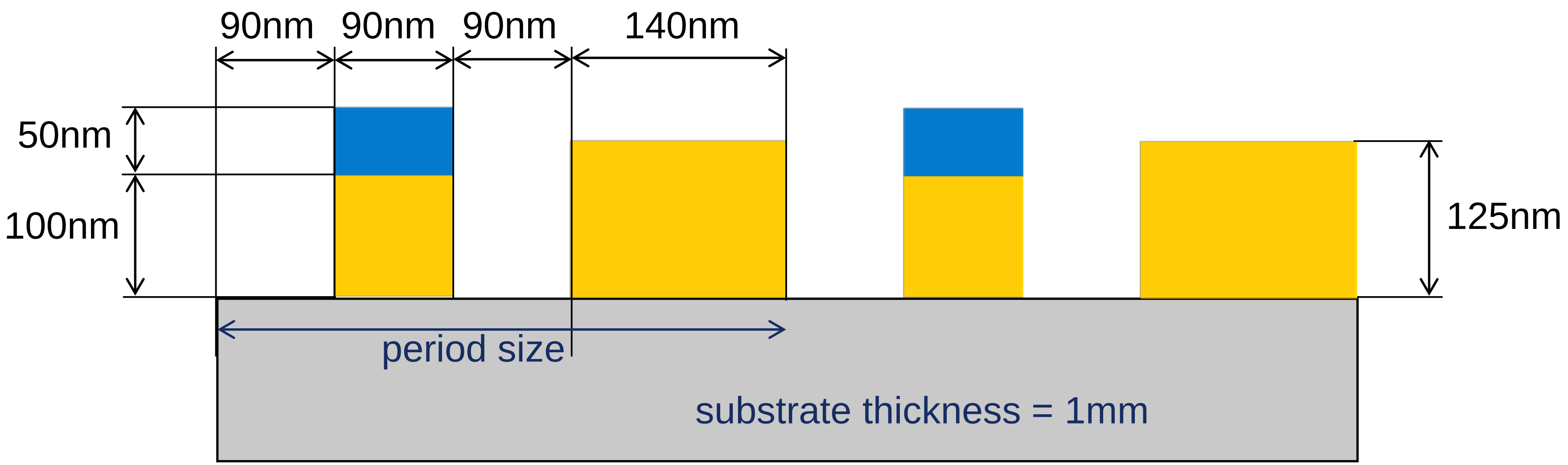


Intensity Image of Grating after Polarizer in Y-Direction

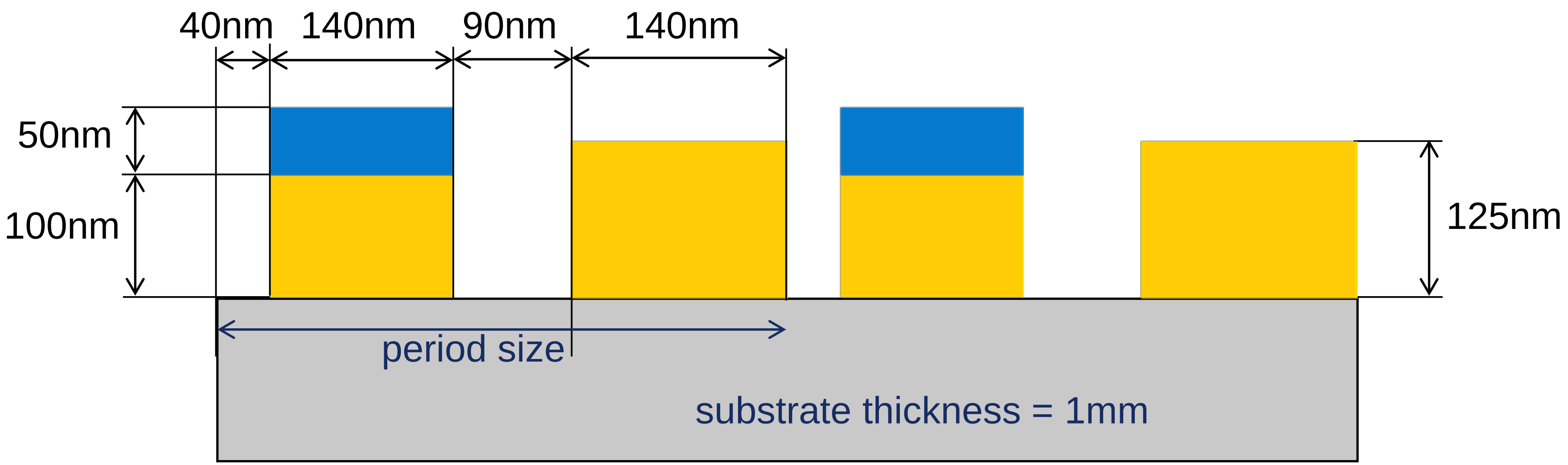


Simulation time few seconds

Base Grating Structure

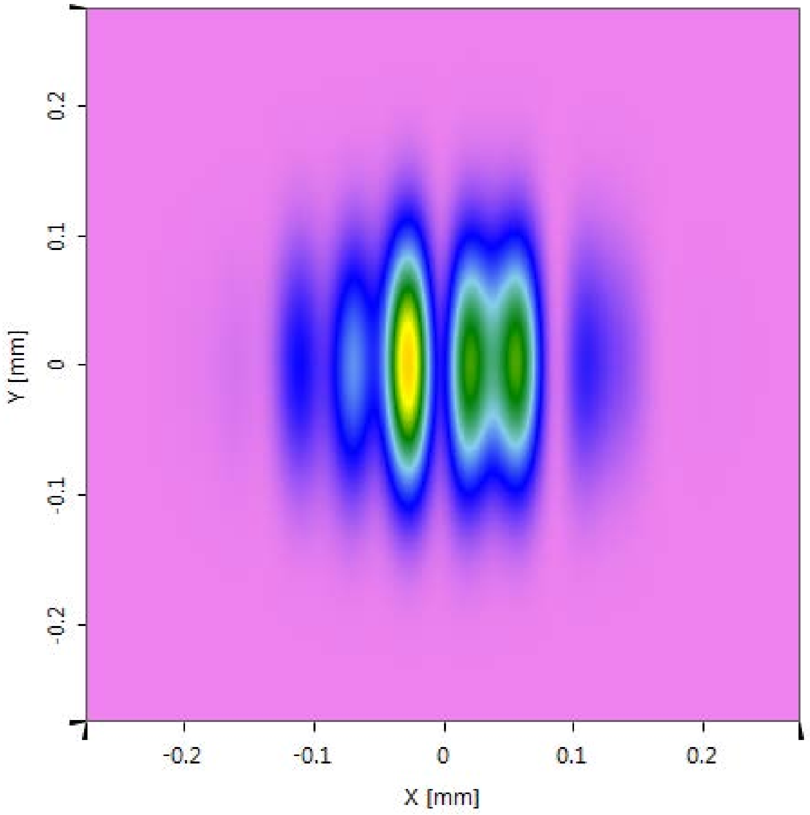


Modified Grating Structure

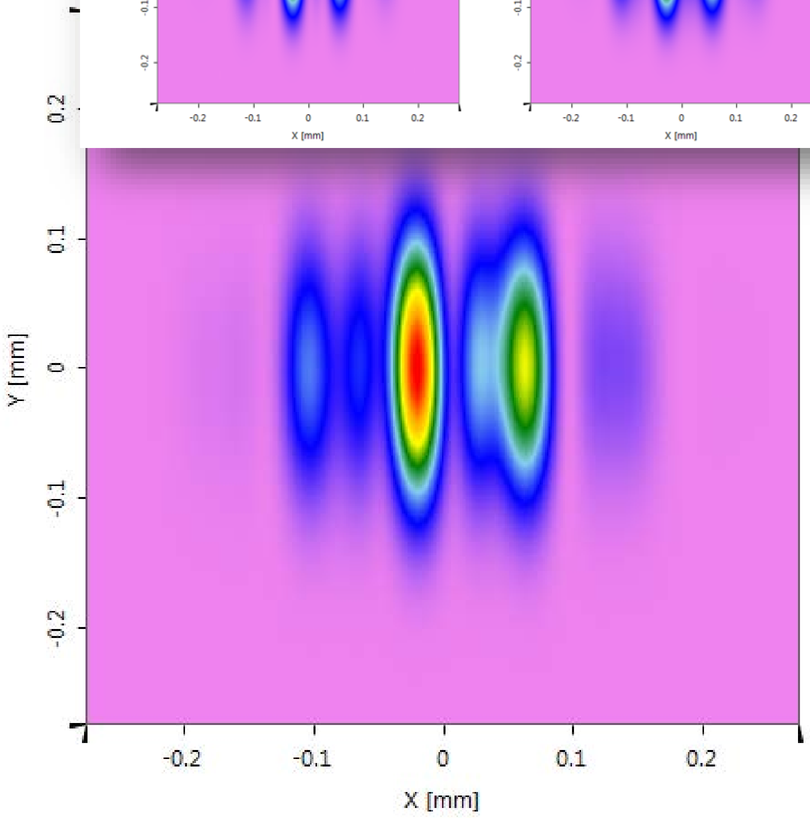


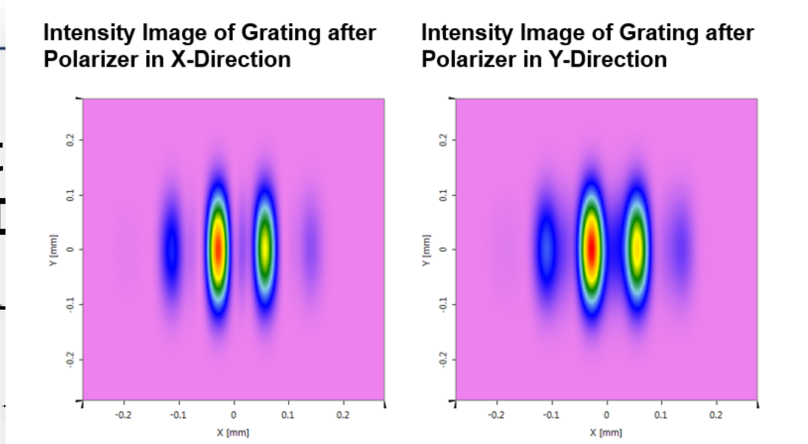
Modified Structure Analysis

Intensity Image of Grating after Polarizer in X-Direction

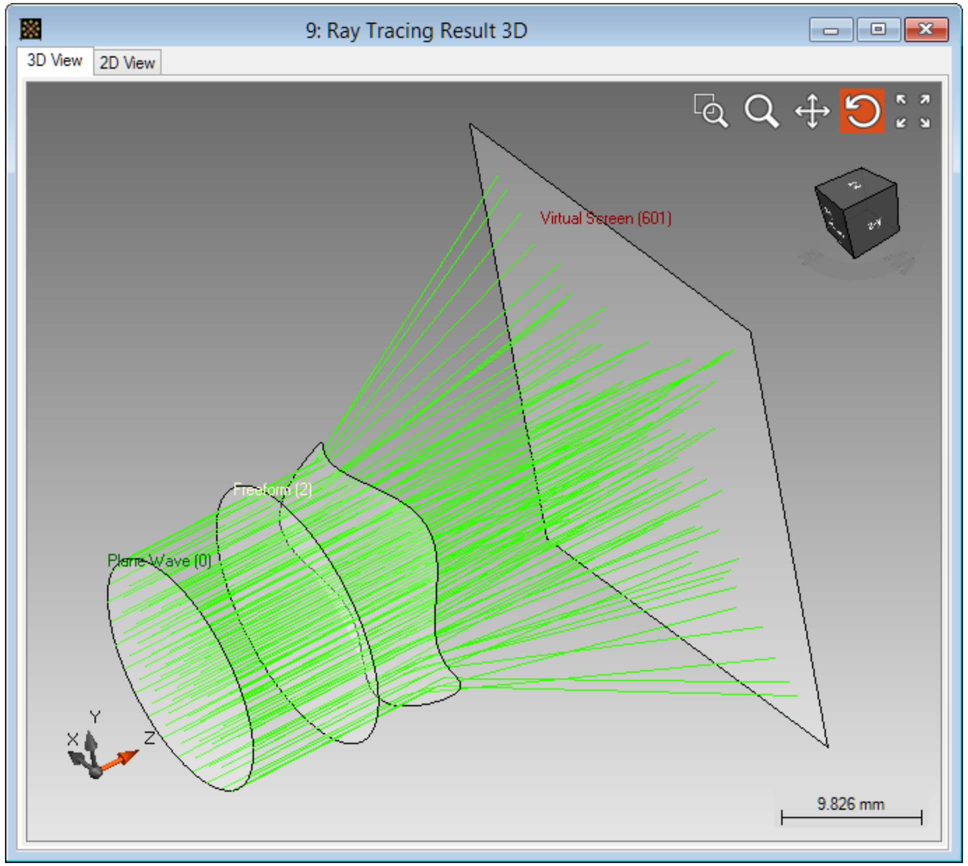


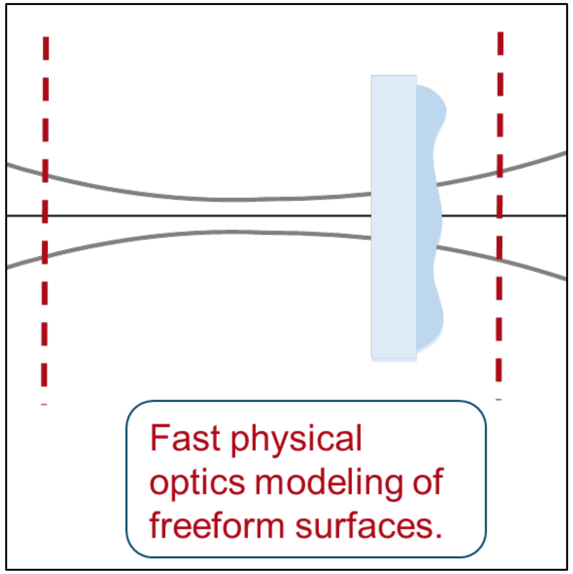
Int larizer in Y-D



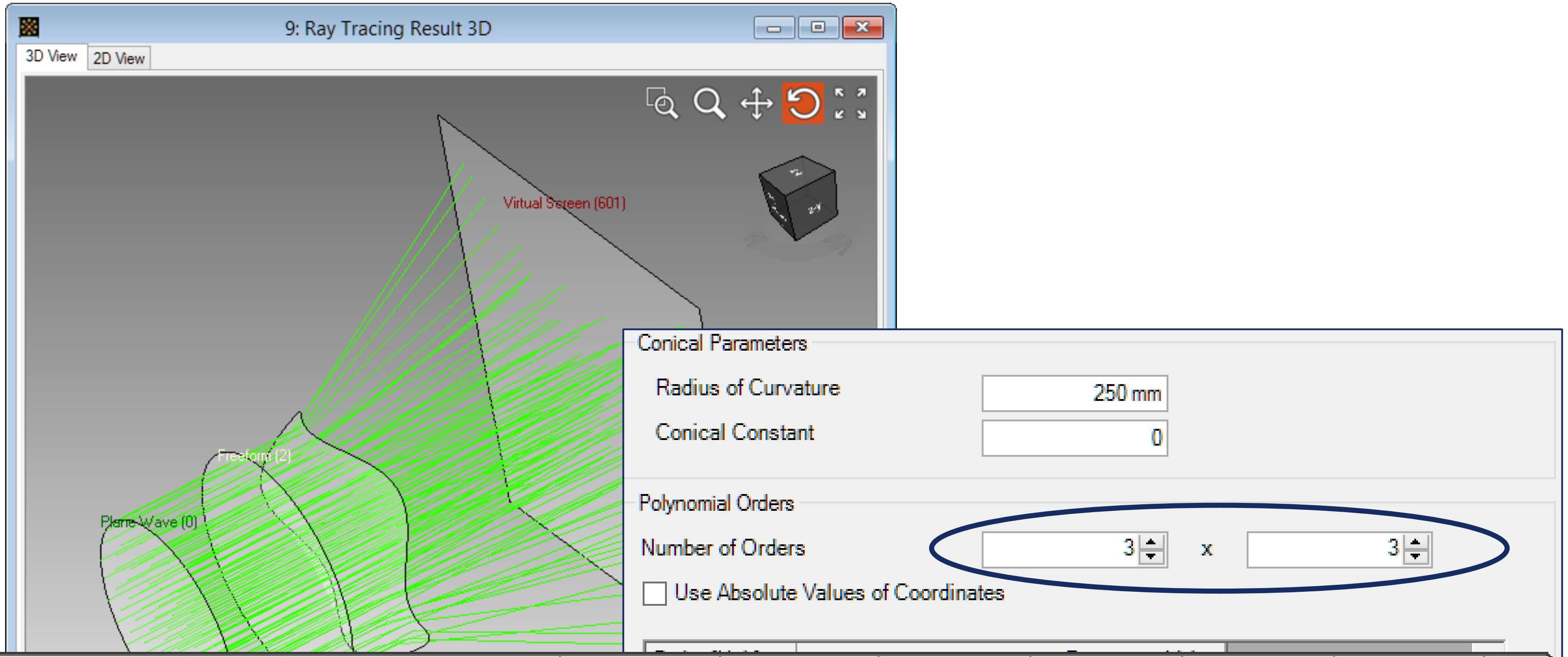


Fast Physical Optics: Freeform Surfaces





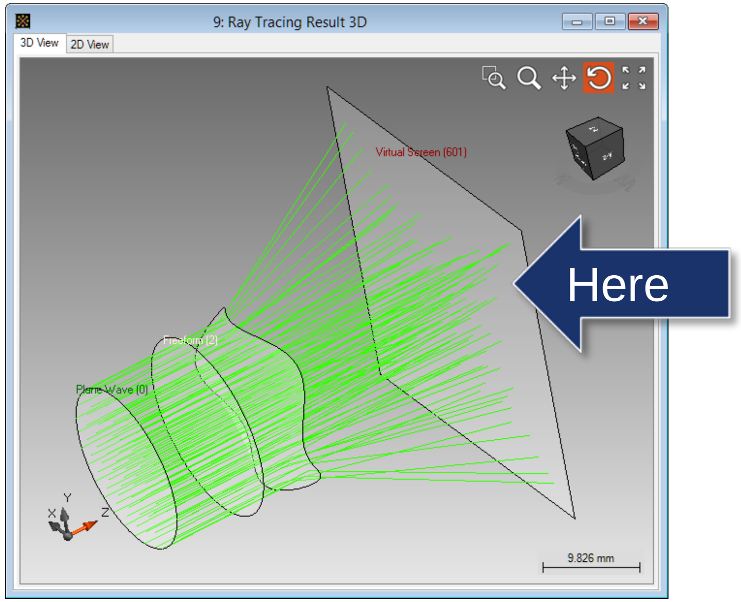
Fast Physical Optics: Freeform Surfaces



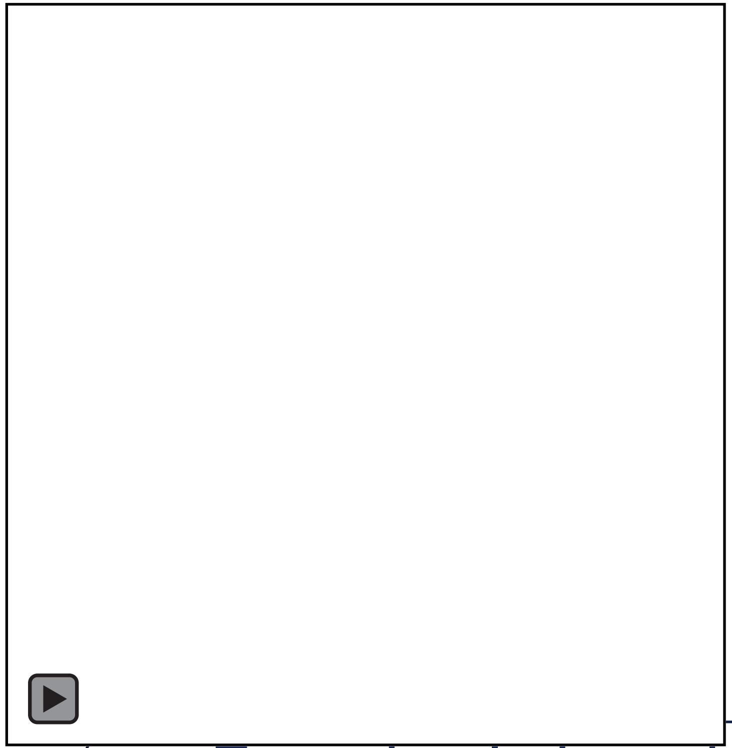
	Iteration Step	1	2	3	4	5	6	7
1	(2,0) [mm^(-1)] (Freeform #2 | Polynomial Interface #1)	0.0024274	0.0031541	0.0041695	0.00035002	0.003082	0.0024793	0.0025
2	(2,1) [mm^(-2)] (Freeform #2 | Polynomial Interface #1)	0.0013393	-0.0017223	0.0020993	0.0010653	-0.0014089	0.0017305	0.0007
3	(0,2) [mm^(-1)] (Freeform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

50 simulations

Fast Physical Optics: Freeform Surfaces



Amplitude $E_x(x,y)$

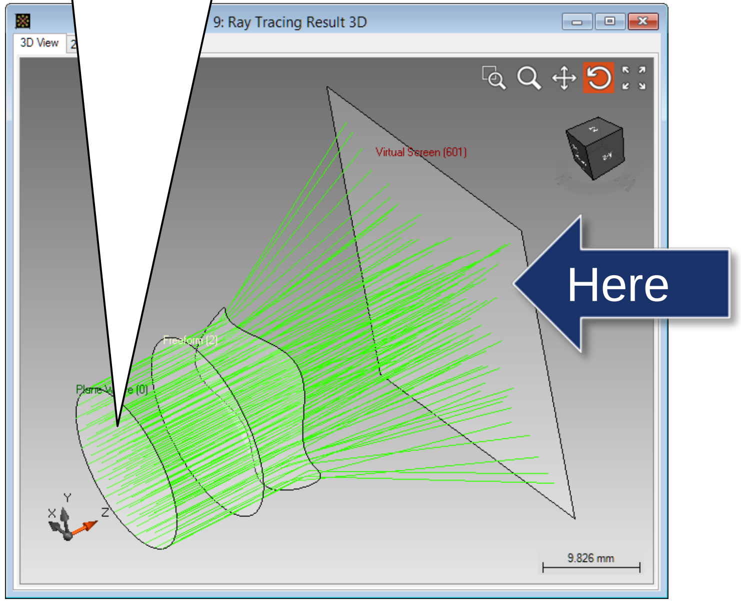


cpu time per simulation < 1 sec

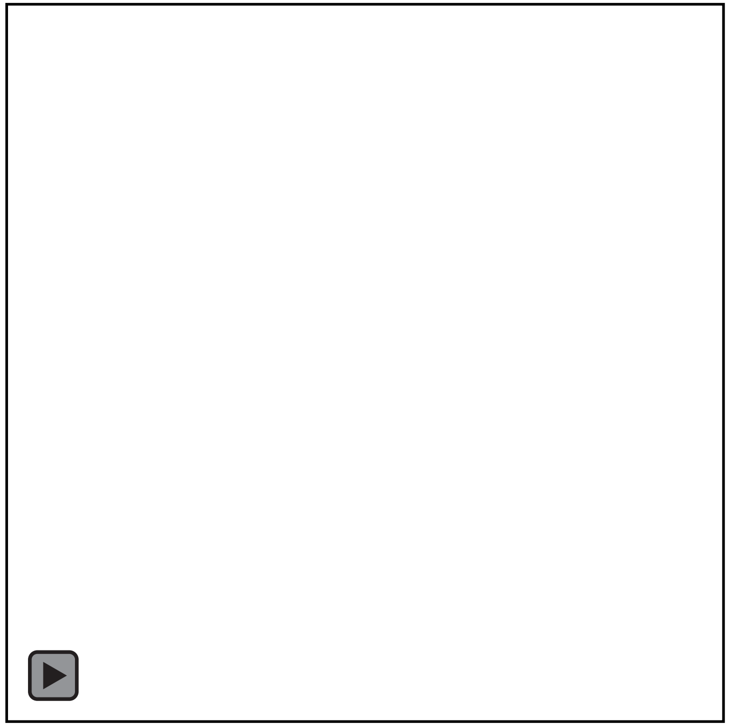
Fast simulation with low number of wavefront samples (similar to number of rays) but noise-free detector signal!

Fast Physical Optics: Freeform Surfaces

Input: Gaussian beam
Diameter 10 mm

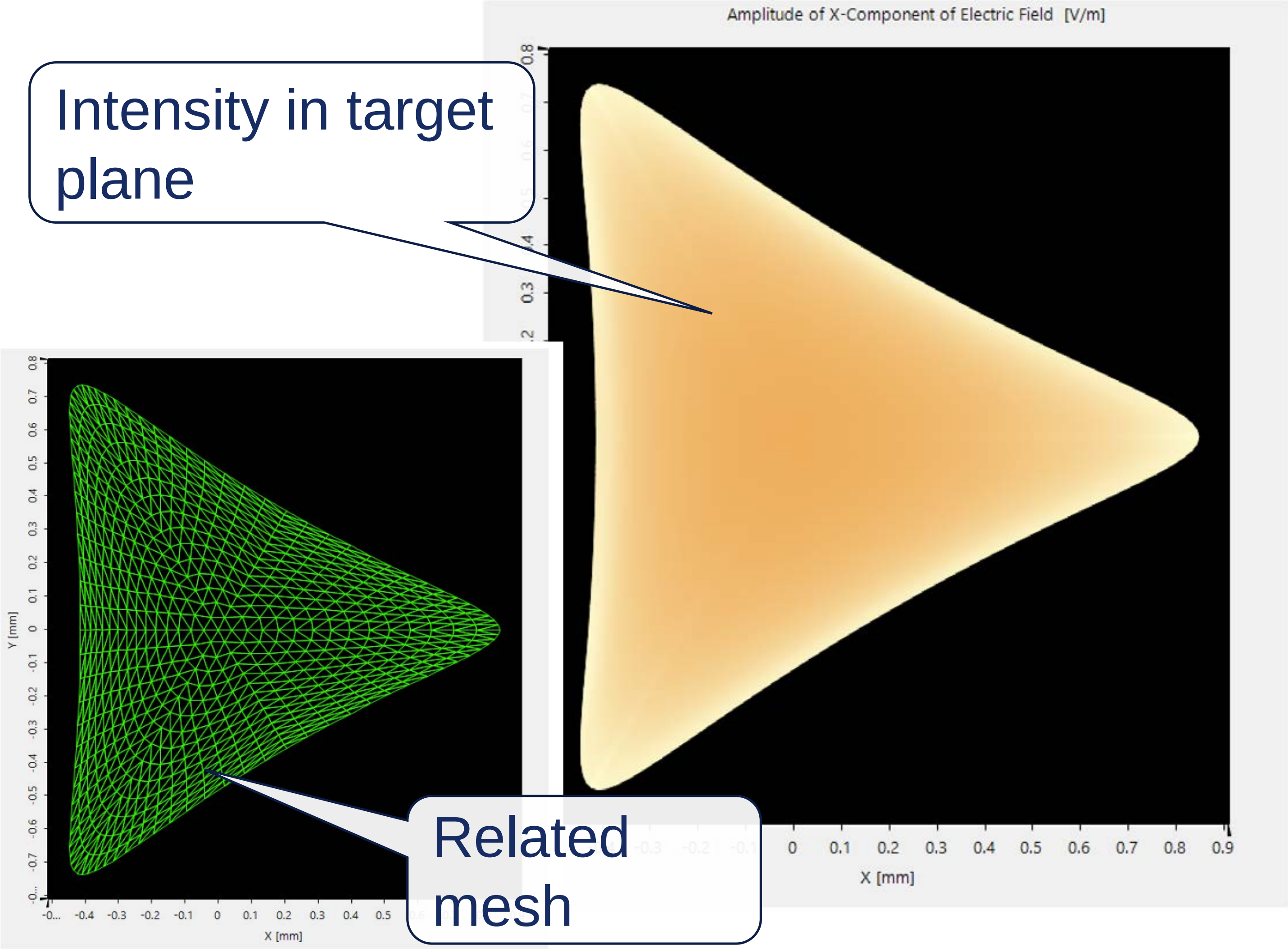


Amplitude $E_x(x,y)$



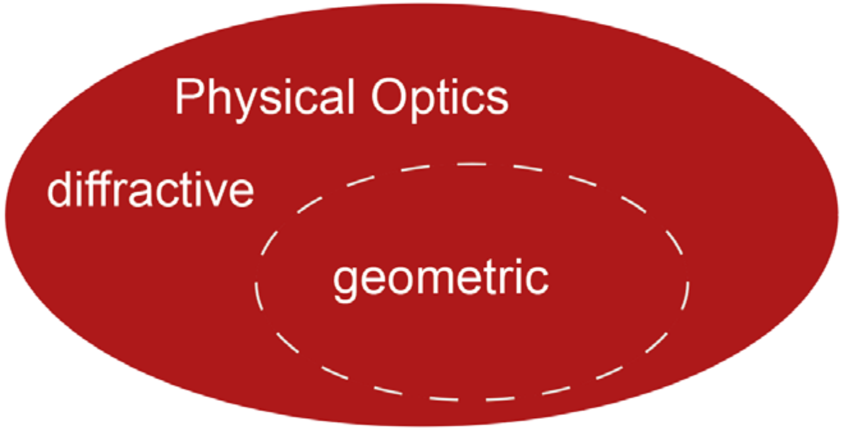
cpu time per simulation < 1 sec

Light Shaping

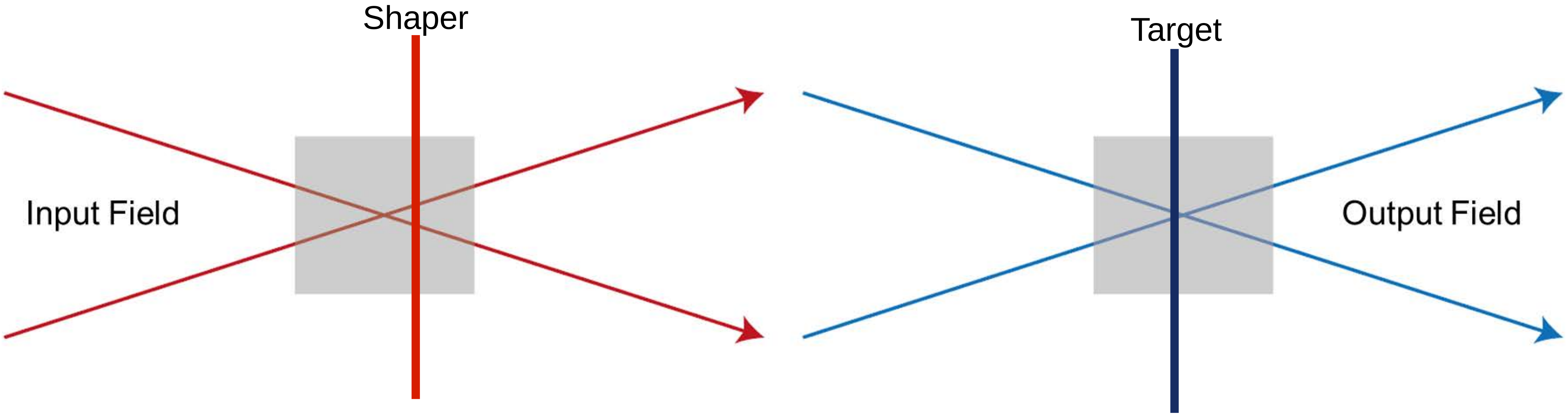


Light Shaping From a Physical Optics Perspective

Diffractive and geometric concepts

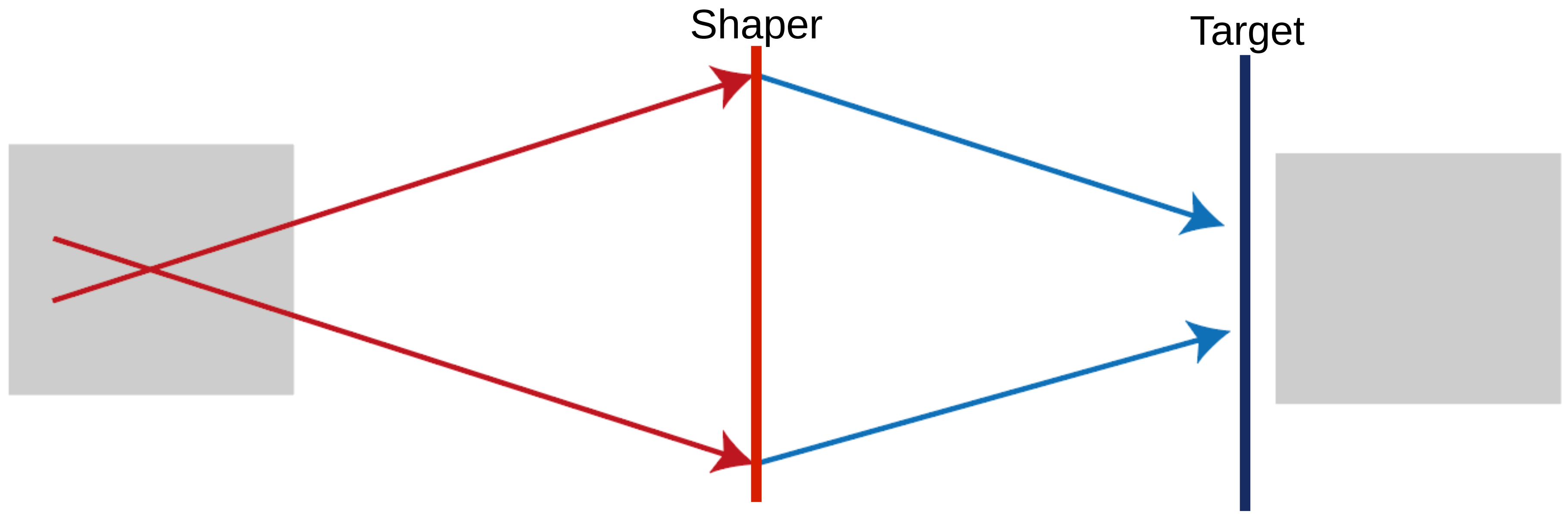


Light Shaping Tasks: Cases



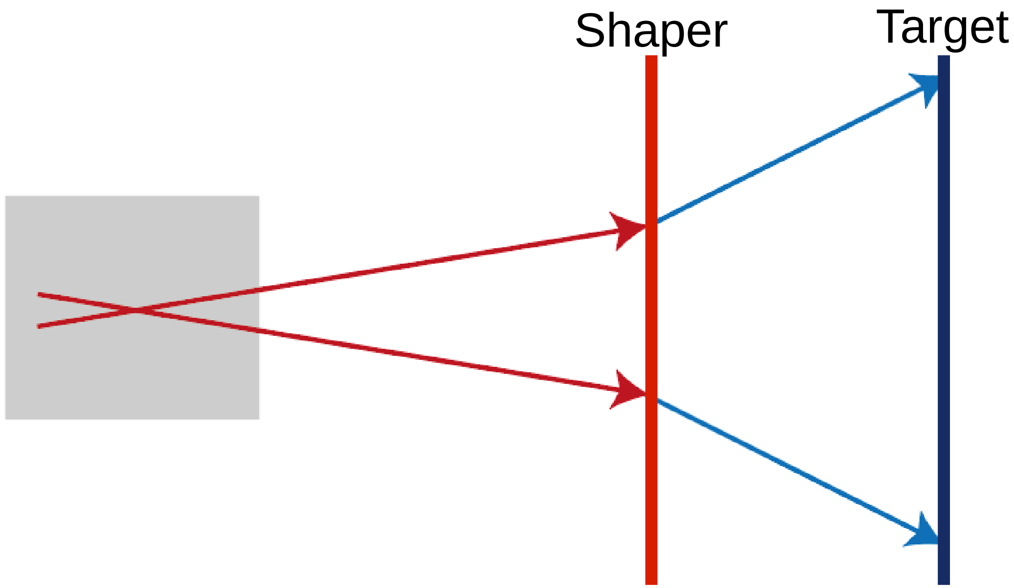
- Input field consists of one source mode
- No restrictions of input field type

Light Shaping Tasks: Cases



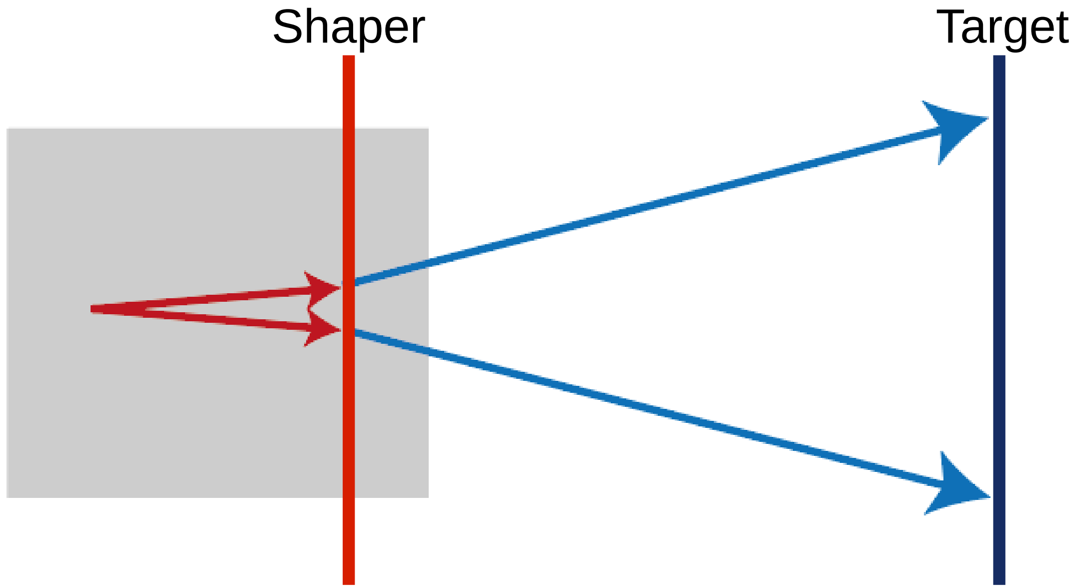
- Shaper in geometric field zone (GFZ)
- Target in geometric field zone (GFZ)

Light Shaping Tasks: Cases



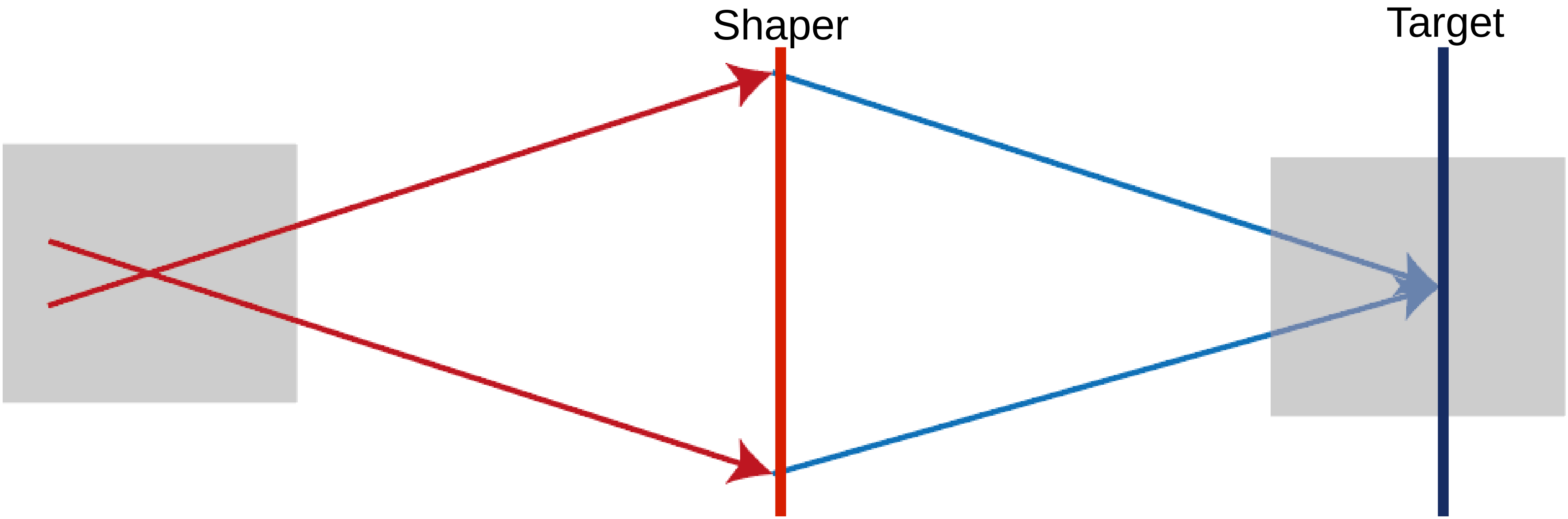
- Shaper in geometric field zone (GFZ)
- Target in geometric field zone (GFZ)

