Webinar LightTrans International, 13.01.2021

Diffractive Lenses: Concept, Modeling, Design, and Fabrication Data

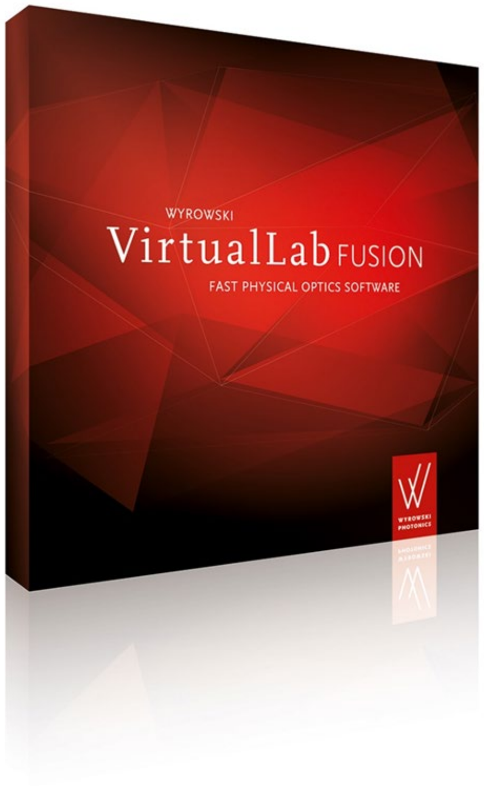
Frank Wyrowski and Christian Hellmann

Webinar LightTrans International, 13.01.2021

Freeform and Flat Optics

Frank Wyrowski and Christian Hellmann

Fast Physical Optics Software VirtualLab Fusion



LUEN SOFT

WAVE OPTO

T.E.M. Incorporated

INFOTEK

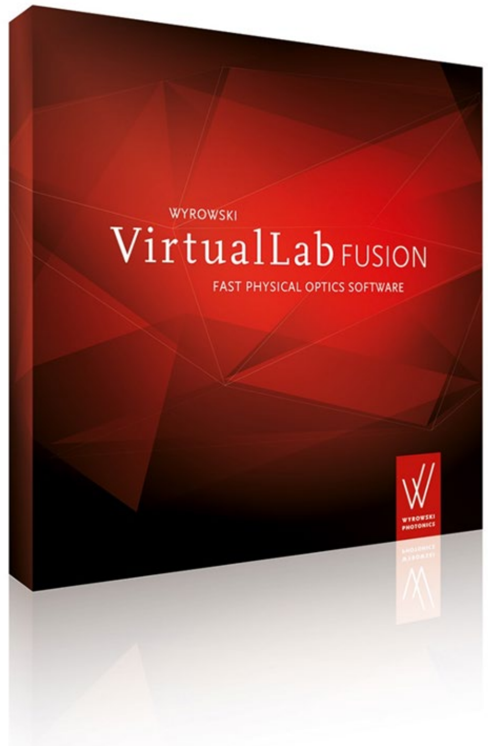
Connecting Field Solvers

Fast physical optics modeling and design in VirtualLab Fusion by:

- Connecting specialized field solvers in different regions of the system.
- VirtualLab Fusion is platform for in-built and customized solvers.
- Often as fast as ray tracing and can be even faster than Monte Carlo ray tracing.

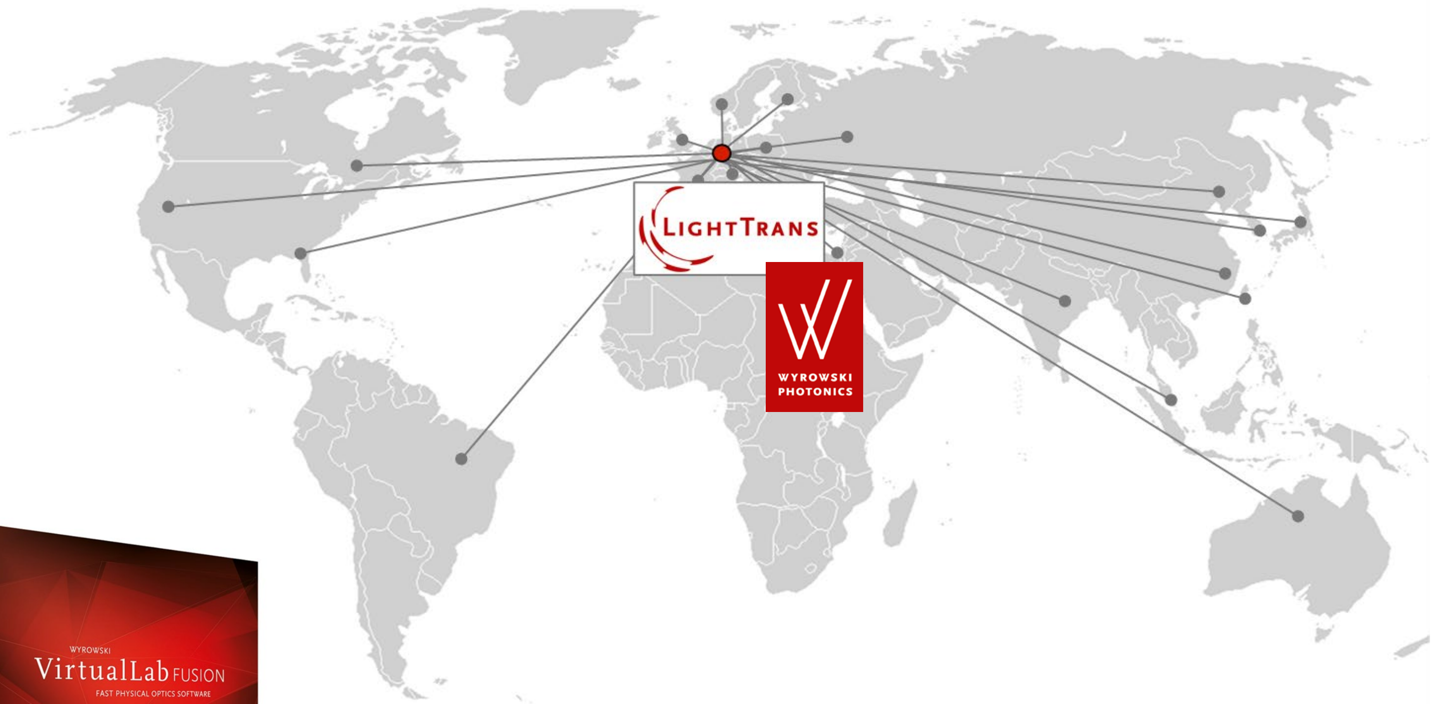
⇩

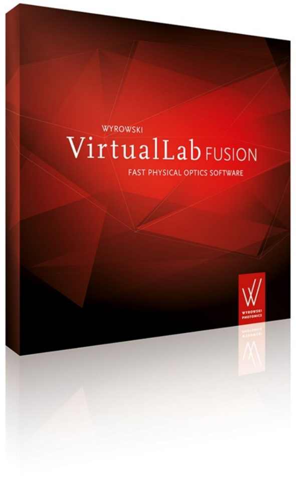
Fast physical optics with VirtualLab Fusion provides new insights and innovative solutions in optical modeling and design.



Typical speed of all modeling and design tasks in talk:
a few seconds to < 1 min

Fast Physical Optics Software VirtualLab Fusion





Our Mission:
Providing fast physical-optics software tools and workflows for modeling and design in optics and photonics.

Current developments in:

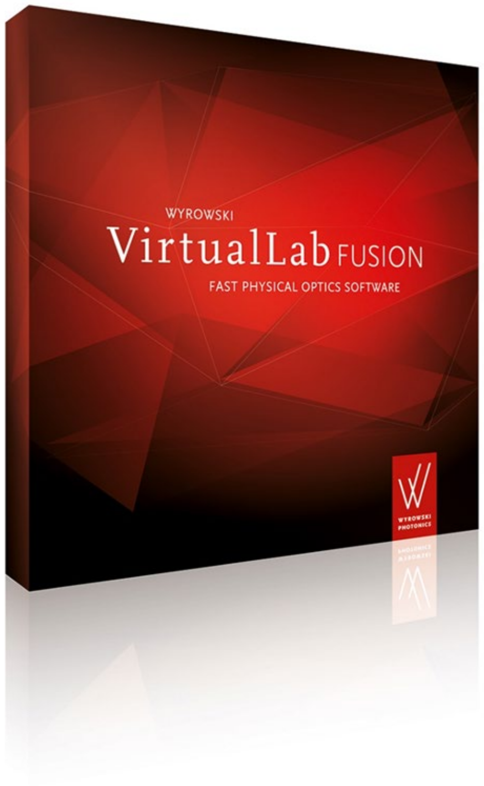
- Flat optics including coatings, gratings, DOEs, diffusers, holograms, metasurfaces, component arrays
- Lenses and freeform optics
- *Imaging & beam transformation*
- *Light shaping & non-imaging optics*
- Microscopy and focusing
- Optical metrology and sensors
- Femtosecond pulse systems
- Fiber optics
- LiDAR
- Light guides for AR/MR
- Scattering and BSDF

Content of Webinar

The webinar provides insights regarding

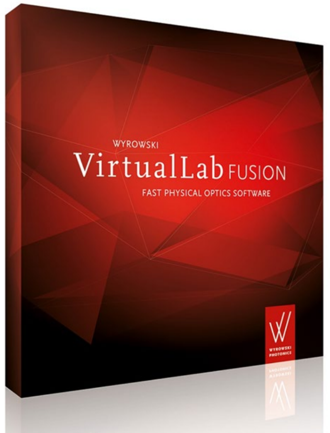
- Our R&D and product developments in
  - Physical-optics design
  - Flat and freeform optics
- Related software tools in VirtualLab Fusion
  - Current version
  - Outlook 2021: new techniques and tools

All examples in webinar are done with the in-house version of VirtualLab Fusion!

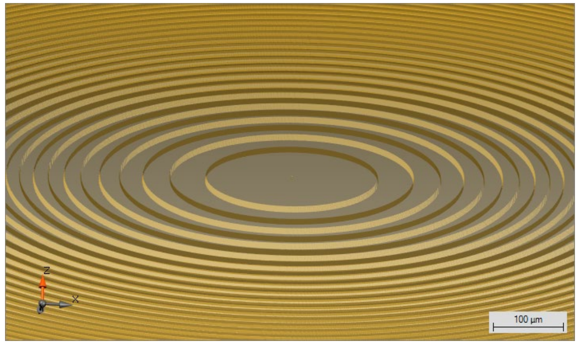


Structure of Webinar

- Why physical optics in design?
- Optical design in physical optics terms
- Diffractive Optical Elements (DOE)
  - Design
  - Modeling
  - Fabrication data
- Design examples



VirtualLab Fusion 2021



Importance of Physical Optics

- Optical lens design is dominated by ray optics and specific well-established workflows.
- The inclusion of freeform surfaces has led to some new challenges like broken symmetries and large number of free parameters.
- The inclusion of flat lenses requires a seamless combination with physical-optics modeling.
- We suggest to go a step further: physical optics may give a fresh view and new ideas to optical design beyond conventional routines.

1831 – 1879

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

Importance of Physical Optics

- Physical optics may give a fresh view and new ideas to optical design beyond conventional routines:
- Algorithms to design freeform surfaces beyond parametric optimization.
- Systematic inclusion of flat optics components including all desired and detrimental effects.
- Evaluation of the potential and limitations of flat optics.

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Freeform and Flat Optics

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"Is it possible to replace a bulky glass system by one metalens (flat lens)" ?

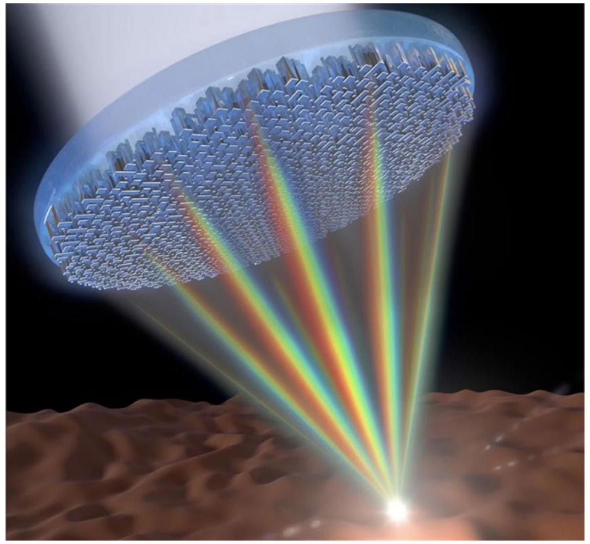
'Metalens' breakthrough may bring a revolution in camera design

Physicists say wafer-thin device can do the job of today's bulky glass lenses.

Jan. 3, 2018, 7:13 PM CET / Updated Jan. 3, 2018, 7:13 PM CET

By Rafi Letzter, Live Science

January 2018



This flat metalens can focus nearly the entire visible spectrum of light in the same spot and in high resolution. Jared Sisler / Harvard SEAS

https://www.nbcnews.com/mach/science/

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“Is it possible to replace a bulky glass system by one metalens (flat lens)” ?

Optica, June 2019

Imaging with flat optics: metalenses or diffractive lenses?

Sourangsu Banerji,[1] Monjurul Meem,[1] Apratim Majumder,[1] Fernando Guevara Vasquez,[2] Berardi Sensale-Rodriguez,[1] and Rajesh Menon[1,3,*]
[1]Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah 84112, USA
[2]Department of Mathematics, University of Utah, Salt Lake City, Utah 84112, USA
[3]Oblate Optics, Inc. 13060 Brixton Place, San Diego, California 92130, USA
*Corresponding author: rmenon@eng.utah.edu

Received 8 February 2019; revised 14 May 2019; accepted 17 May 2019 (Doc. ID 359356); published 10 June 2019

COMMENT
https://doi.org/10.1038/s41467-020-15972-9 OPEN

The advantages of metalenses over diffractive lenses

Jacob Engelberg[1] & Uriel Levy[1]

Nature Communication, April 2020

Freeform and Flat Optics

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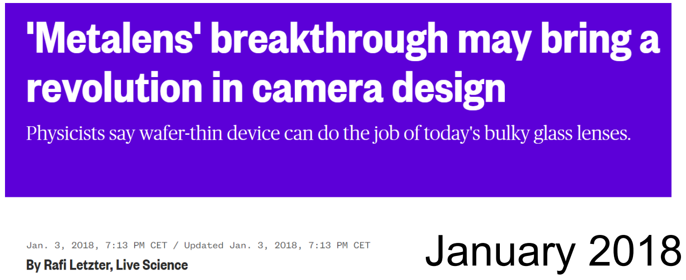

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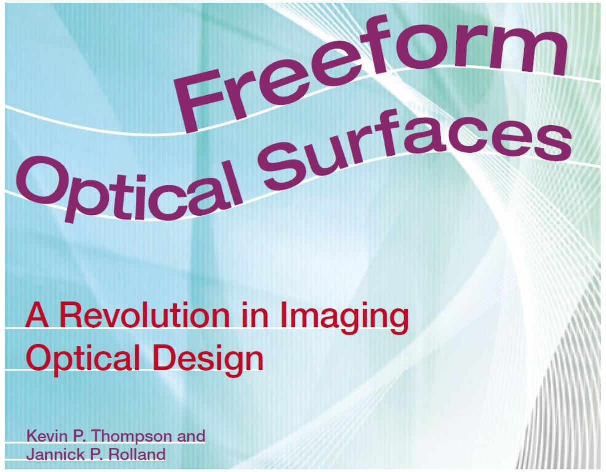

OPN Optics & Photonics News,
June 2012

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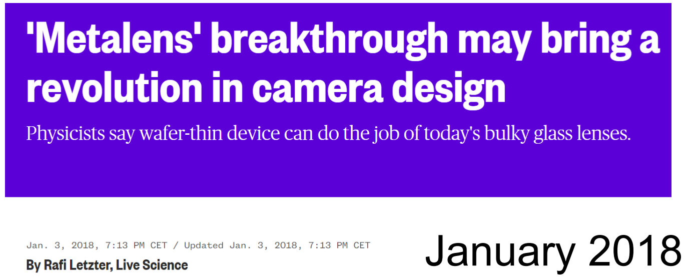
Strategies and modern tools to investigate and exploit the potential of freeform and flat optics by physical optics.