Light Shaping Tasks: Cases



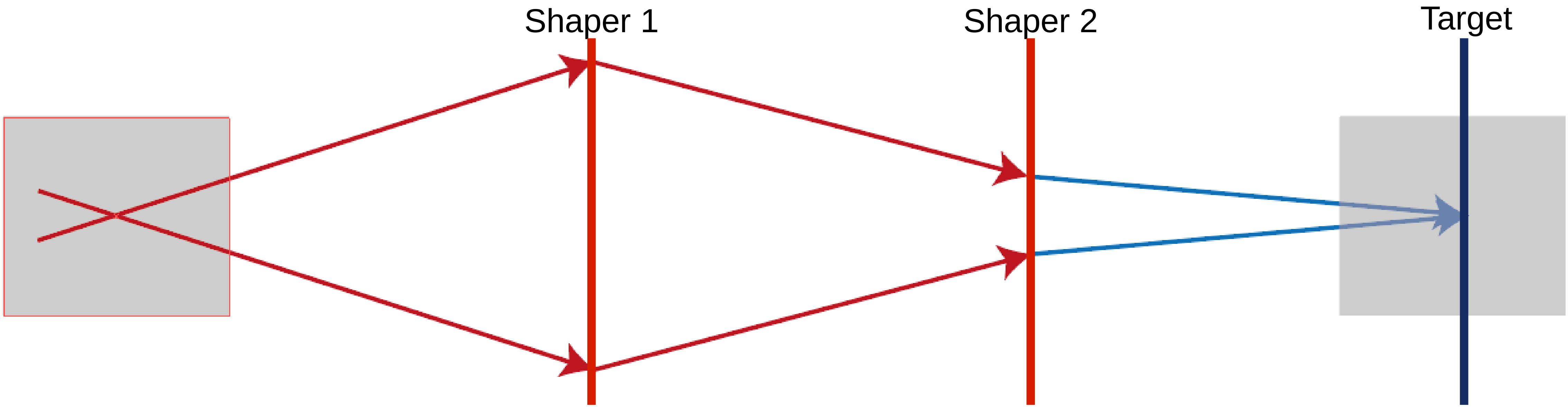
- Shaper in diffractive field zone (DFZ)
- Target in geometric field zone (GFZ)

Light Shaping Tasks: Cases



- Shaper in geometric field zone (GFZ)
- Target in diffractive field zone

Light Shaping Tasks: Cases

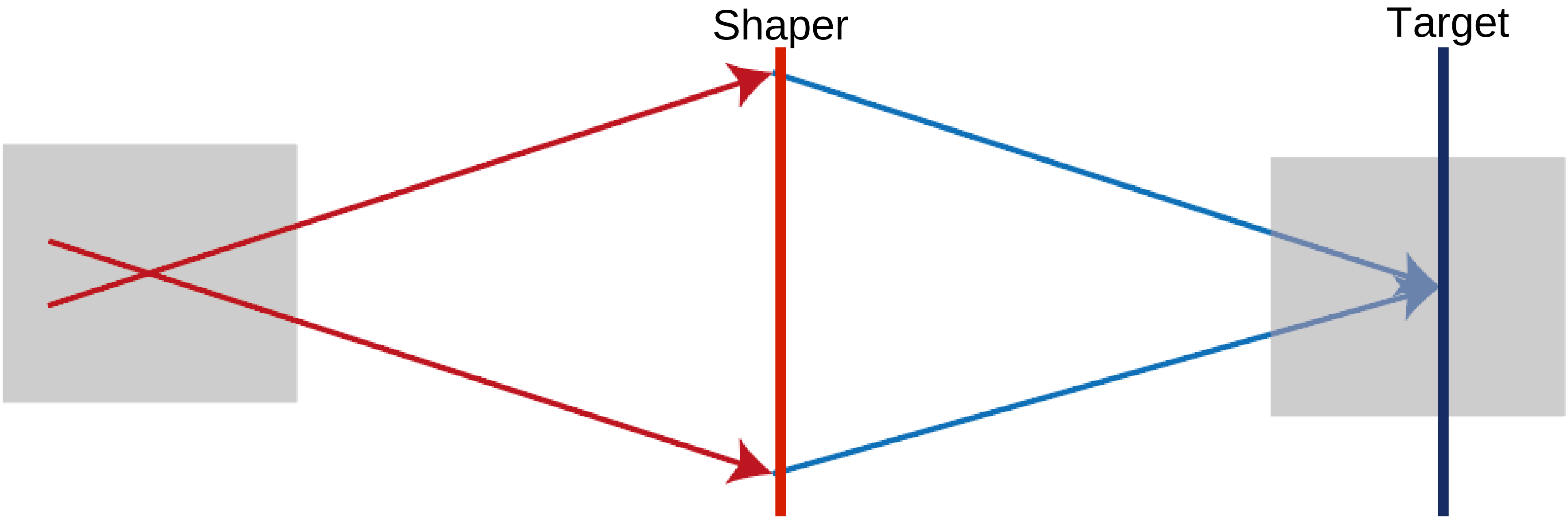


- Shaper in geometric field zones (GFZ)
- Target in diffractive field zone (DFZ)

Light shaping in geometric zones

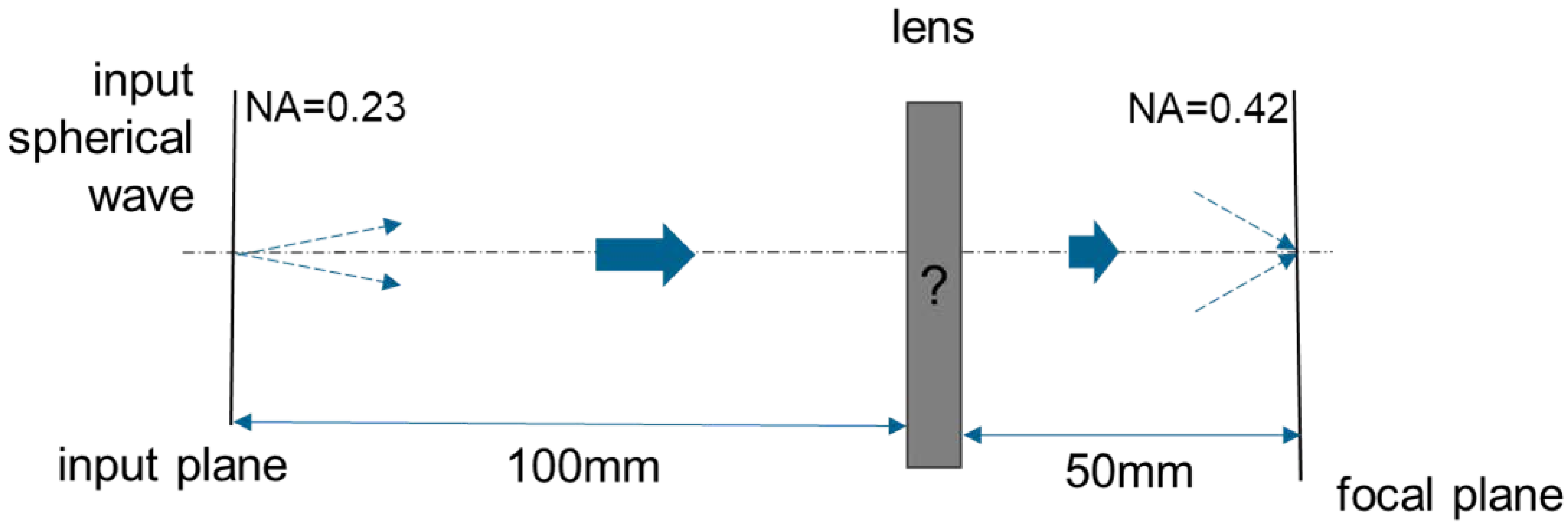
Diffractive (HOE) and refractive (freeform) approaches

Light Shaping Tasks: Focussing

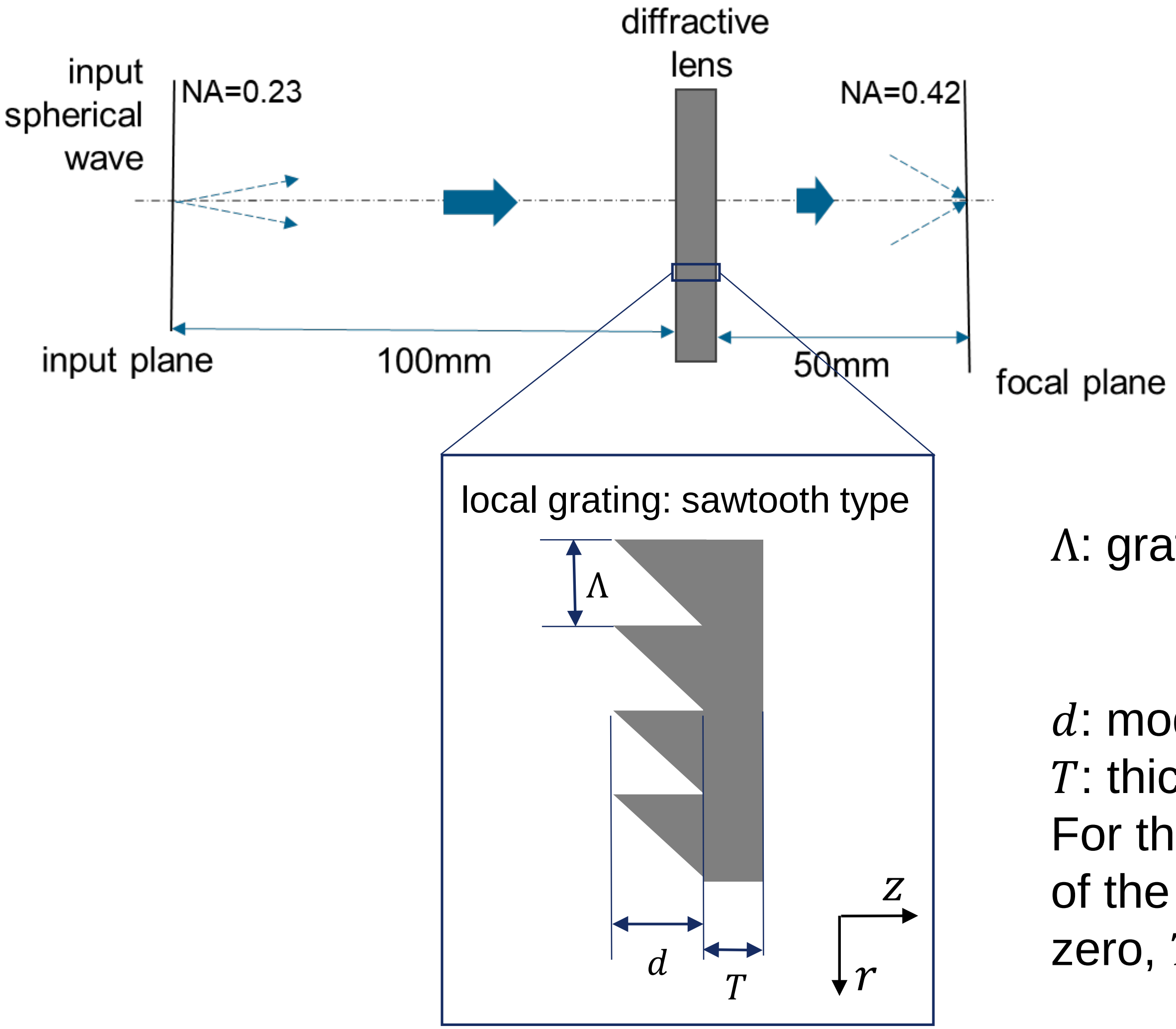


- Shaper in geometric field zone (GFZ)
- Target in diffractive field zone (DFZ)

Light Shaping Tasks: Focussing



Light Shaping Tasks: Focussing



Λ: grating period

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

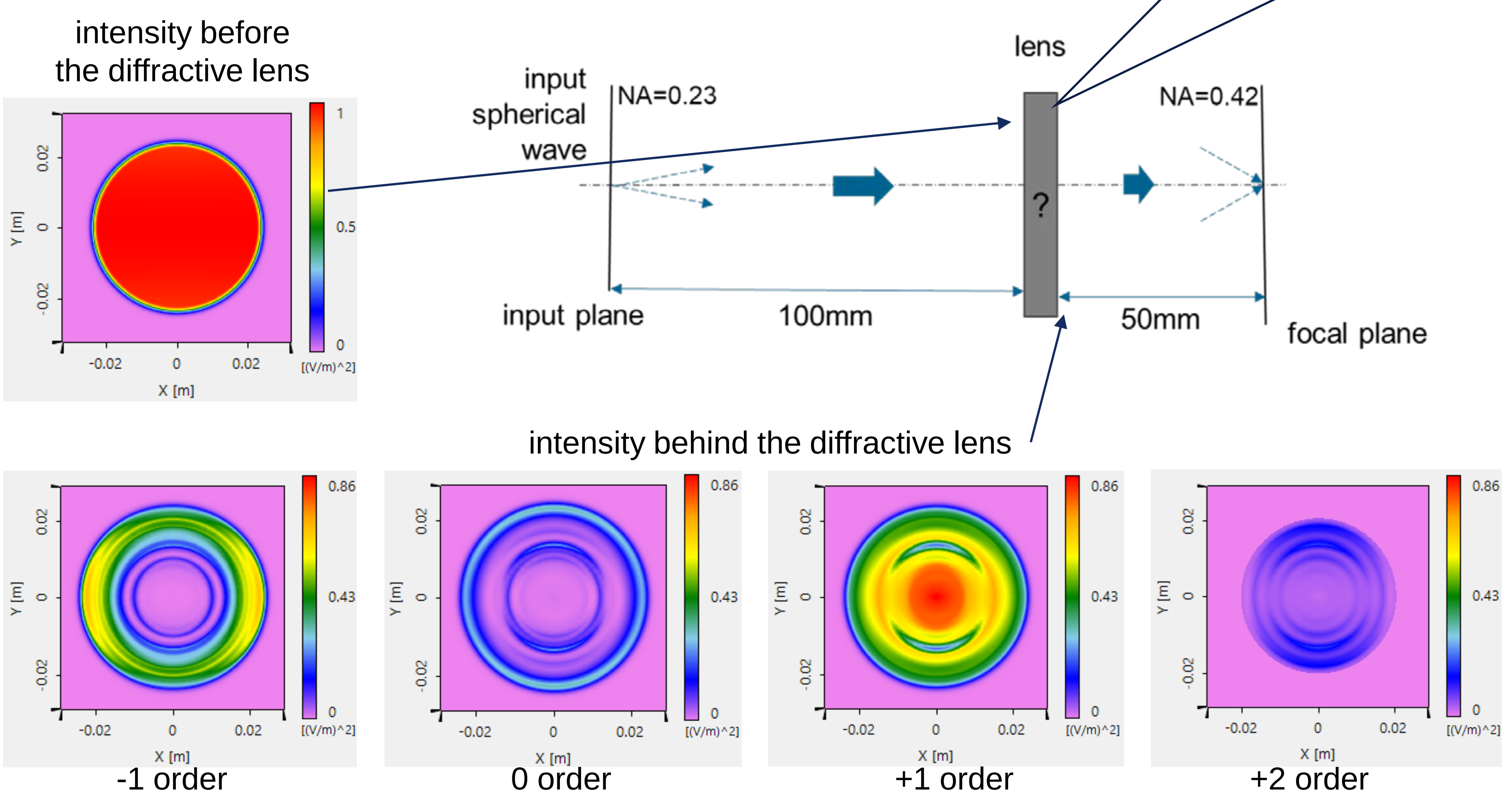
d: modulation depth

T: thickness of base block.

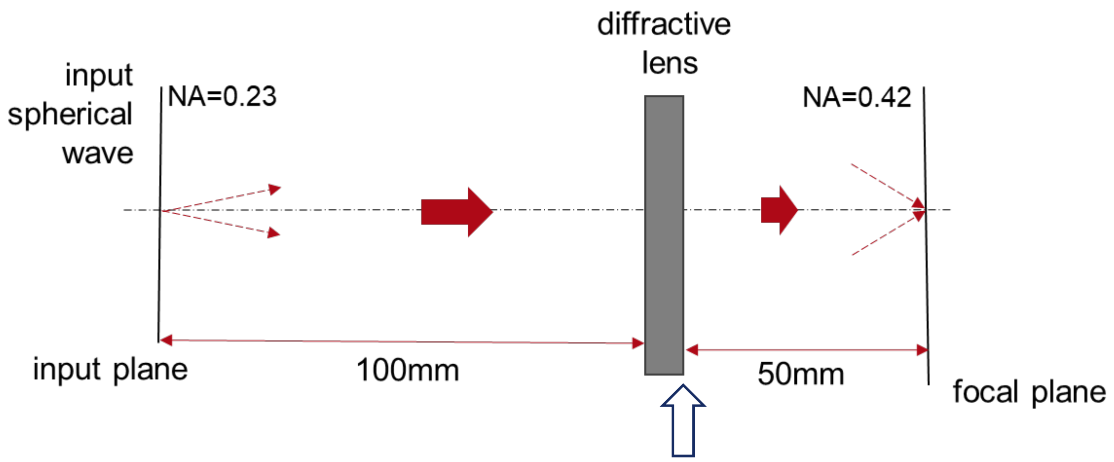
For the design, the thickness of the base block is set as zero, $T = 0$

Light Shaping Tasks: Focussing

Modeling with Fourier Modal Method (FMM)

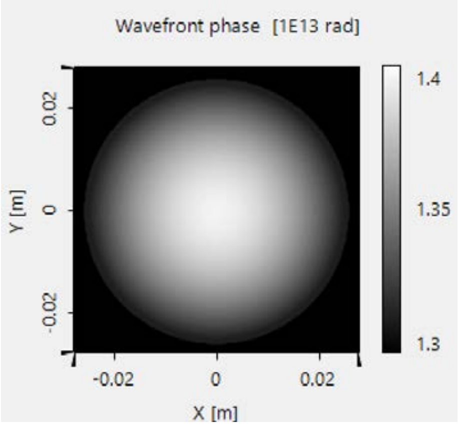


Light Shaping Tasks: Focussing

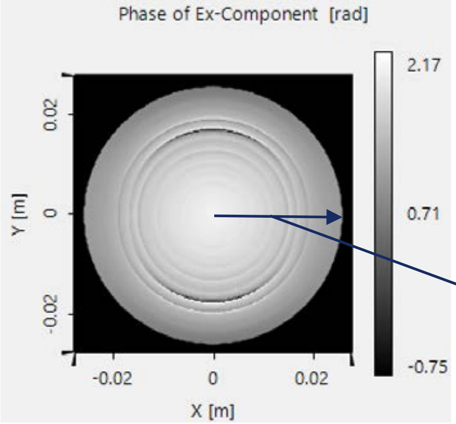


phase of the working order behind the diffractive lens

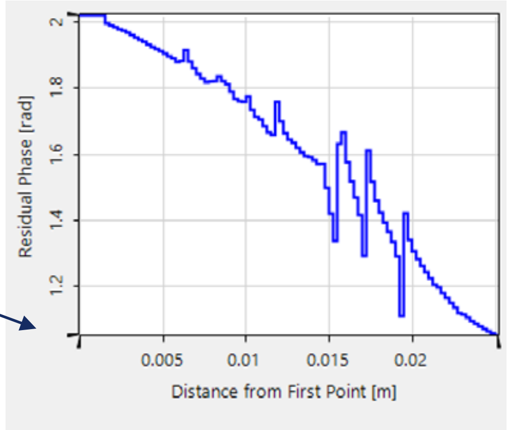
calculated phase of
Rayleigh coefficient of Ex



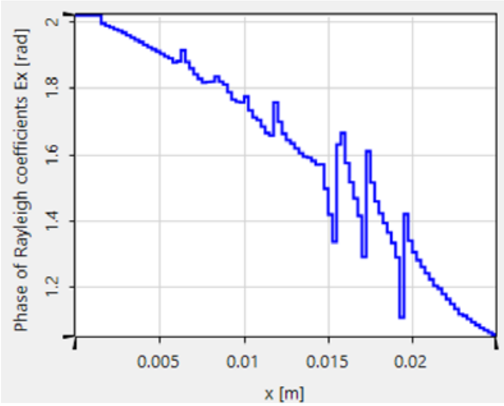
wavefront phase



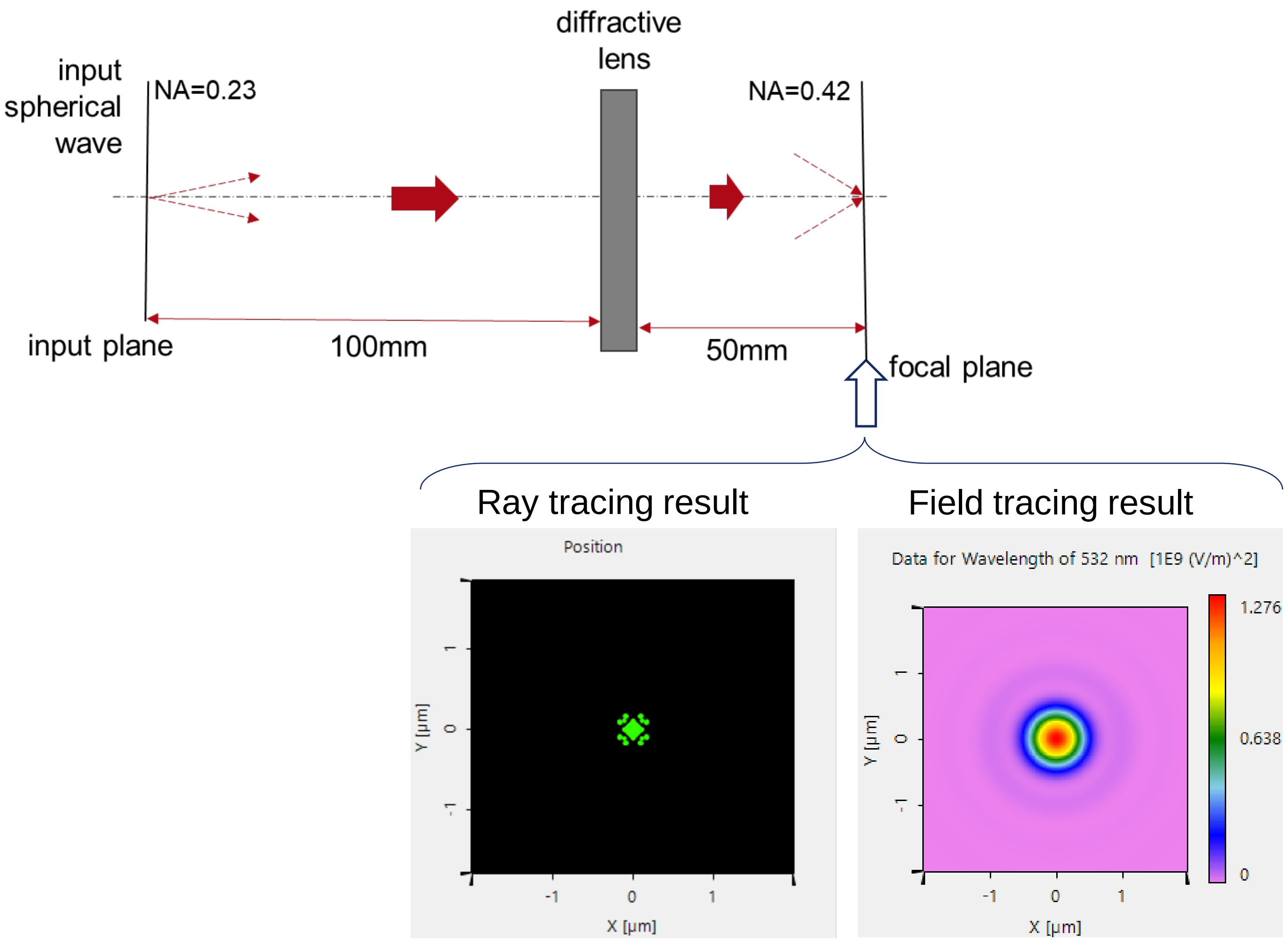
residual phase



residual phase along cross-section



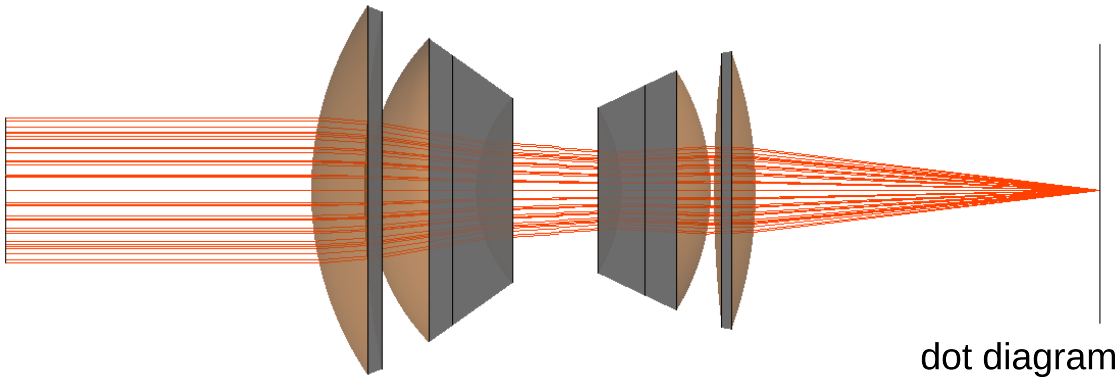
1. single lens design



Dot pattern of the working order

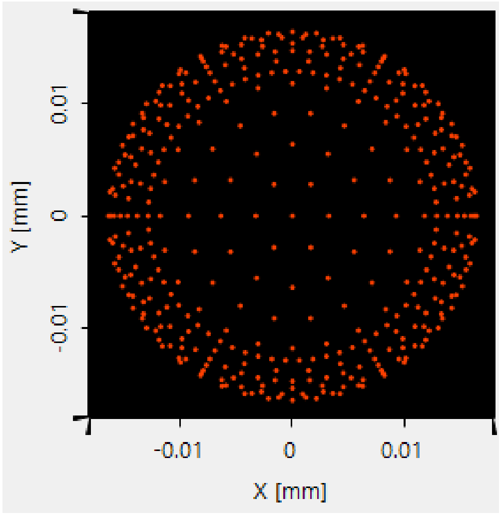
PSF

Example: Focusing Lens w/o Freeform

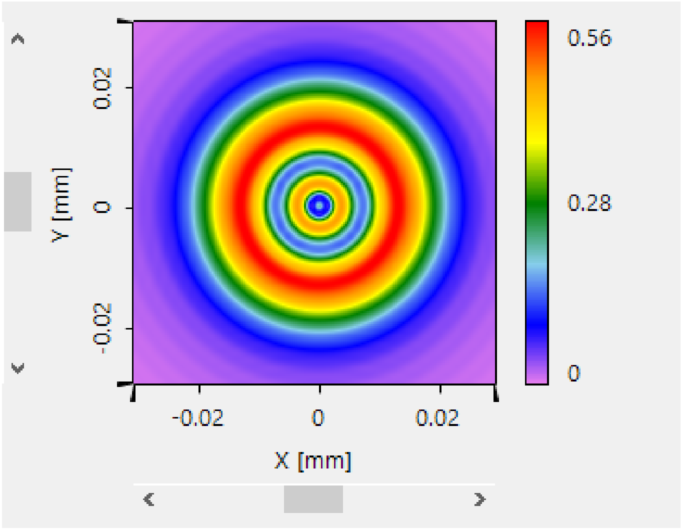


dot diagram

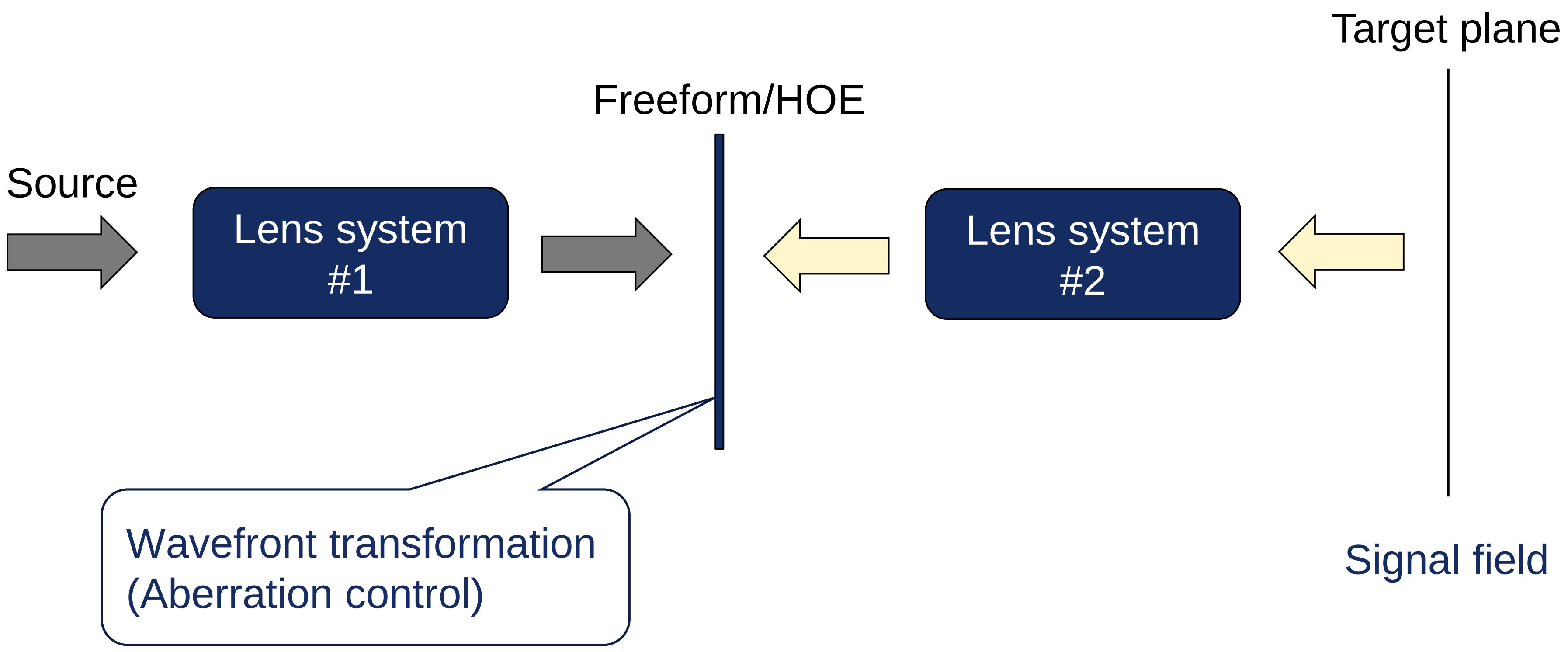
PSF



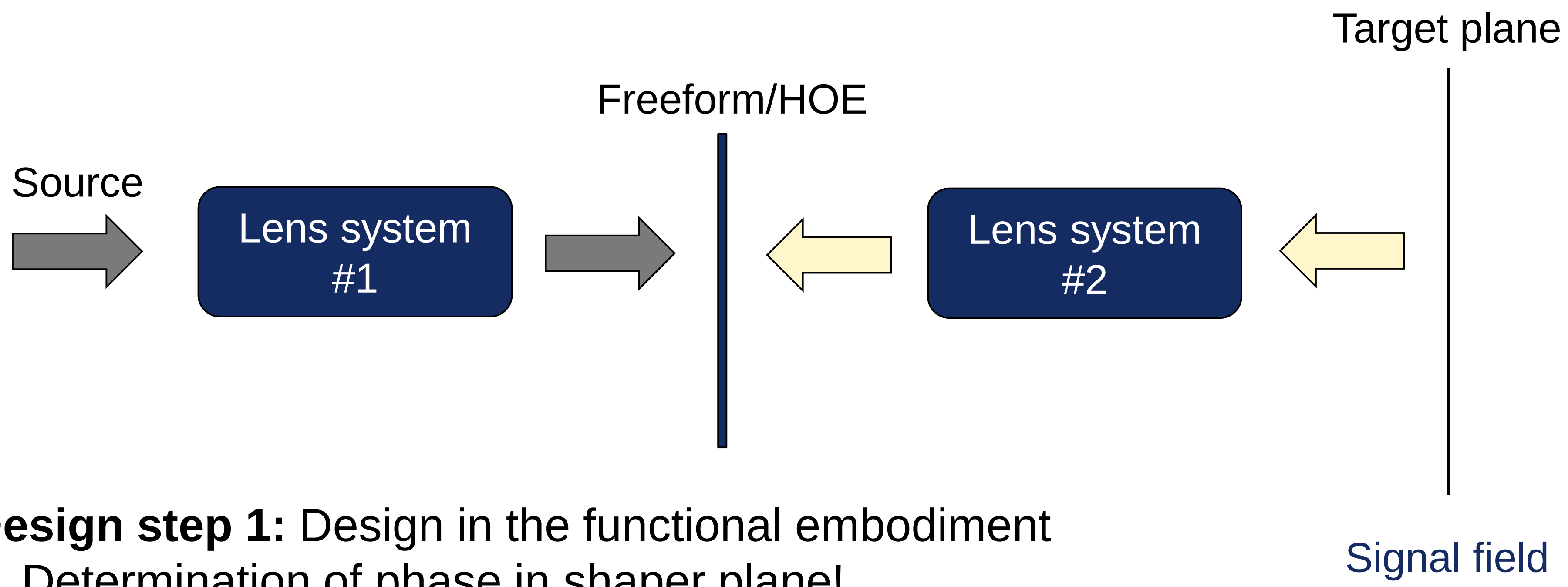
$\text{Size} = 42.27\mu\text{m}$



Design Concept: HOE and Freeform



Design Concept: HOE and Freeform



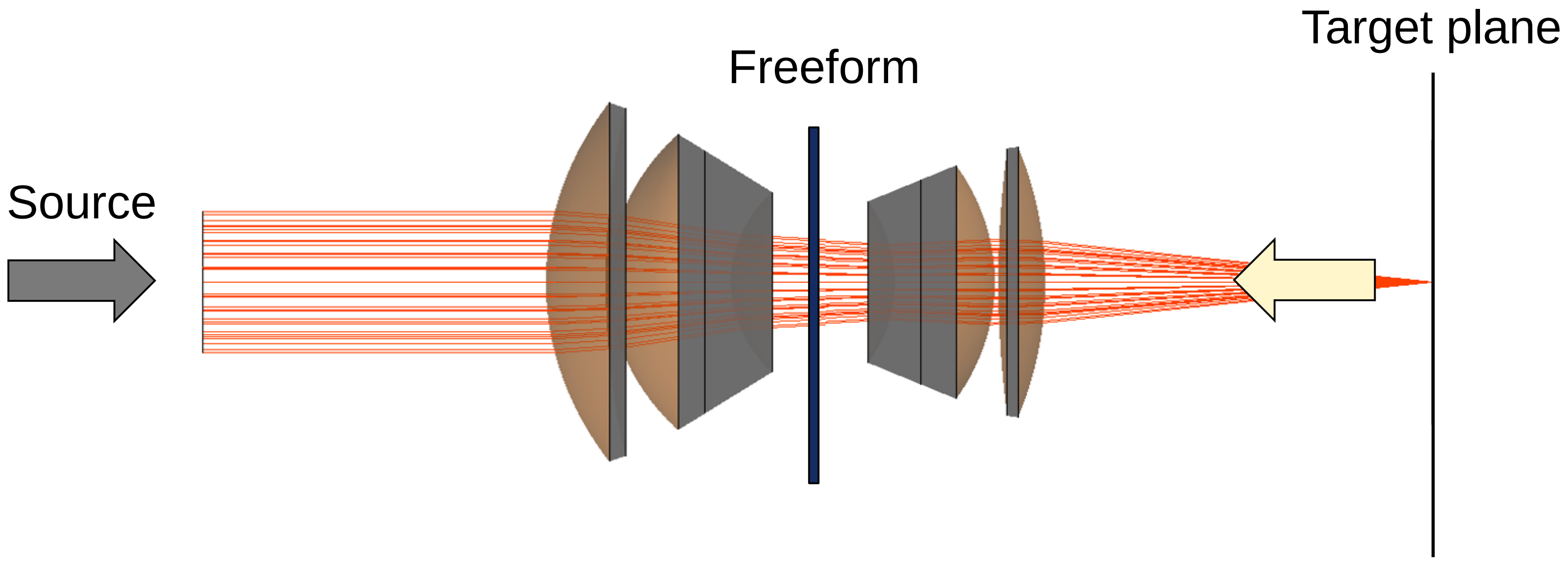
Design step 1: Design in the functional embodiment

- Determination of phase in shaper plane!

Design step 2: Design in structural embodiment

- Design of HOE or refractive surface in order to obtain the required phase change

Freeform Design Algorithm: Example



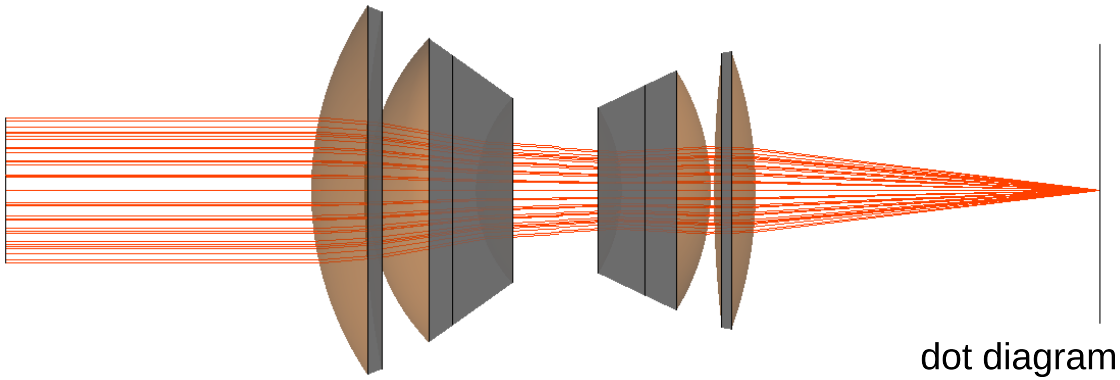
Design step 1: Design in the functional embodiment

- Inverse **field** propagation approach

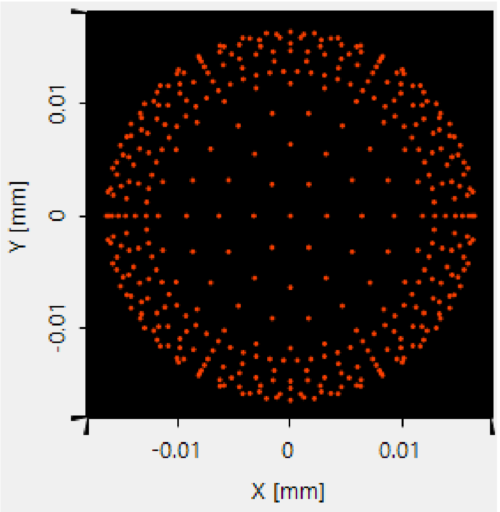
Design step 2: Design in structural embodiment

- Fast recursive design of freeform surface using spline interpolation approach based on full phase information (no parametric optimization)

Example: Focusing Lens w/o Freeform

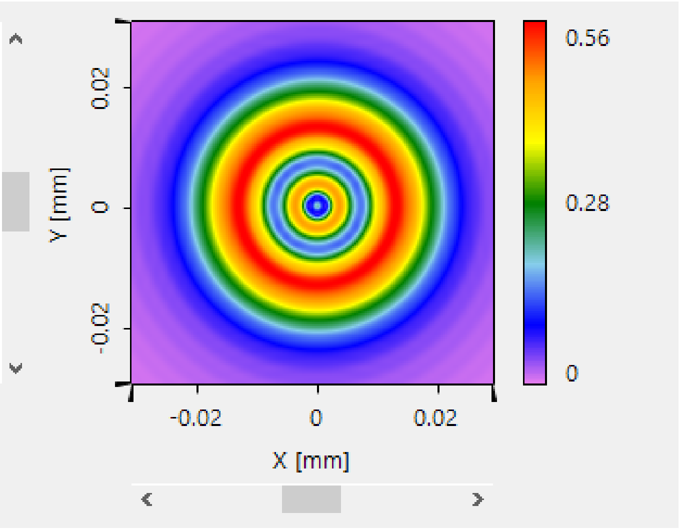


dot diagram

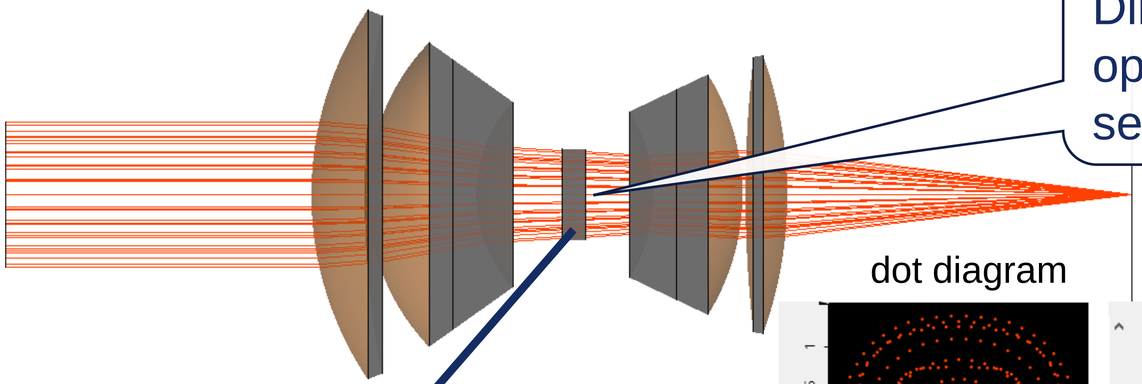


$\text{Size} = 42.27\mu\text{m}$

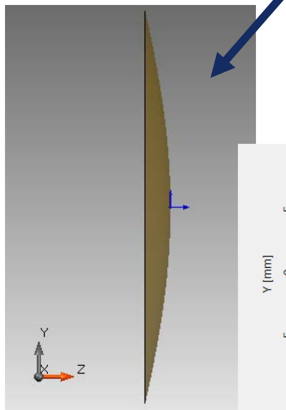
PSF



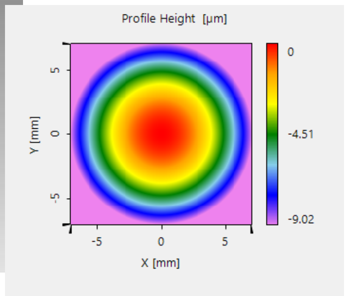
Example: Focusing Lens w/ Freeform



Direct calculation without optimization in a few seconds!

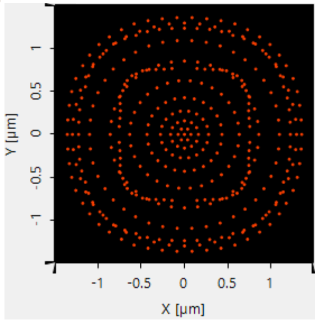


Height Profile (3D view)



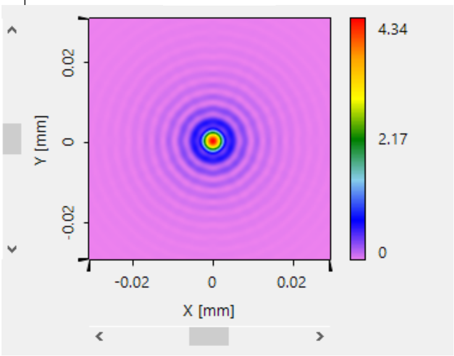
Height Profile (2D view)

dot diagram

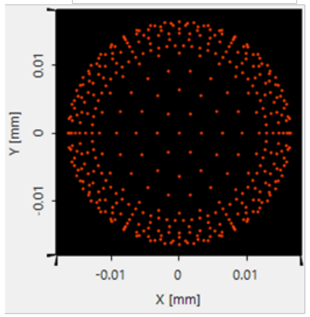


Size $= 2.08\mu m$

PSF

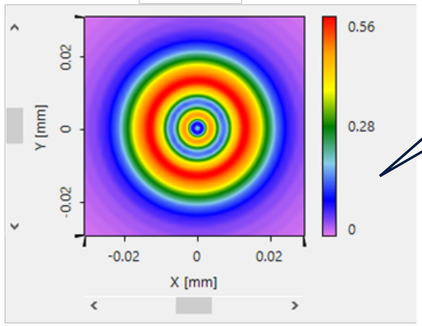


dot diagram



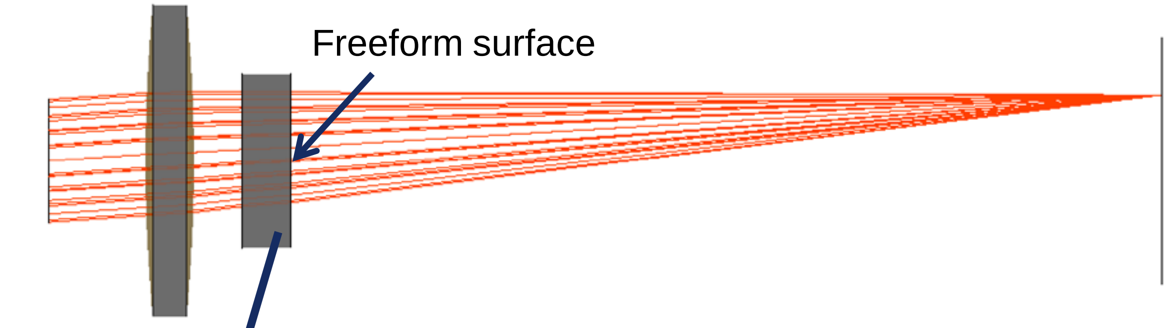
Size $= 42.27\mu m$

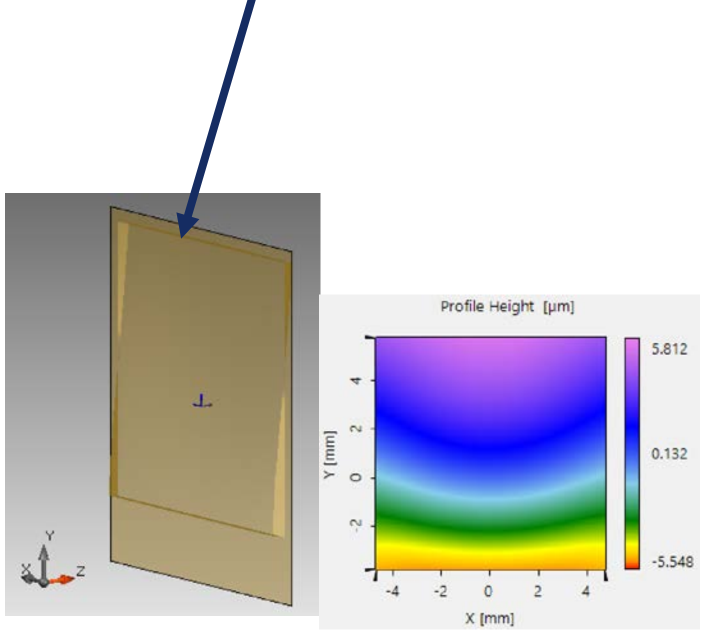
PSF



Result without correction with freeform surface!

Example: Focusing Lens Off-Axis



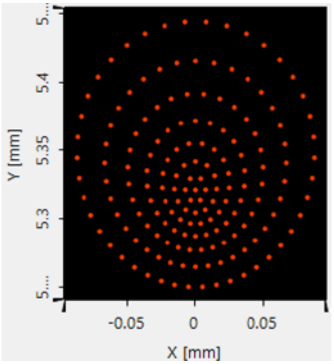


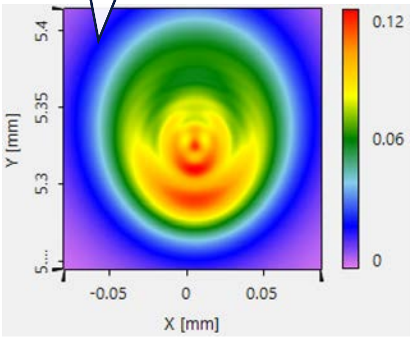
3D view

2D view

Result without correction with freeform surface!

Size $= 0.76\mu m$

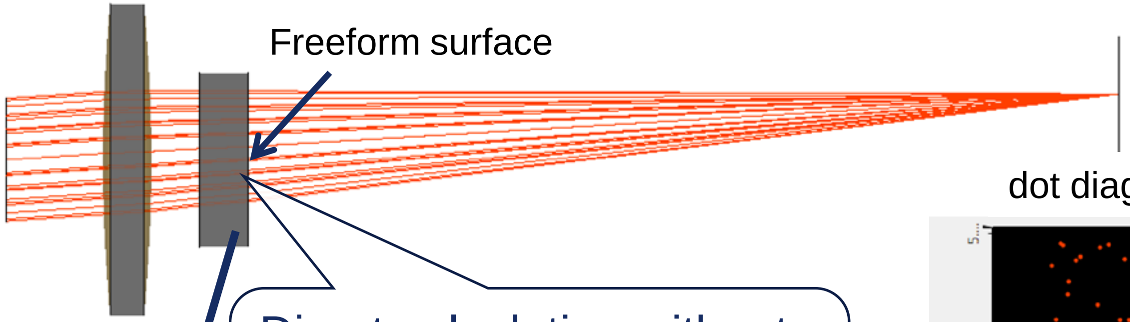




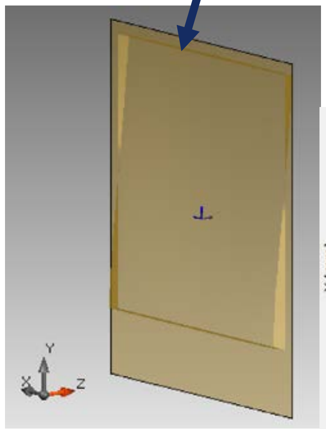
Size $= 127.9\mu m$

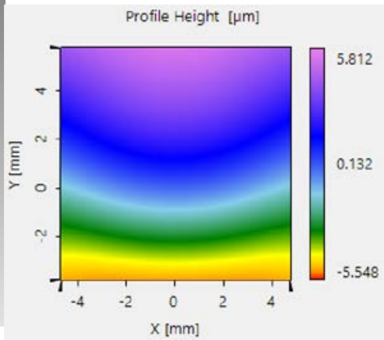
Example: Focusing Lens Off-Axis

Freeform surface



Direct calculation without optimization in a few seconds!

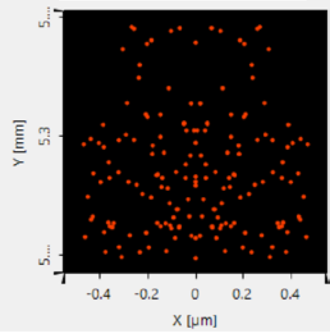




3D view

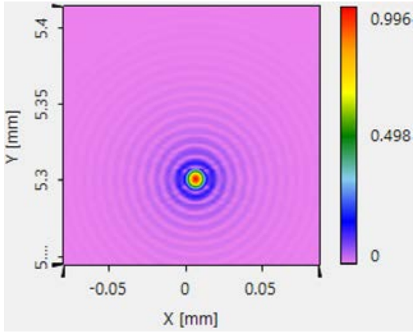
2D view

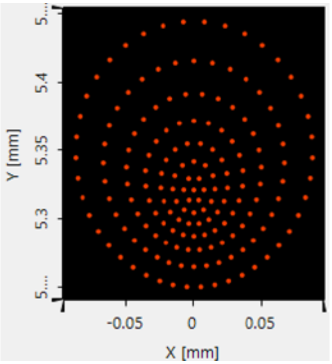
dot diagram



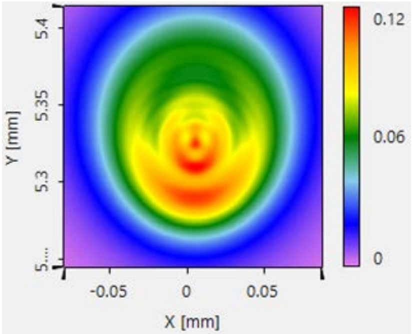
$\text{Size} = 0.76\mu\text{m}$

PSF

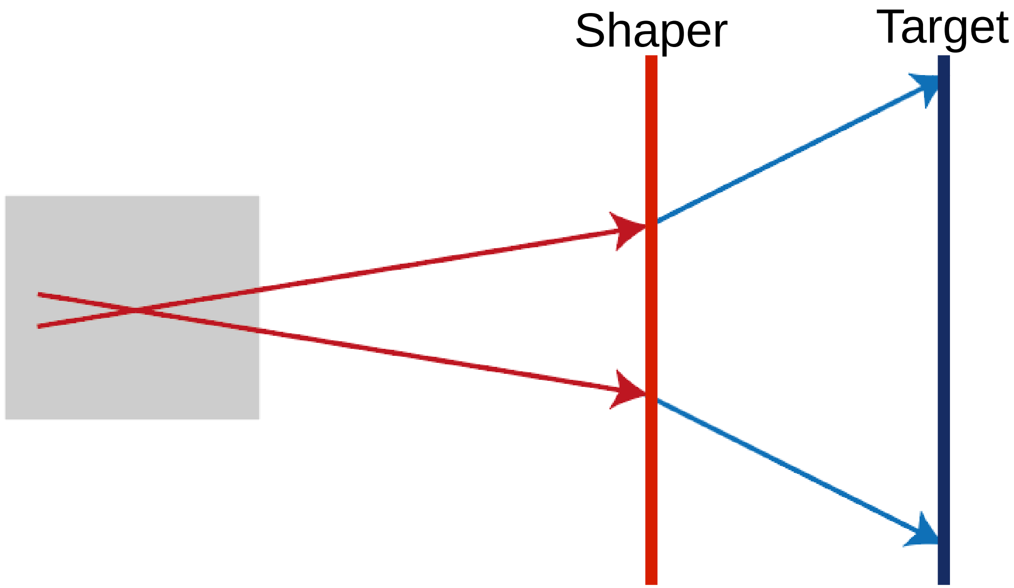




$\text{Size} = 127.9\mu\text{m}$

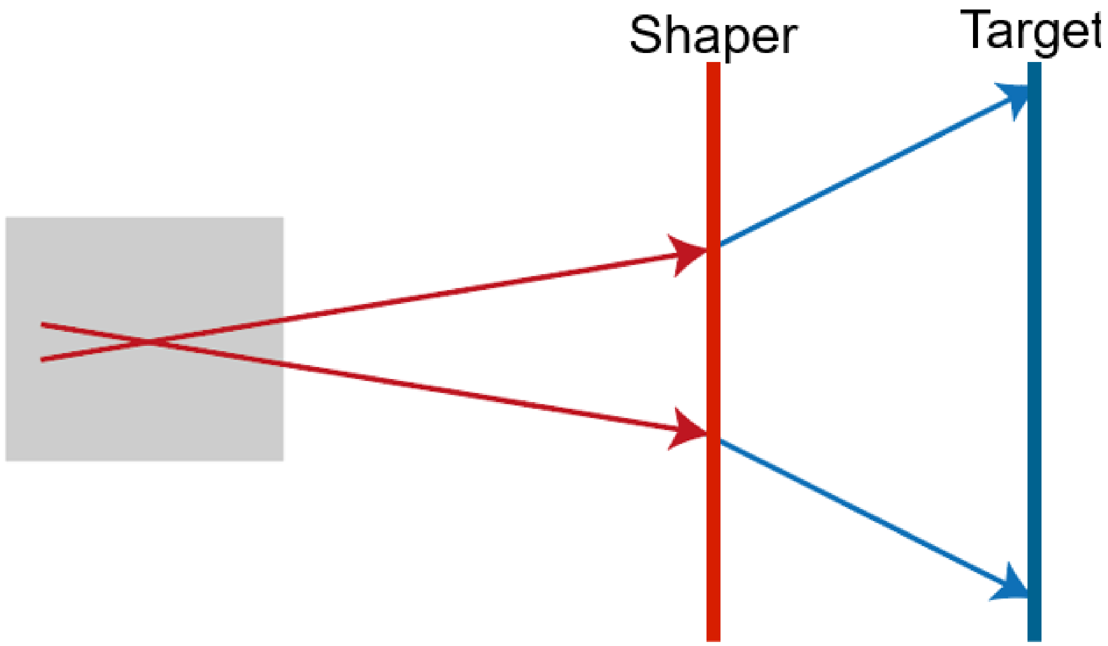


Light Shaping Tasks: Geometric Zones Only



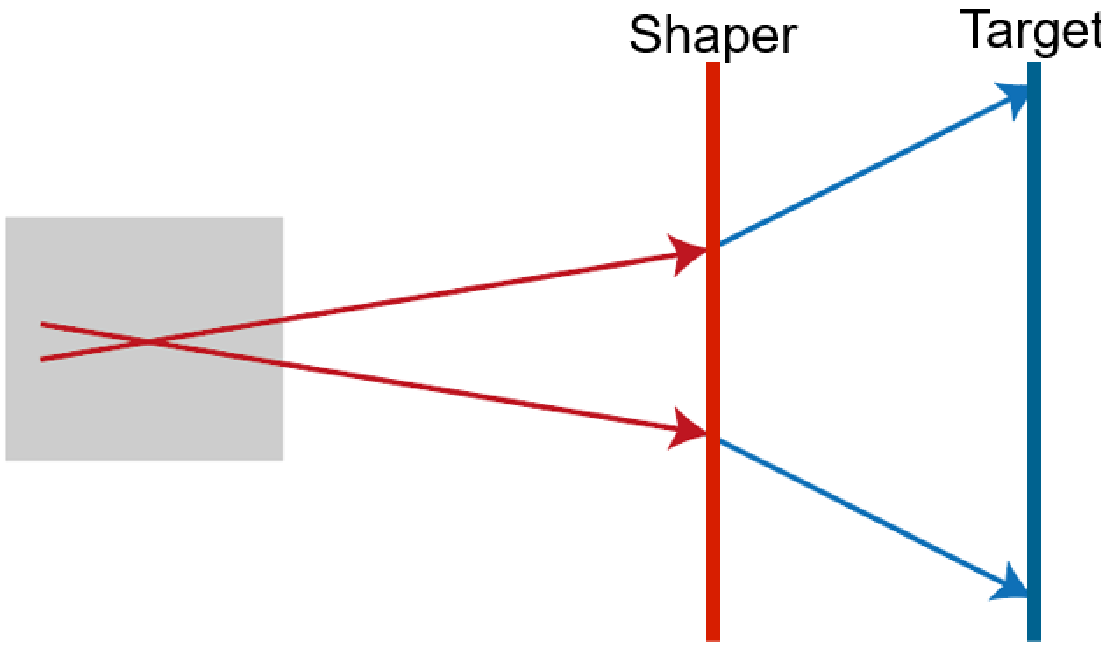
- Shaper in geometric field zone (GFZ)
- Target in geometric field zone (GFZ)

Light Shaping Tasks: Geometric Zones Only

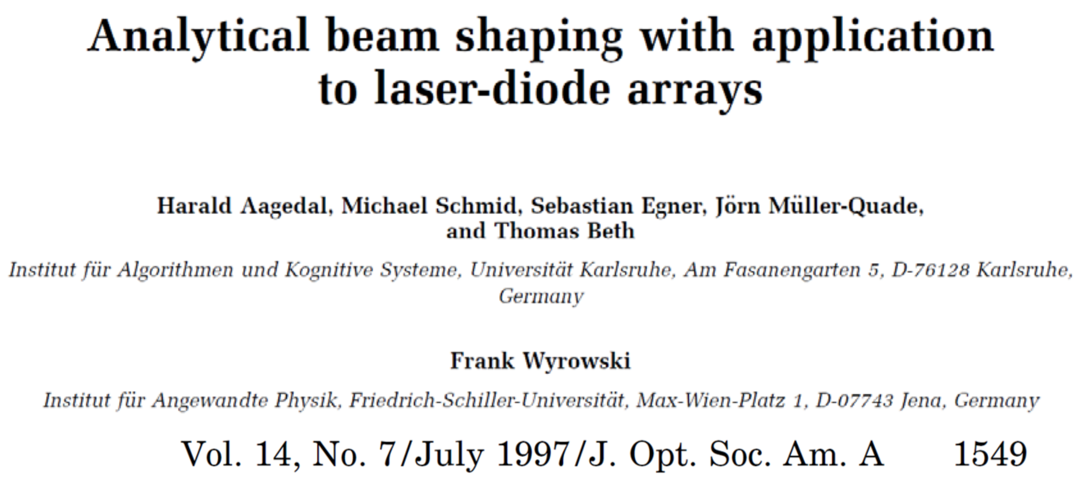


- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed

Light Shaping Tasks: Geometric Zones Only



- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed



Analytical beam shaping with application to laser-diode arrays

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

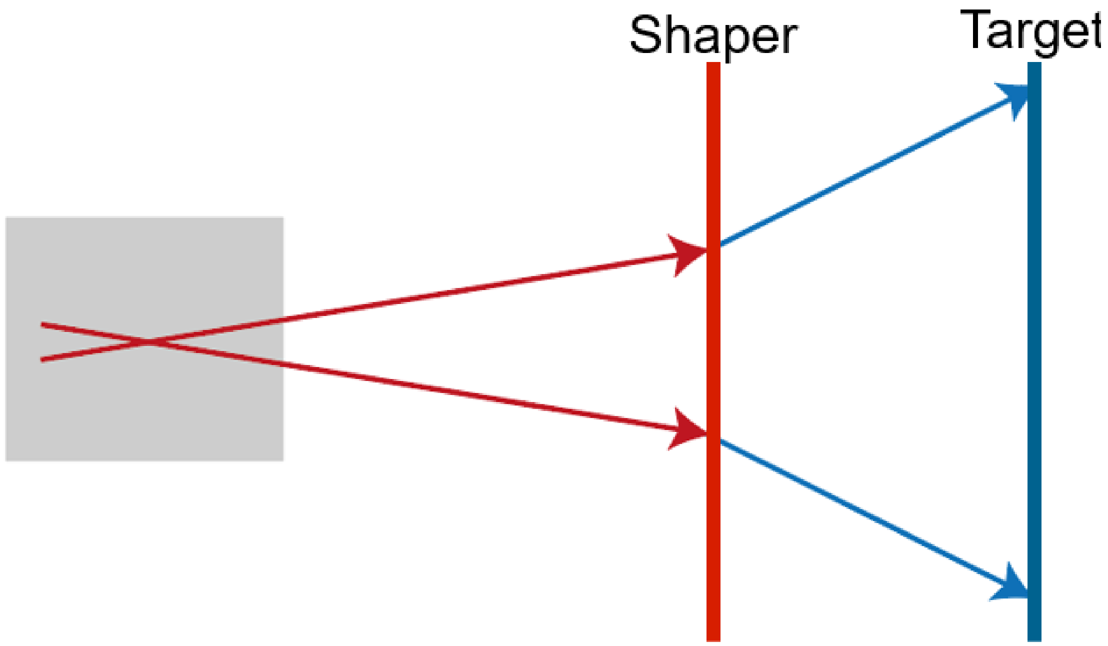
Institut für Algorithmen und Kognitive Systeme, Universität Karlsruhe, Am Fasanengarten 5, D-76128 Karlsruhe, Germany

Frank Wyrowski

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

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

Light Shaping Tasks: Geometric Zones Only



- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed

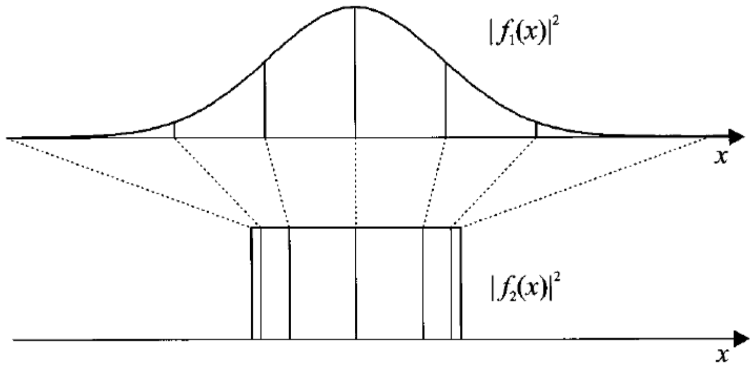
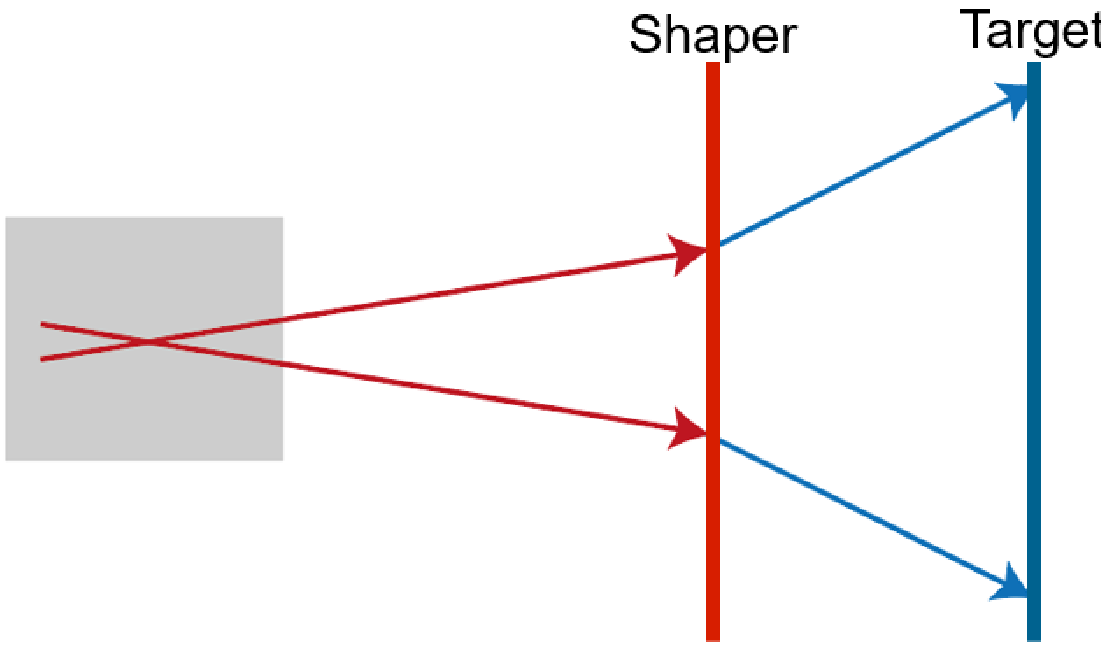


Fig. 1. Distortion transforming a Gaussian beam to a uniform distribution.

Light Shaping Tasks: Geometric Zones Only



- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed

Design of diffractive beam-shaping elements for non-uniform illumination waves

Andreas Hermerschmidt and Hans J. Eichler

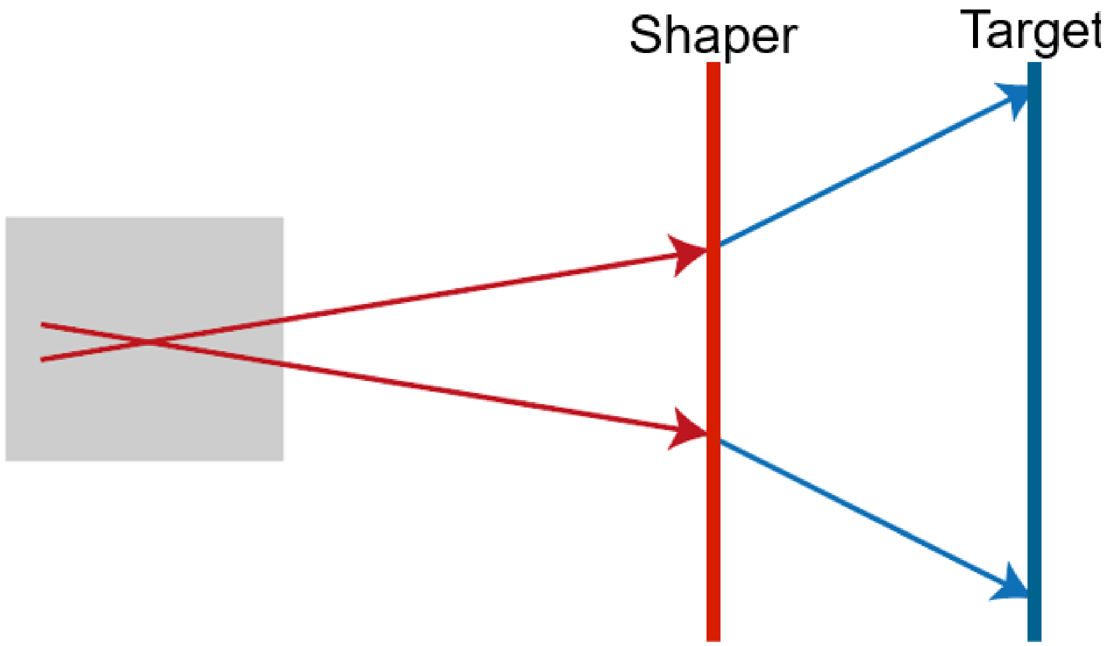
Technical University of Berlin, Optisches Institut P11
Strasse des 17. Juni 135, 10623 Berlin, Germany

Stephan Teiwes and Joerg Schwartz

Berlin Institute of Optics (BIFO), Department of Diffractive Optics
Rudower Chaussee 6, 12484 Berlin, Germany

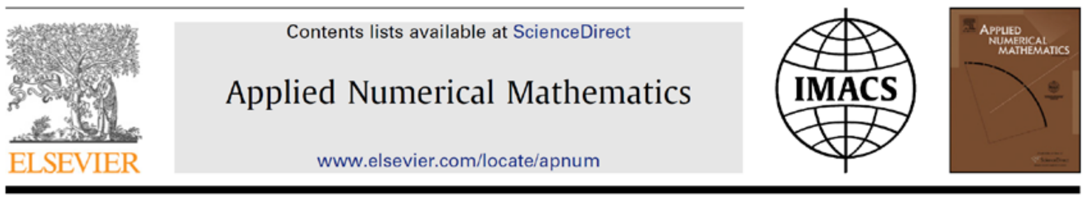
Proc. SPIE 1998

Light Shaping Tasks: Geometric Zones Only



- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed

2011



Applied Numerical Mathematics 61 (2011) 298–307

Contents lists available at ScienceDirect

Applied Numerical Mathematics

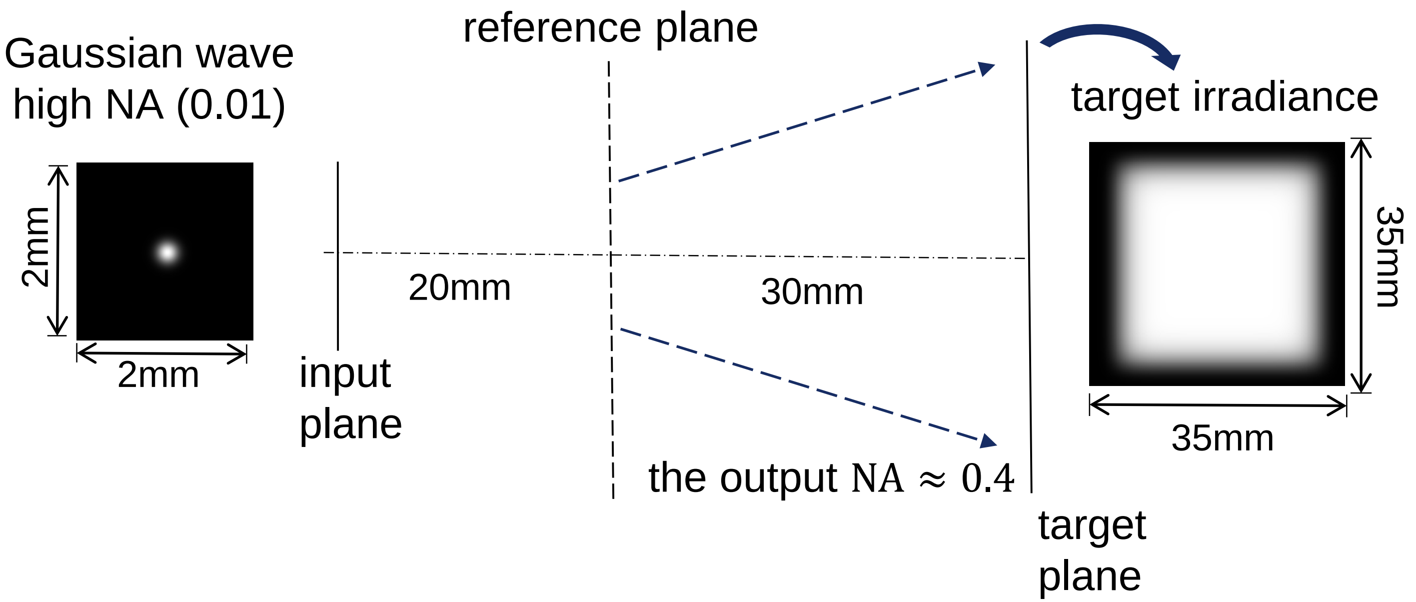
www.elsevier.com/locate/apnum

An efficient approach for the numerical solution of the Monge–Ampère equation

Mohamed M. Sulman *, J.F. Williams, Robert D. Russell

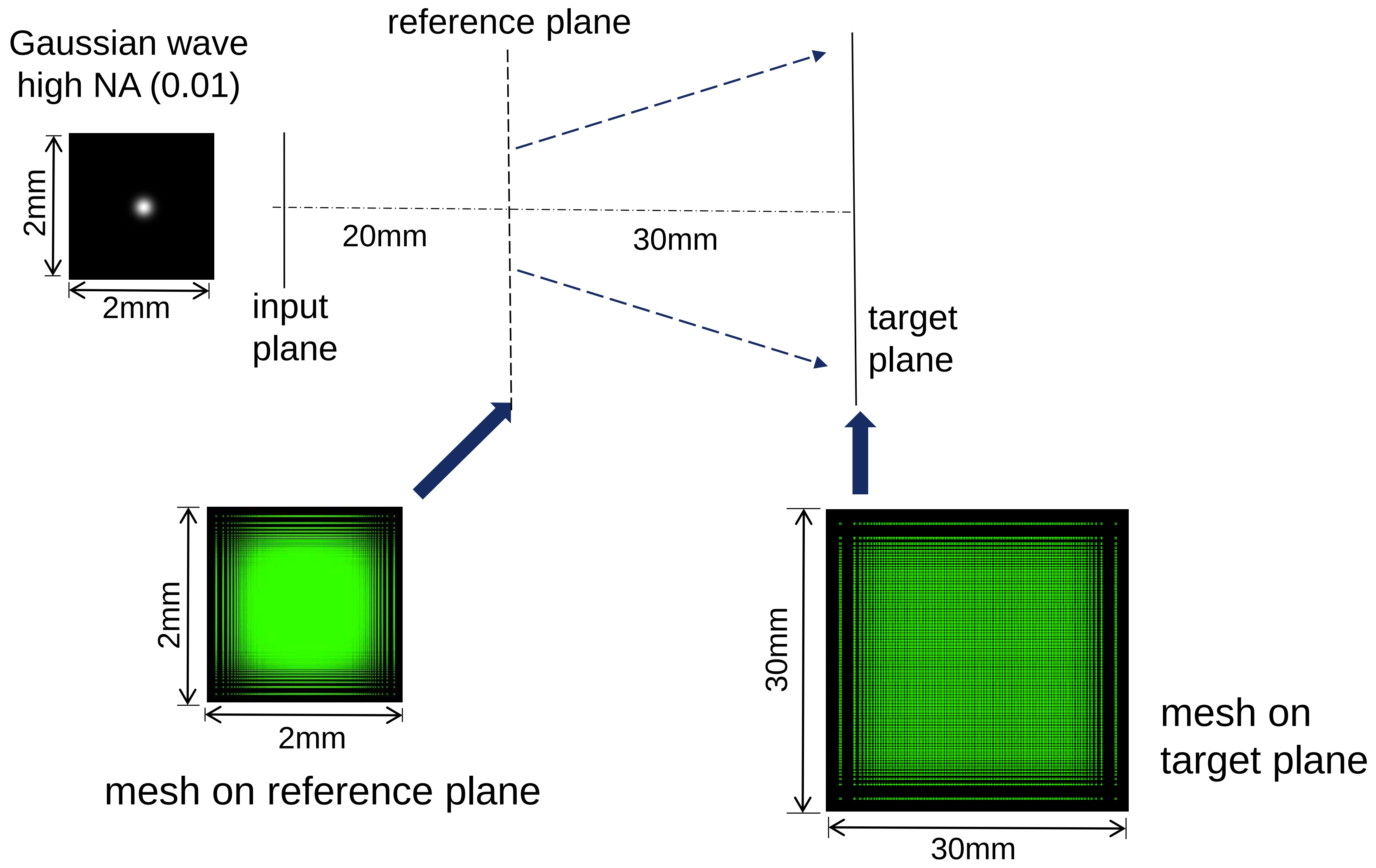
Department of Mathematics, Simon Fraser University, Burnaby, British Columbia, V5A 1S6 Canada

Gaussian to Top-Hat (Non-paraxial)