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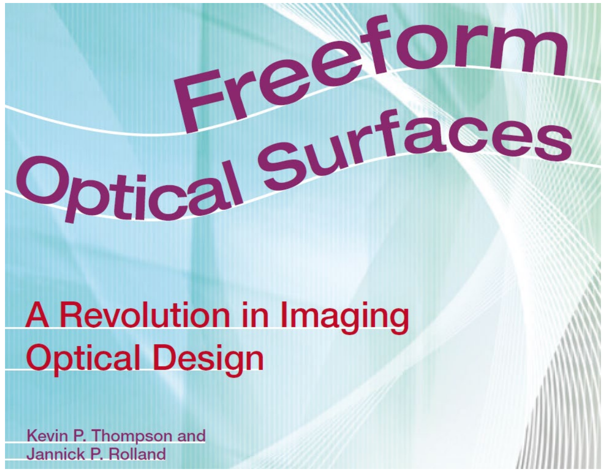

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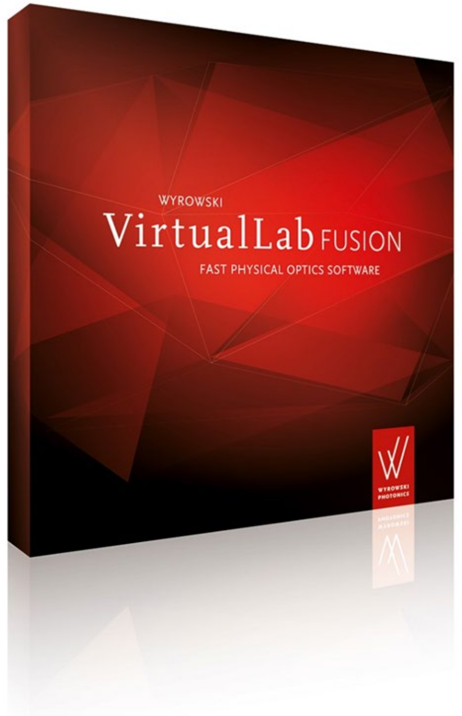

VirtualLab Fusion 2021

Structure of Webinar

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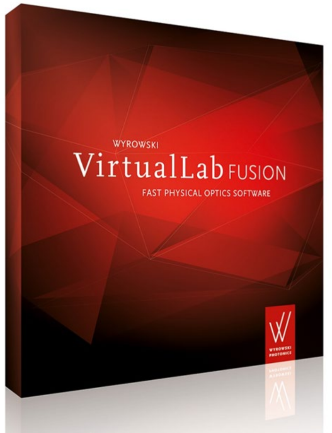
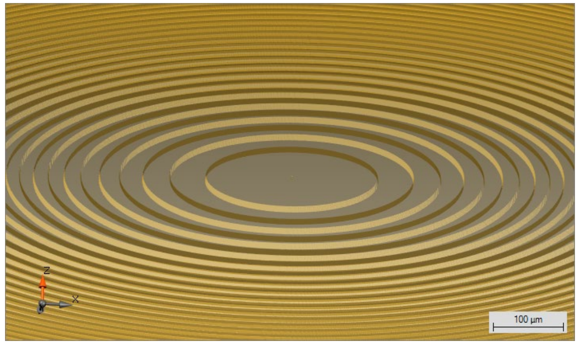


VirtualLab Fusion 2021



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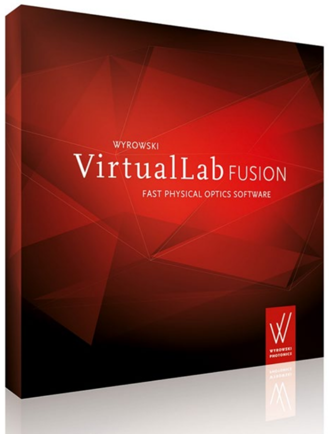
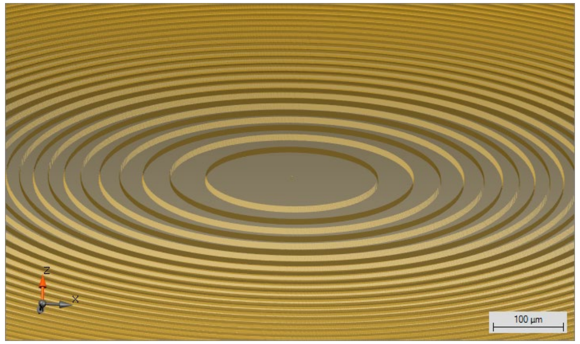


VirtualLab Fusion 2021



Light Representation in Physical Optics

- In physical optics light is described by vectorial electromagnetic fields.
- The electric field is denoted by the three components

$$\boldsymbol{E}(\boldsymbol{r},\omega)=\begin{pmatrix}E_x(\boldsymbol{r},\omega)\\E_y(\boldsymbol{r},\omega)\\E_z(\boldsymbol{r},\omega)\end{pmatrix}.$$

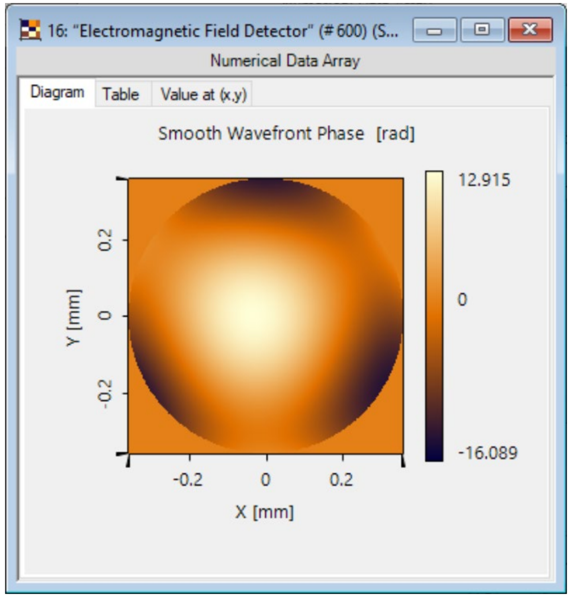
$$\lambda=\frac{2\pi}{\omega}\,n$$

- The components typically possess a common wavefront phase $\psi(\boldsymbol{r},\omega)$ and we write

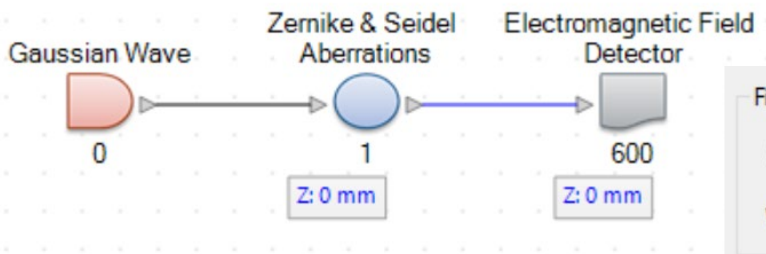
$$\boldsymbol{E}(\boldsymbol{r},\omega)=\boldsymbol{U}(\boldsymbol{r},\omega)\exp\left(\mathrm{i}\psi(\boldsymbol{r},\omega)\right)=\begin{pmatrix}U_x(\boldsymbol{r},\omega)\\U_y(\boldsymbol{r},\omega)\\U_z(\boldsymbol{r},\omega)\end{pmatrix}\exp\left(\mathrm{i}\psi(\boldsymbol{r},\omega)\right),$$

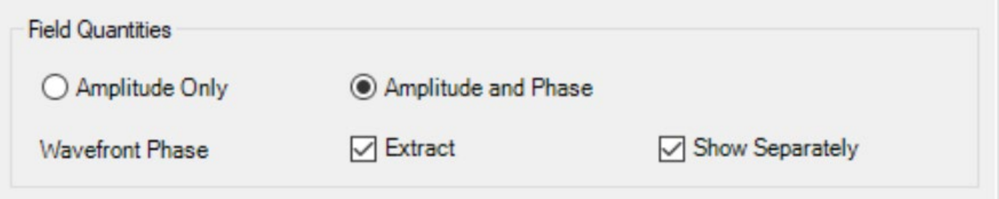
with $(\ell=x,y,z)$

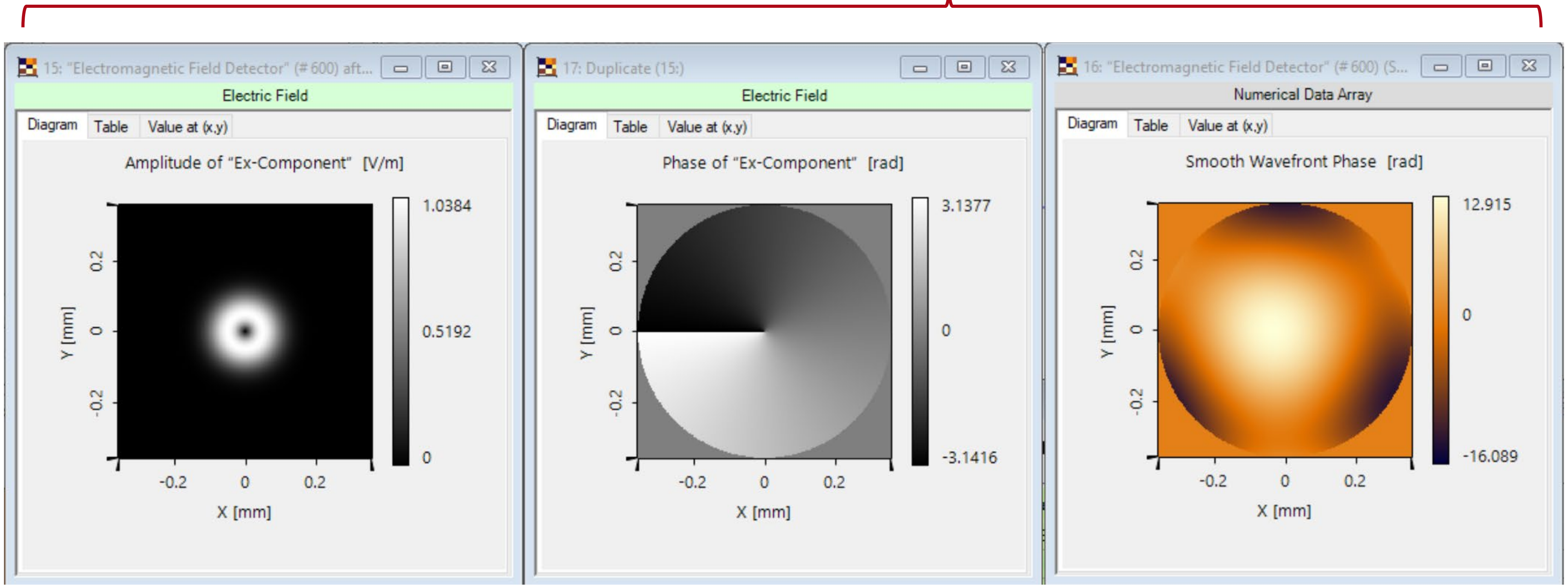
$$\psi(\boldsymbol{r},\omega)=\arg\left(E_\ell(\boldsymbol{r},\omega)\right)-\arg\left(U_\ell(\boldsymbol{r},\omega)\right).$$



Light Representation in Physical Optics: Example

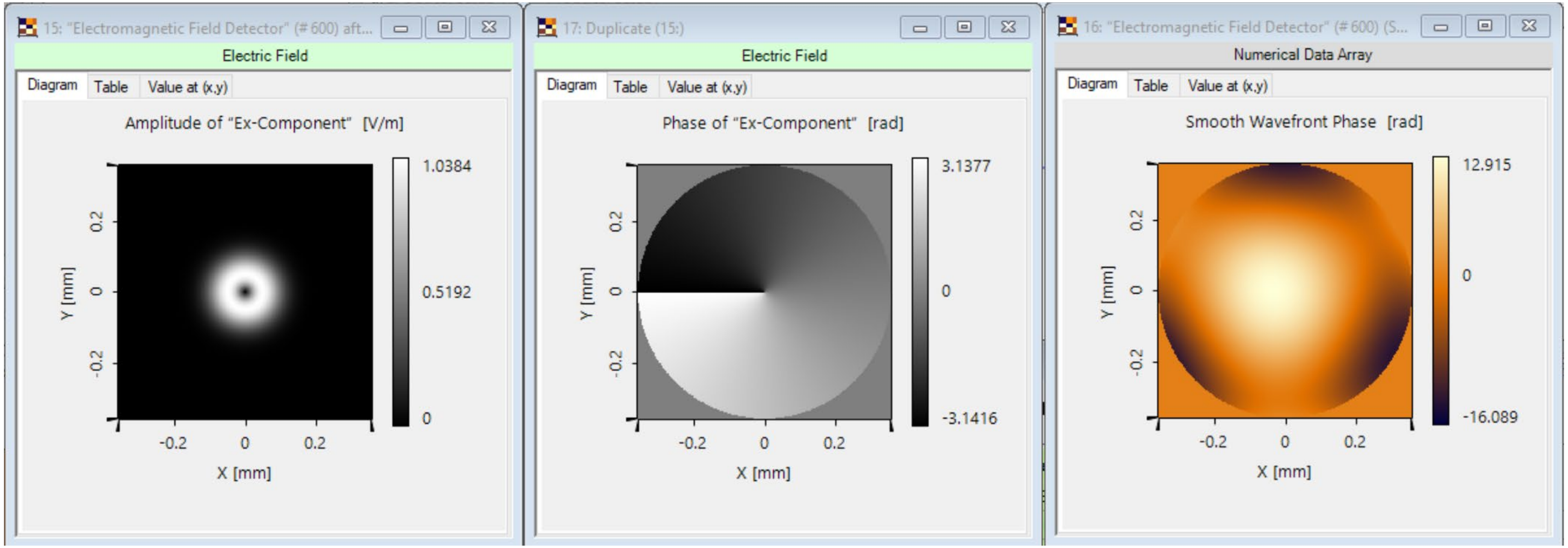






Light Representation in Physical Optics: Example

$$E_x(\boldsymbol{\rho}) = |U_x(\boldsymbol{\rho})| \exp\left(\mathrm{i}\arg(U_x)(\boldsymbol{\rho})\right) \exp\left(\mathrm{i}\psi(\boldsymbol{r},\omega)\right)$$