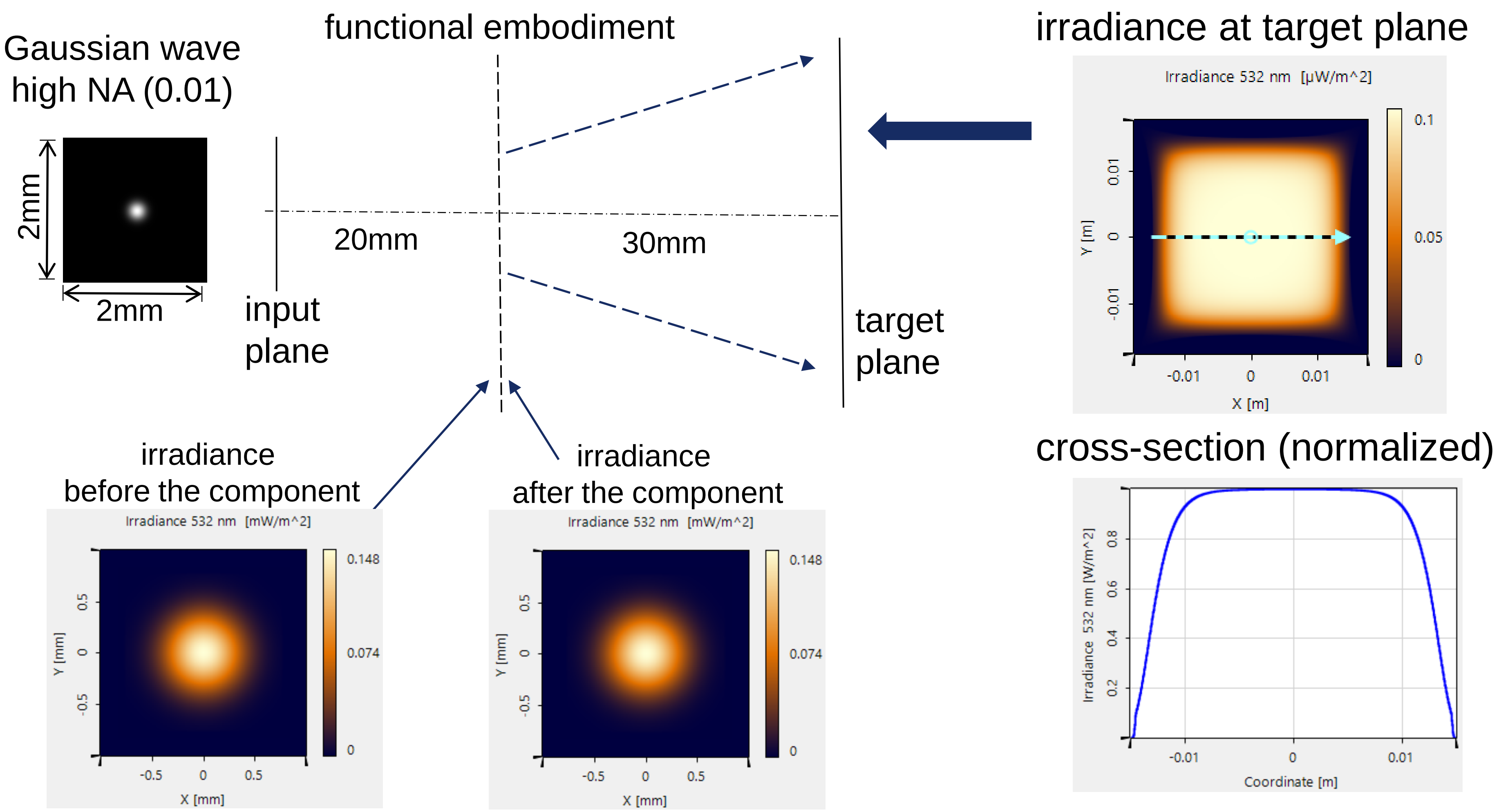


The Rayleigh lengths of the input Gaussian is $555.6\mu\mathrm{m}$

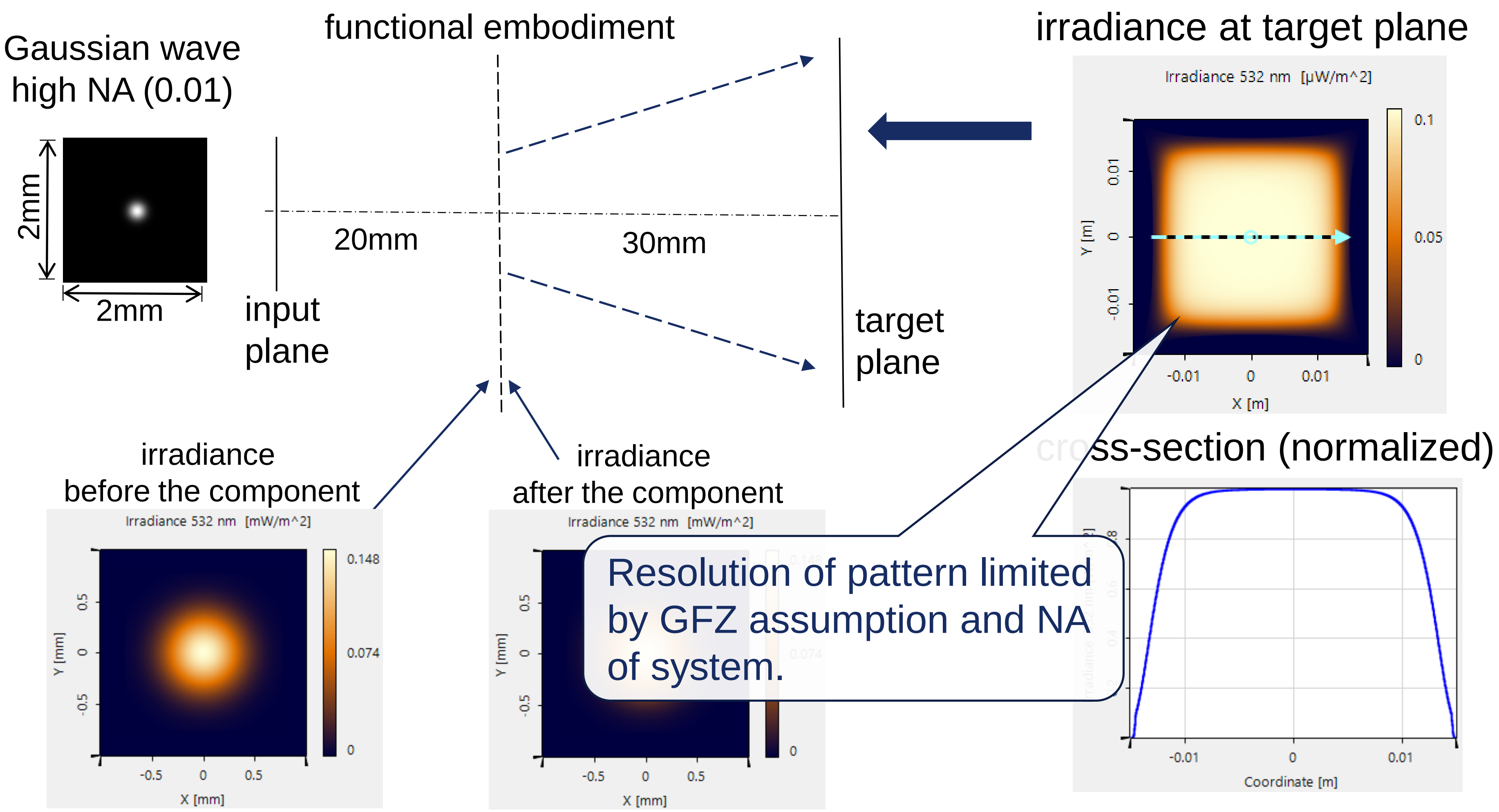
Gaussian to Top-Hat (Non-paraxial): Phase Design via Meshes



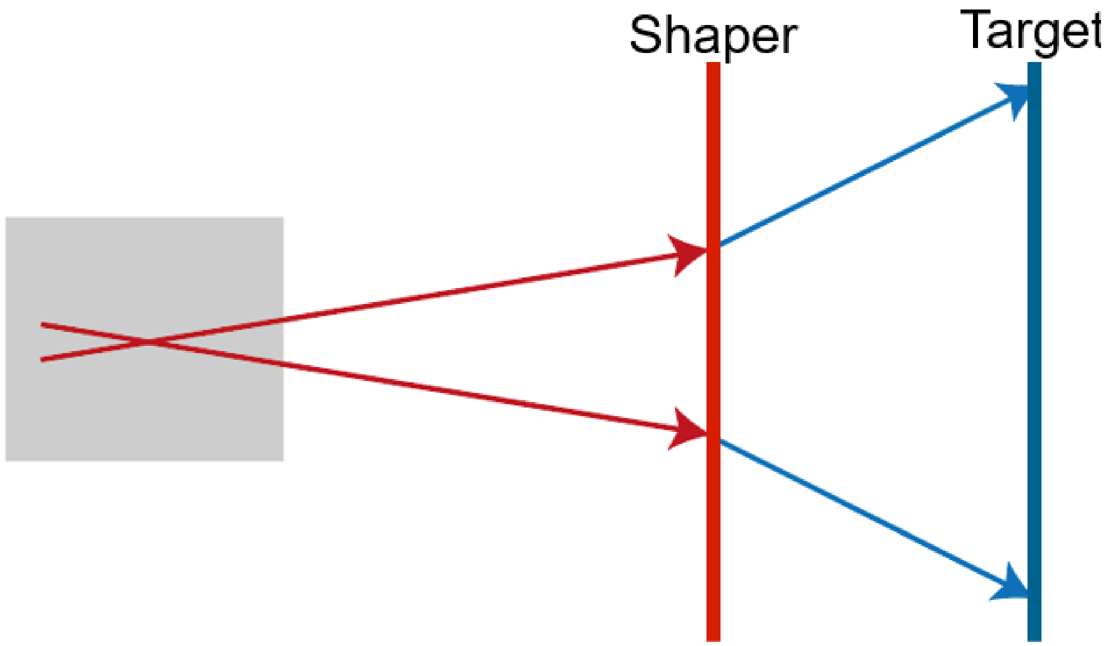
Gaussian to Top-Hat (Non-paraxial): Functional Embodiment



Gaussian to Top-Hat (Non-paraxial): Functional Embodiment

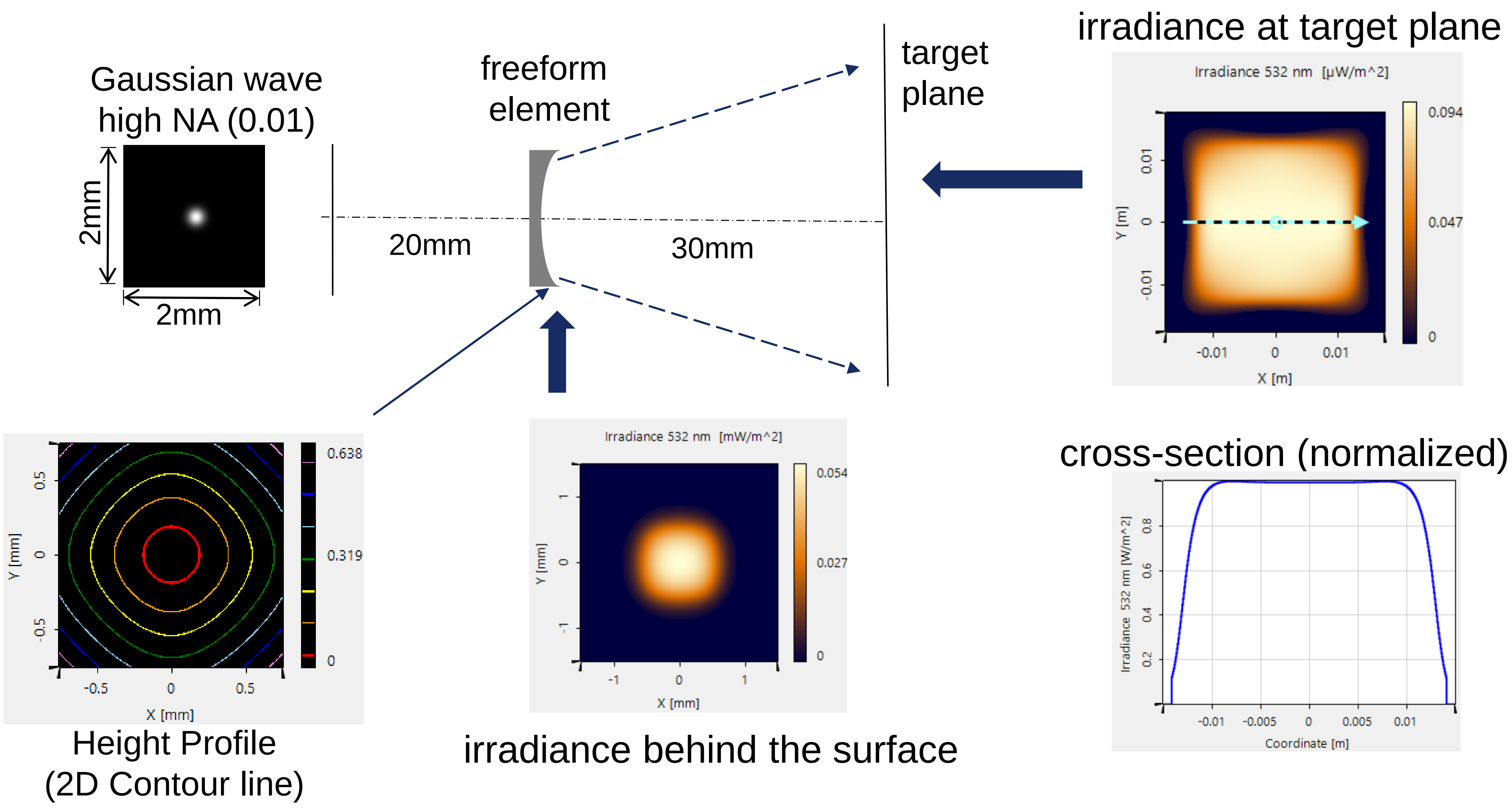


Light Shaping Tasks: Geometric Zones Only

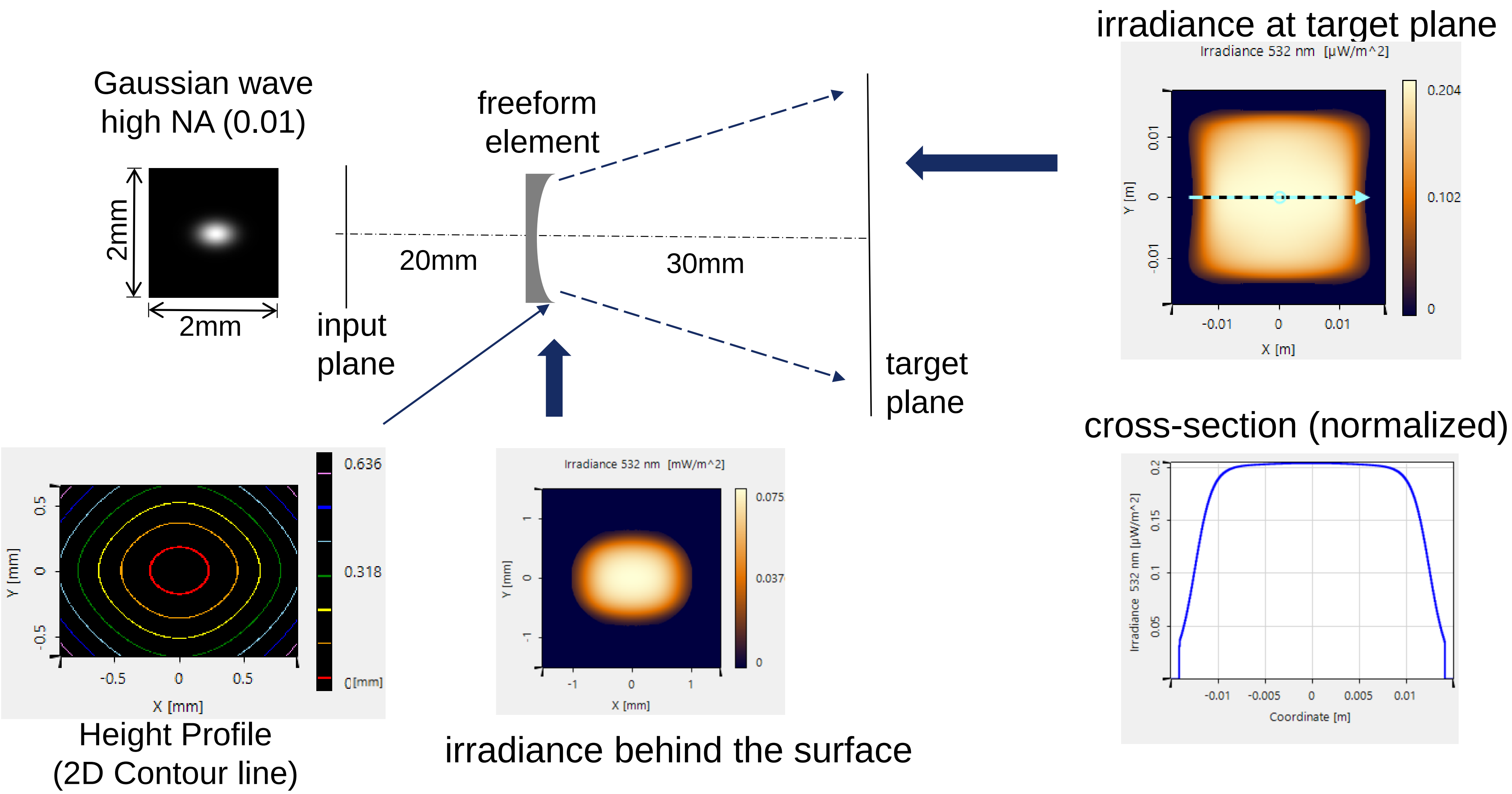


- Functional design
  - Propagation of field from DFZ into GFZ
  - Energy conservation leads to identity of intergal over irradiances in shaper and target planes.
  - Together with GFZ assumption phase can be designed
- Structural design altrnatives
  - Freeform surface design (convergent, iterative algorithm)
  - HOE design (direct design)

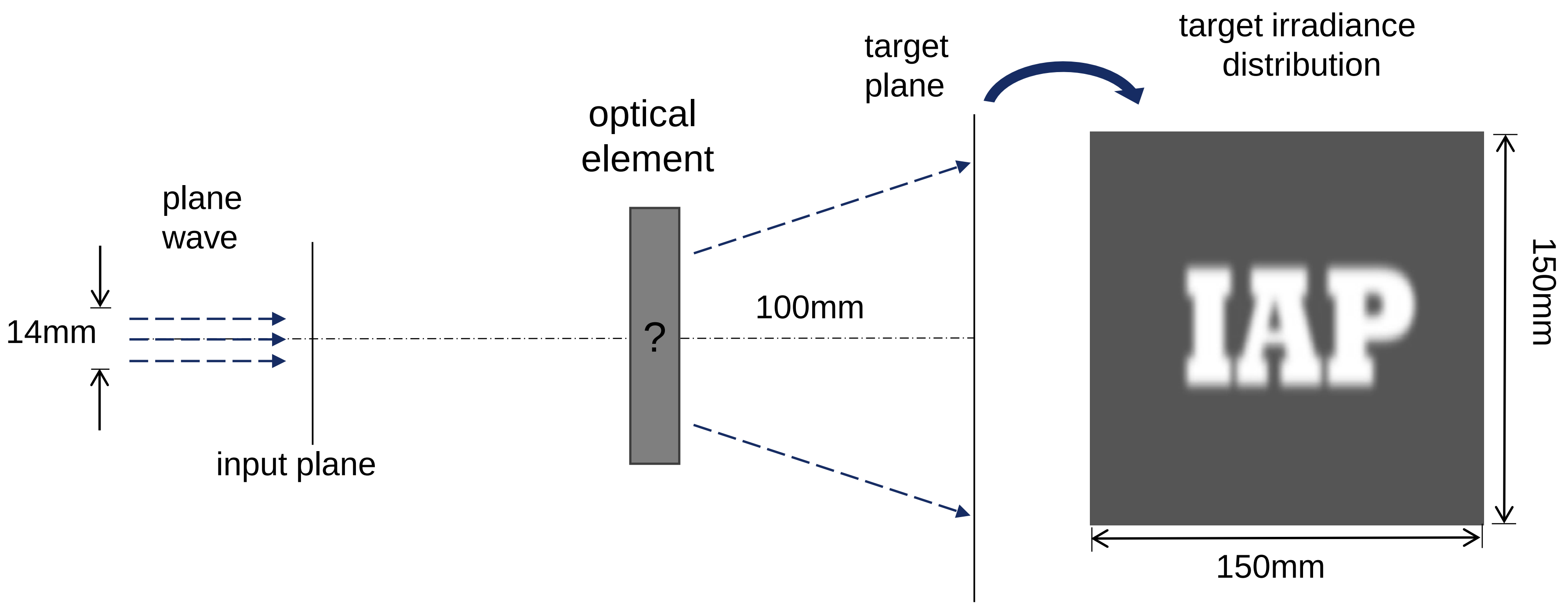
Gaussian to Top-Hat (Non-paraxial): Freeform Surface



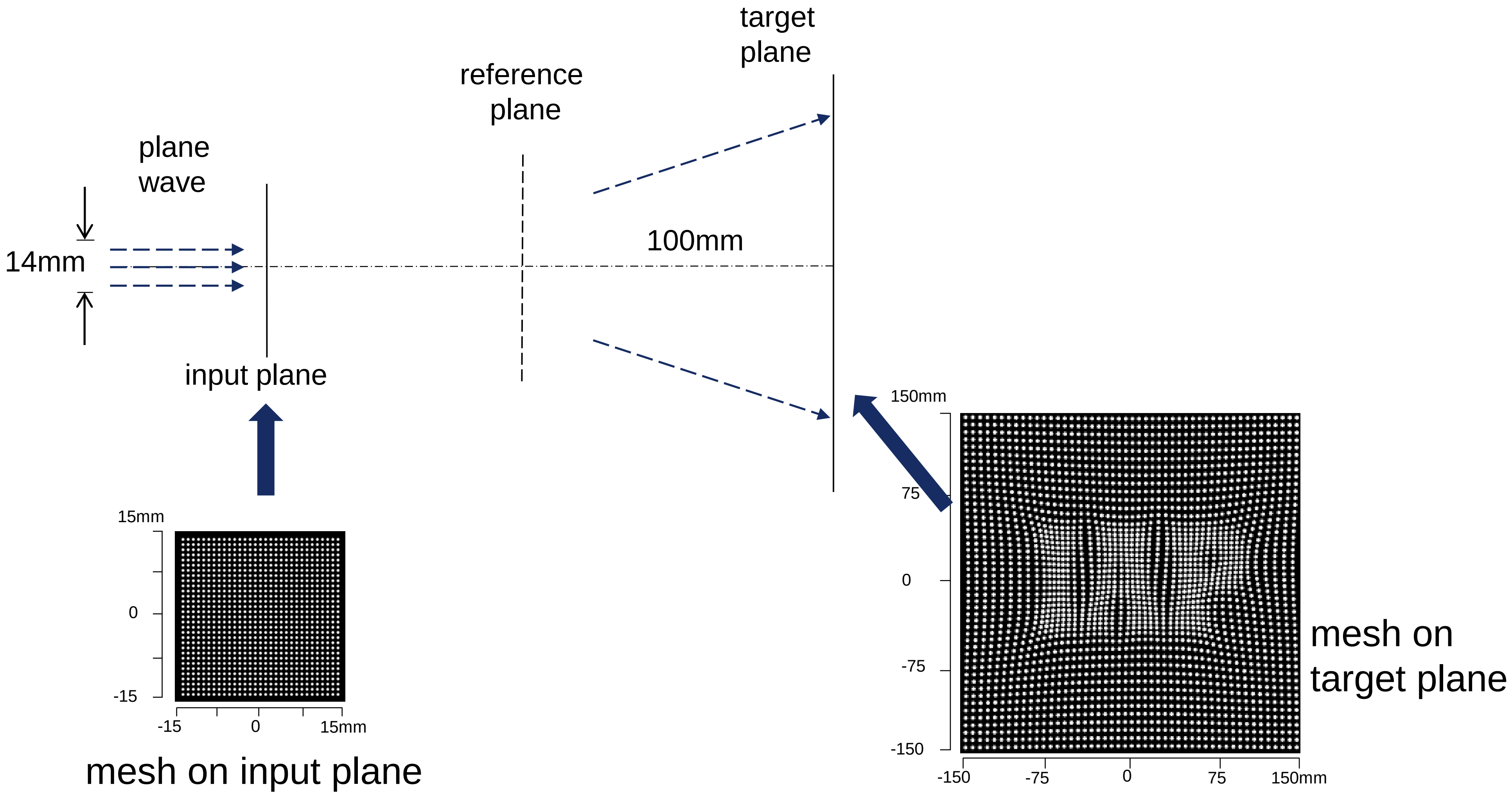
Elliptical Gaussian to Top-Hat (Non-paraxial): Freeform Surface



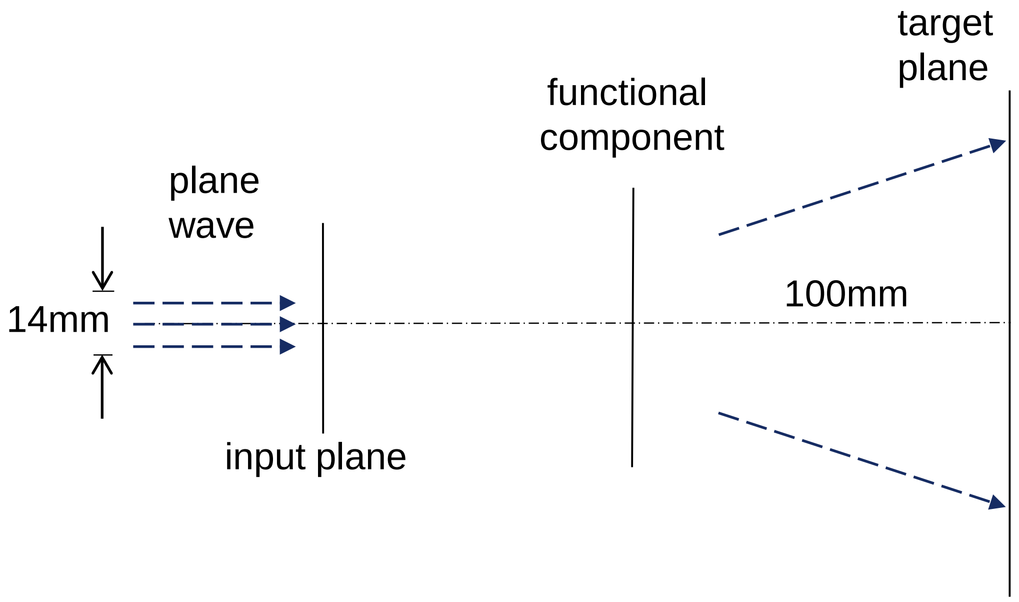
Plane Wave to Far Field Pattern (Non-paraxial)



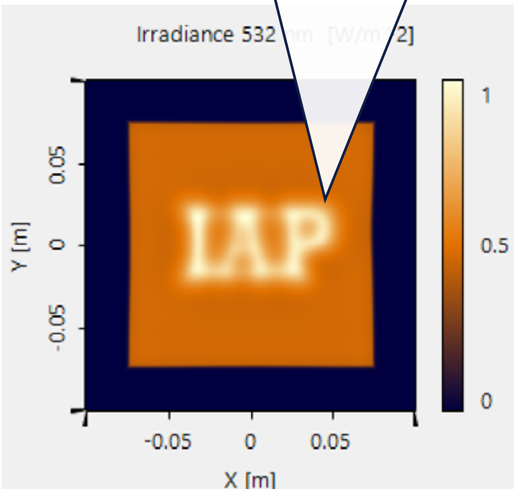
Plane Wave to Far Field Pattern (Non-paraxial): Functional Design



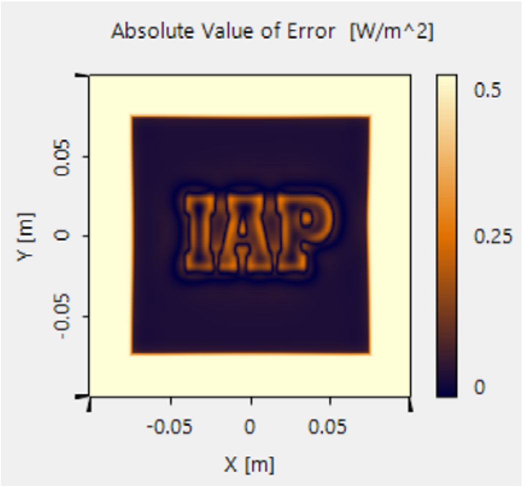
Plane Wave to Far Field Pattern (Non-paraxial): Functional



Resolution of pattern limited by GFZ assumption.



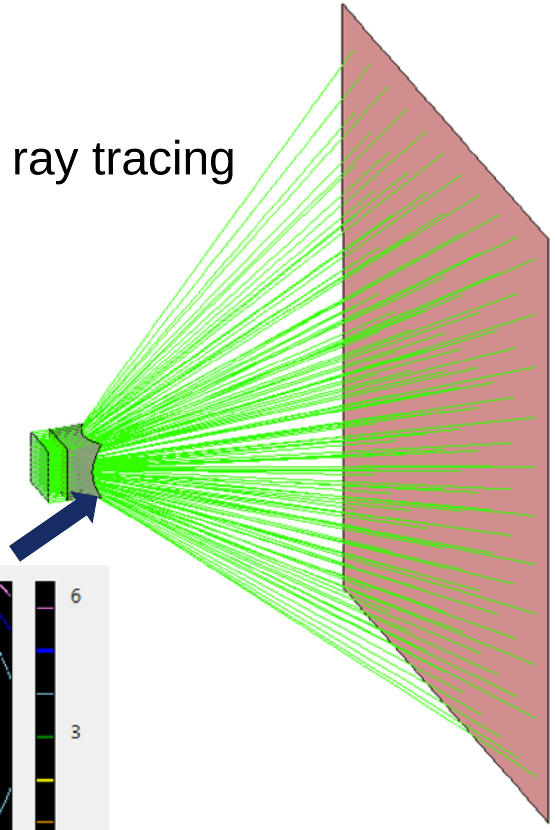
irradiance at target plane (normalized)

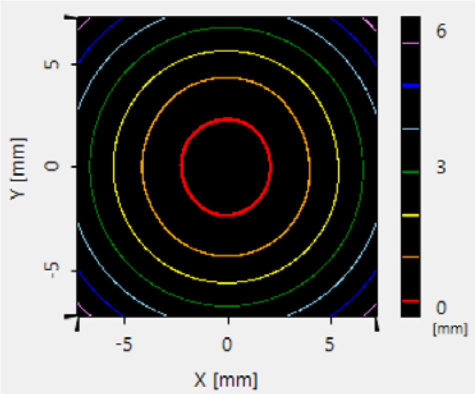


error from target irradiance

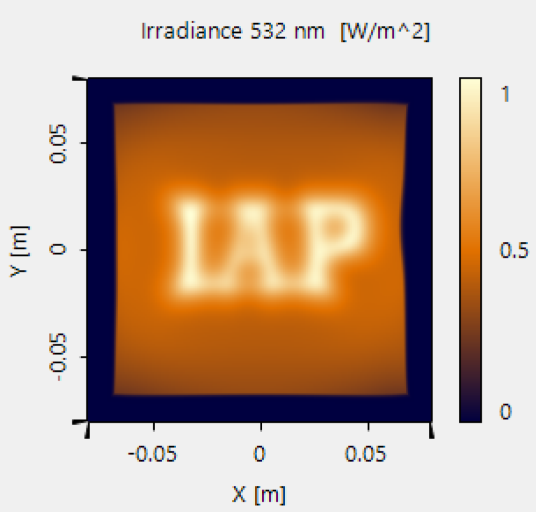
Plane Wave to Far Field Pattern (Non-paraxial): Freeform Surface

ray tracing

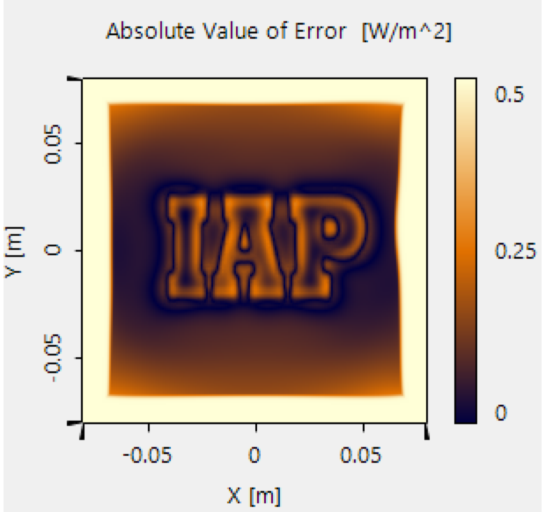




Height Profile
(2D Contour line)

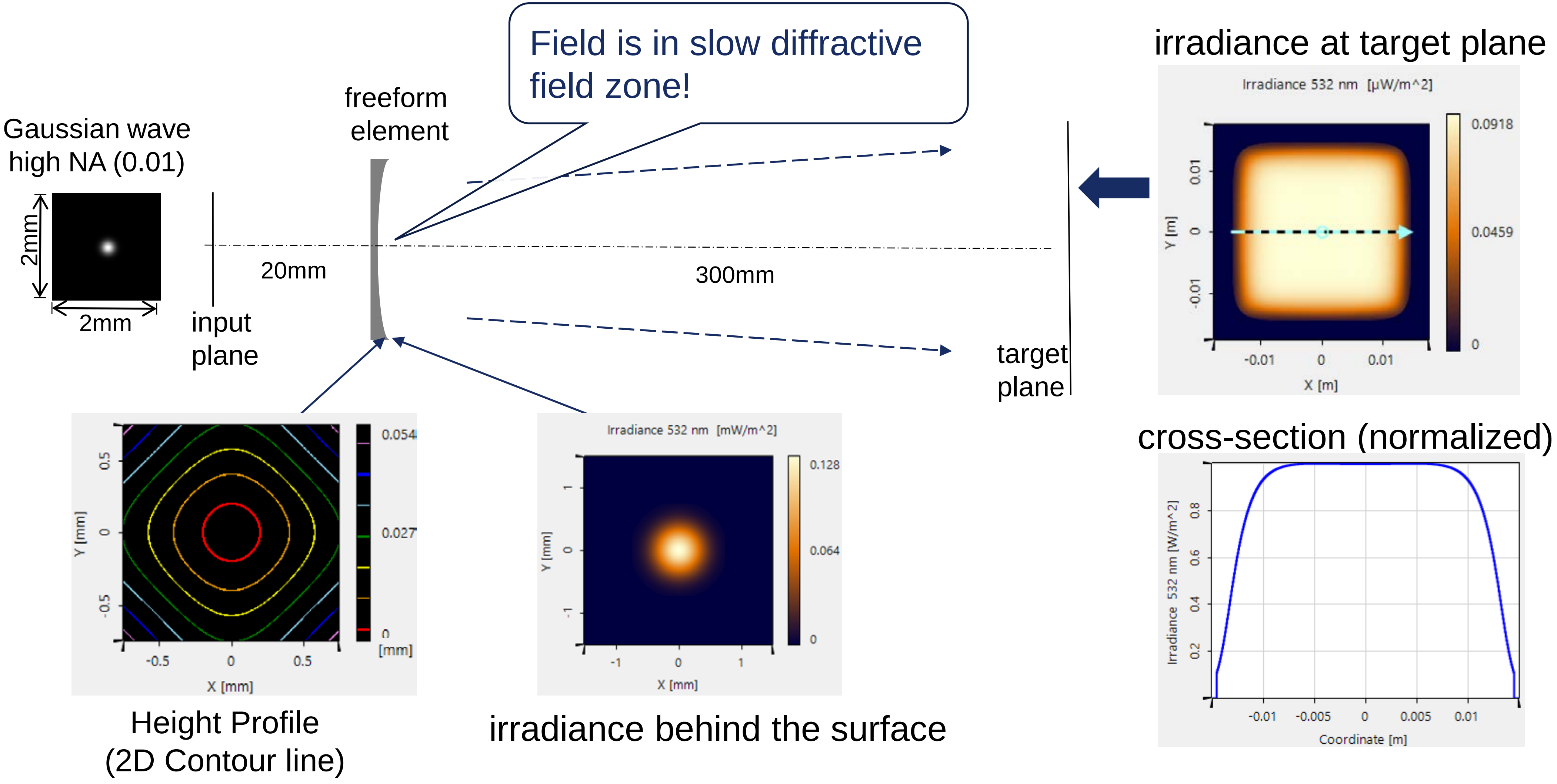


irradiance at target plane
(normalized)

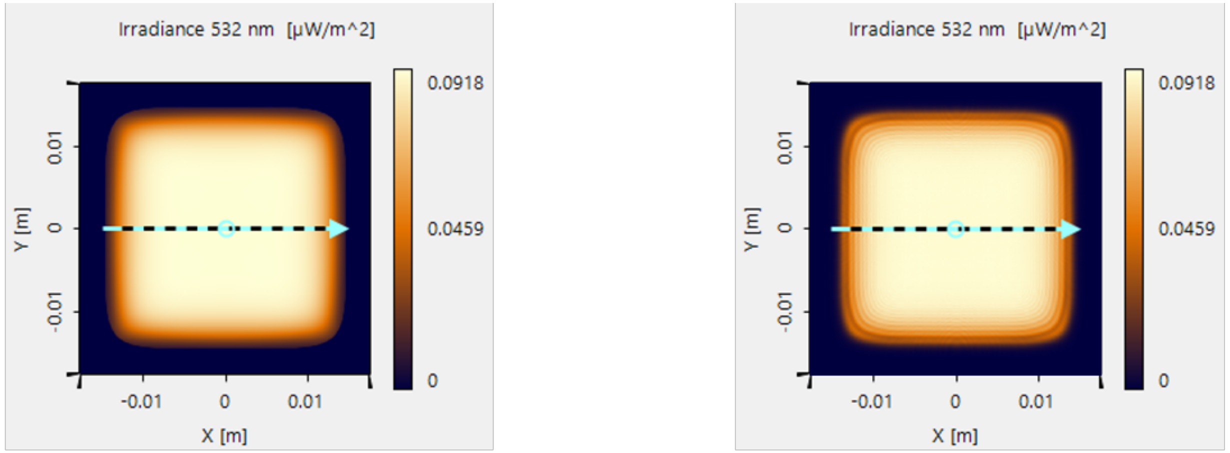


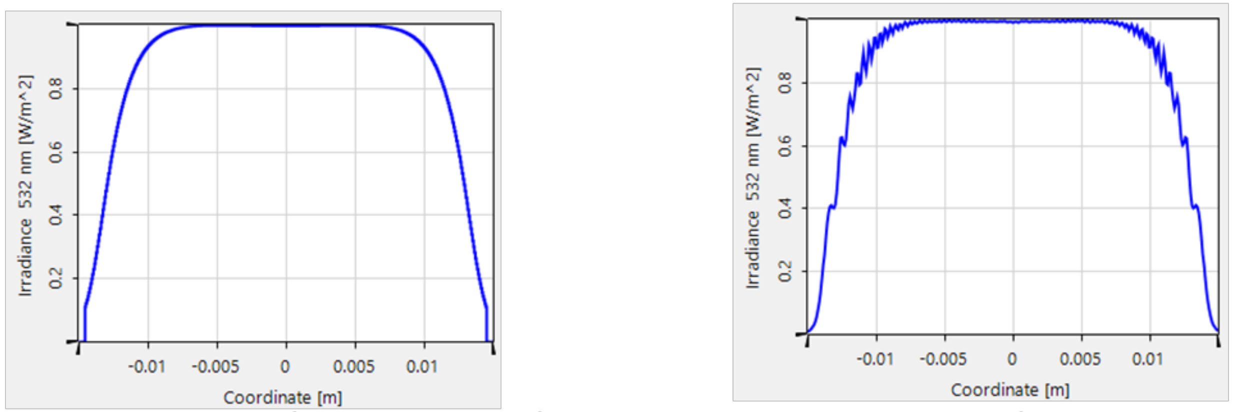
error from target irradiance

Gaussian to Top-Hat (Paraxial): Freeform Surface



Gaussian to Top-Hat (Paraxial): Freeform Surface

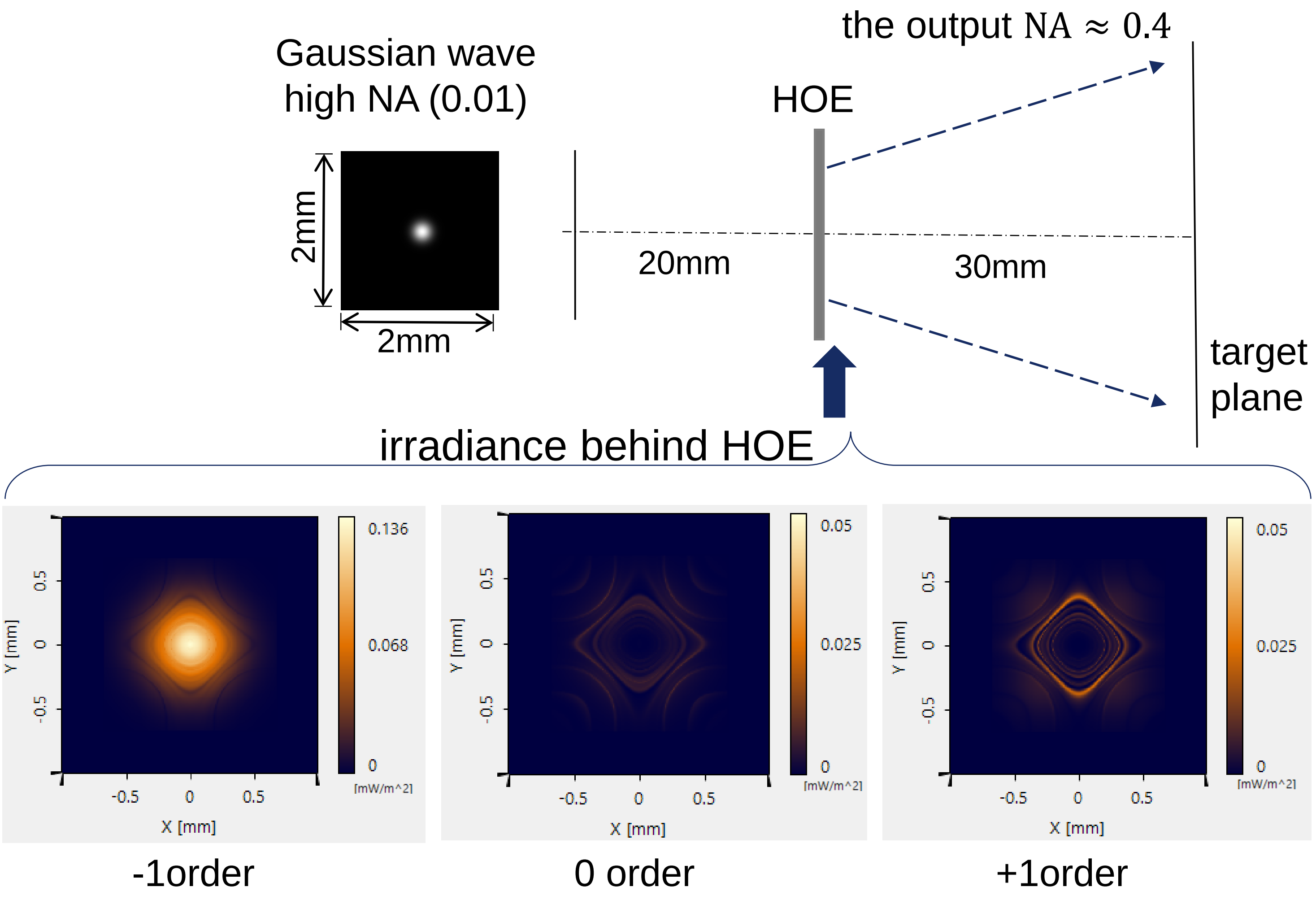




cross-section (normalized) cross-section (normalized)

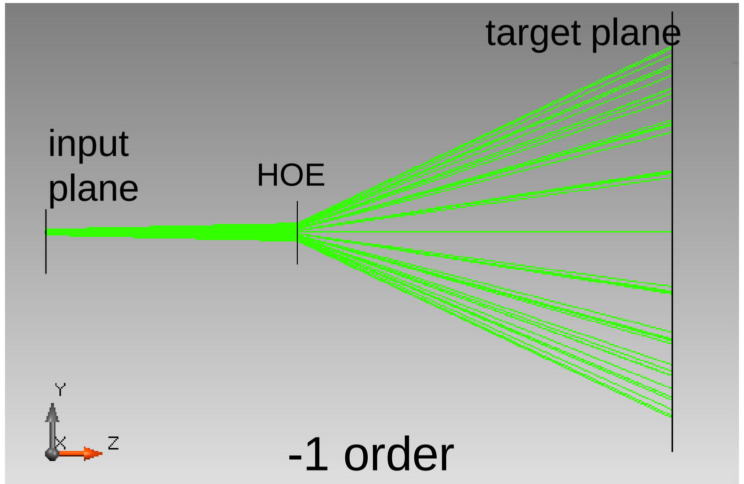
- Because of paraxial field (slow beams) shaper is in DFZ and not GFZ.
- That results in slight diffractive effects which are not included in design.
- By subsequent iterative Fourier transform algorithm which takes DFZ into account that can be corrected.