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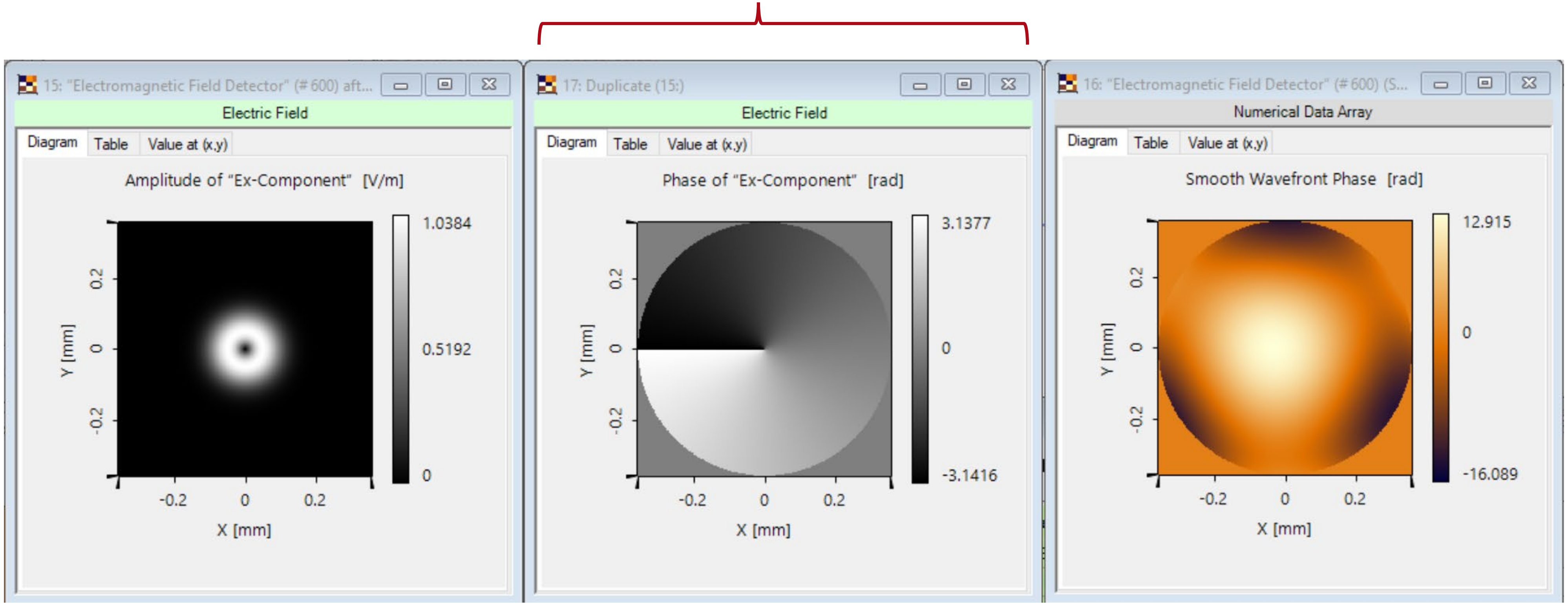

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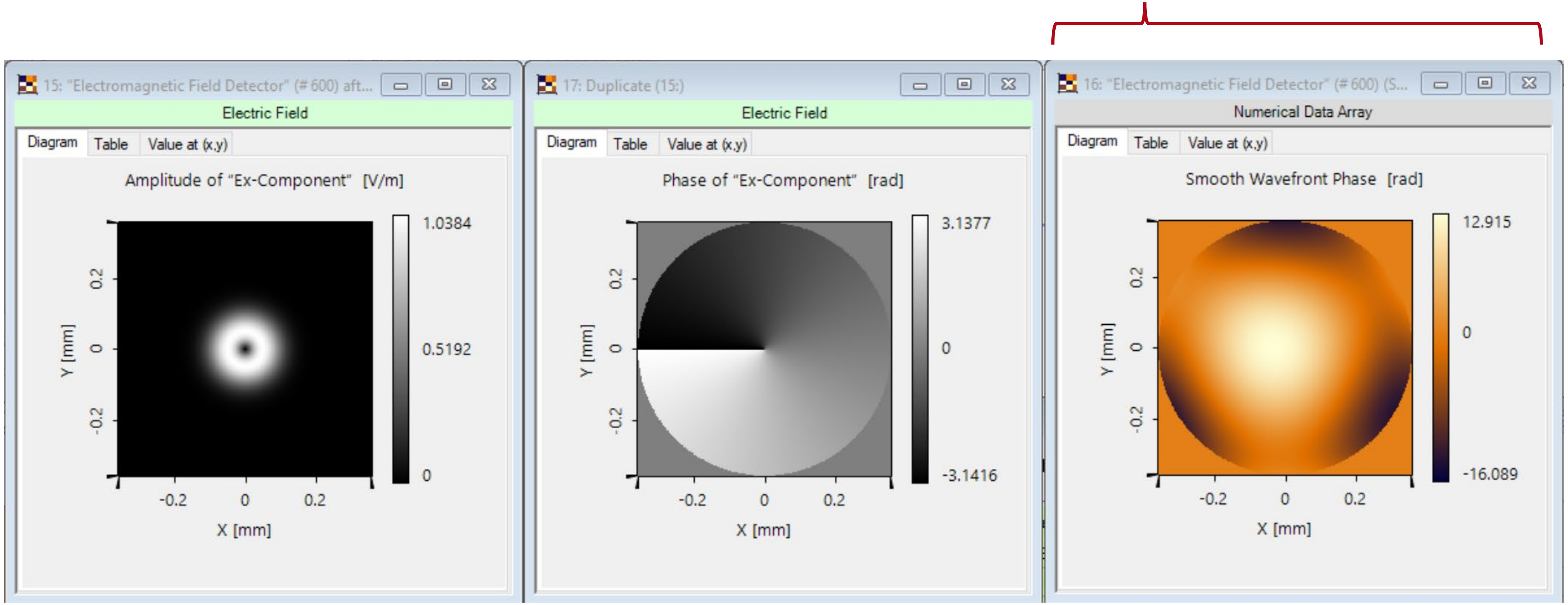


Design Scenarios: Field Transformation

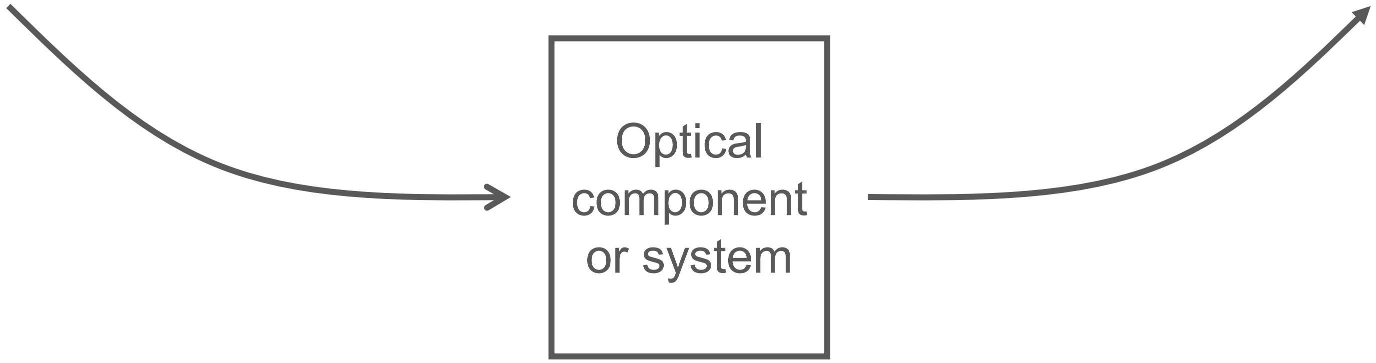
Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

with $\boldsymbol{\rho} = (x, y)$

Output fields (index α)

$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$



Scenarios:

Single-field design One input and output field only ($\alpha = 1$; skipped)

Multi-field design Set of input and output fields ($\alpha \in \mathbb{N}$)

Monochromatic or polychromatic design

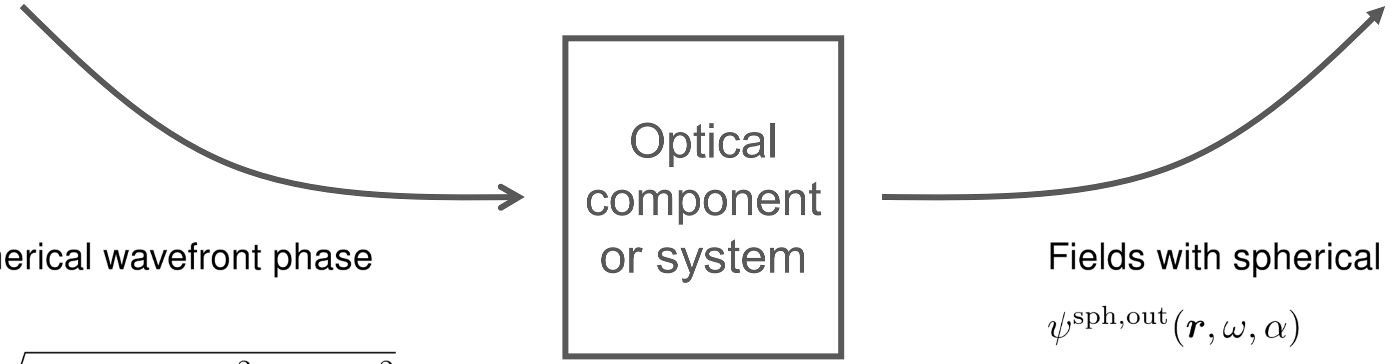
Design Scenarios: Imaging

Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Output fields (index α)

$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$



Input fields with spherical wavefront phase

$$\psi^{\text{sph,in}}(\boldsymbol{\rho},\omega,\alpha) = \operatorname{sign}(z^{\text{in}})k_0 n^{\text{in}}\sqrt{\left\|\boldsymbol{\rho}-\boldsymbol{\rho}^{\text{in}}(\alpha)\right\|^2 + \left(z^{\text{in}}\right)^2}$$

($z < 0$: convergent, $z > 0$: divergent)

Fields with spherical wavefront phase

$$\psi^{\text{sph,out}}(\boldsymbol{r},\omega,\alpha) = \operatorname{sign}(z^{\text{out}})k_0 n^{\text{out}}\sqrt{\left\|\boldsymbol{\rho}-M\boldsymbol{\rho}^{\text{in}}(\alpha)\right\|^2 + \left(z^{\text{out}}\right)^2}$$

($z < 0$: convergent, $z > 0$: divergent)

Scenario:

Multi-field design FOV: Set of input and output fields ($\alpha \in \mathbb{N}$)

Monochromatic or polychromatic design

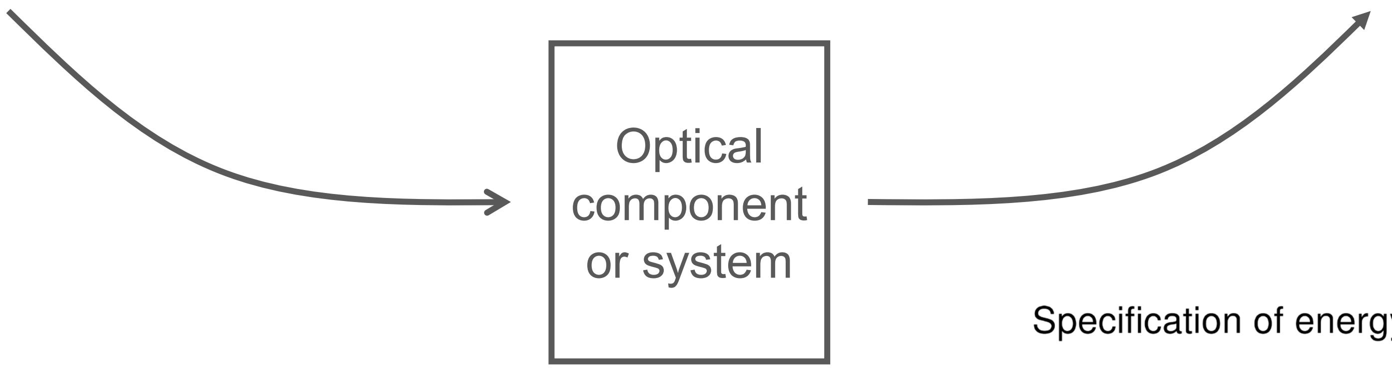
Design Scenarios: Light Shaping

Input fields (index α)

$\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$

Output fields (index α)

$\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$



Specification of energy quantity like

- Irradiance $E_{\mathrm{e}}\left\{\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\right\}$
- Radiant Intensity $I_{\mathrm{e}}\left\{\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\right\}$

Scenarios:

Single-field design One input and output field only ($\alpha = 1$; skipped)

Multi-field design Set of input and output fields ($\alpha \in \mathbb{N}$)

Monochromatic or polychromatic design

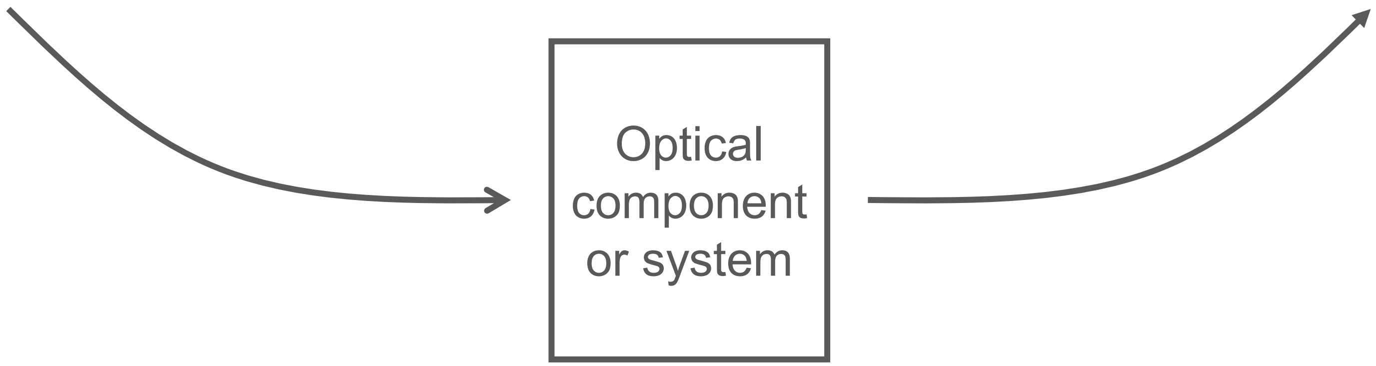
Manipulation of Input Fields by System

Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)=\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Output fields (index α)

$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)=\boldsymbol{U}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$



How to achieve the specified transformations with sufficient accuracy?