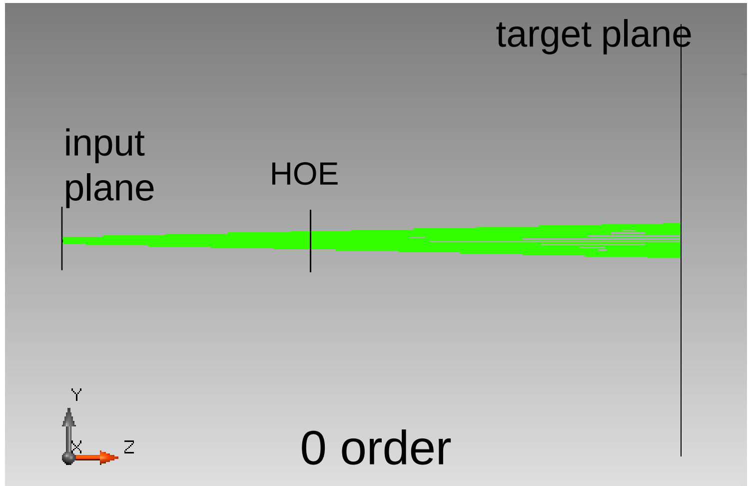
Gaussian to Top-Hat (Non-paraxial): HOE

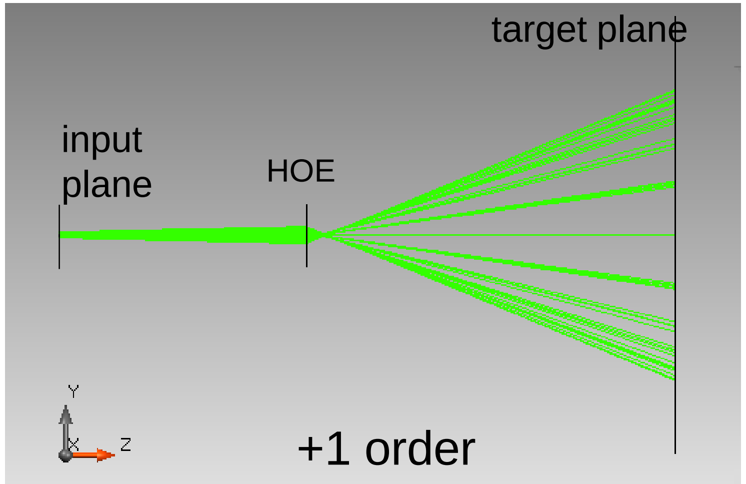


Gaussian to Top-Hat (Non-paraxial): HOE

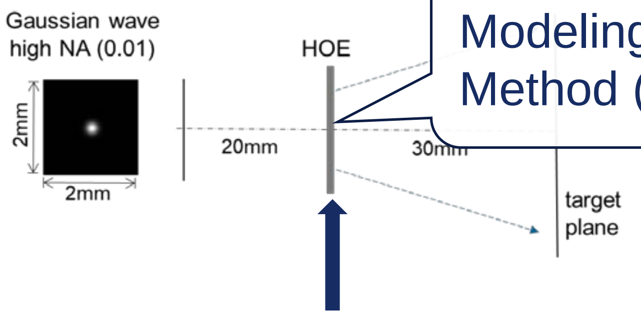
ray tracing result with HOE (with the working order of -1 order)





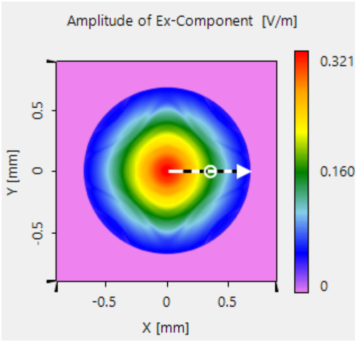


Investigate Rayleigh Coefficient

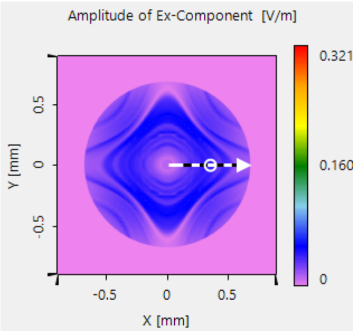


Modeling with Fourier Modal Method (FMM)

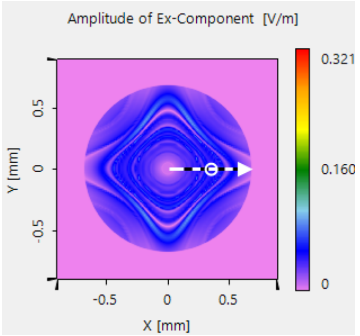
Ex Component behind HOE



-1order

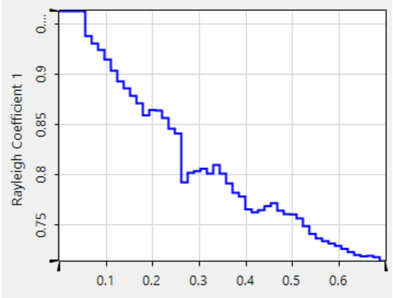
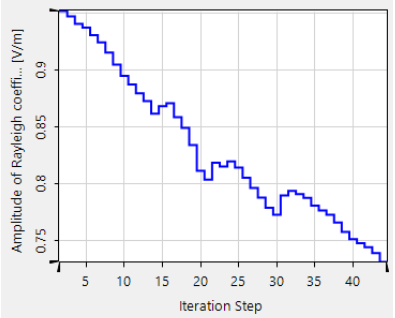
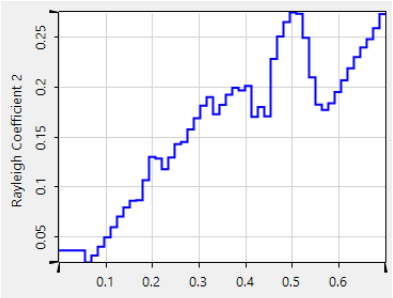
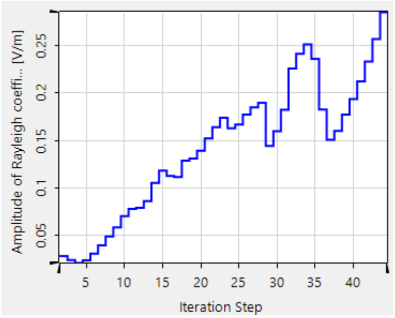
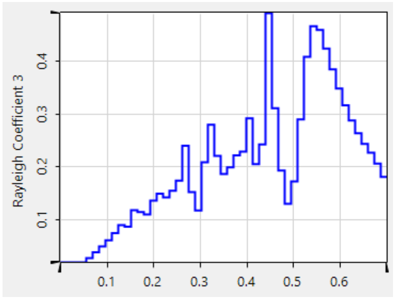
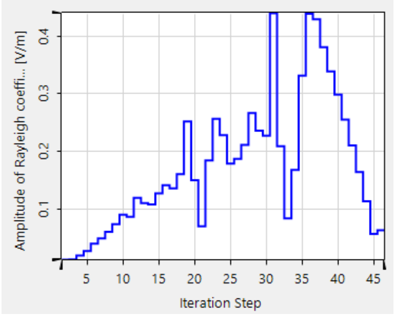


0 order

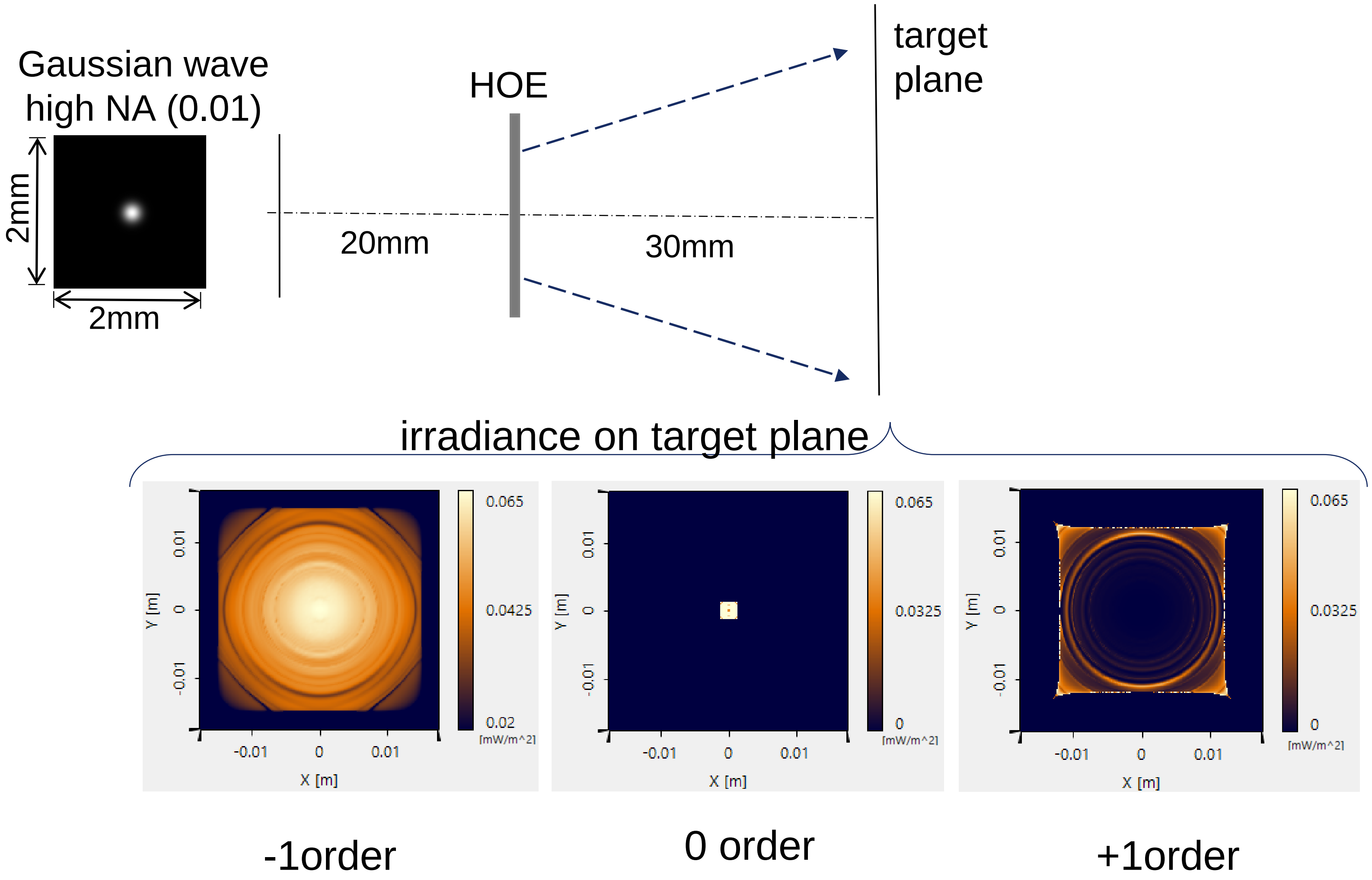


+1order

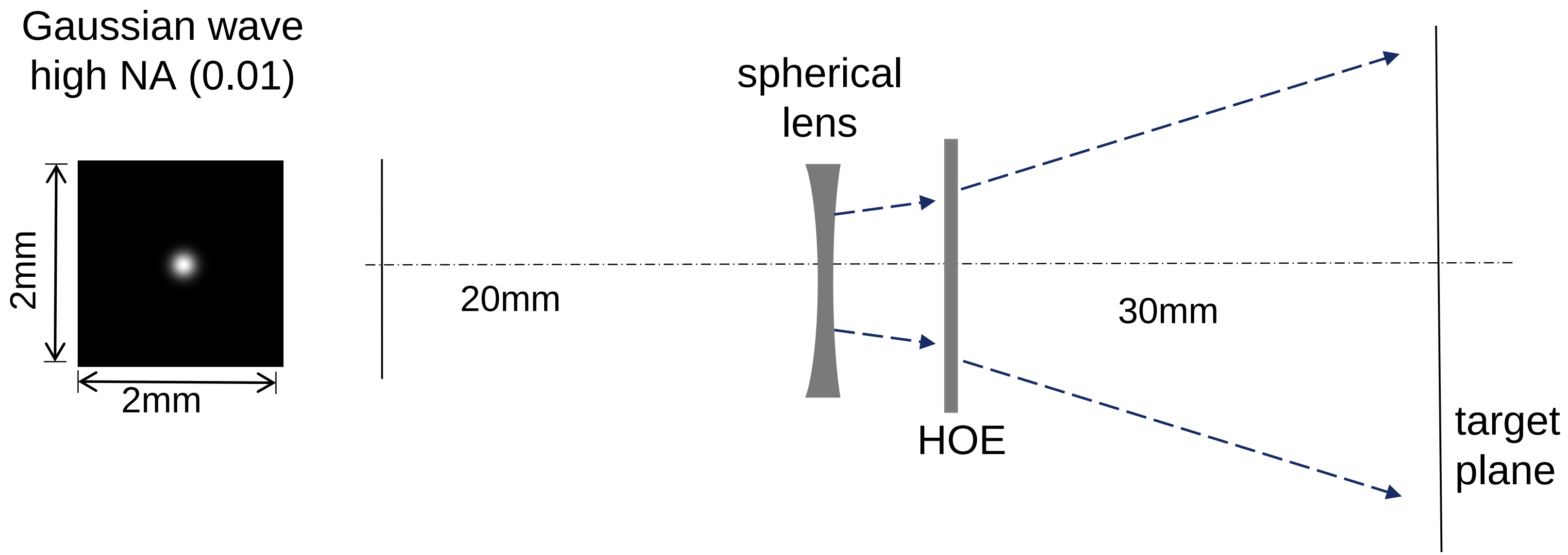
the Rayleight coefficient along the cross-section is compared with the result from Grating Toolbox

	cross-section profile	result from Grating Toolbox
-1 order		
0 order		
+1 order		

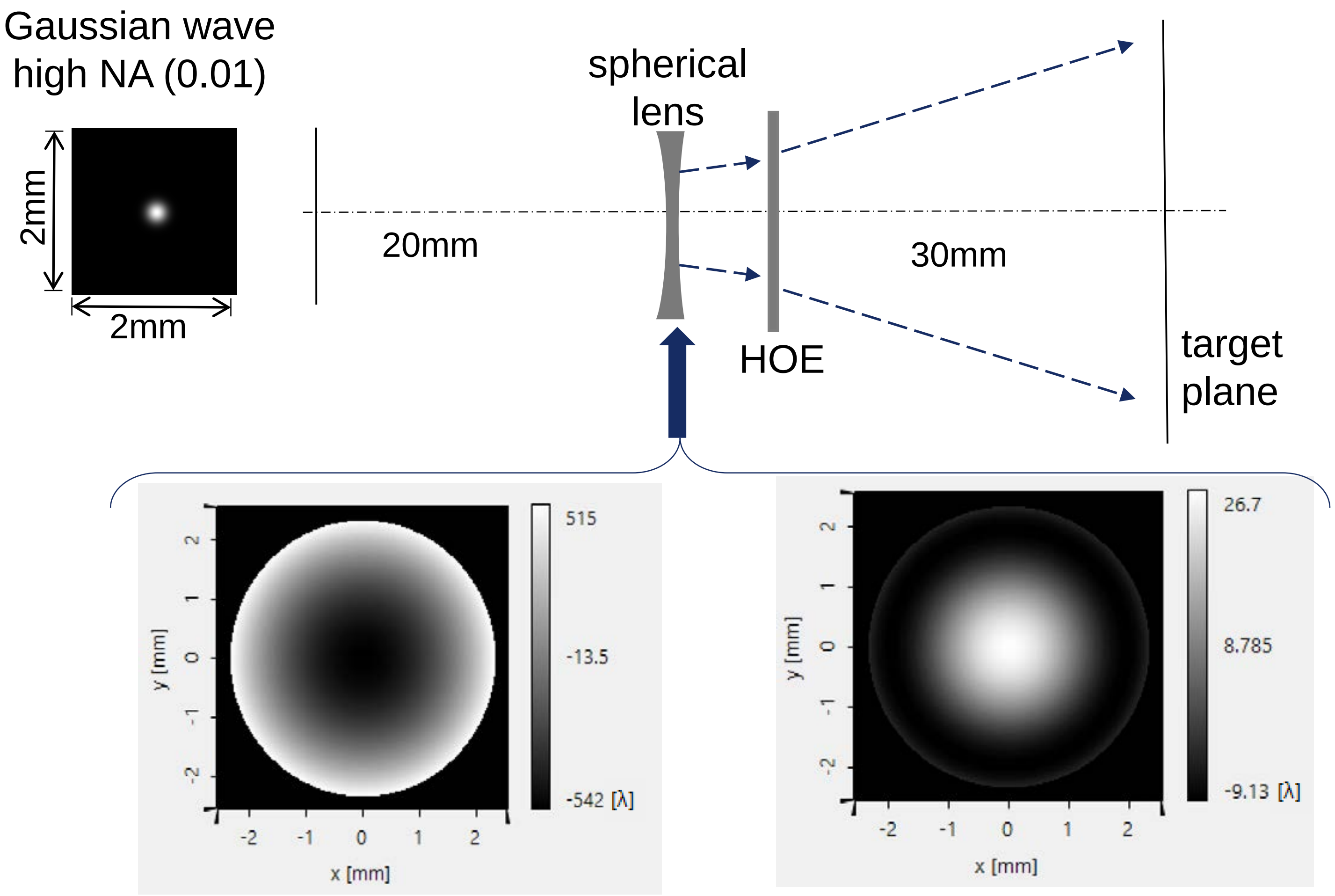
Gaussian to Top-Hat (Non-paraxial): HOE



Gaussian to Top-Hat (Non-paraxial): Lens + HOE



Gaussian to Top-Hat (Non-paraxial): Lens + HOE



wavefront behind spherical lens

wavefront error
with respect to spherical wavefront

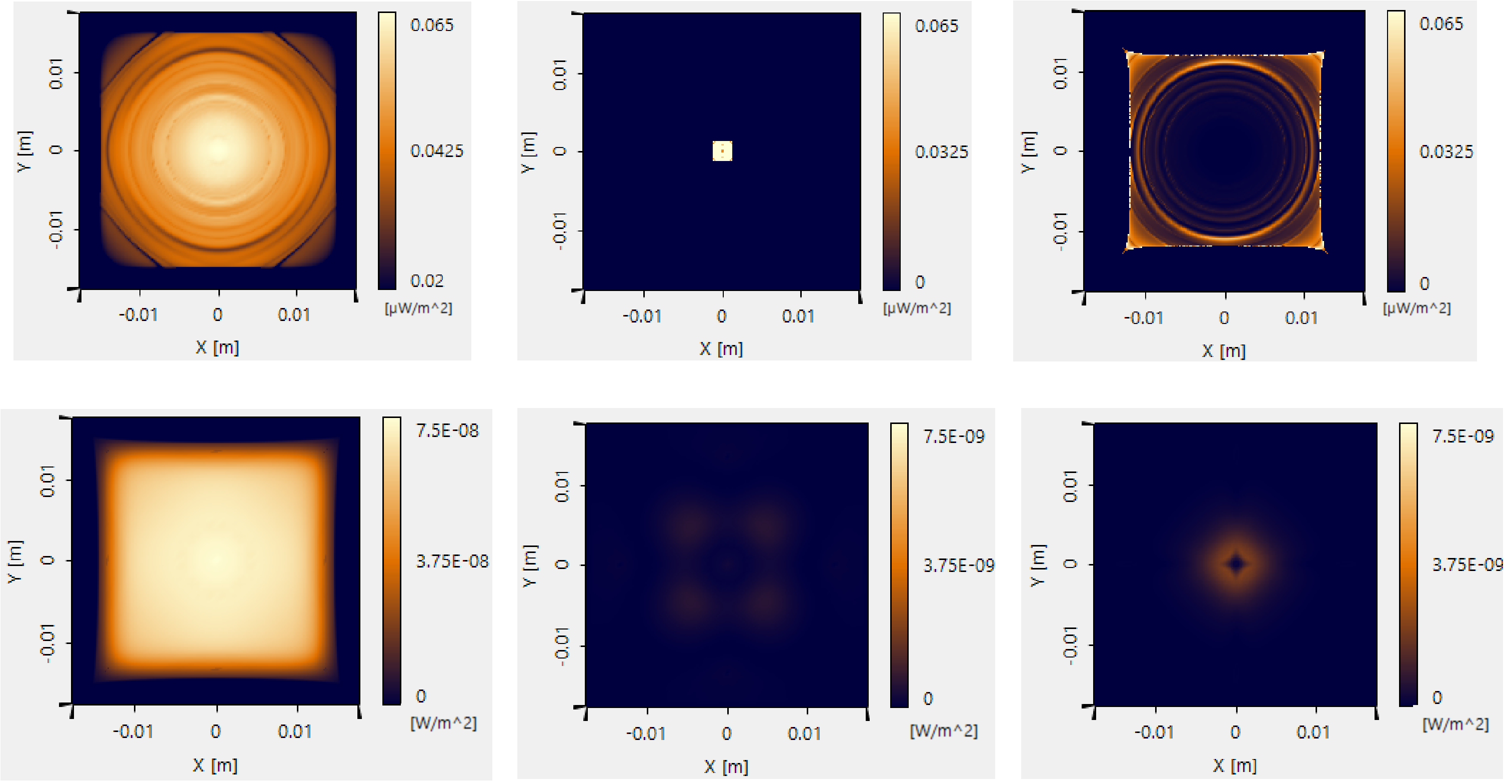
the Peak-to-Valley wavefront error is 35.83λ

Gaussian to Top-Hat (Non-paraxial): Lens + HOE

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

without the lens

with the lens

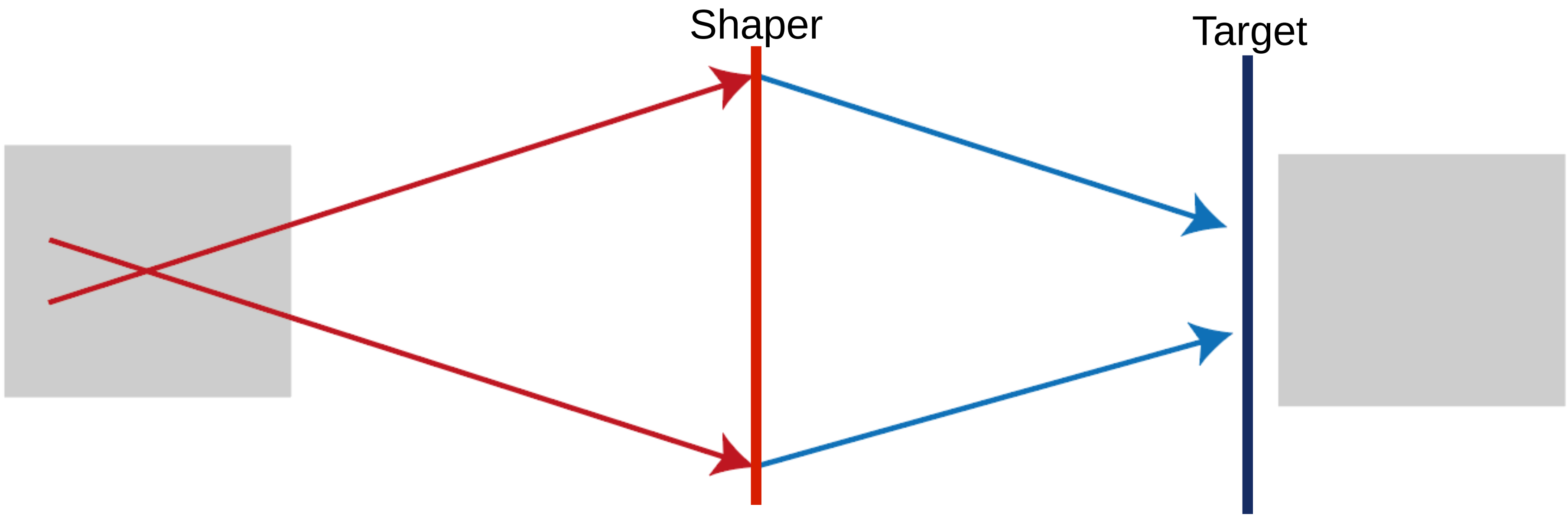


-1order

0 order

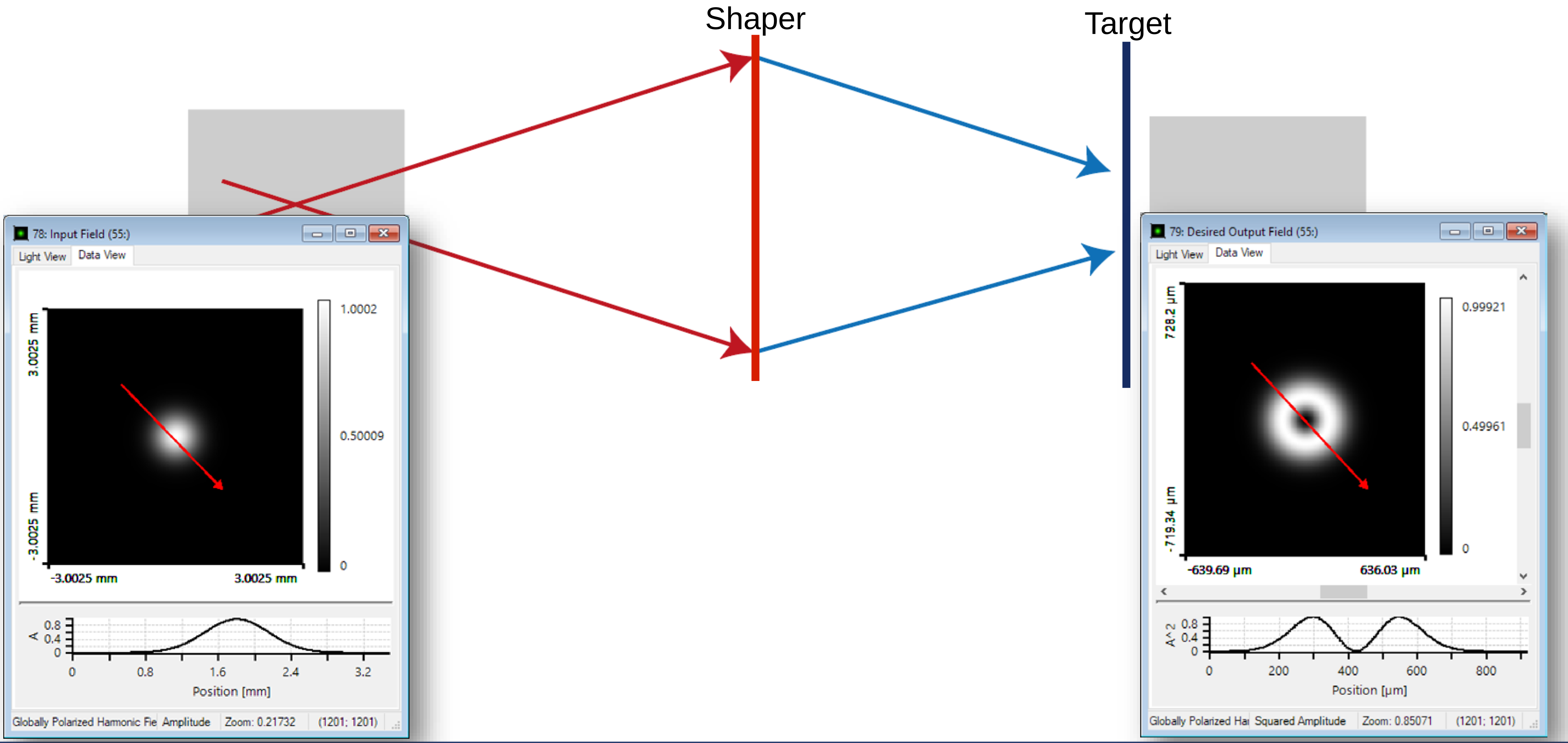
+1order

Light Shaping Tasks: Cases

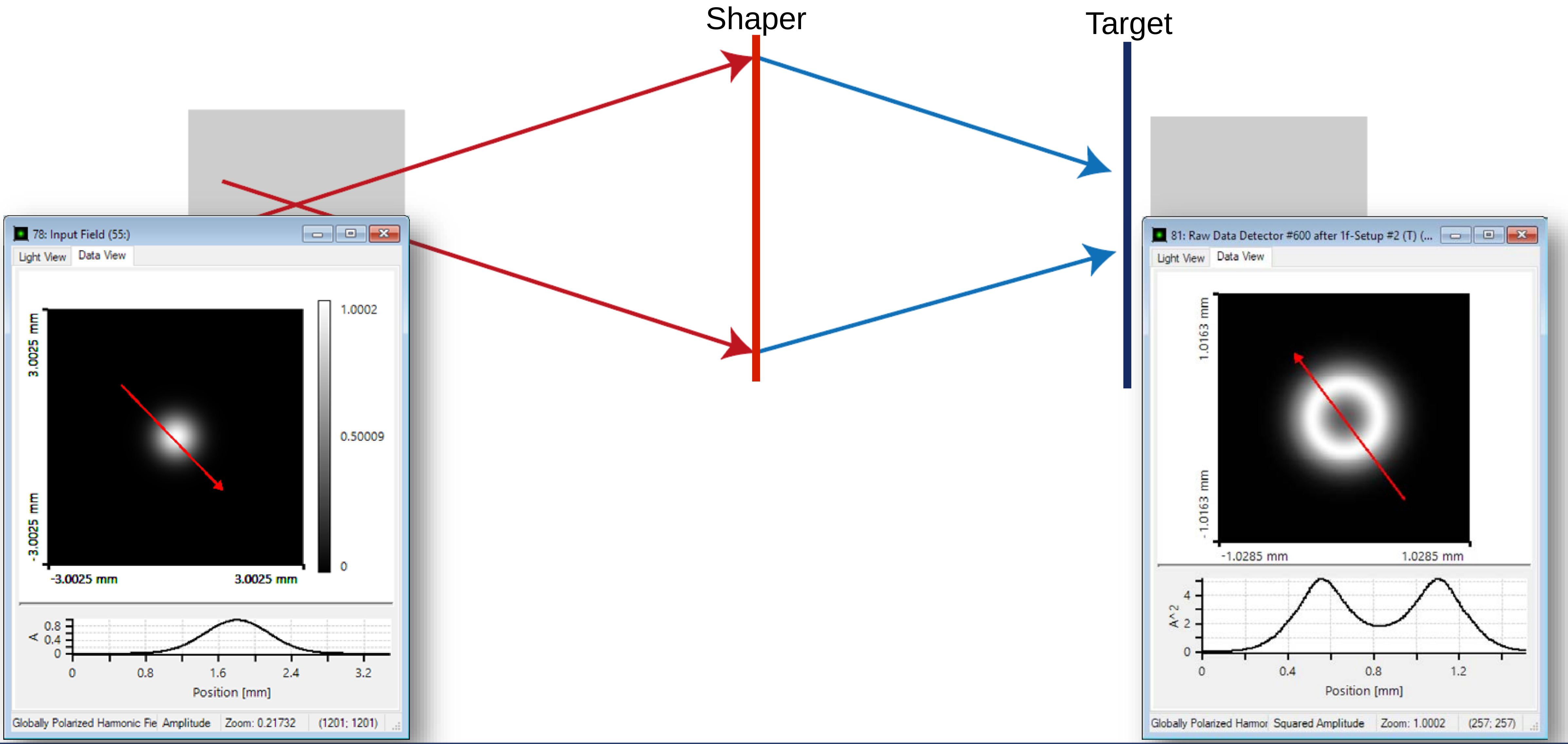


- Shaper in geometric field zone (GFZ)
- Target in geometric field zone (GFZ)

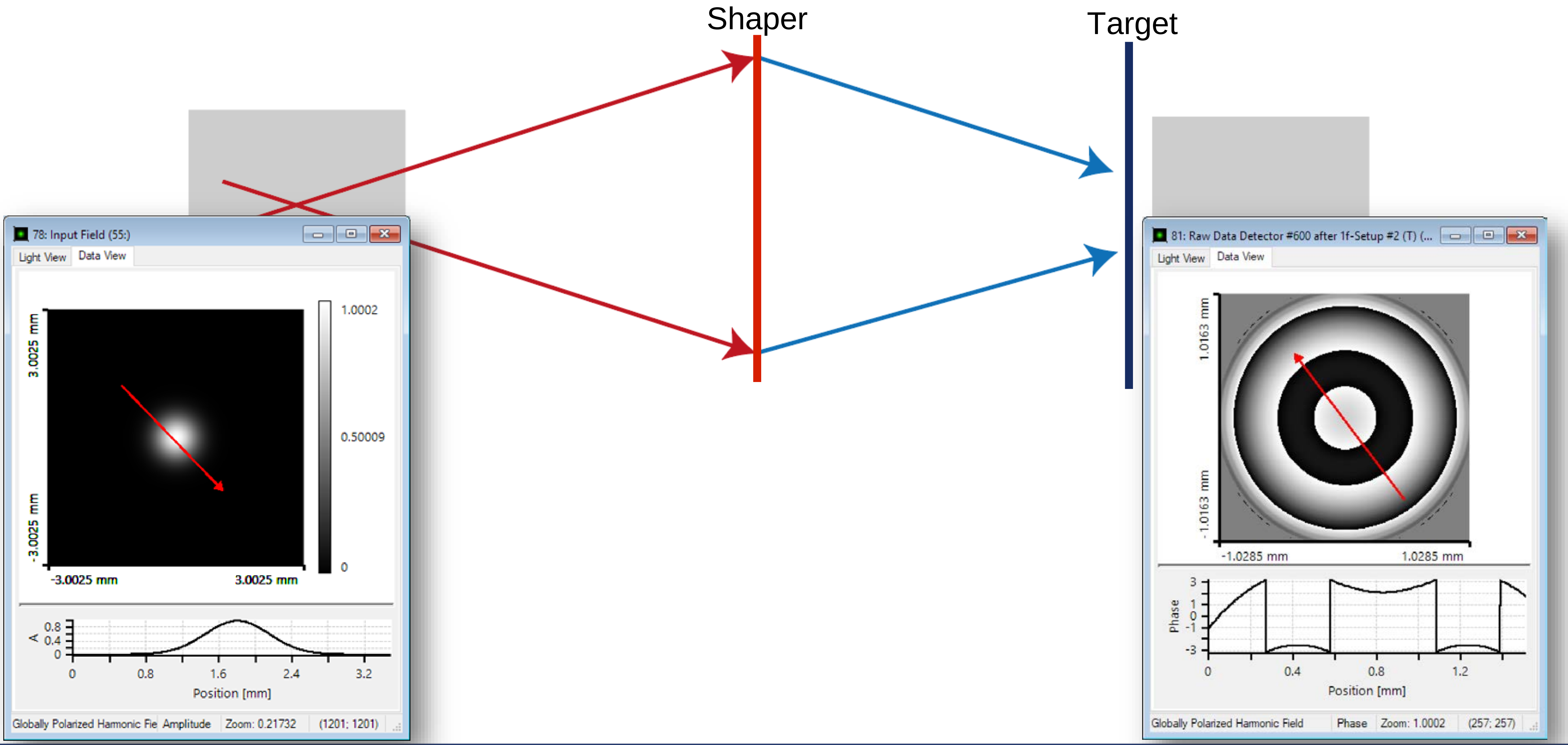
Light Shaping Tasks: Gaussian to Ringmode