Manipulation of Input Fields by System

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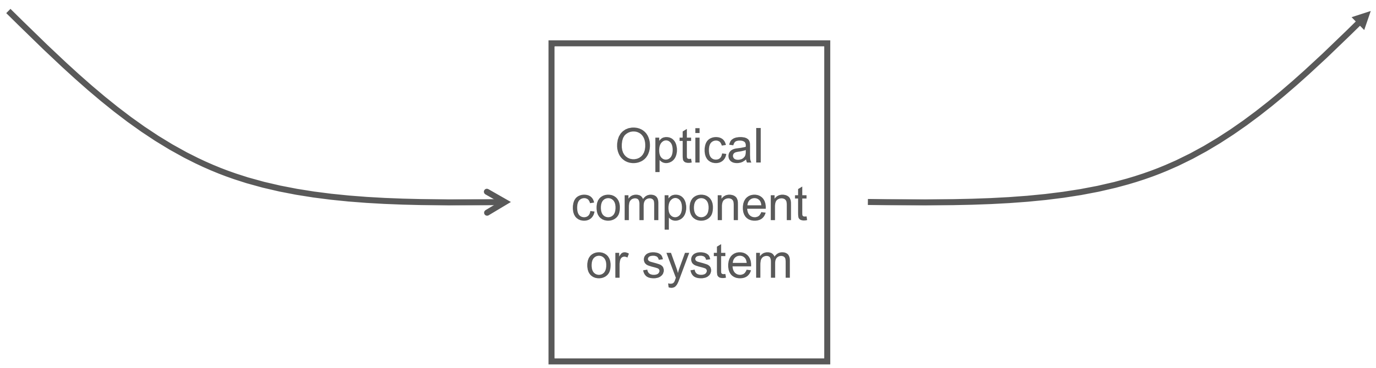

Major manipulations of fields on their way through system:

- **Wavefront phase control:** $\psi^{\mathrm{in}} \to \ldots \psi_j \ldots \to \psi^{\mathrm{out}}$
- **Irradiance shaping:** $E_{\mathrm{e}}^{\mathrm{in}} \to \ldots E_{\mathrm{e},j} \ldots \to E_{\mathrm{e}}^{\mathrm{out}}$

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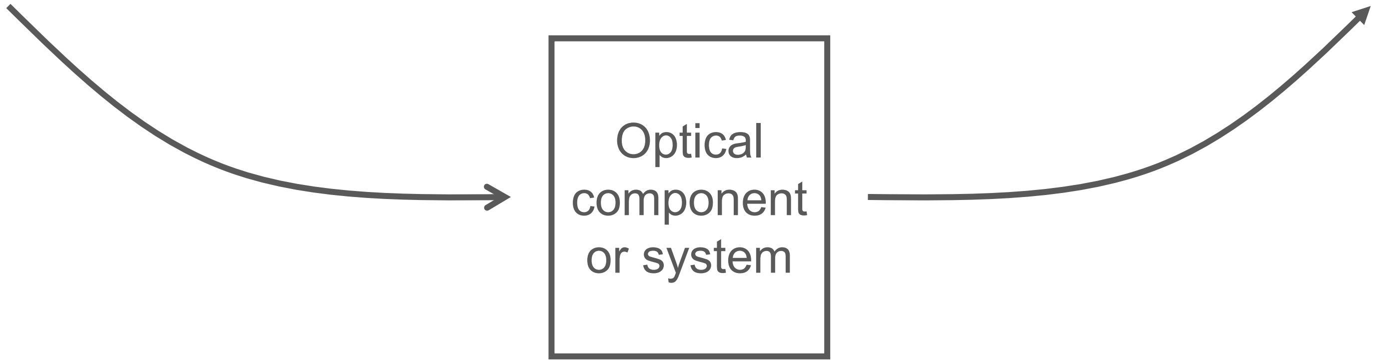

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Field Response Operator: Integral

Input fields (index α)

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Output fields (index α)

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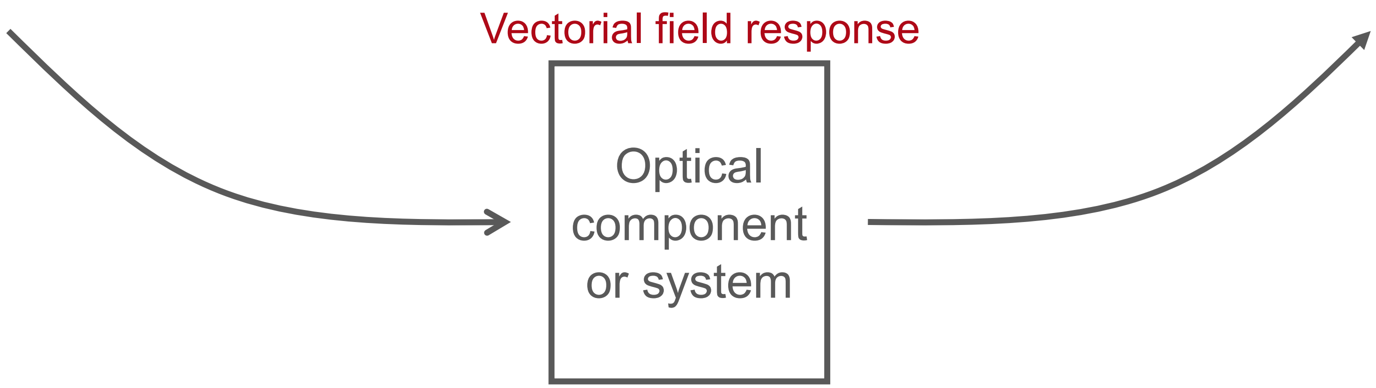

$$\begin{aligned}\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}) &= \boldsymbol{\mathcal{B}}\big(\boldsymbol{\rho}'\mapsto\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\big)(\boldsymbol{\rho})\\ &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}')\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'\end{aligned}$$

with the matrix integral kernel $\mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}'):\mathbb{R}^2\times\mathbb{R}^2\to\mathbb{C}^{3\times3}$

Field Response Operator: Integral

Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

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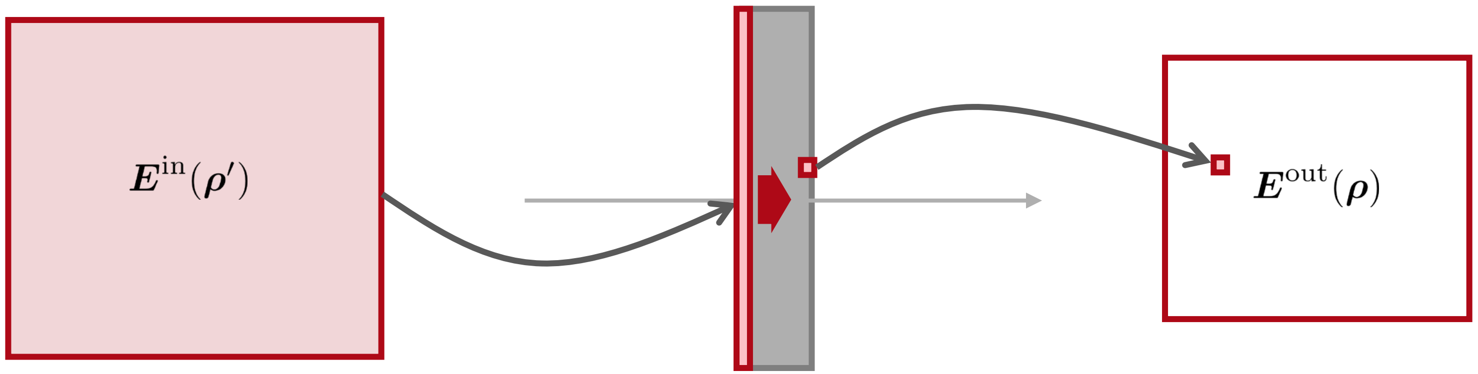
$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Vectorial field response



$$\begin{aligned}\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}) &= \boldsymbol{\mathcal{B}}\left(\boldsymbol{\rho}' \mapsto \boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\right)(\boldsymbol{\rho}) \\ &= \int\int_{X^{\text{in}}} \mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}')\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'\end{aligned}$$

with the matrix integral kernel $\mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}') : \mathbb{R}^2 \times \mathbb{R}^2 \to \mathbb{C}^{3\times 3}$

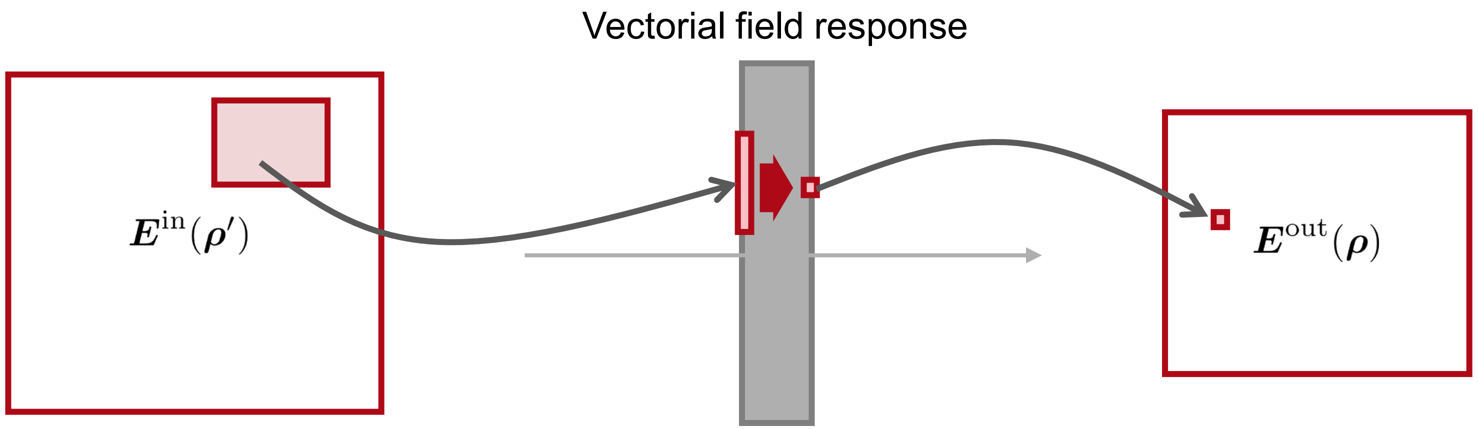
Field Response Operator: Local Integration Sufficient

Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Output fields (index α)

$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$



$$\begin{aligned}\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}) &= \boldsymbol{\mathcal{B}}\big(\boldsymbol{\rho}' \mapsto \boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\big)(\boldsymbol{\rho}) \\ &= \int\int_{X\subset X^{\text{in}}} \mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}')\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'\end{aligned}$$

with the matrix integral kernel $\mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}') : \mathbb{R}^2 \times \mathbb{R}^2 \rightarrow \mathbb{C}^{3\times 3}$

Field Response Operator: Pointwise

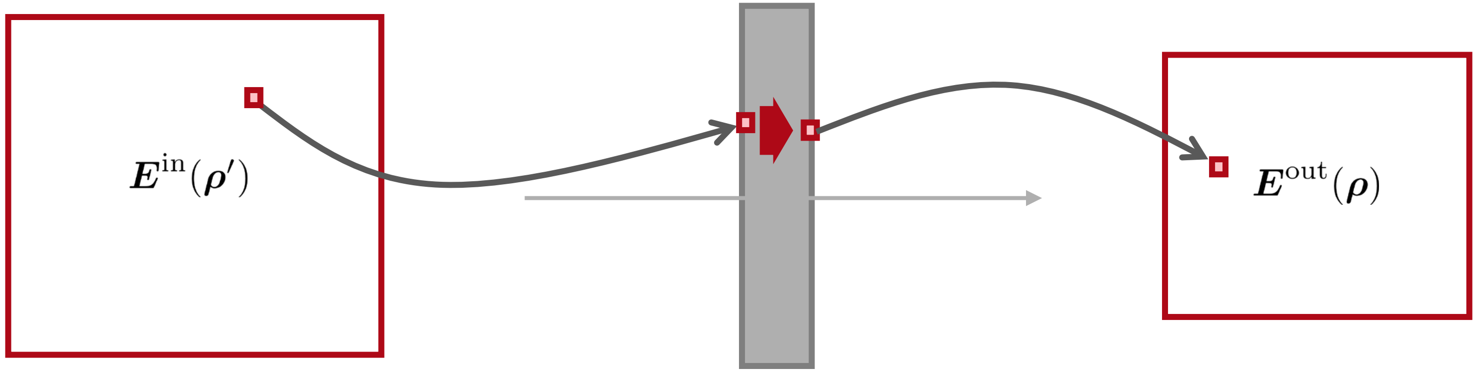
Input fields (index α)

$$\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Output fields (index α)

$$\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Vectorial field response



$$\begin{aligned}\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho}) &= \boldsymbol{\mathcal{B}}\big(\boldsymbol{\rho}' \mapsto \boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho}')\big)(\boldsymbol{\rho}) \\ &= \int\int_{X\subset X^{\mathrm{in}}} \mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}')\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'\end{aligned}$$

with the matrix integral kernel $\mathbf{B}(\boldsymbol{\rho},\boldsymbol{\rho}') : \mathbb{R}^2 \times \mathbb{R}^2 \to \mathbb{C}^{3\times 3}$

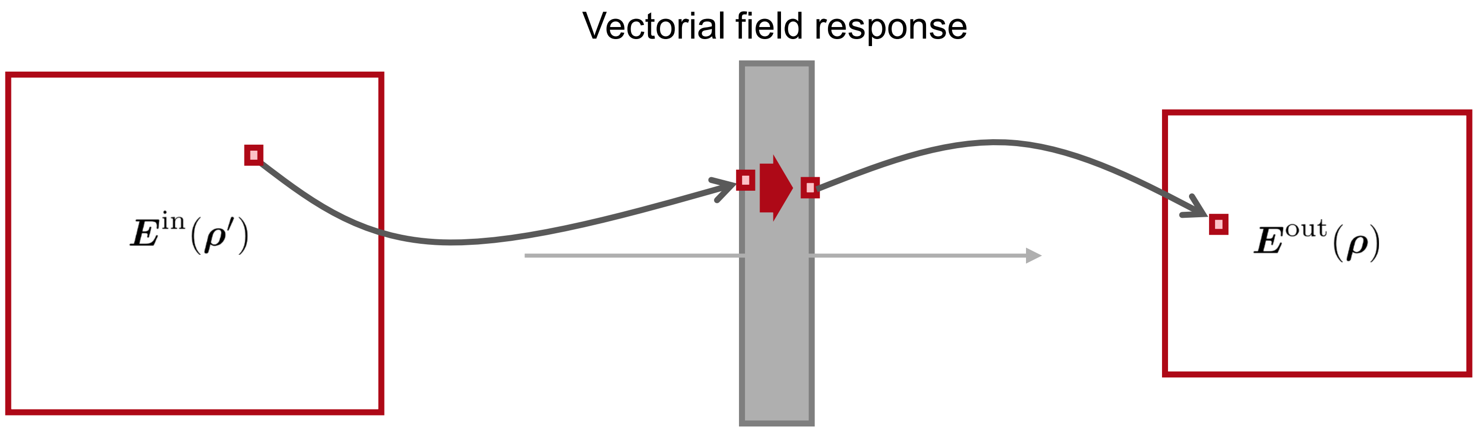
Field Response Operator: Pointwise

Input fields (index α)

$$\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}, \omega, \alpha) = \boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}, \omega, \alpha) \exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho}, \omega, \alpha)\right)$$

Output fields (index α)

$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}, \omega, \alpha) = \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho}, \omega, \alpha) \exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho}, \omega, \alpha)\right)$$



Field response: $\underline{\mathbf{B}}(\boldsymbol{\rho}')\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{E}^{\text{out}}(\boldsymbol{\rho})$

with the field response matrix $\underline{\mathbf{B}}(\boldsymbol{\rho}) : \mathbb{R}^2 \to \mathbb{C}^{3\times 3}$

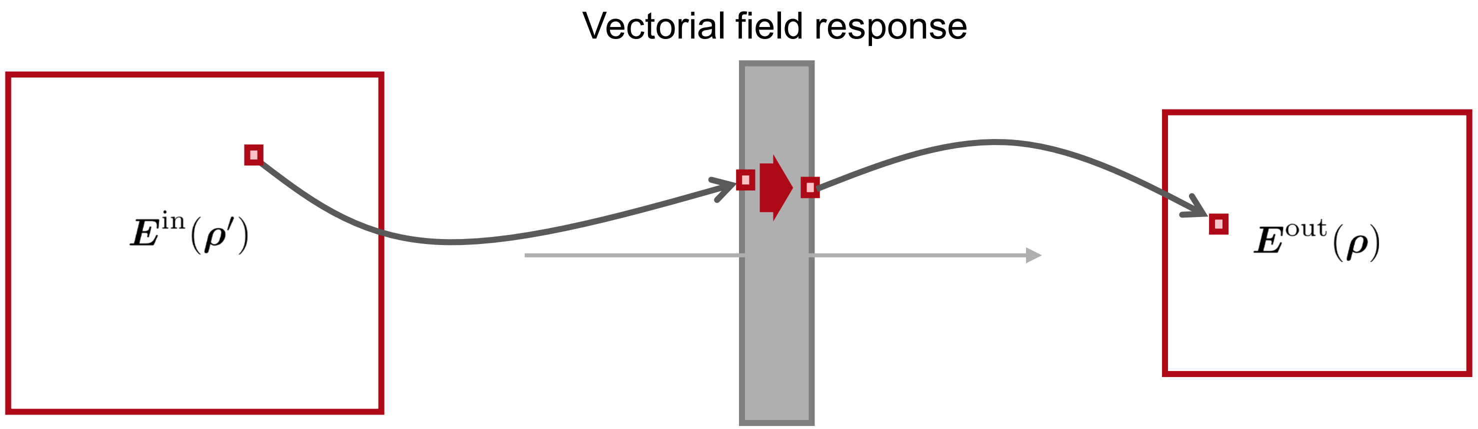
Field Response Operator: Pointwise

Input fields (index α)

$$\boldsymbol{E}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho},\omega,\alpha)\right)$$

Output fields (index α)

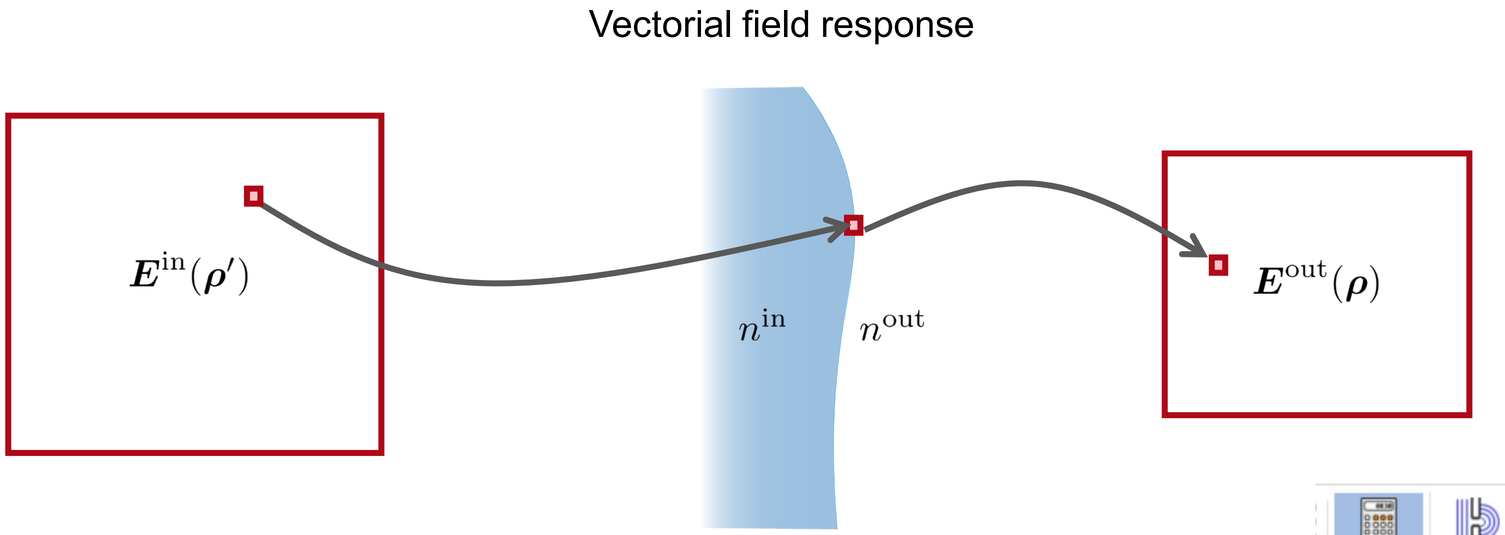
$$\boldsymbol{E}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha) = \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\exp\left(\mathrm{i}\psi^{\mathrm{out}}(\boldsymbol{\rho},\omega,\alpha)\right)$$



U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho})$

Wavefront phase response: $\psi^{\mathrm{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho})$

Field Response Operator: Freeform Surfaces



U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho})$

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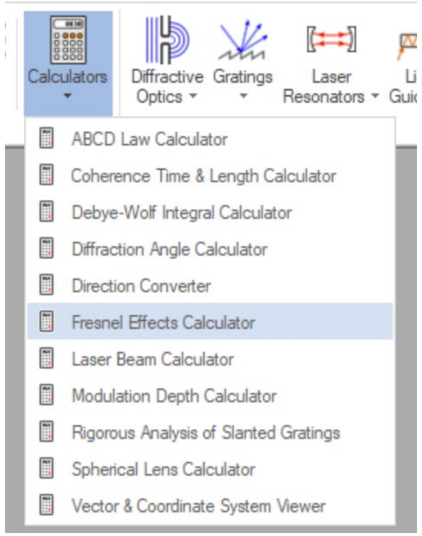
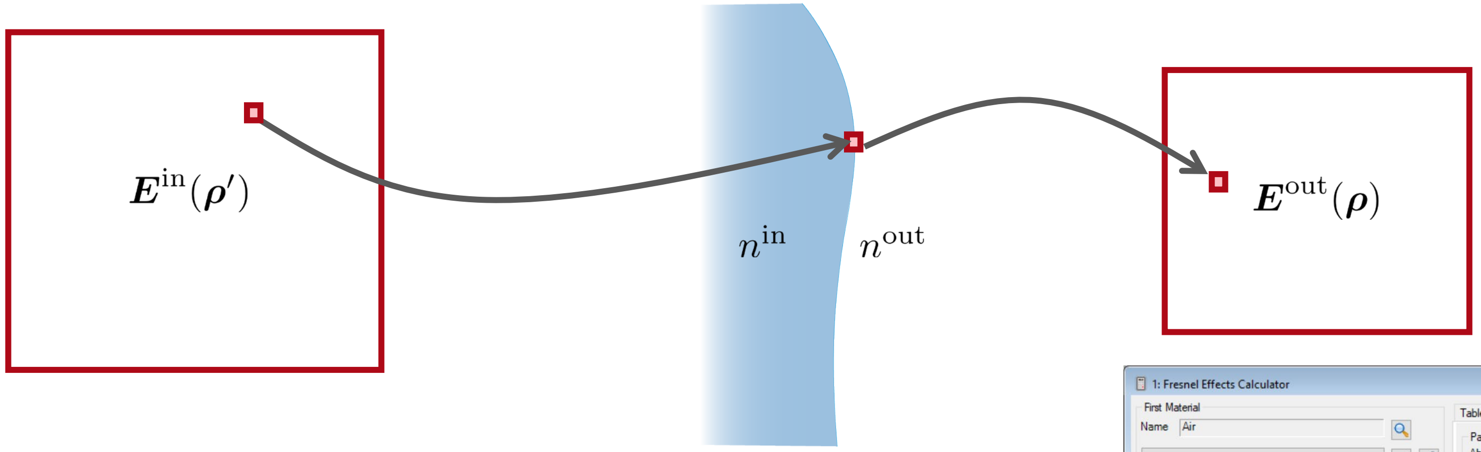


Field Response Operator: Freeform Surfaces

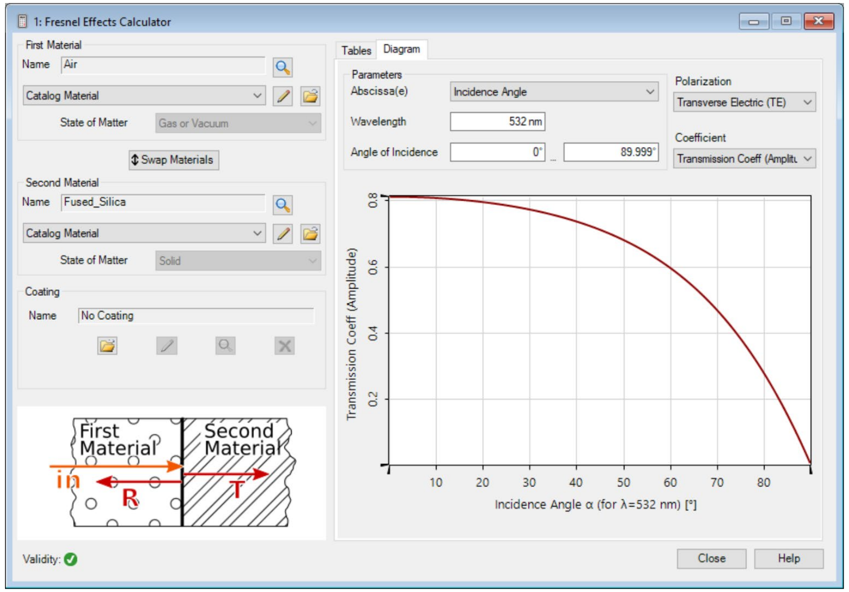
Vectorial field response



U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')U^{\mathrm{in}}(\boldsymbol{\rho}') \mapsto U^{\mathrm{out}}(\boldsymbol{\rho})$

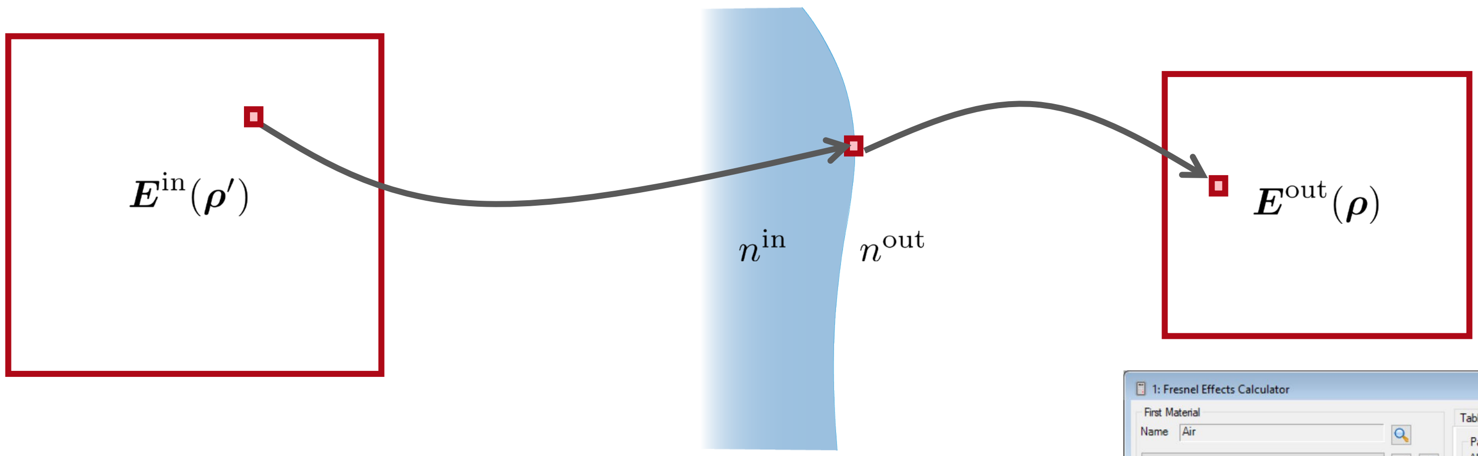
U-field response by Fresnel equations (S-matrix): TE and TM

Wavefront phase response: $\psi^{\mathrm{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho})$



Field Response Operator: Freeform Surfaces

Vectorial field response

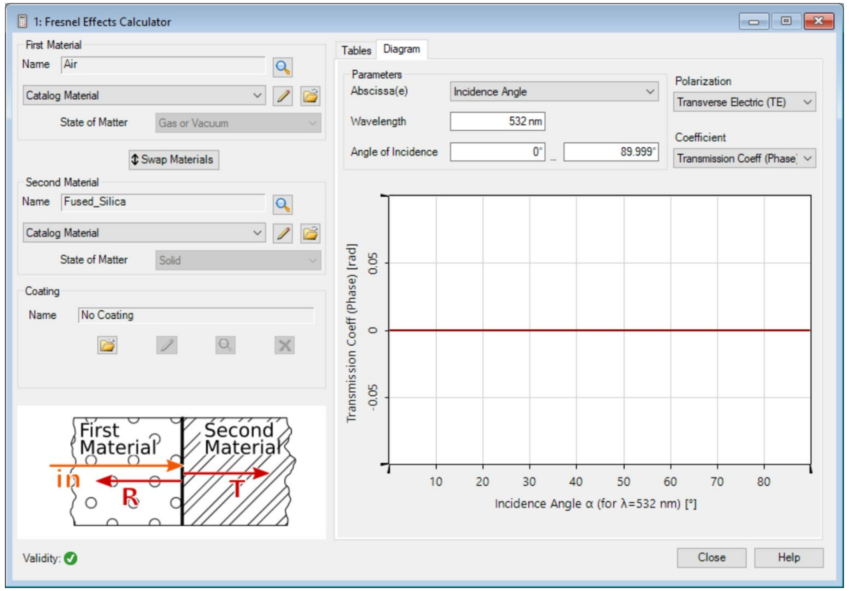


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

U-field response by Fresnel equations (S-matrix): TE and TM

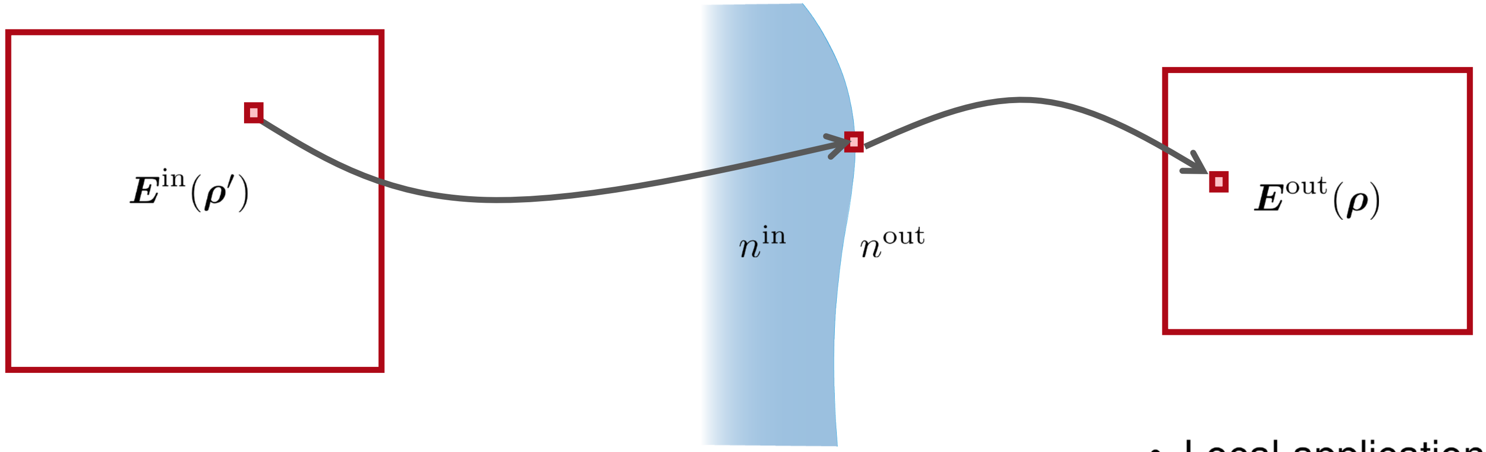
Wavefront phase response: $\psi^{\text{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\text{out}}(\boldsymbol{\rho})$

Wavefront response by Fresnel equations (S-matrix): $\Delta\psi \stackrel{!}{=} 0$

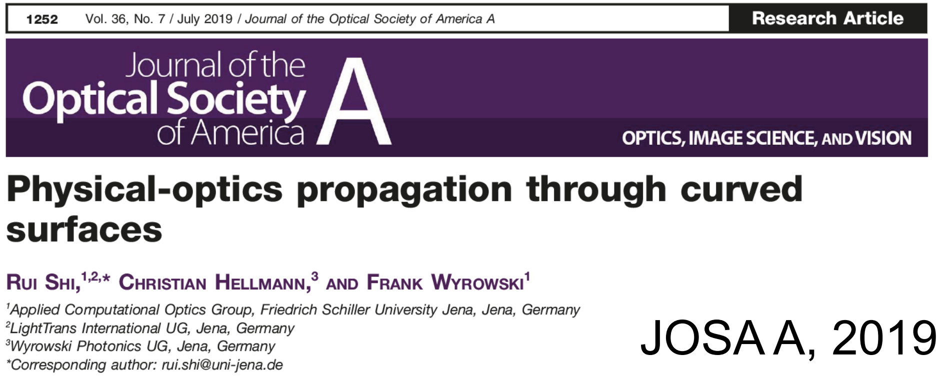


Field Response Operator: Freeform Surfaces

Vectorial field response



- Local application of S-matrix for curved surfaces: Local Plane Interface Approximation (LPIA).