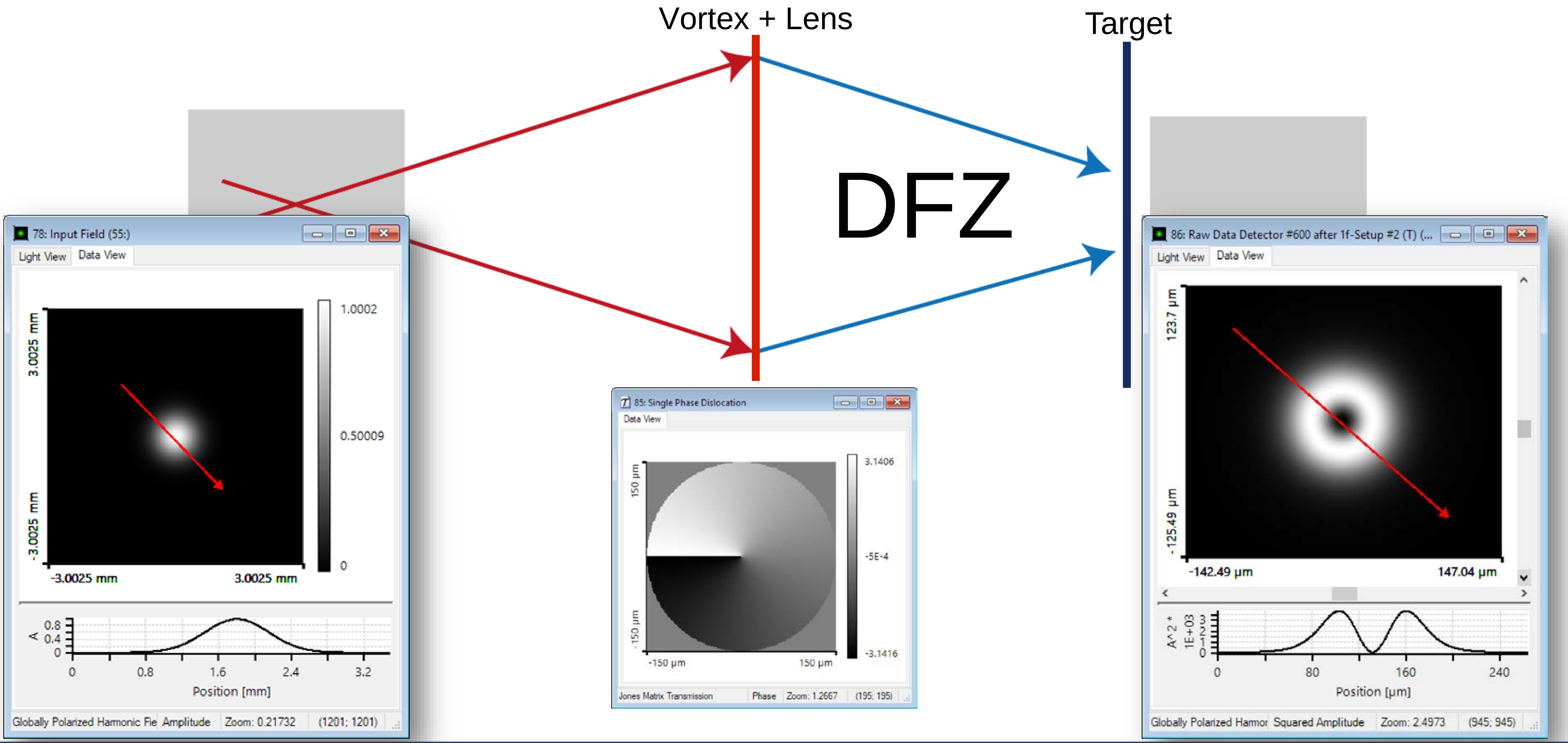
Gaussian to Ringmode: Refractive Approach (GFZ)



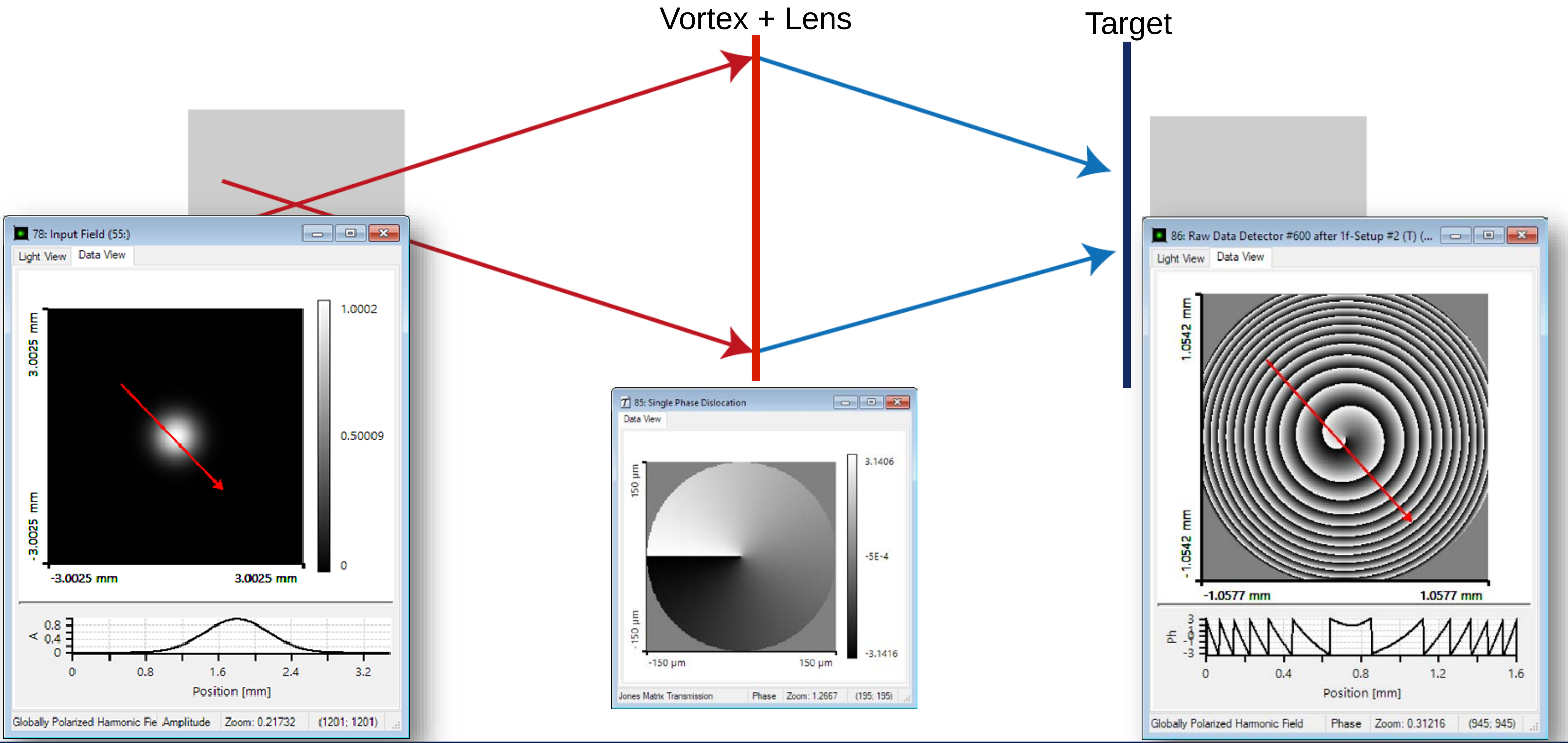
Gaussian to Ringmode: Refractive Approach (GFZ)



Gaussian to Ringmode: Diffractive Approach (DFZ)



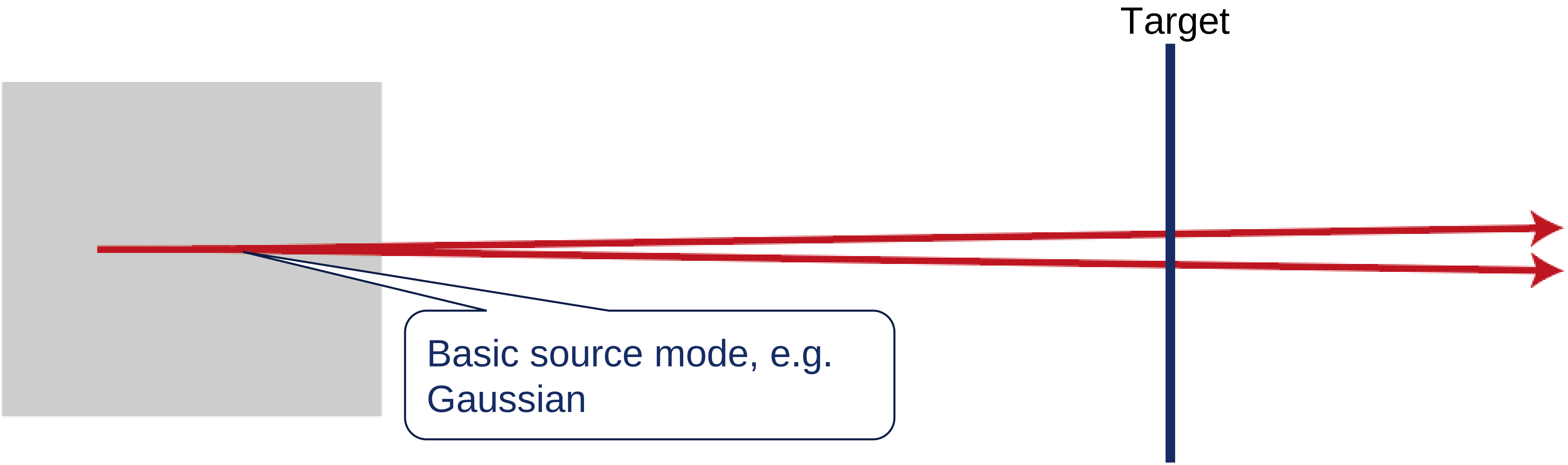
Gaussian to Ringmode: Diffractive Approach (DFZ)



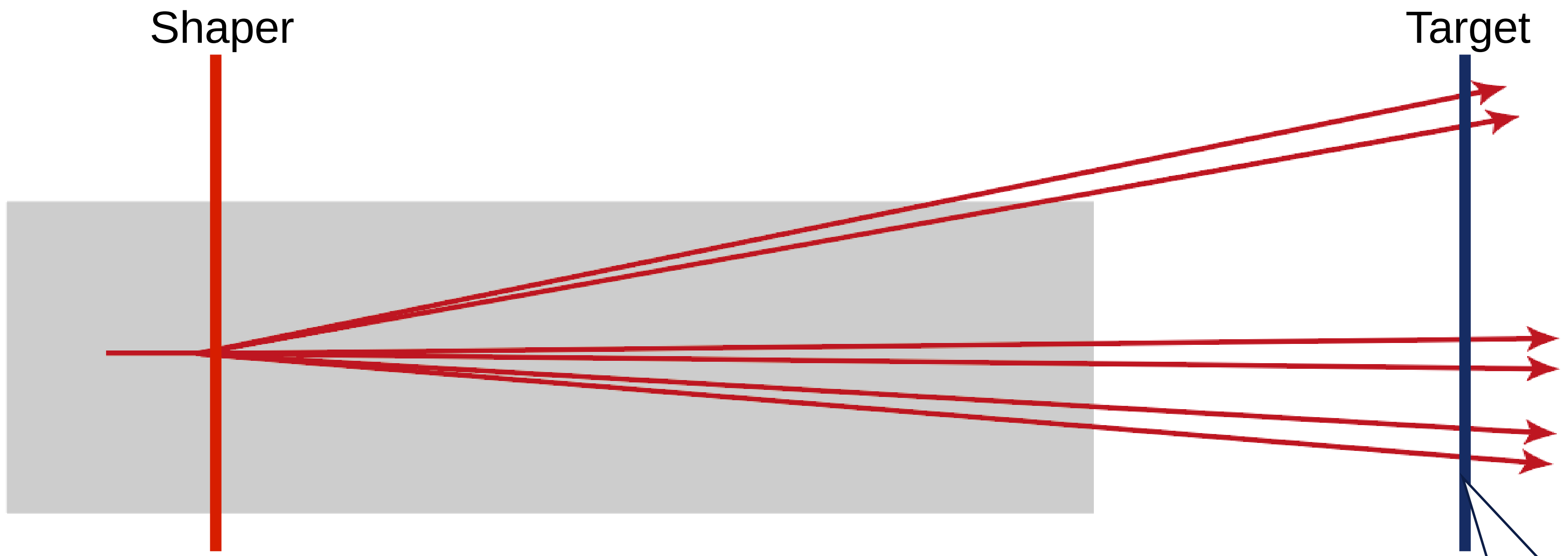
Diffractive light shaping by coherent superposition

Diffractive beam splitter and diffuser

Shaping by “Beam Scanning”



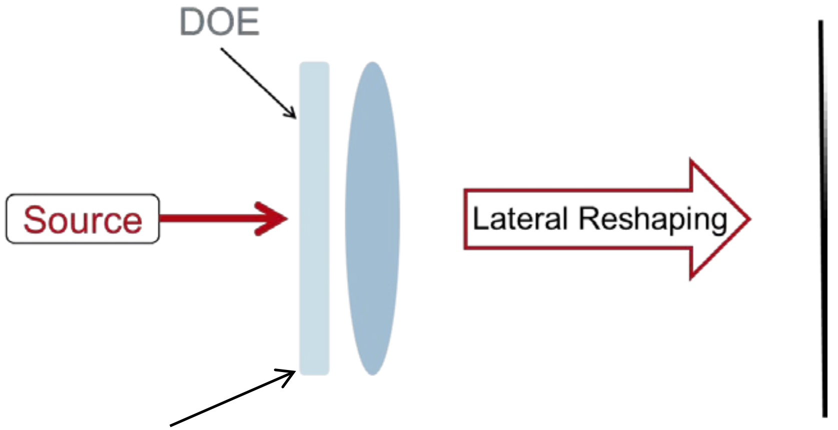
Shaping by “Beam Scanning”



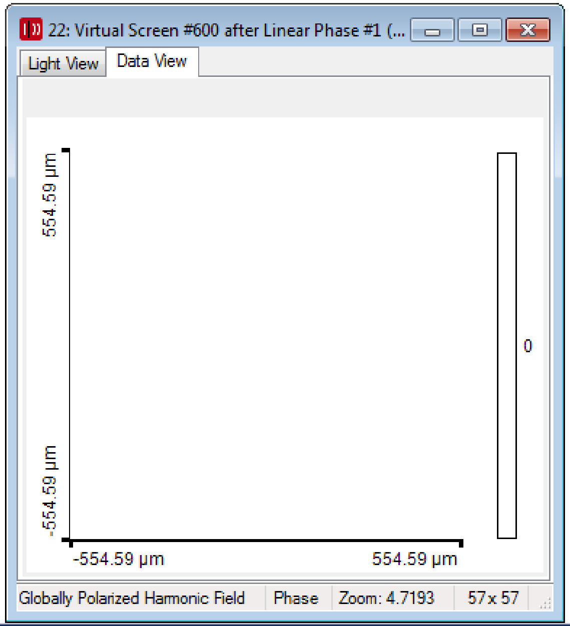
- Beam splits at shaper
- Field behind shaper is in diffractive field zone
- Shaper is grating: DOE

Target pattern is “written” by scanned beam in target plane.

Illustration of Deflection



Phase of transmission



Intensity in target

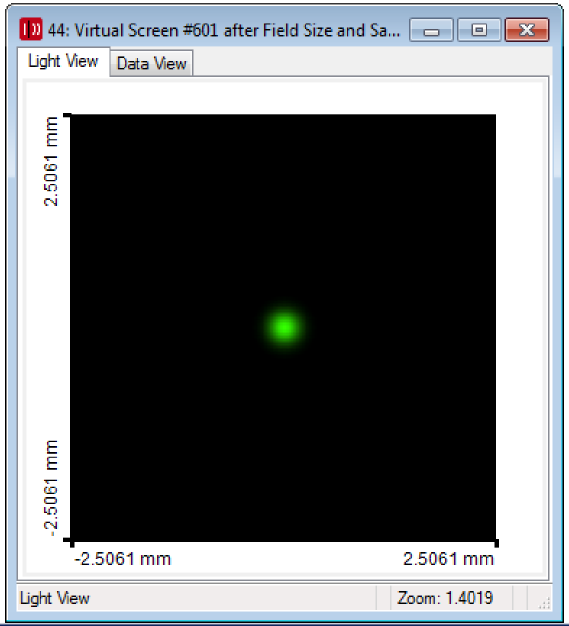
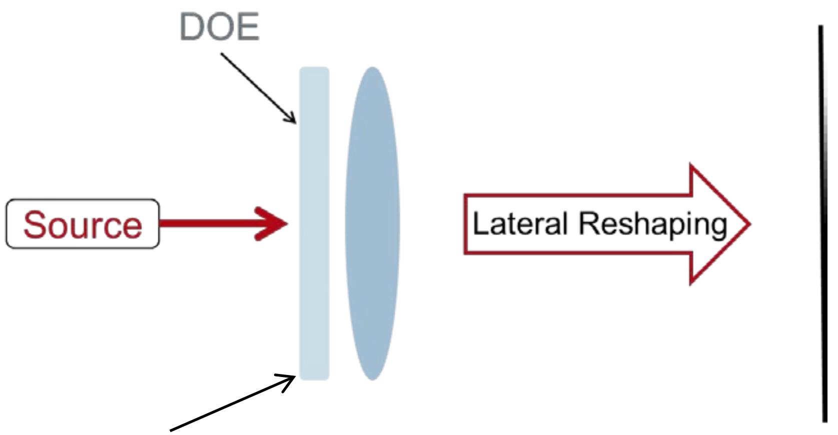
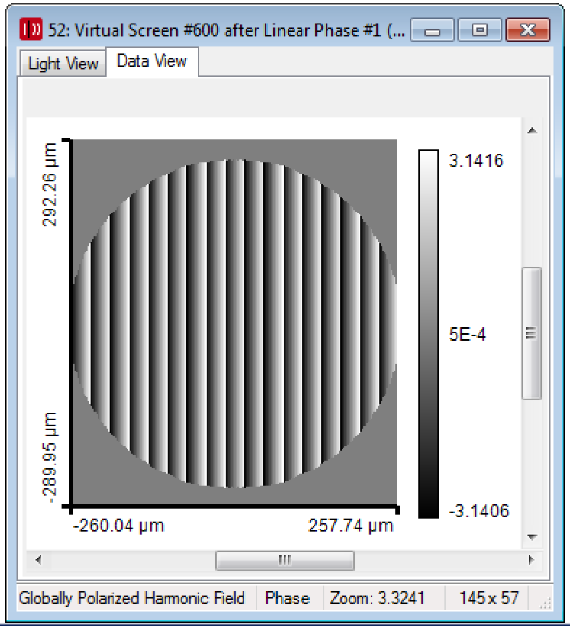


Illustration of Deflection



Phase of transmission



Intensity in target

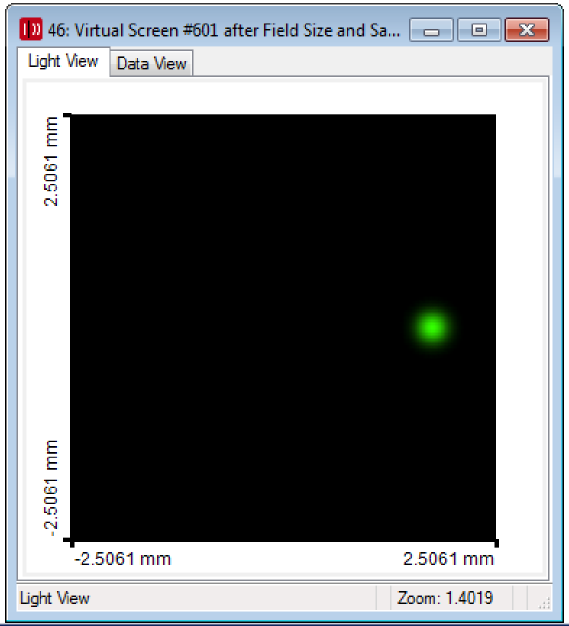


Illustration of Deflection

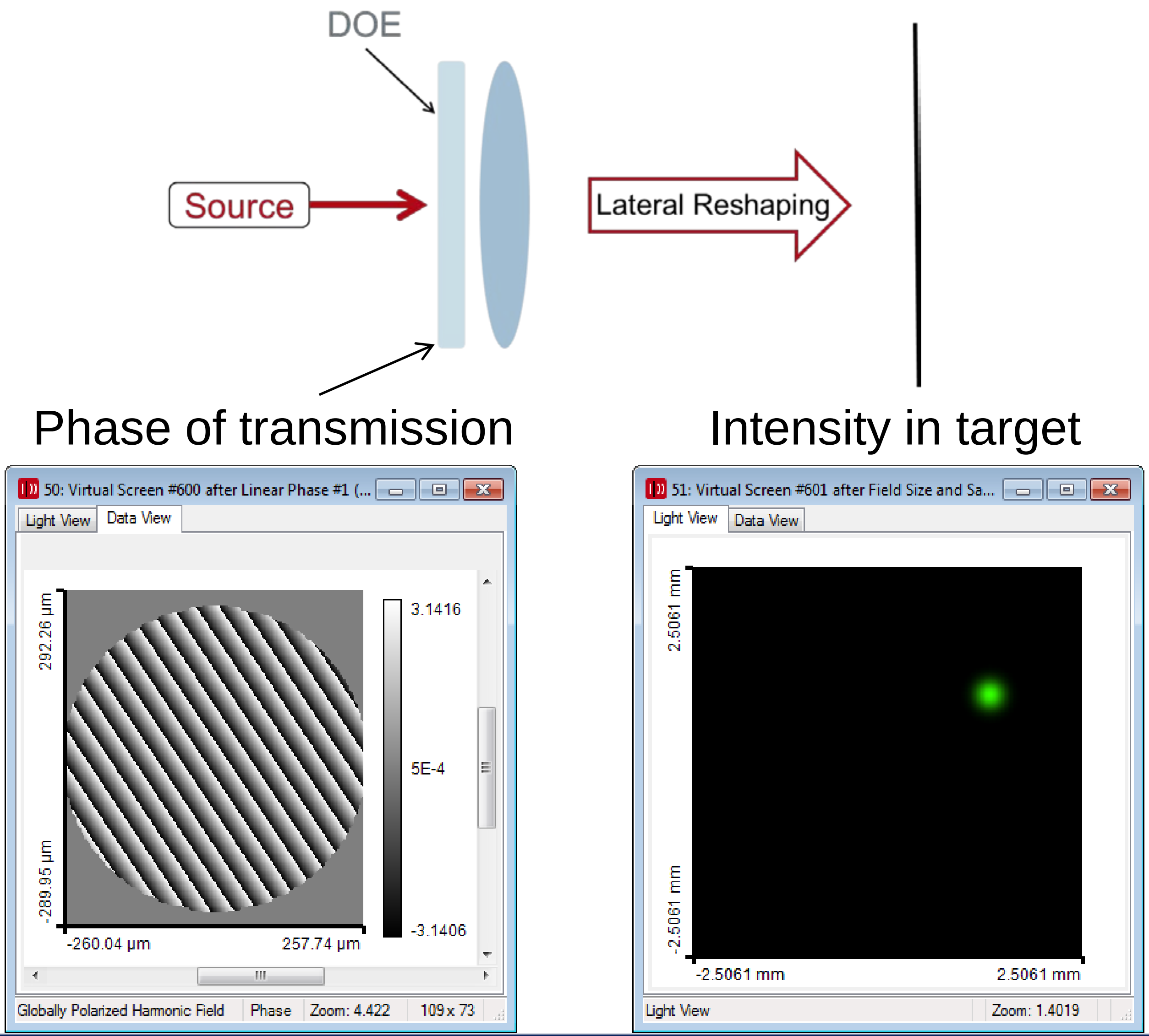


Illustration of Deflection

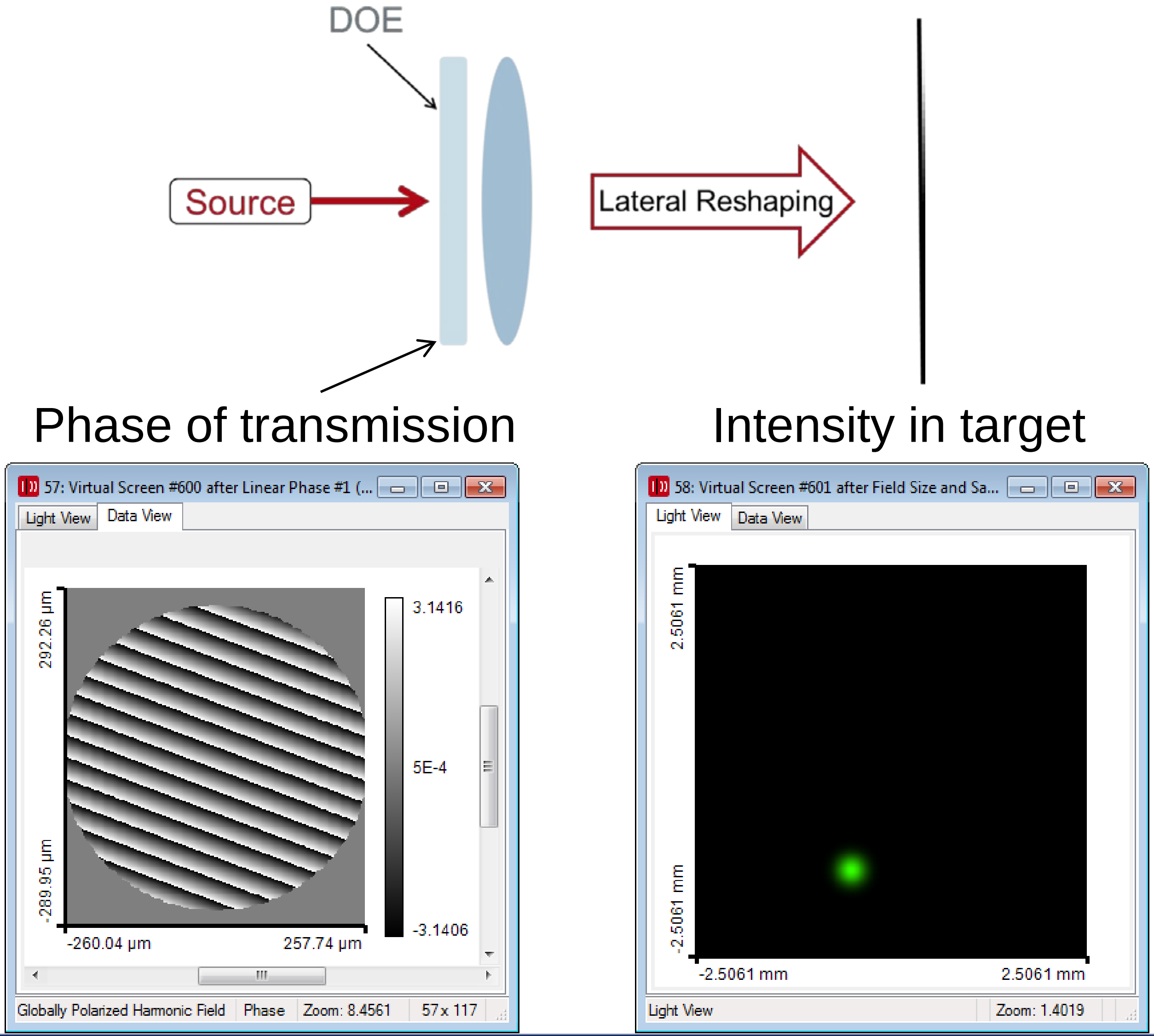


Illustration of Deflection

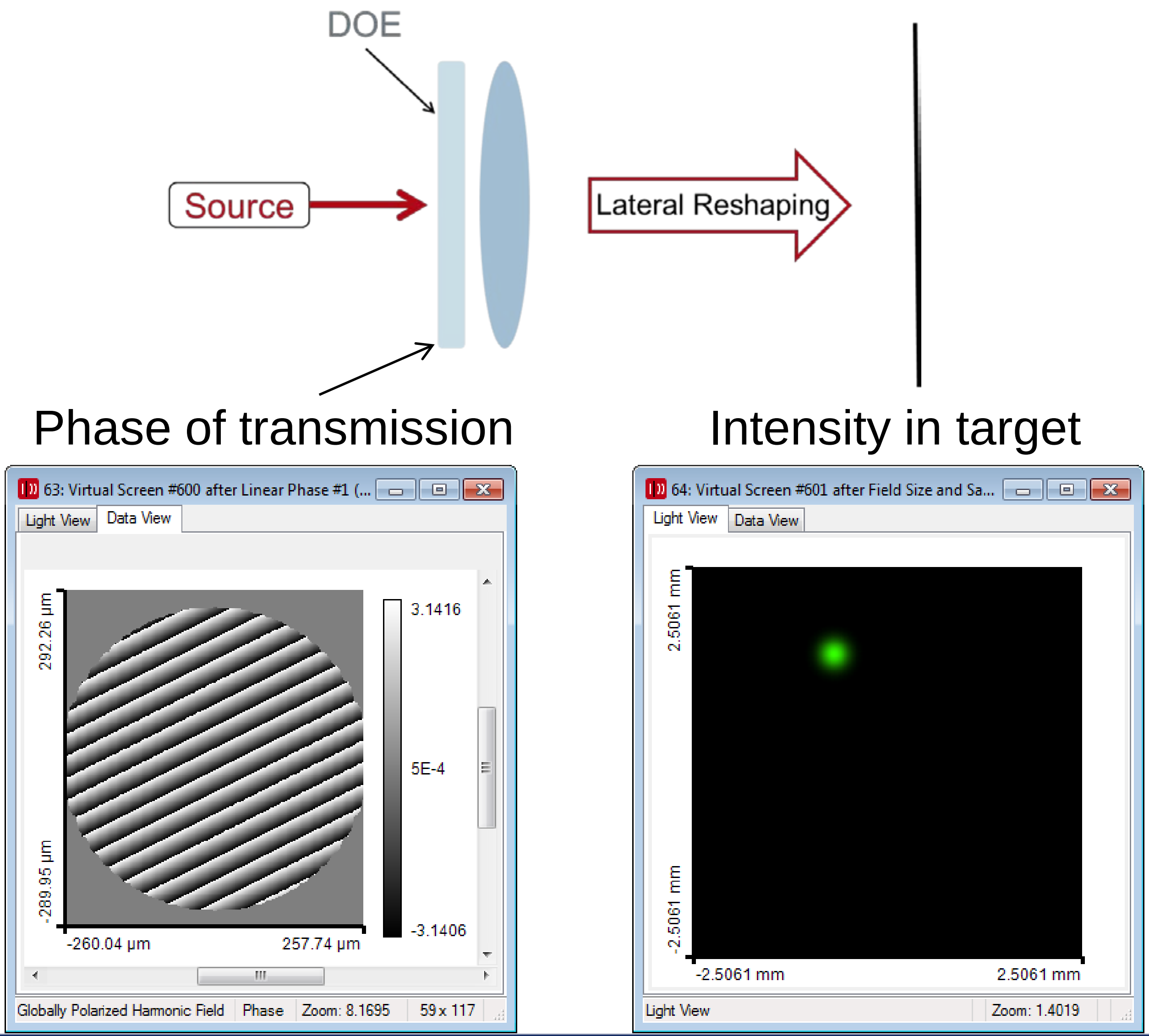
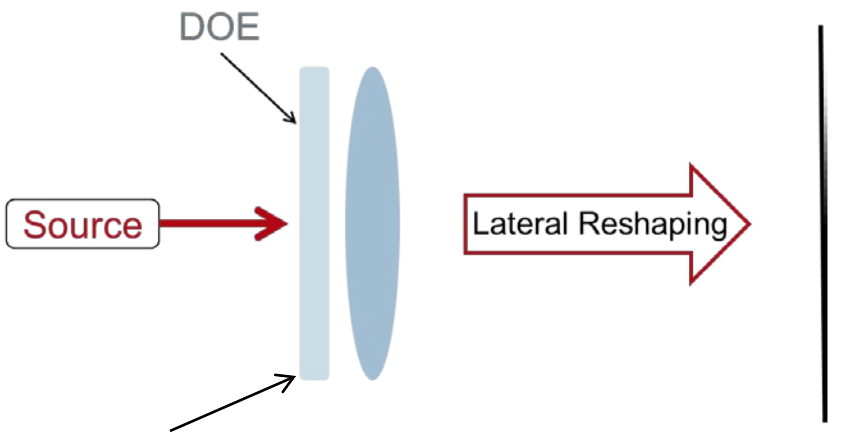
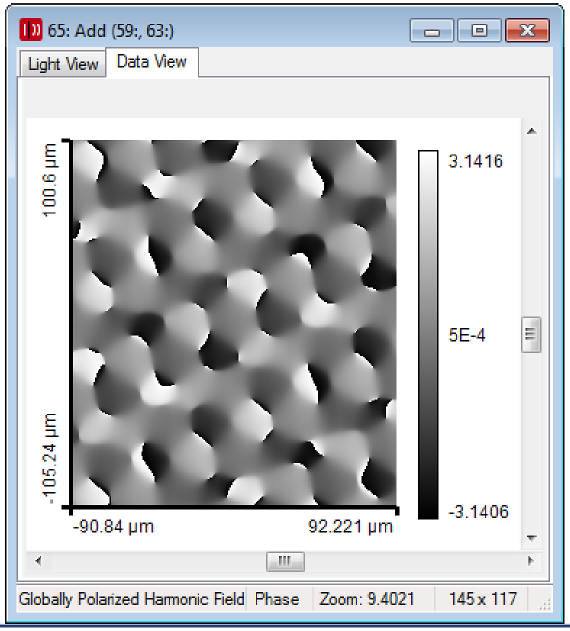


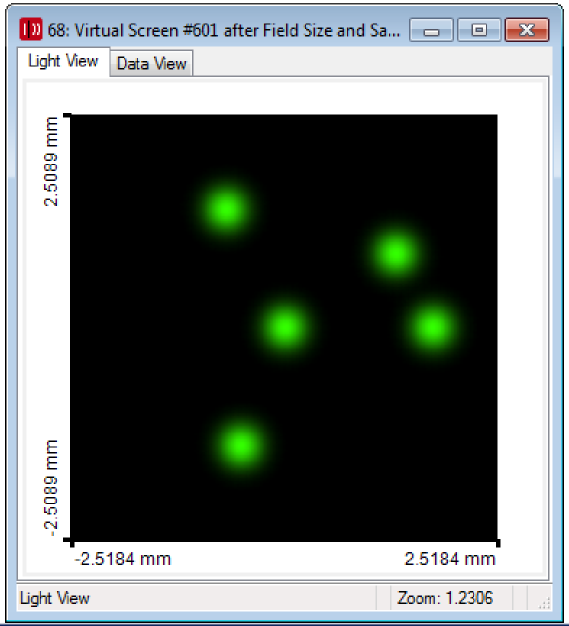
Illustration of Deflection: Sum



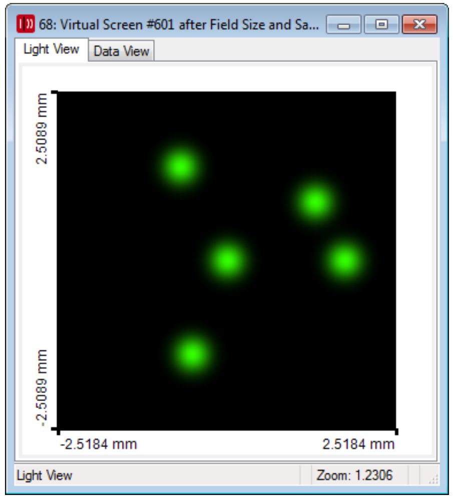
Phase of transmission

Intensity in target

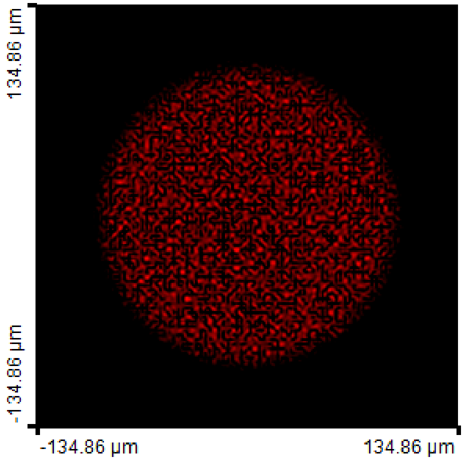




Basic Design Situations: Splitting



- Spots in target pattern do not overlap: diffractive beam splitter

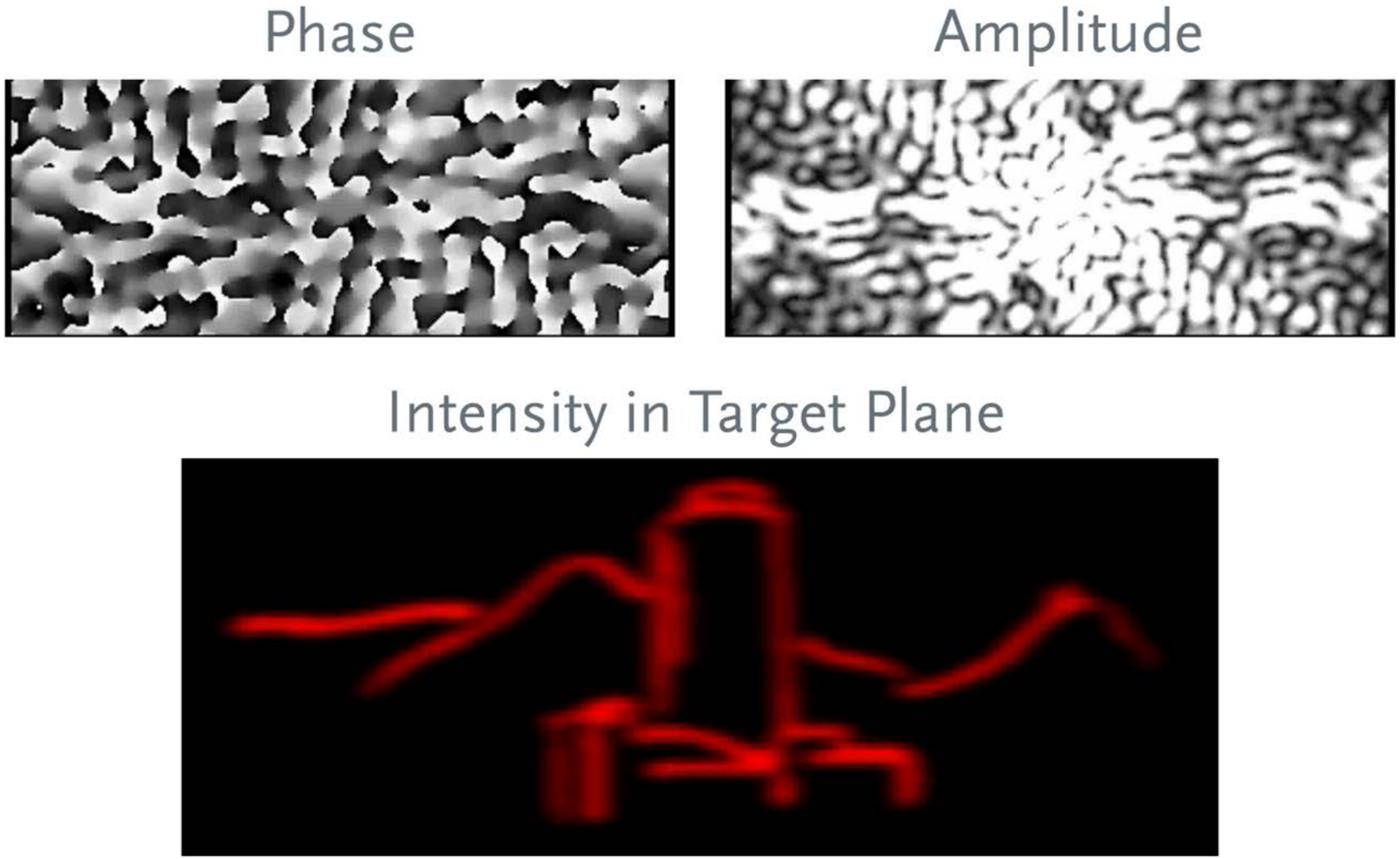


- Spots overlap in target patten: diffractive diffuser

Basic Design Situations: Splitting

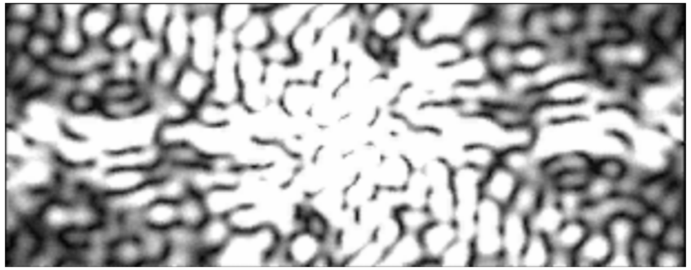
- Spots in target pattern do not overlap: diffractive beam splitter
- Spots overlap in target patten: diffractive diffuser