1252 Vol. 36, No. 7 / July 2019 / Journal of the Optical Society of America A **Research Article**

Journal of the Optical Society of America A

OPTICS, IMAGE SCIENCE, AND VISION

Physical-optics propagation through curved surfaces

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[2]LightTrans International UG, Jena, Germany
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*Corresponding author: rui.shi@uni-jena.de

JOSA A, 2019

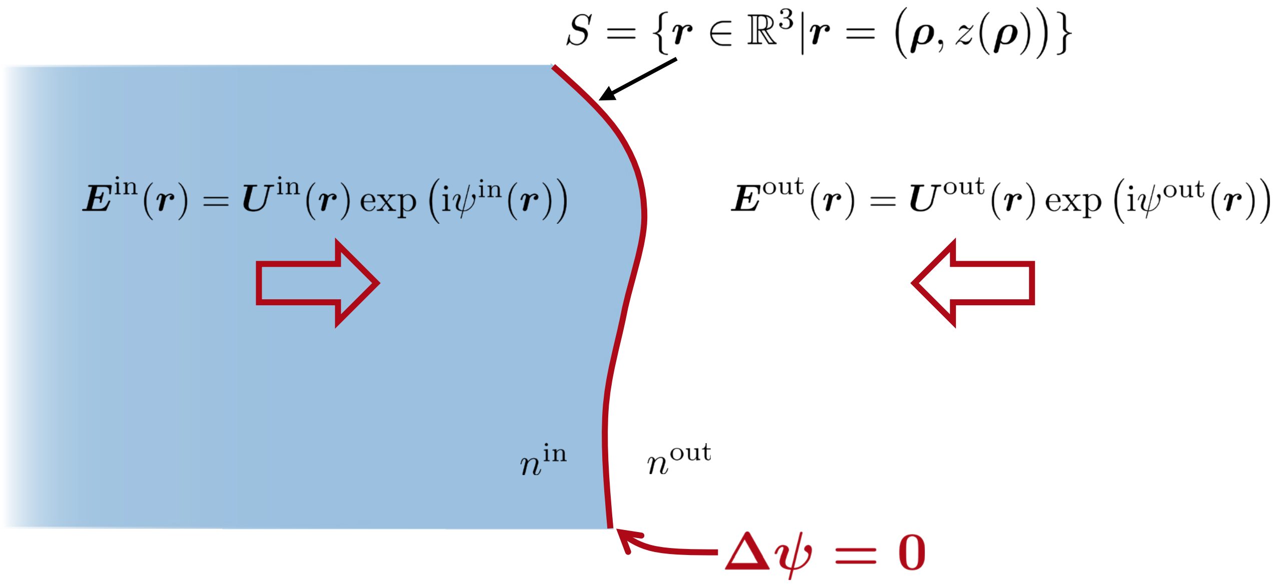
U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

U-field response by Fresnel equations (S-matrix): TE and TM

Wavefront phase response: $\psi^{\text{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\text{out}}(\boldsymbol{\rho})$

Wavefront response by Fresnel equations (S-matrix): $\Delta\psi \overset{!}{=} 0$

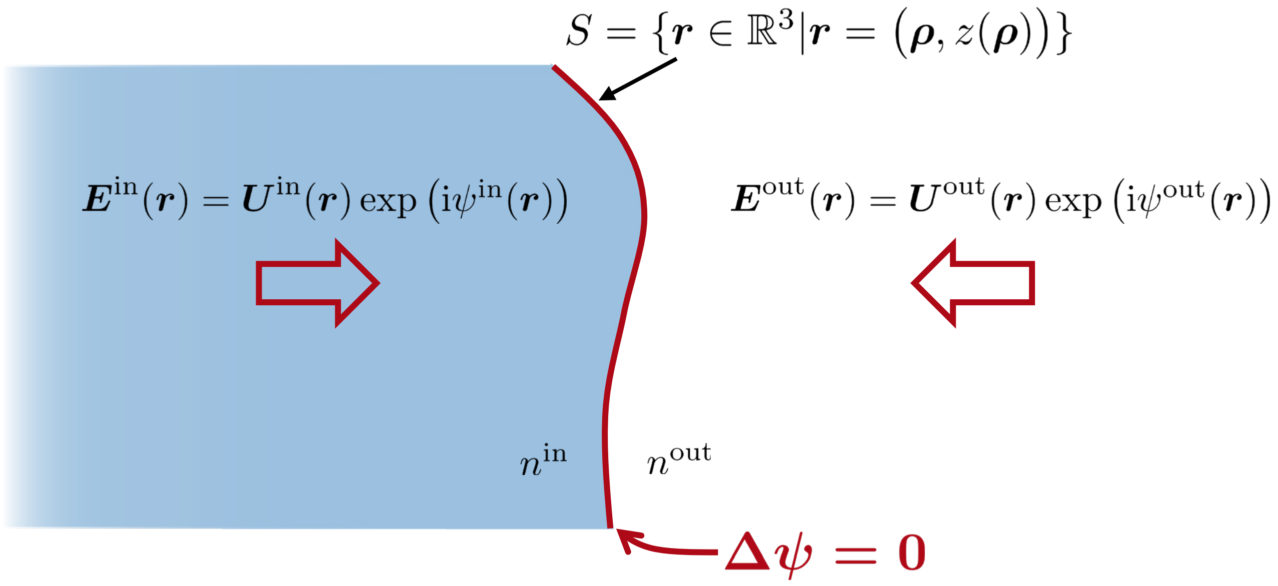
Freeform Surface Design: Inverse Propagation

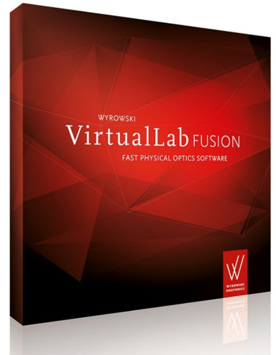


Calculate the surface $S \subset \mathbb{R}^3$ on which:

$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} 0$$

Freeform Surface Design: Inverse Propagation





VirtualLab Fusion 2021

Calculate the surface $S \subset \mathbb{R}^3$ on which:

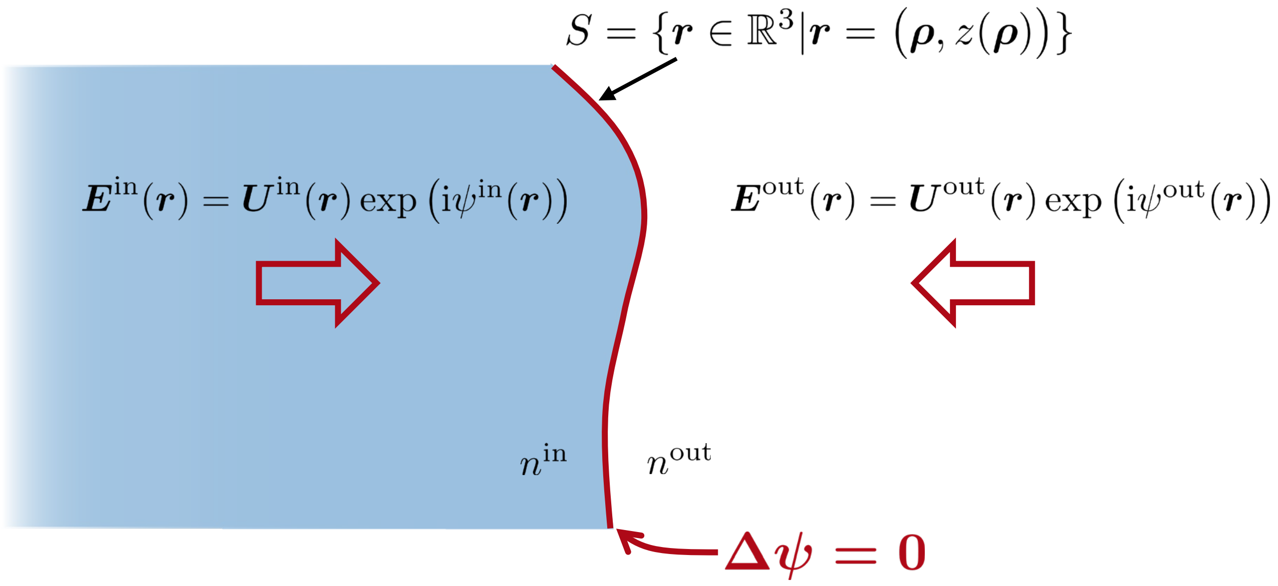
$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \overset{!}{=} 0$$

VirtualLab Fusion provides an algorithm to calculate the freeform surface for any type of specified wavefront phase transformation.

Available surface representations include

- Point cloud & B-Splines
- Zernike polynomials (recursive)
- Forbes polynomials
- Aspherical polynomial series
- Polynomial series

Freeform Surface Design: Inverse Propagation



Calculate the surface $S \subset \mathbb{R}^3$ on which:

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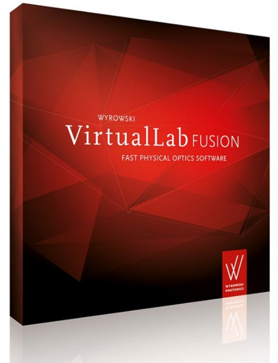
VirtualLab Fusion provides an algorithm to calculate the freeform surface for any type of specified wavefront phase transformation.



VirtualLab Fusion 2021

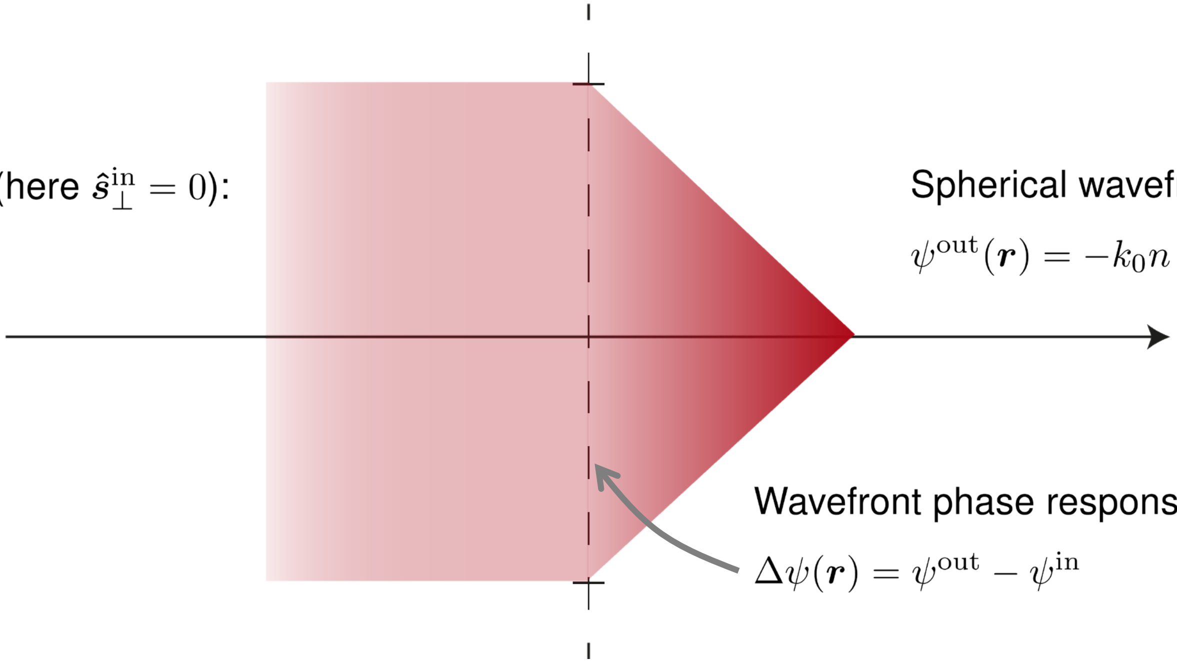
- The algorithm directly calculates the surface by inverse propagation techniques.
- No parametric optimization is involved.
- Thus, a high number of freeform surface parameters is not critical.

Example Focusing

Focusing Lens: Scenario

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_\perp^{\text{in}} = 0$):

$\psi^{\text{in}}(\boldsymbol{r}) = k_0 n \, \hat{\boldsymbol{s}}_\perp^{\text{in}}(\alpha) \cdot \boldsymbol{\rho}$



Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

$\psi^{\text{out}}(\boldsymbol{r}) = -k_0 n \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{out}}(\alpha)\|^2 + f^2}$

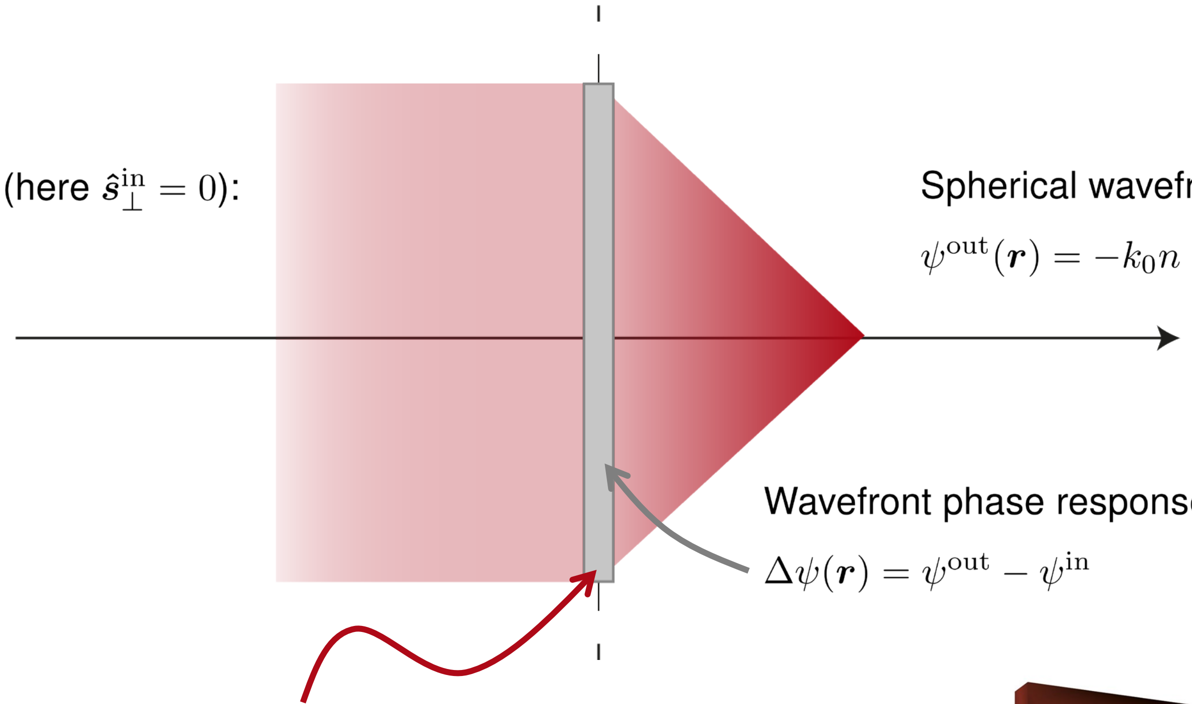
Wavefront phase response function:

$\Delta\psi(\boldsymbol{r}) = \psi^{\text{out}} - \psi^{\text{in}}$

Focusing Lens: Functional Design

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_\perp^{\mathrm{in}} = 0$):

$$\psi^{\mathrm{in}}(\boldsymbol{r}) = k_0 n\, \hat{\boldsymbol{s}}_\perp^{\mathrm{in}}(\alpha) \cdot \boldsymbol{\rho}$$



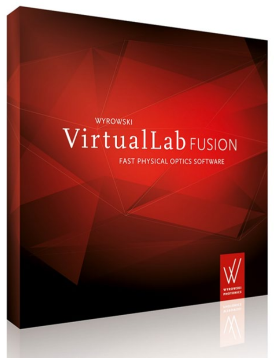
Spherical wavefront phase (here $\boldsymbol{\rho}^{\mathrm{out}} = 0$):

$$\psi^{\mathrm{out}}(\boldsymbol{r}) = -k_0 n \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\mathrm{out}}(\alpha)\|^2 + f^2}$$

Wavefront phase response function:

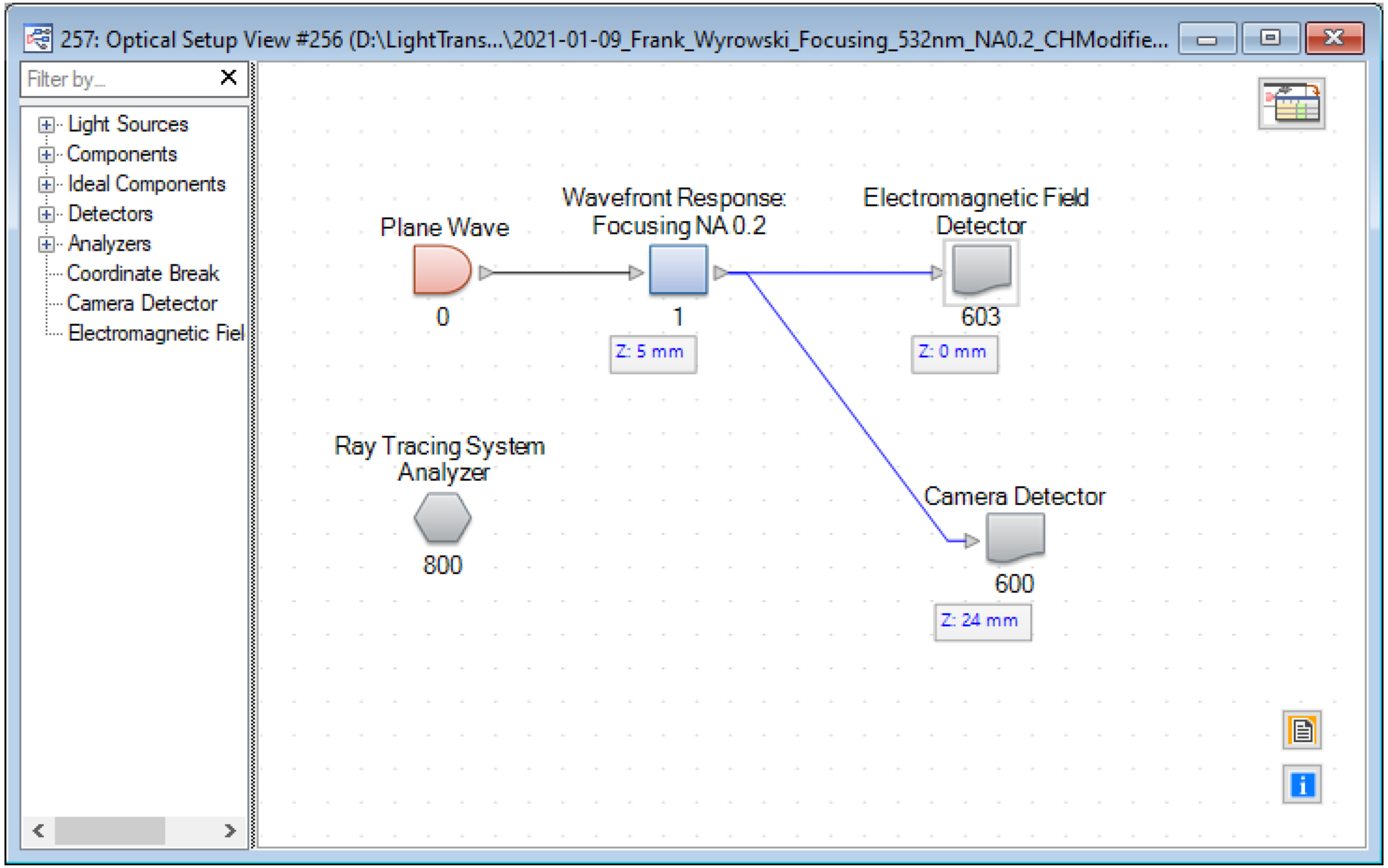
$$\Delta\psi(\boldsymbol{r}) = \psi^{\mathrm{out}} - \psi^{\mathrm{in}}$$

- VirtualLab Fusion introduces **Functional Components** as generalization of the current ideal components.
- They enable design in functional embodiment of a system as initial step of component and system design.
- Important examples: Functional Wavefront Response Component and Functional Gratings.

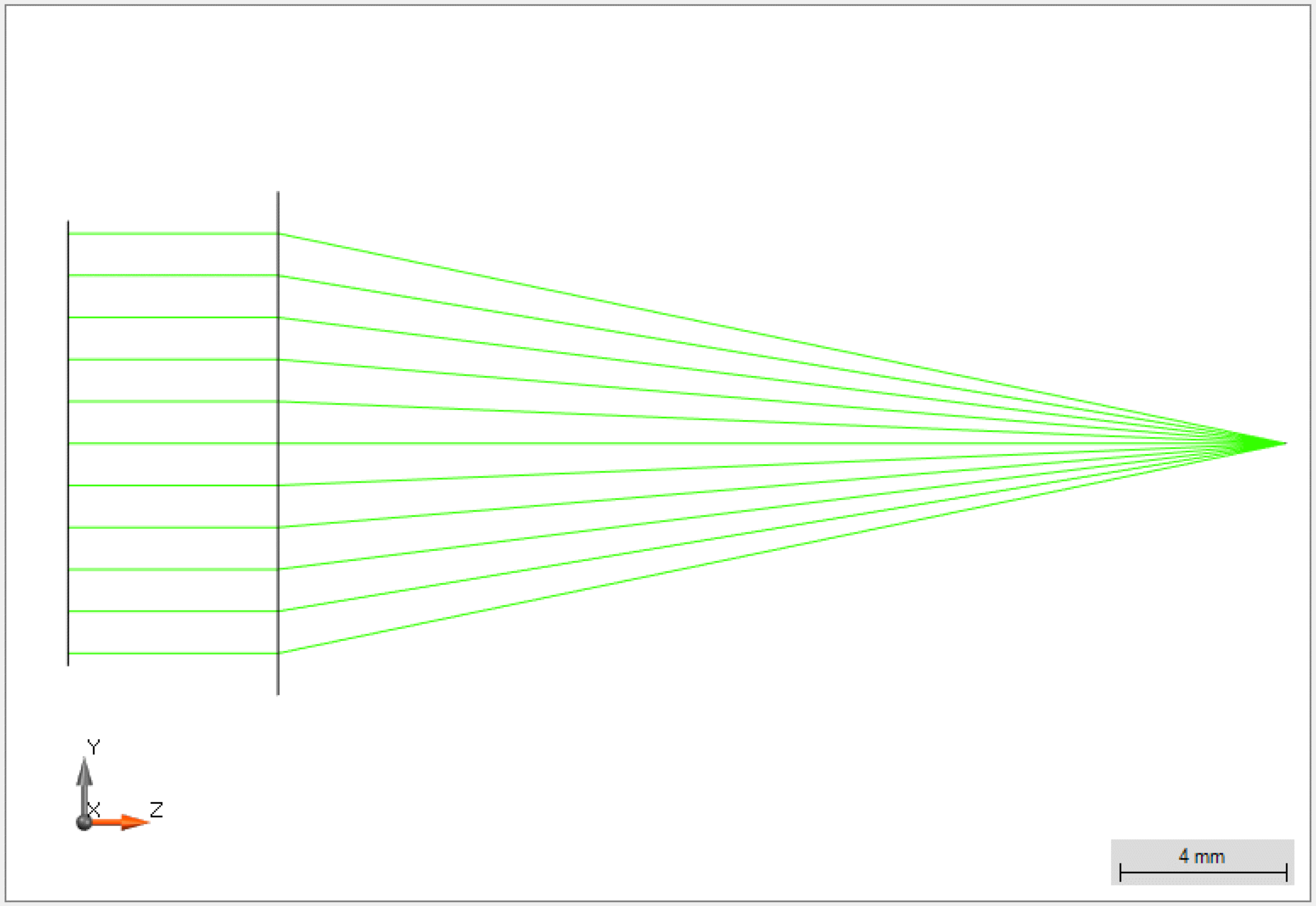


VirtualLab Fusion 2021

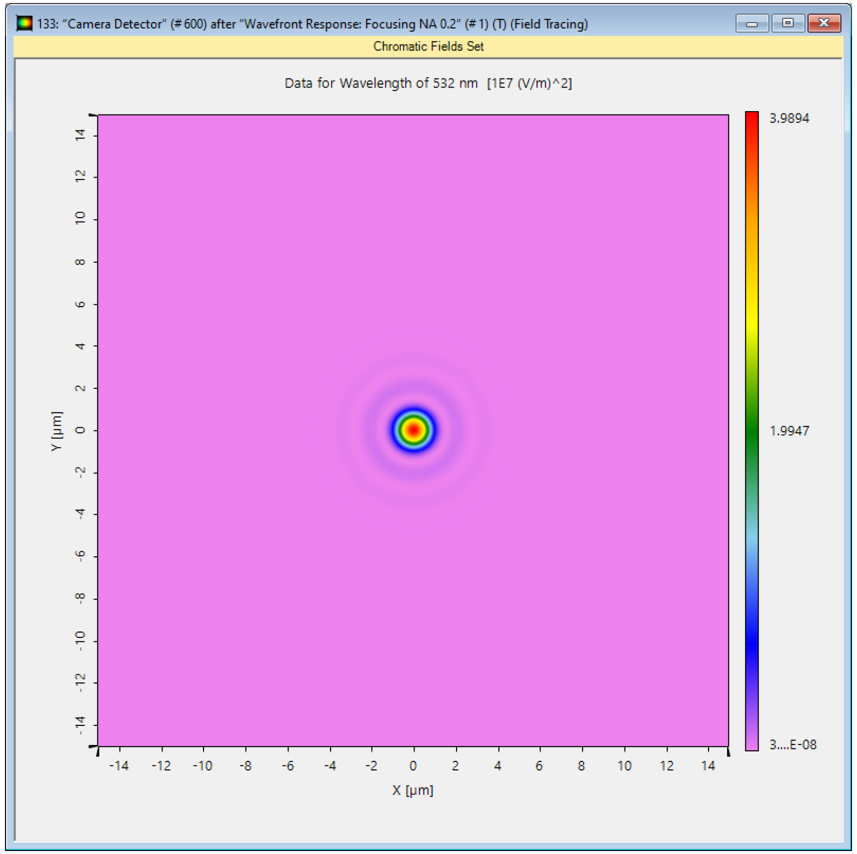
Functional Design: Focusing (NA = 0.2)



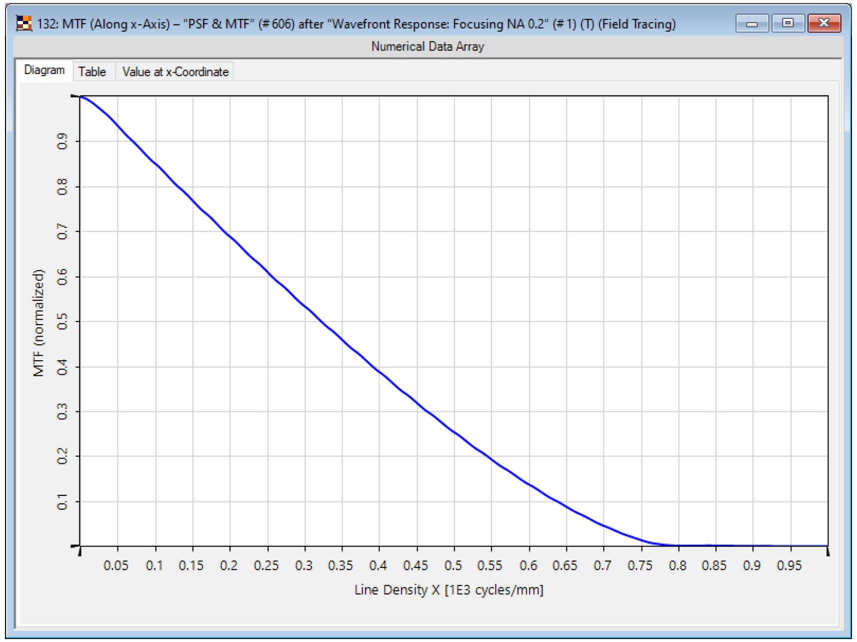
Functional Design: Focusing (NA = 0.2) – Ray Tracing



Functional Design: Focusing (NA = 0.2) – Field Tracing



Field in Focus (False Color)



MTF

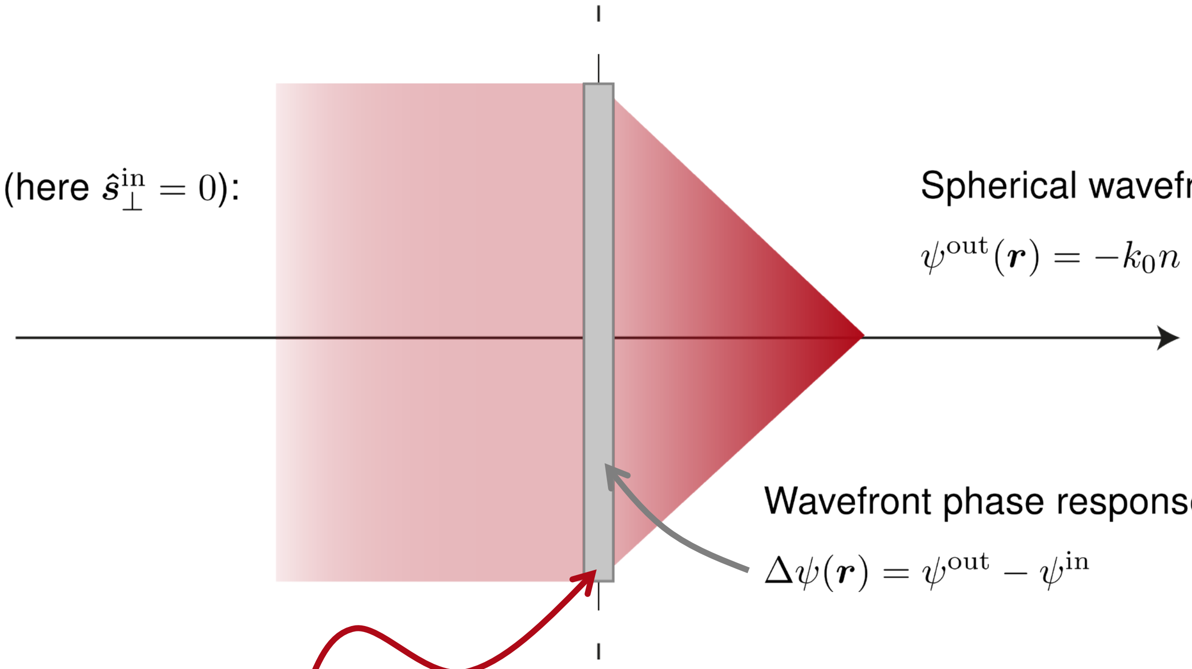
Focusing Lens: Structural Design

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_{\perp}^{\text{in}} = 0$):

$$\psi^{\text{in}}(\boldsymbol{r}) = k_0 n\, \hat{\boldsymbol{s}}_{\perp}^{\text{in}}(\alpha) \cdot \boldsymbol{\rho}$$

Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

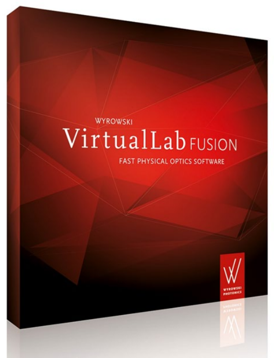
$$\psi^{\text{out}}(\boldsymbol{r}) = -k_0 n \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{out}}(\alpha)\|^2 + f^2}$$



Wavefront phase response function:

$$\Delta\psi(\boldsymbol{r}) = \psi^{\text{out}} - \psi^{\text{in}}$$

- VirtualLab Fusion provides **Structure Design Algorithms** to transfer Functional Wavefront Response Components into material components.
- Example types: smooth surfaces (freeform), DOE, meta surfaces, segmented surfaces (generalized Fresnel lenses), modulated volume gratings.