Shaping by “Beam Scanning”

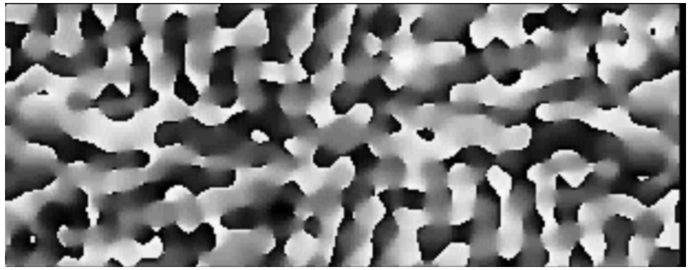


Iterative Fourier Transform Algorithm

Amplitude

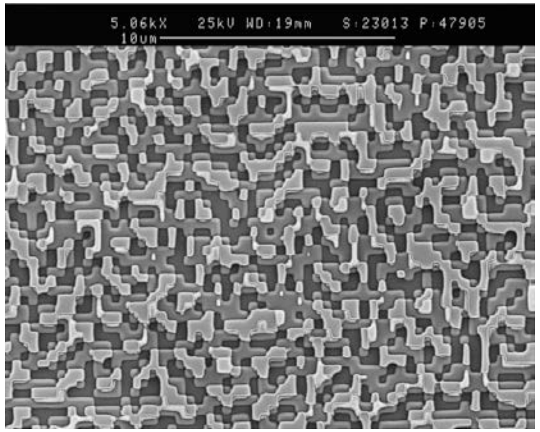


Phase



Advanced diffractive optics design techniques

Design technique (IFTA) implemented in VirtualLab™



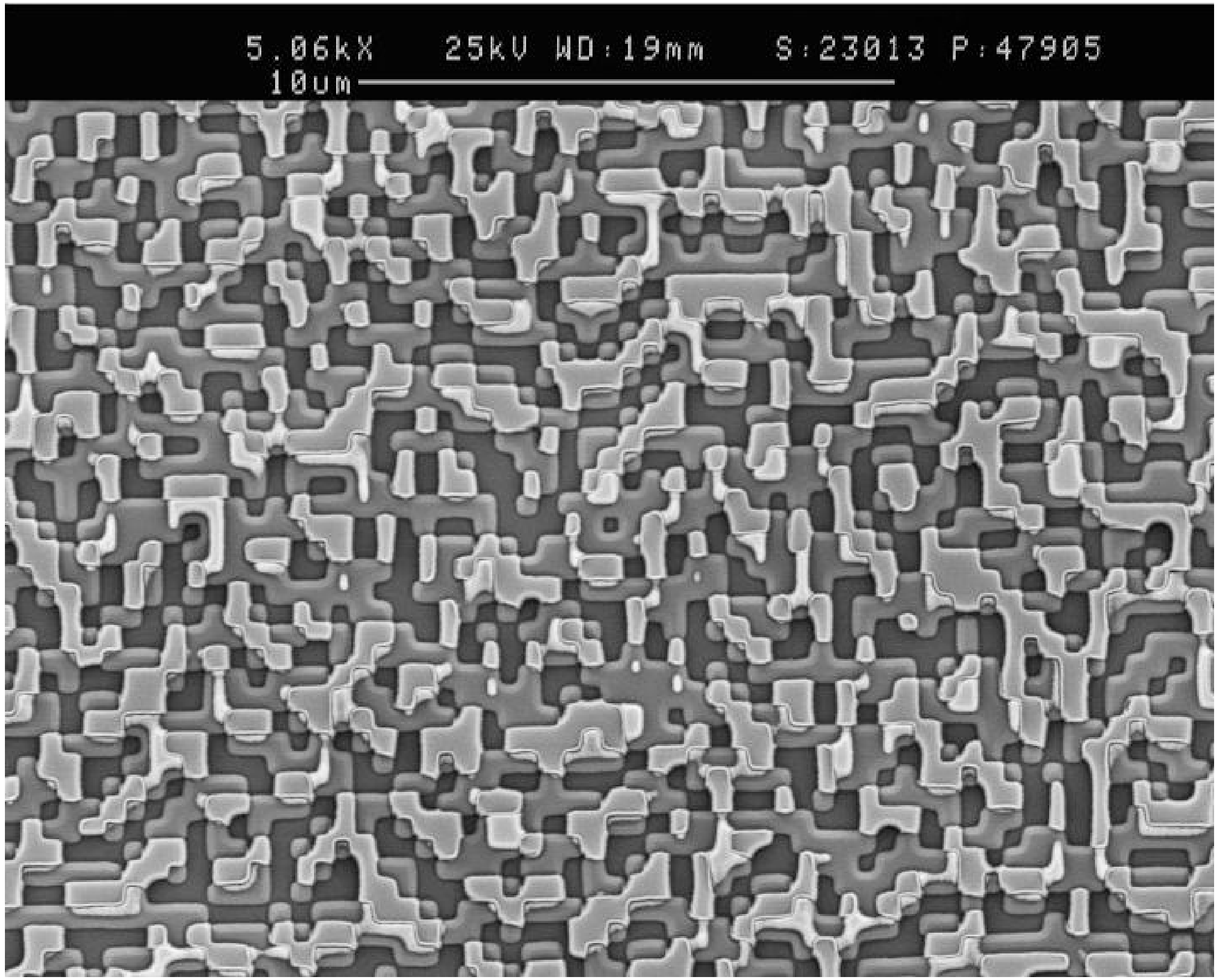
Micro-structured surface profile

Fabricated at IAP, University of Jena

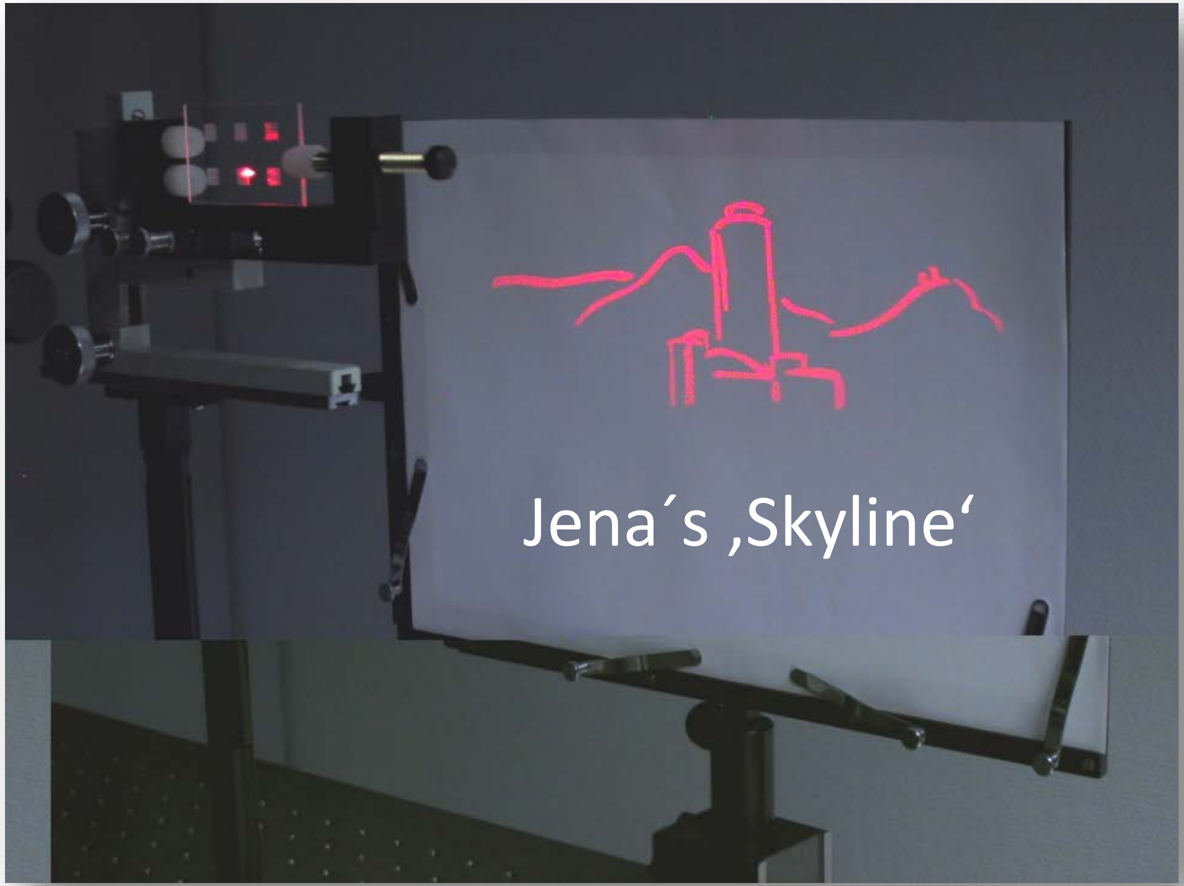
Feature Sizes of Element

Feature size
about 400 nm

4 height levels



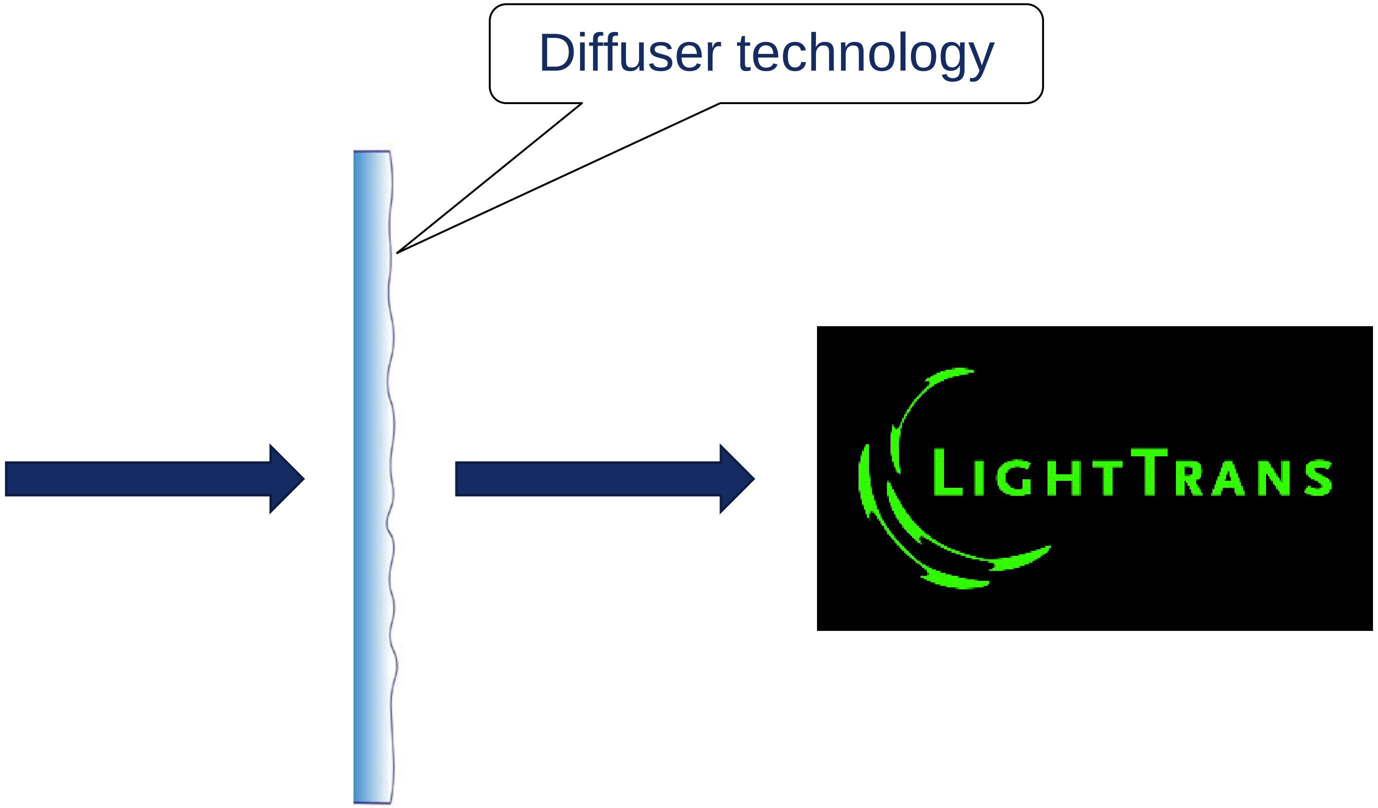
Optical Experiment



Comments on Diffuser Technology

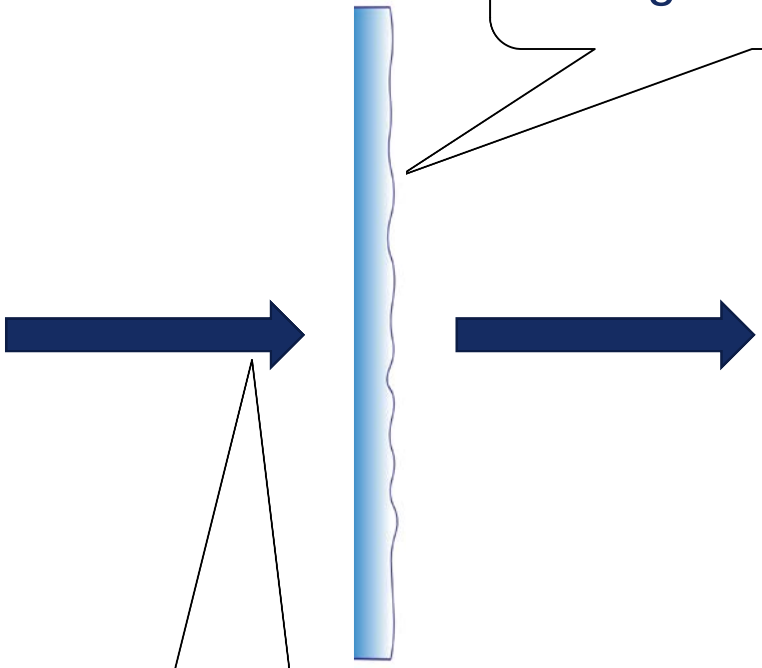
- Very flexible in light pattern generation
- Robust against adjustment problems
- Coherent light leads to speckle pattern
- Size of speckle features can be adjusted by focusing system
- Diffusers work for partially coherent beams
- Partially coherent beams smooth the speckle pattern; effect can be simulated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

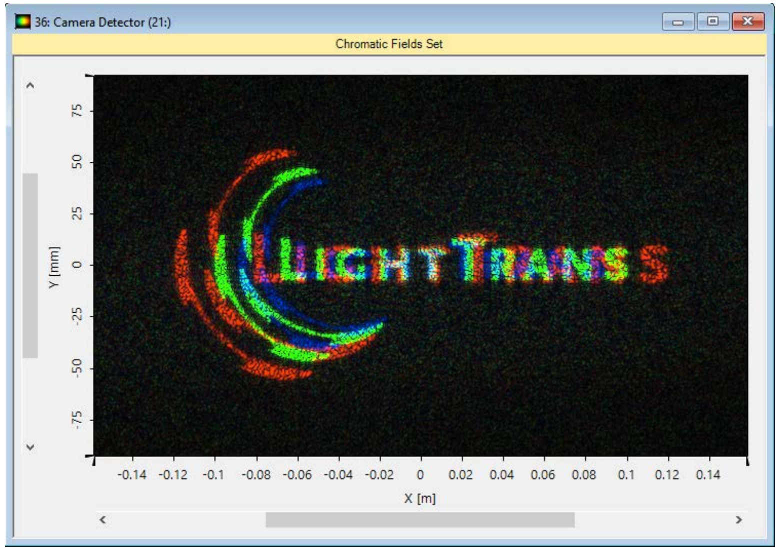
Diffractive Optics: Pattern Generation



Diffractive Optics: Pattern Generation

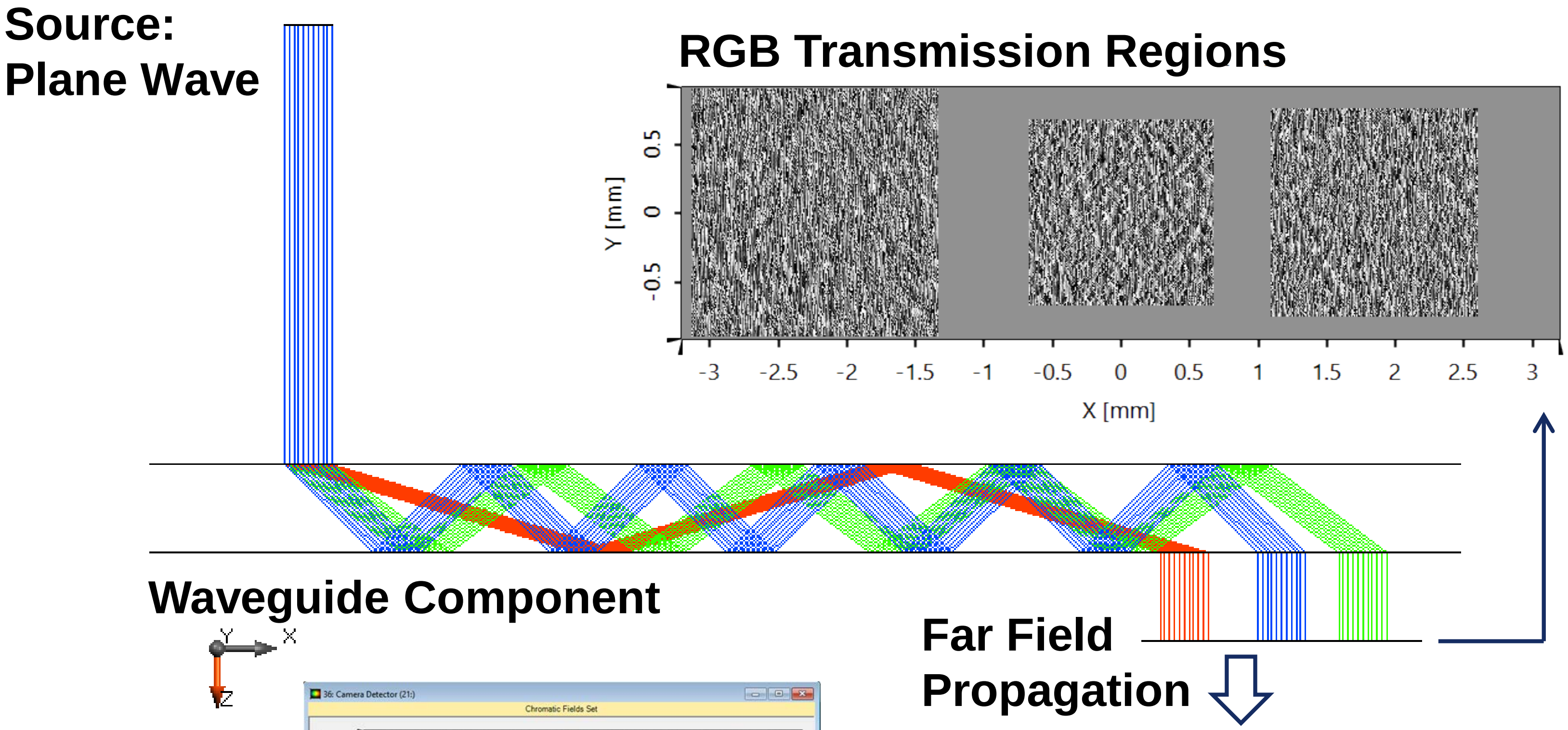
Diffuser technology:
Design very chromatic

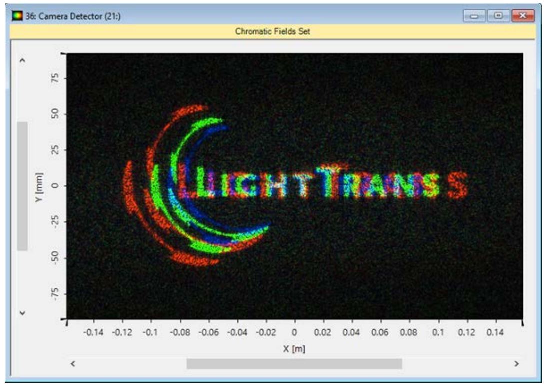


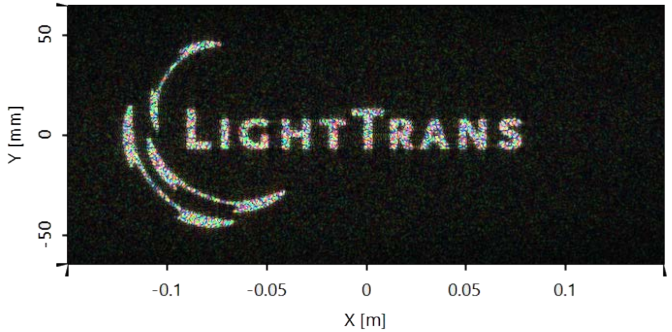


Source RGB

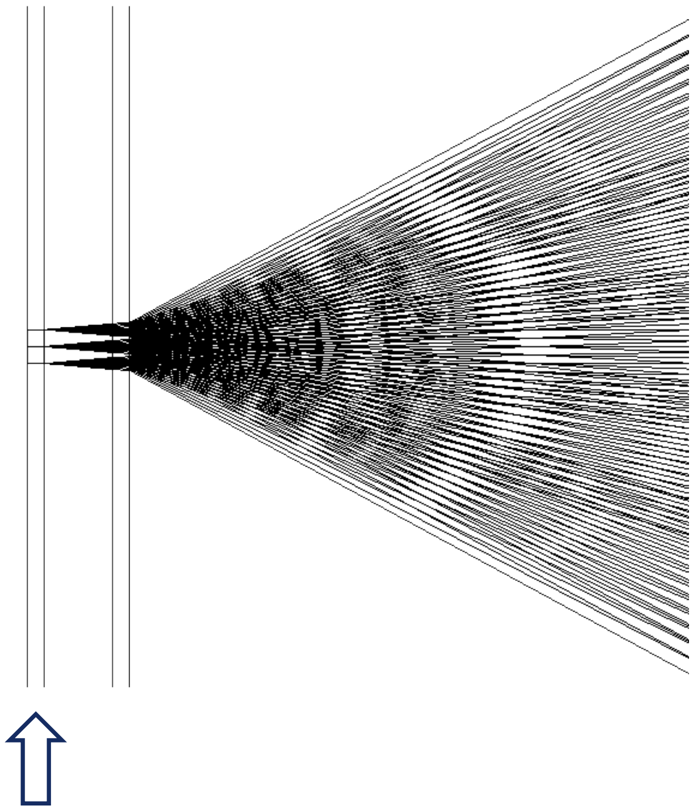
Solution by Integrated Diffractive Optics







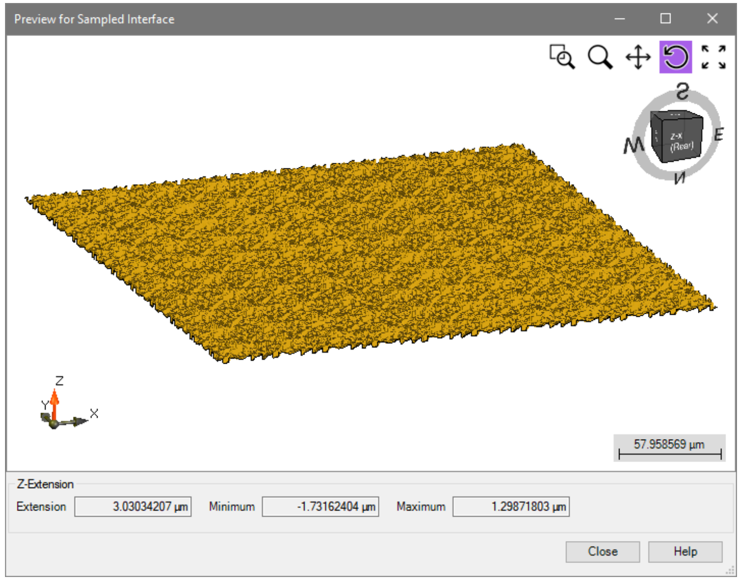
High NA Beam Splitter by Two DOE‘s



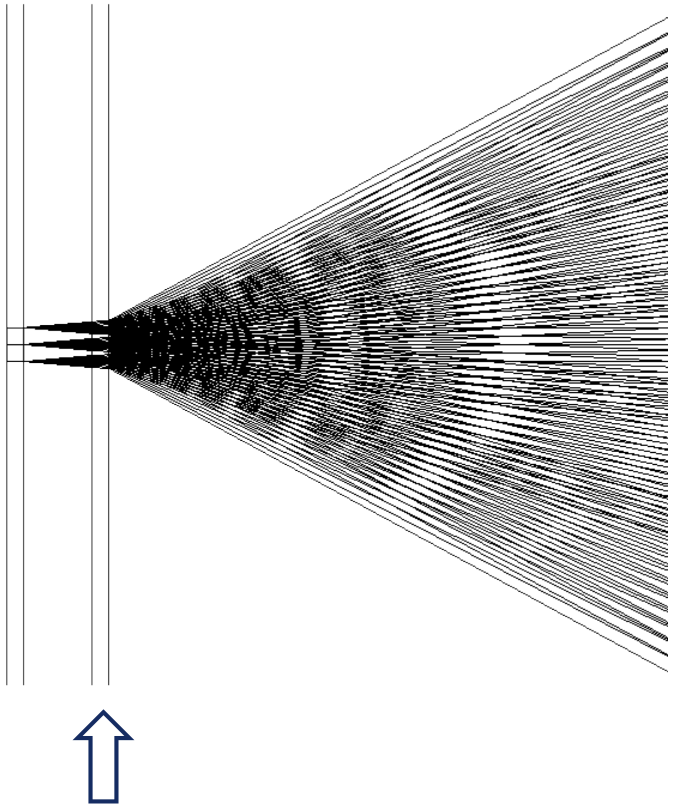
paraxial beam splitter

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



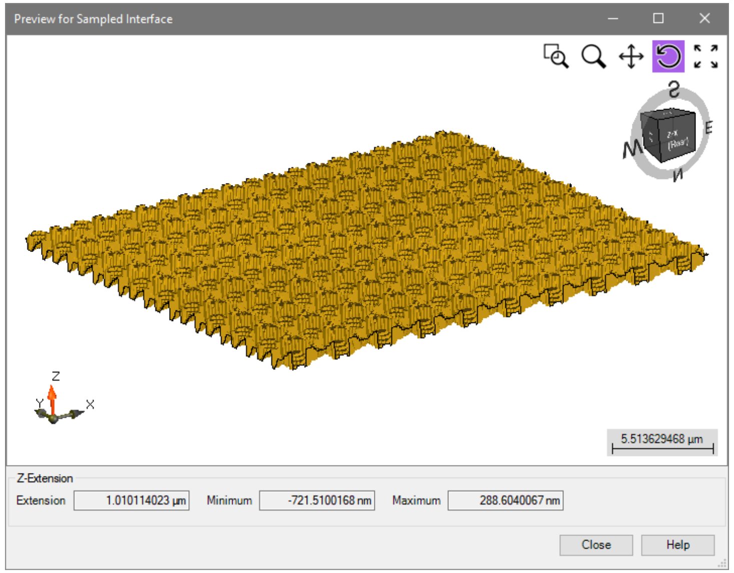
Specification: Second Beam Splitter



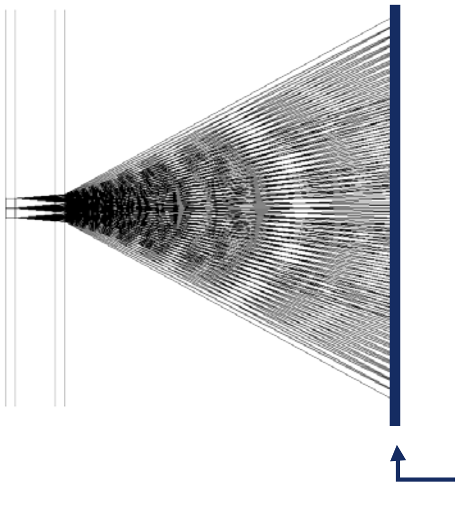
high-NA beam splitter

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

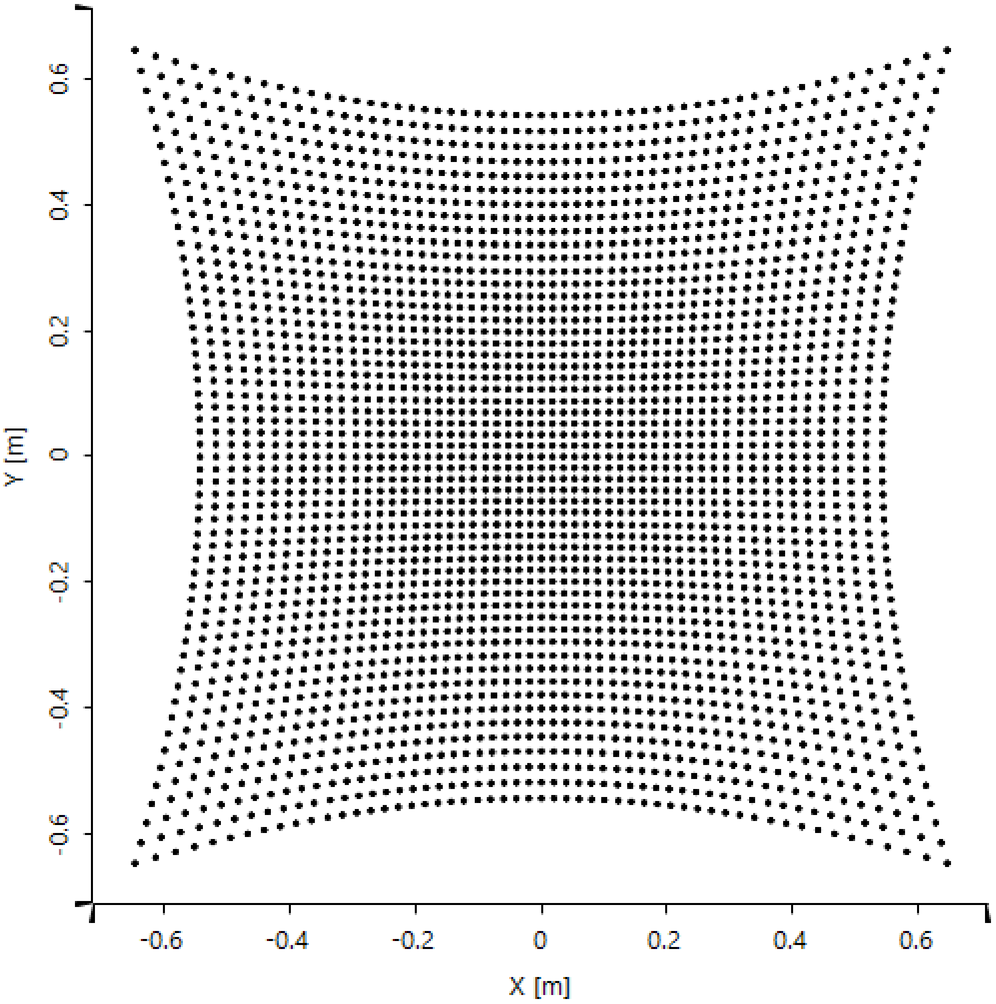
surface profile



Results: Spot Diagram

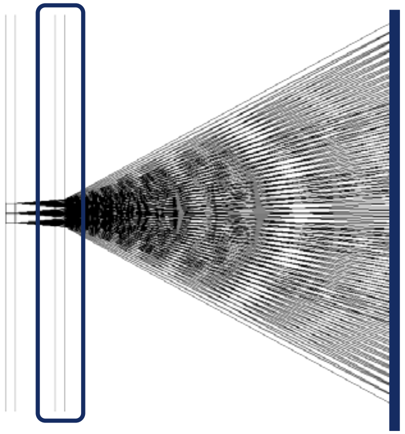


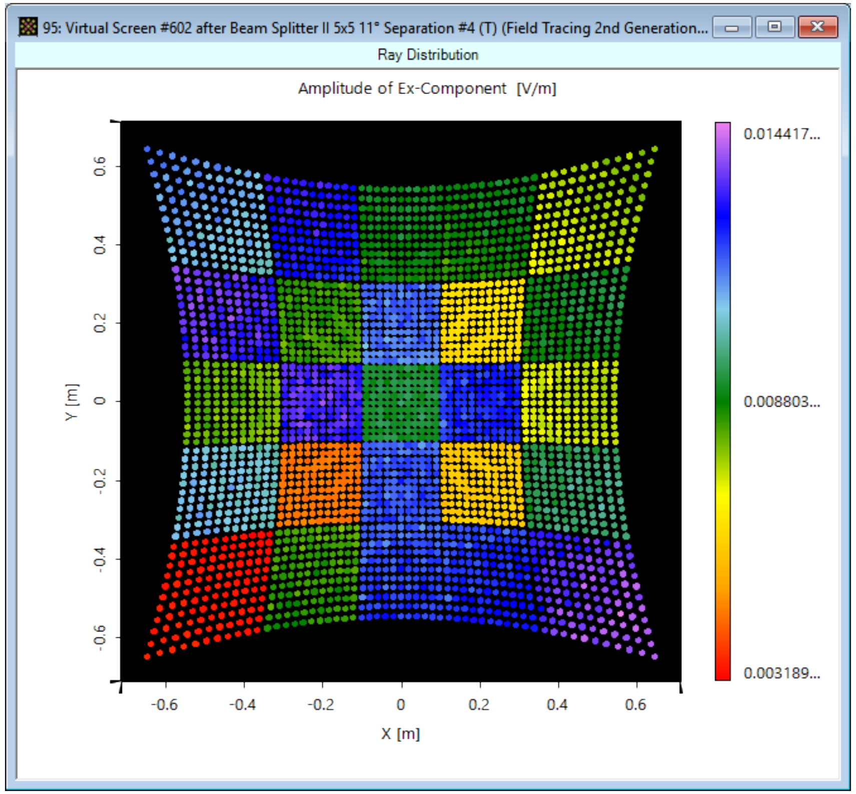
combination of both beam splitter generate 55x55 order with 55x55° full opening spread



spot diagram

Results: Output Evaluation with FMM

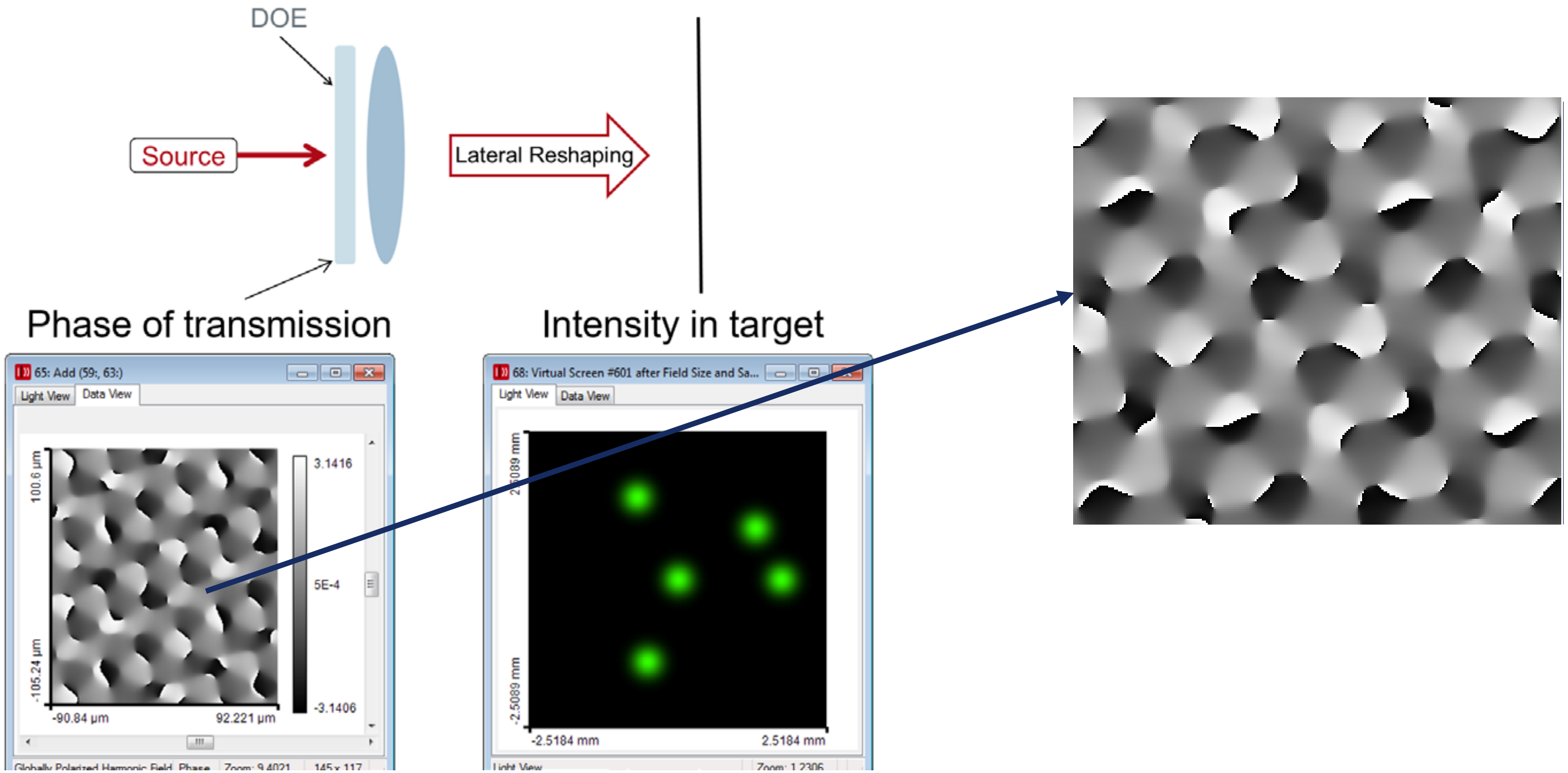




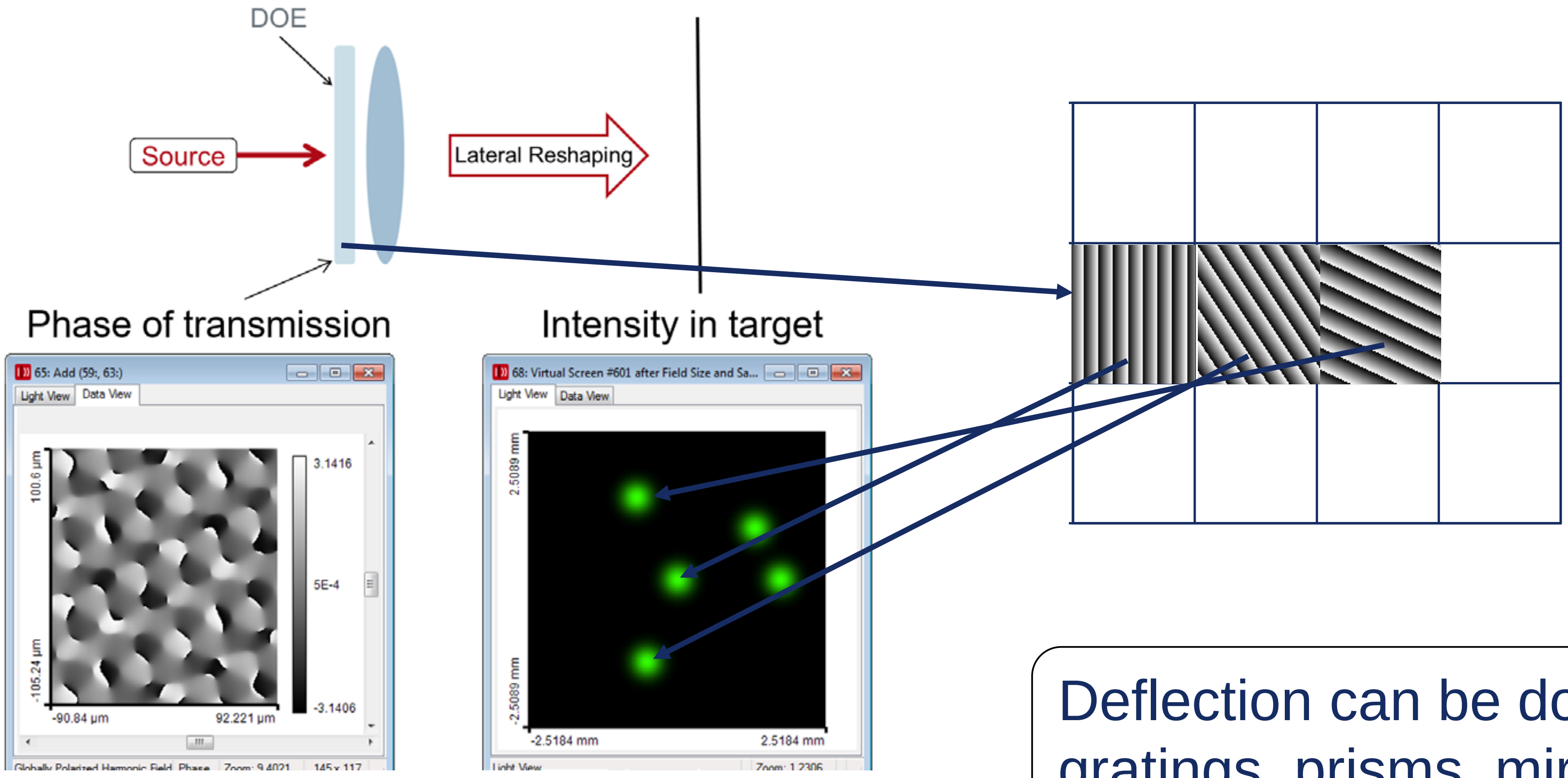
Light shaping by lateral decomposition

Elementary cell array components

Array of Deflectors

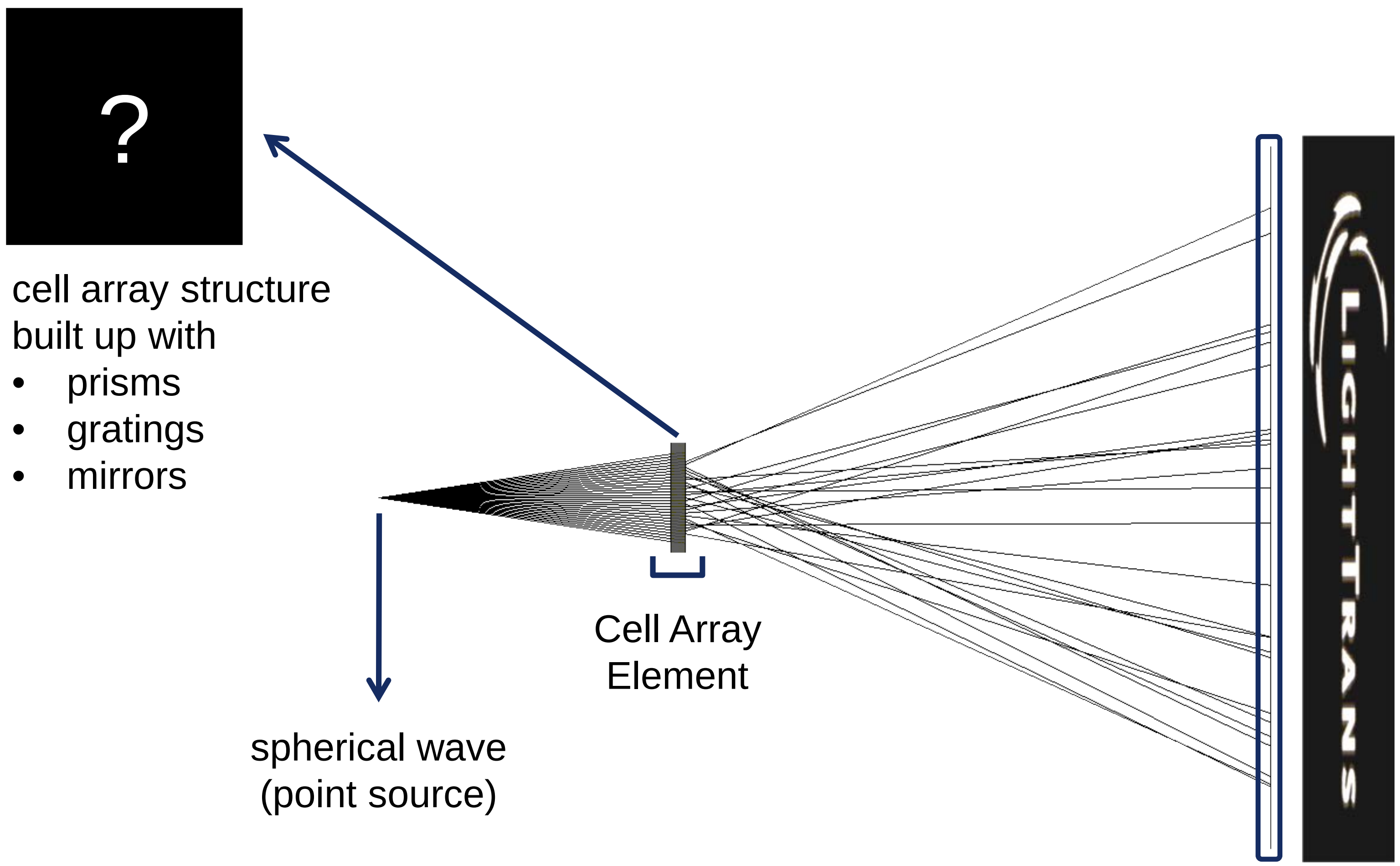


Array of Deflectors

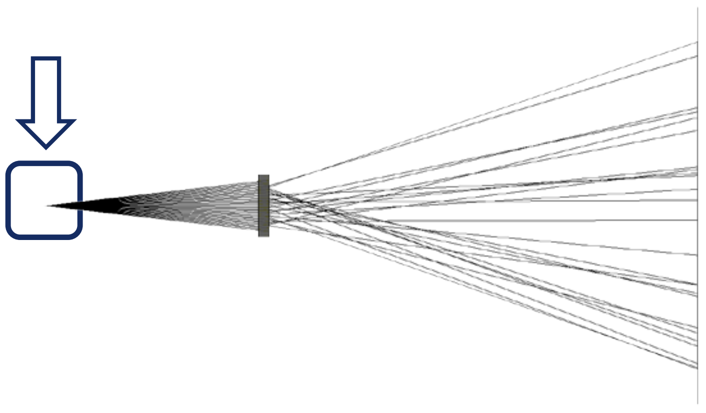


Deflection can be done by gratings, prisms, mirrors.

Task/System Illustration

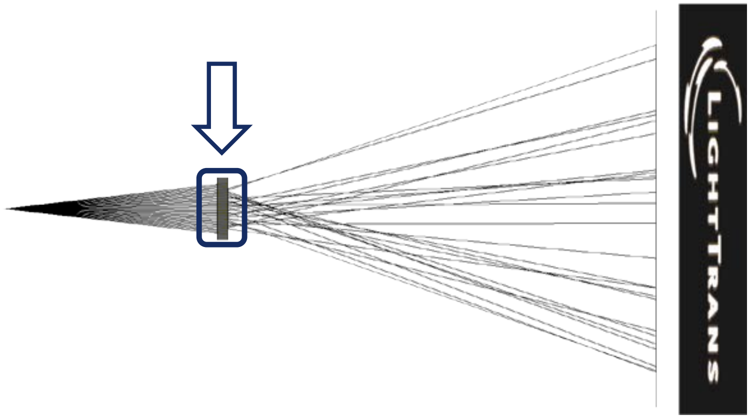


Specification: Light Source



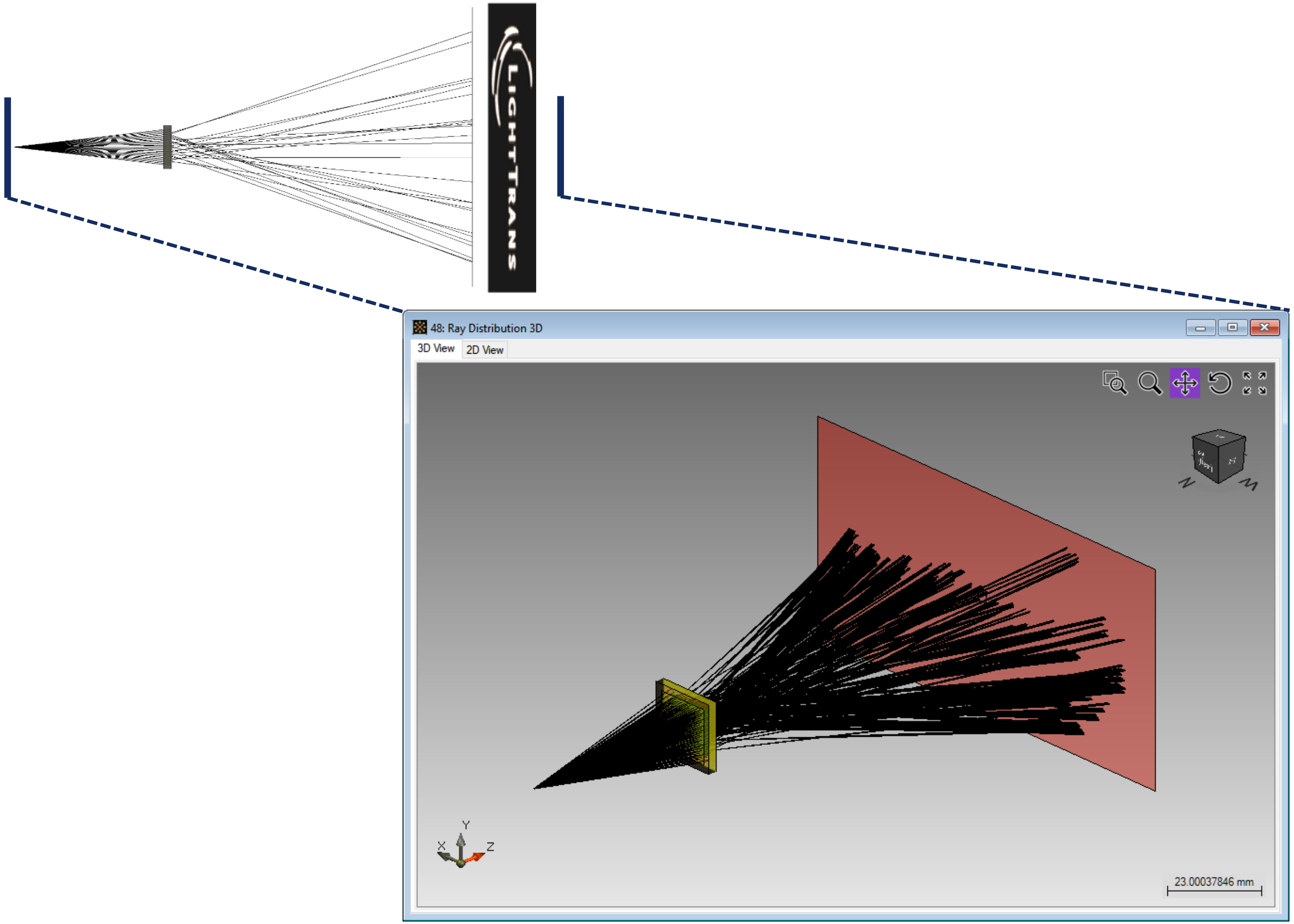
Parameter	Description / Value & Unit
type	RGB LED
emitter size	100x100 µm
wavelength	(473, 532, 635) nm
polarization	right circularly polarized light
number of lateral modes	3x3
Total number of lateral and spectral modes	27

Specification: Cell Array

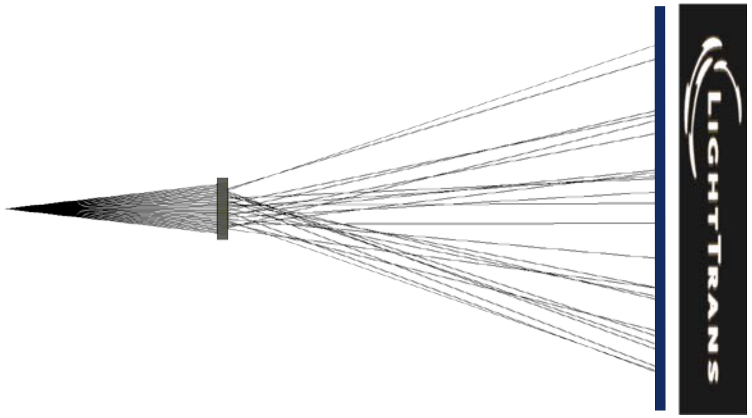


Parameter	Value & Unit
number of cells	100x100
cell size	125x125µm
array aperture	12.5x12.5mm

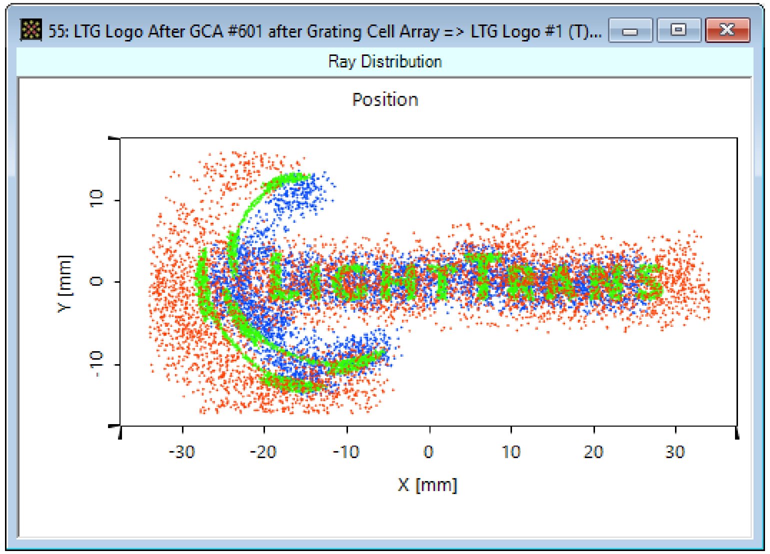
Results: 3D System Ray Tracing



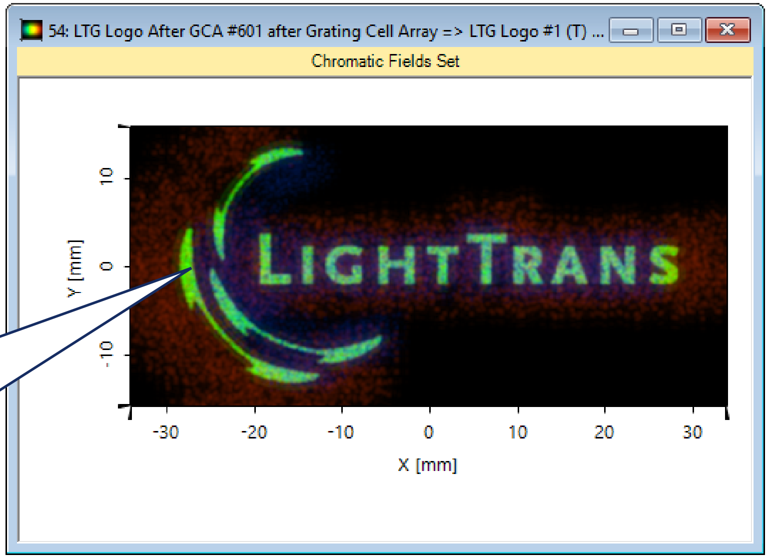
Results: Grating Cells Array



spot diagram

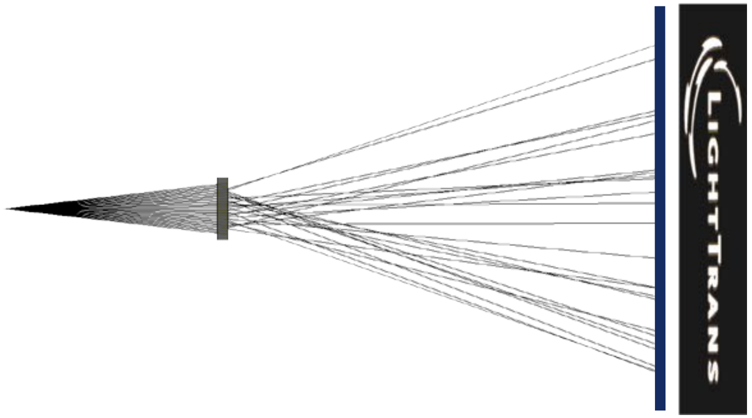


y pattern
olor view)

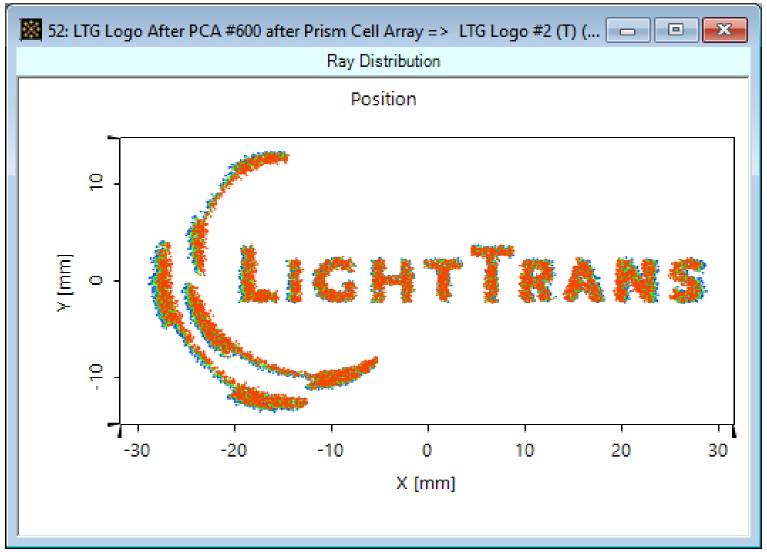


for grating cells array strong dispersion effects occur

Results: Prism Cells Array

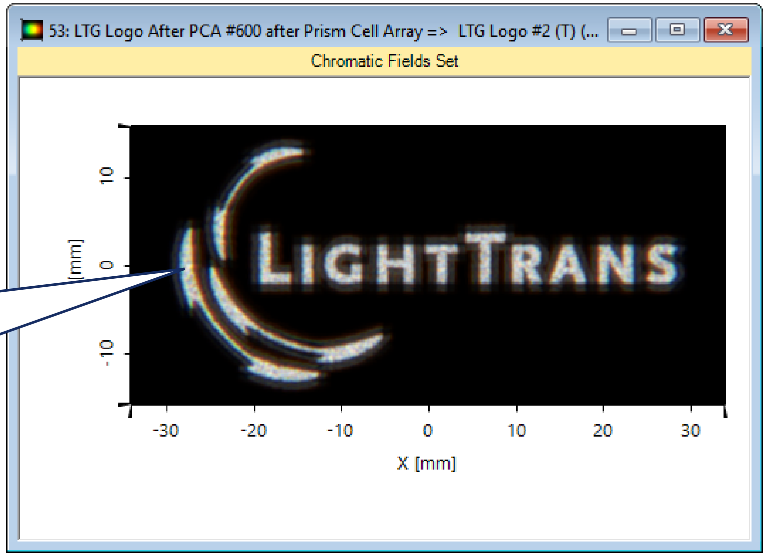


spot diagram



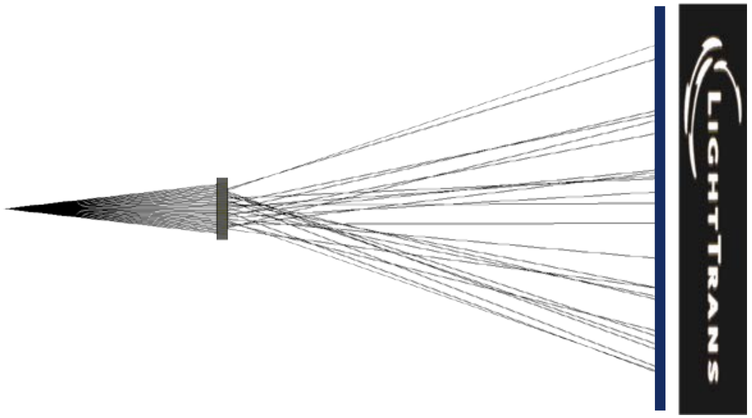
pattern

(real or view)

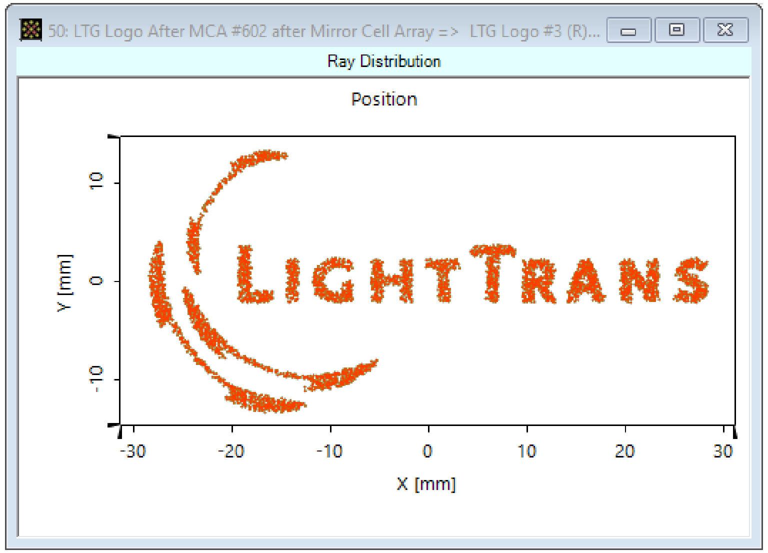


the dispersion is significantly reduced by using prisms

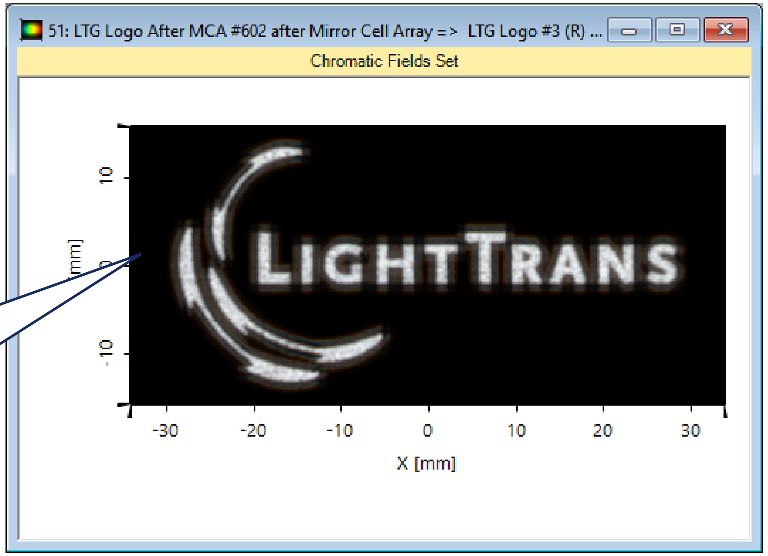
Results: Mirror Cells Array



spot diagram



y pattern
(rea
olor view)

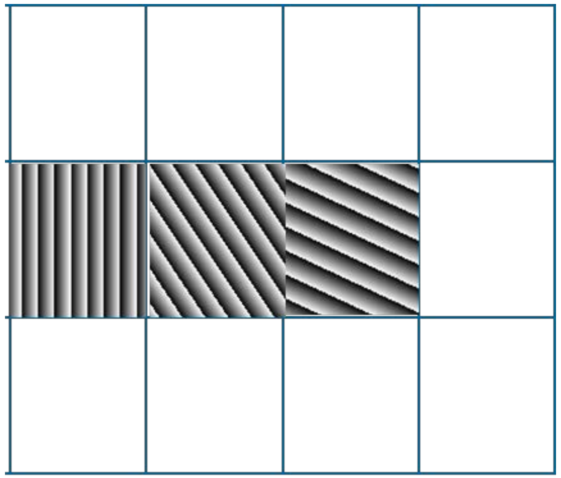


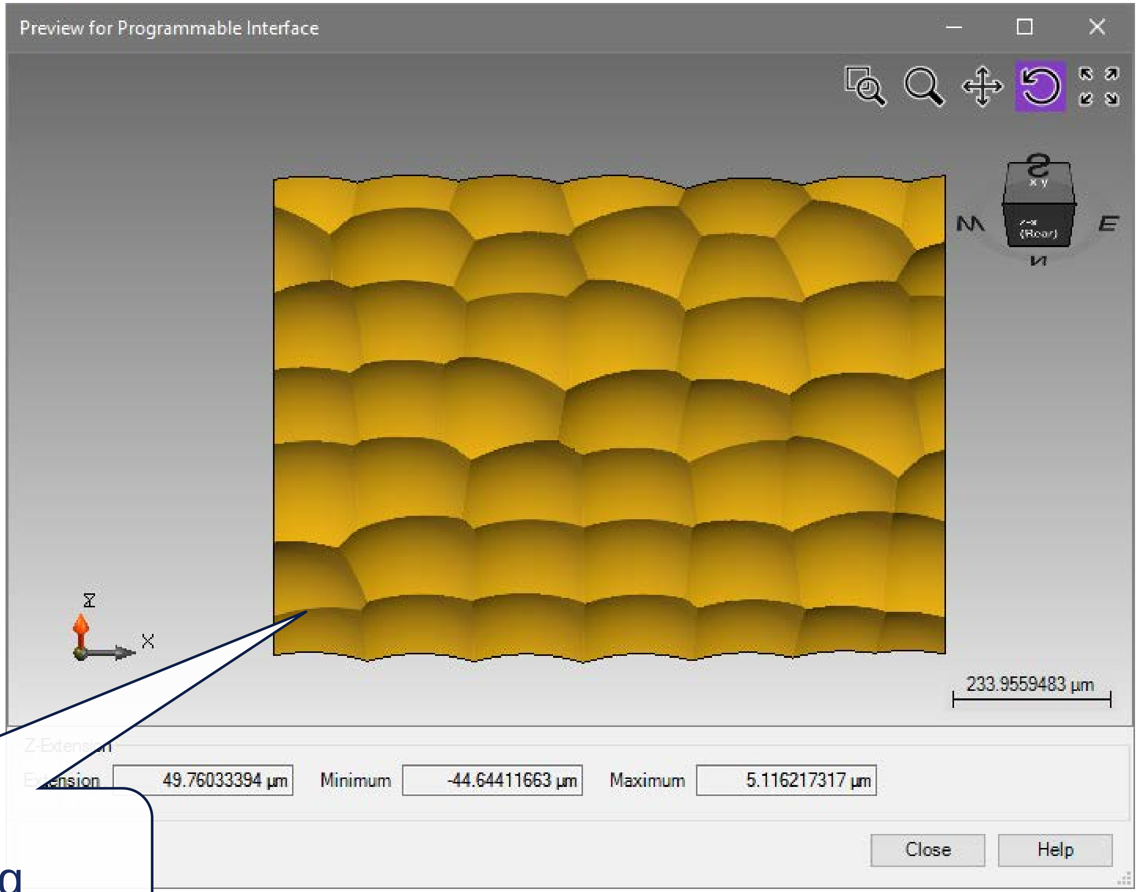
due to reflective approach no dispersion effects occur

Light shaping by lateral decomposition

Lens and freeform array components

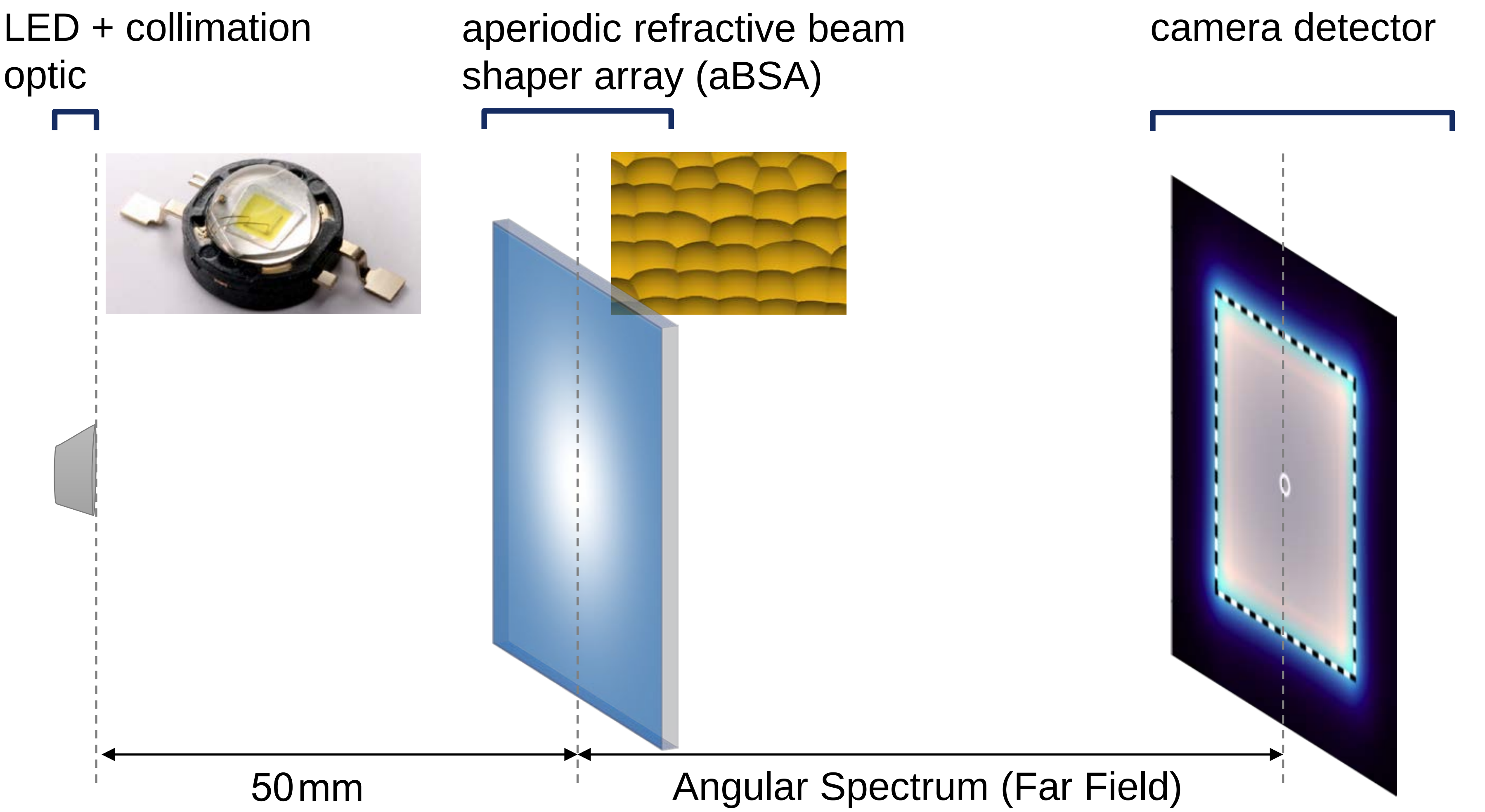
Array of Micro-optical Components



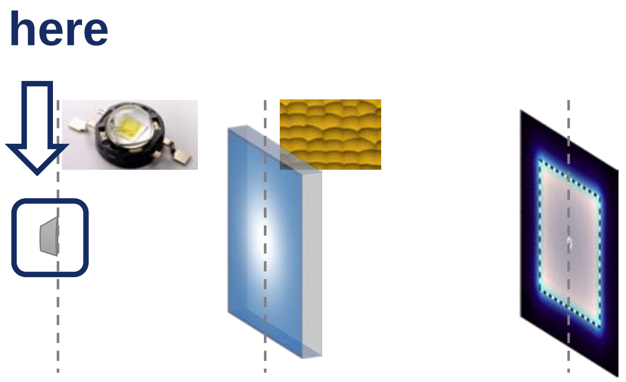


Lateral combination of elementary light shaping solutions

Task/System Illustration

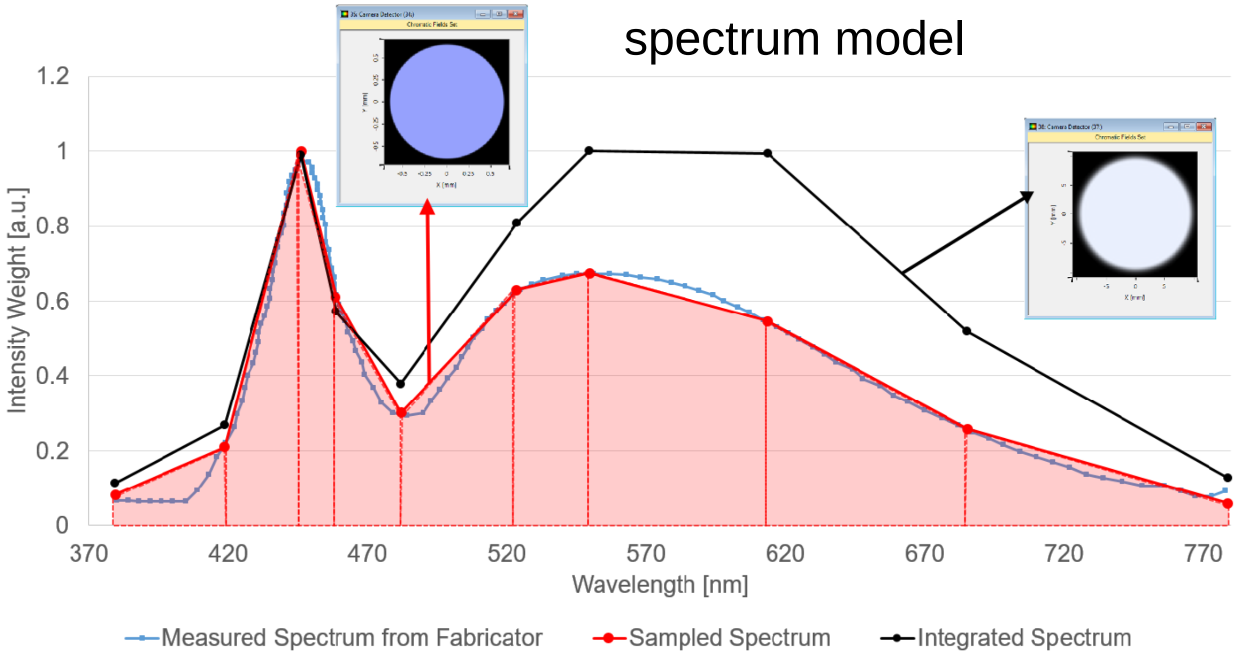


Specs: Light Source

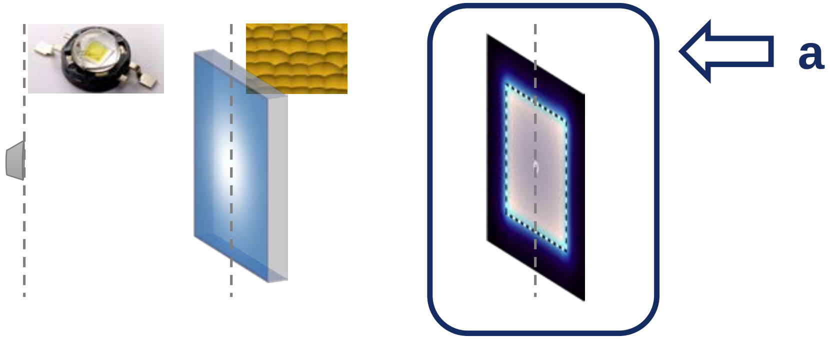


Highlights

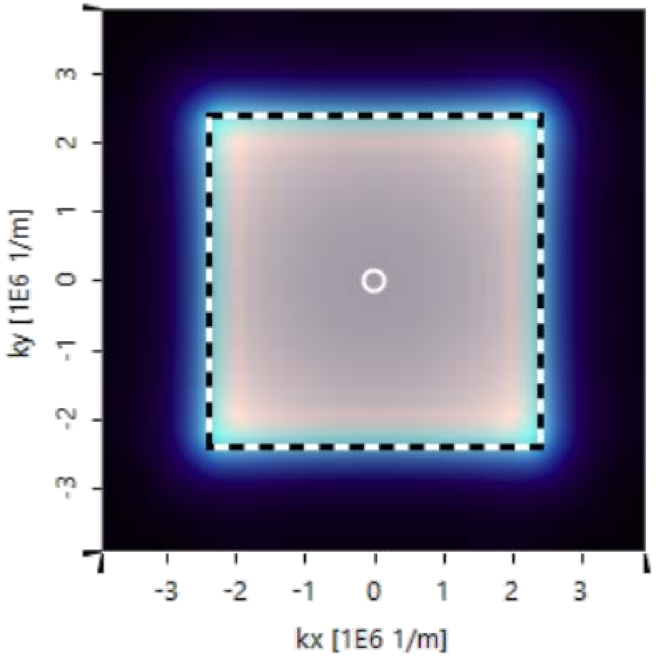
- fast and accurate modeling of a white light LED
- design and analysis an aperiodic refractive beam shaper array to optimize a top hat intensity pattern



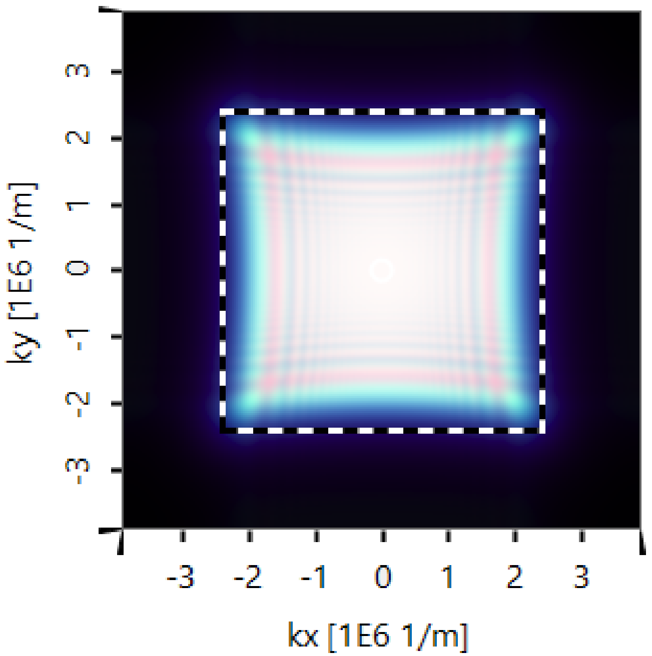
Results: Intensity Pattern (real color view)



aperiodic beam shaper array



periodic microlens array



Summary

- Introduction of a geometric branch of physical optics with the help of the geometric Fourier transform.
- Refractive and diffractive light shaping concepts follow a unified theory in physical optics.
- Classification of light shaping concepts dependent of positions of shaper(s) and target in field zones.
- Elementary shaping concepts can be combined
  - Superposition in same area, e.g. beam splitter
  - Laterally combined, e.g. cell array-type components
- Further investigations on the basis of the unified theory will reveal further concepts and deeper understanding of light shaping.

- Designs and simulations done with VirtualLab Fusion software.