VirtualLab Fusion 2021

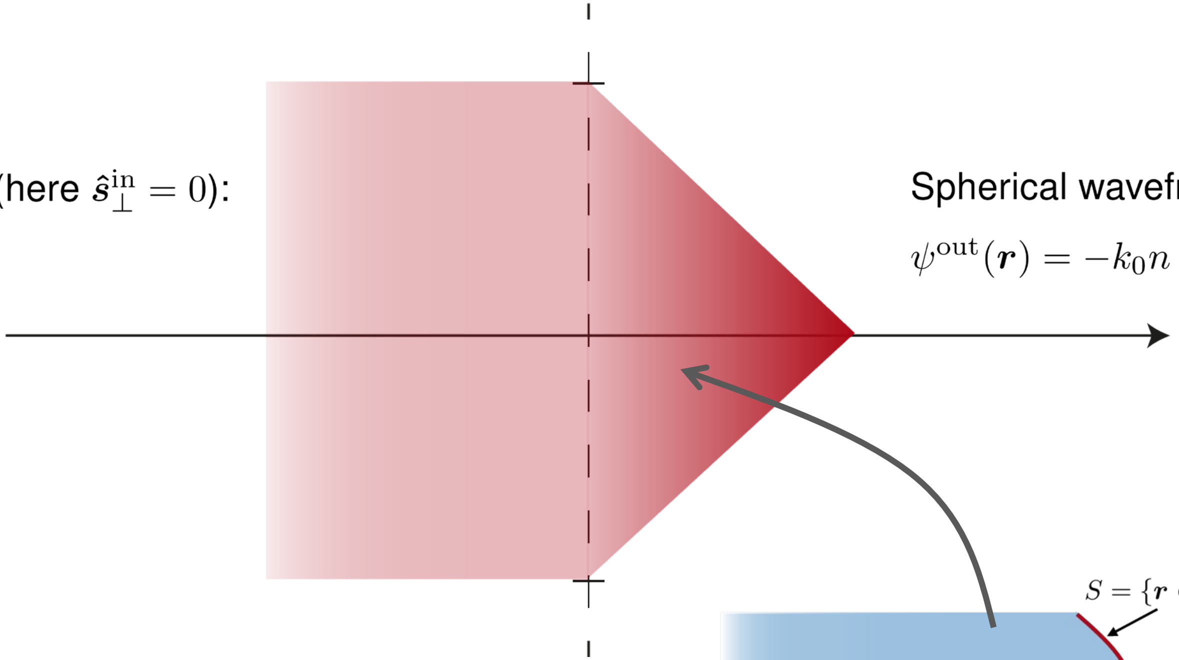
Focusing Lens: Surface Design

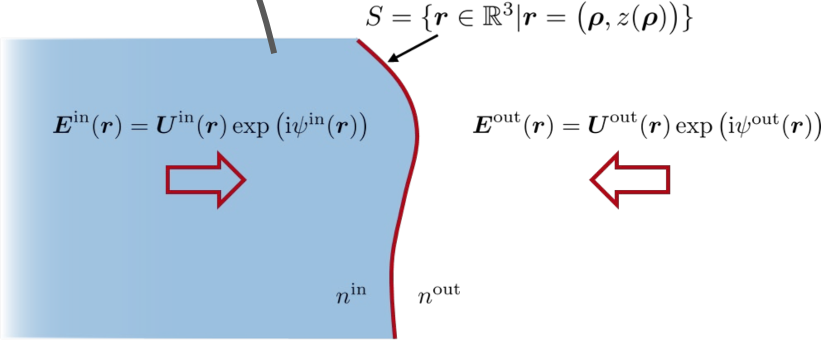
Planar input wavefront phase (here $\hat{\boldsymbol{s}}_{\perp}^{\text{in}} = 0$):

$$\psi^{\text{in}}(\boldsymbol{r}) = k_0 n \, \hat{\boldsymbol{s}}_{\perp}^{\text{in}}(\alpha) \cdot \boldsymbol{\rho}$$

Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

$$\psi^{\text{out}}(\boldsymbol{r}) = -k_0 n \, \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{out}}(\alpha)\|^2 + f^2}$$





Calculate the surface $S \subset \mathbb{R}^3$ on which:

$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} 0$$

Focusing Lens: Surface Design

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_\perp^{\text{in}} = 0$):

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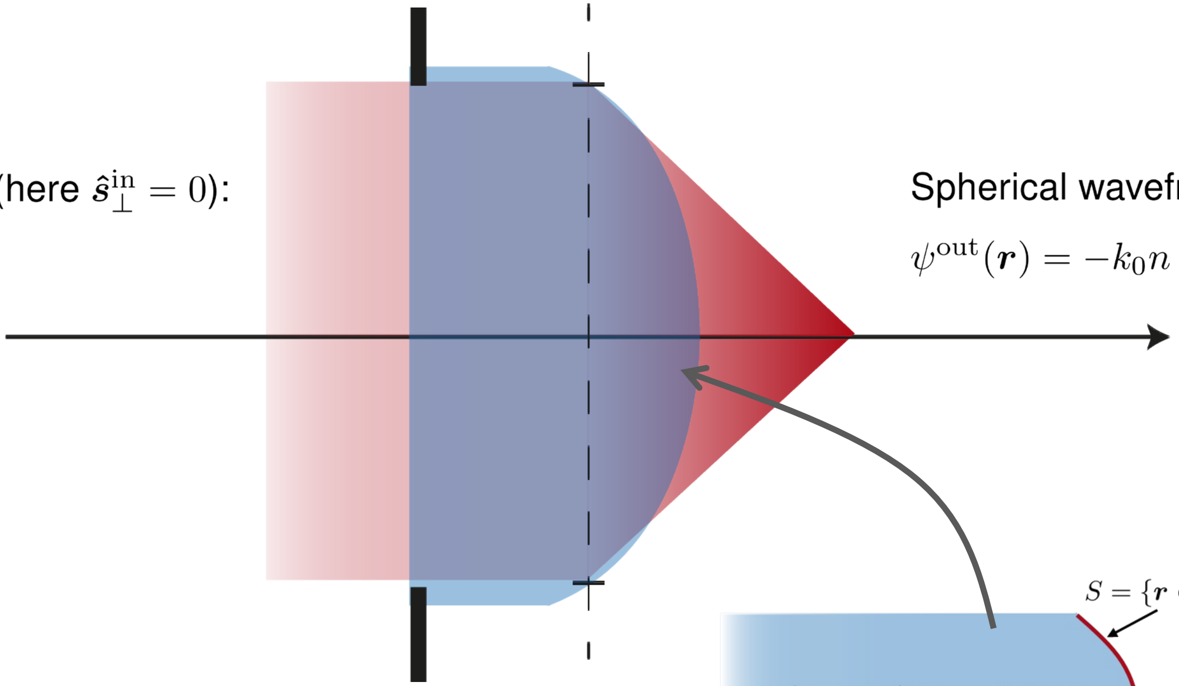
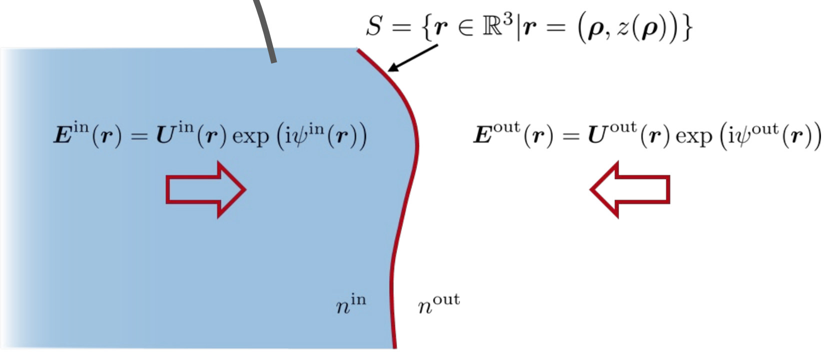
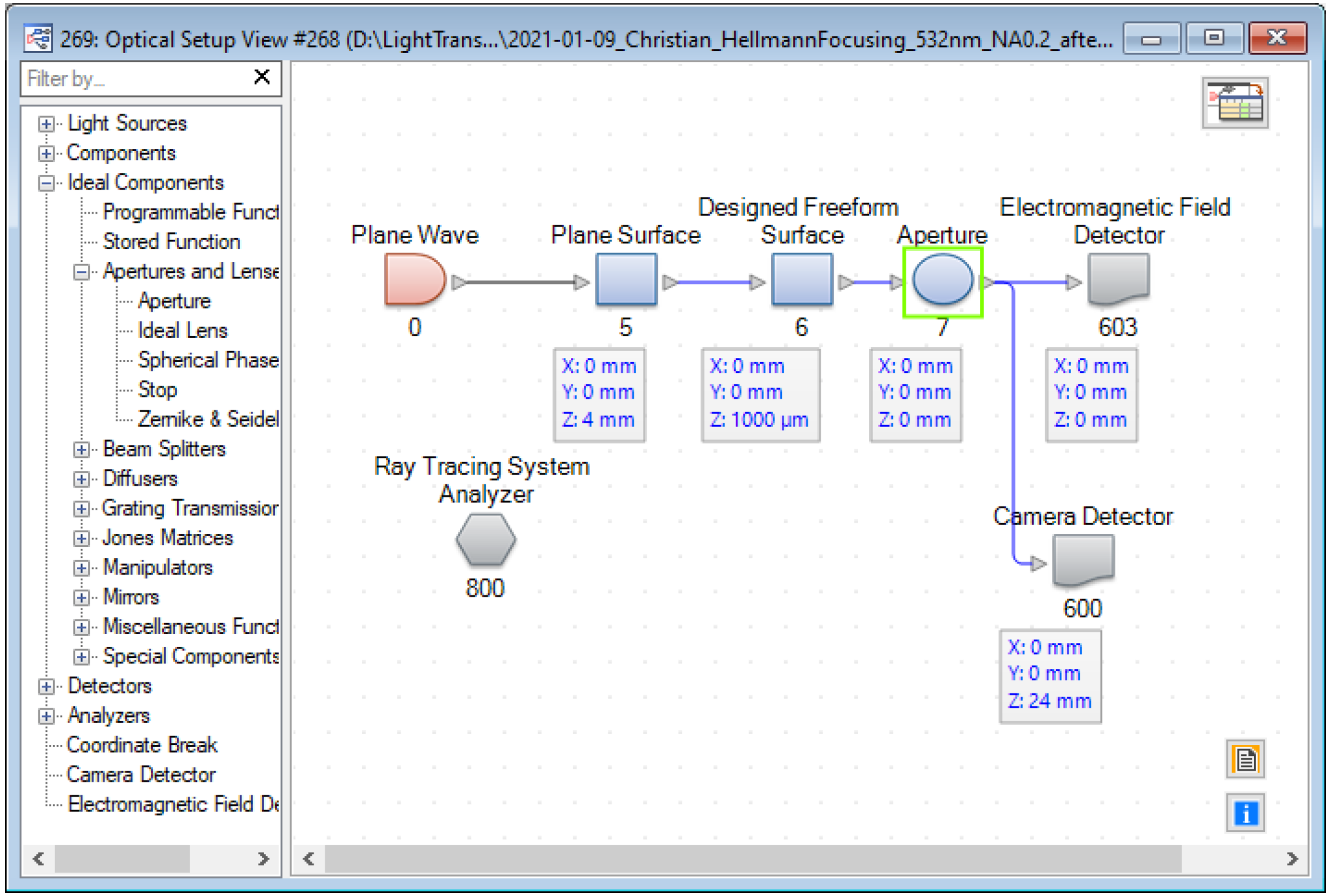




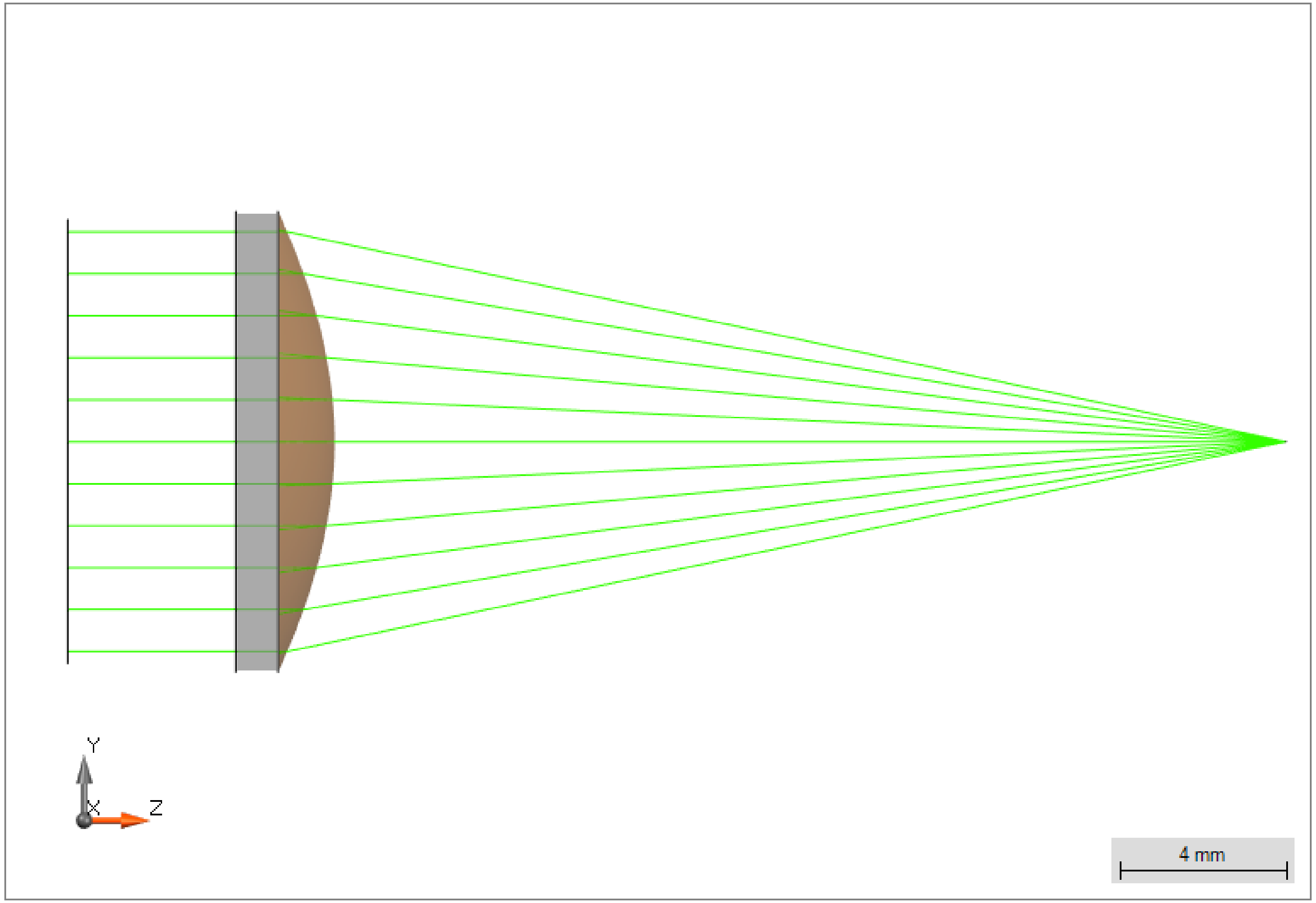
Calculate the surface $S \subset \mathbb{R}^3$ on which:

$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} 0$$

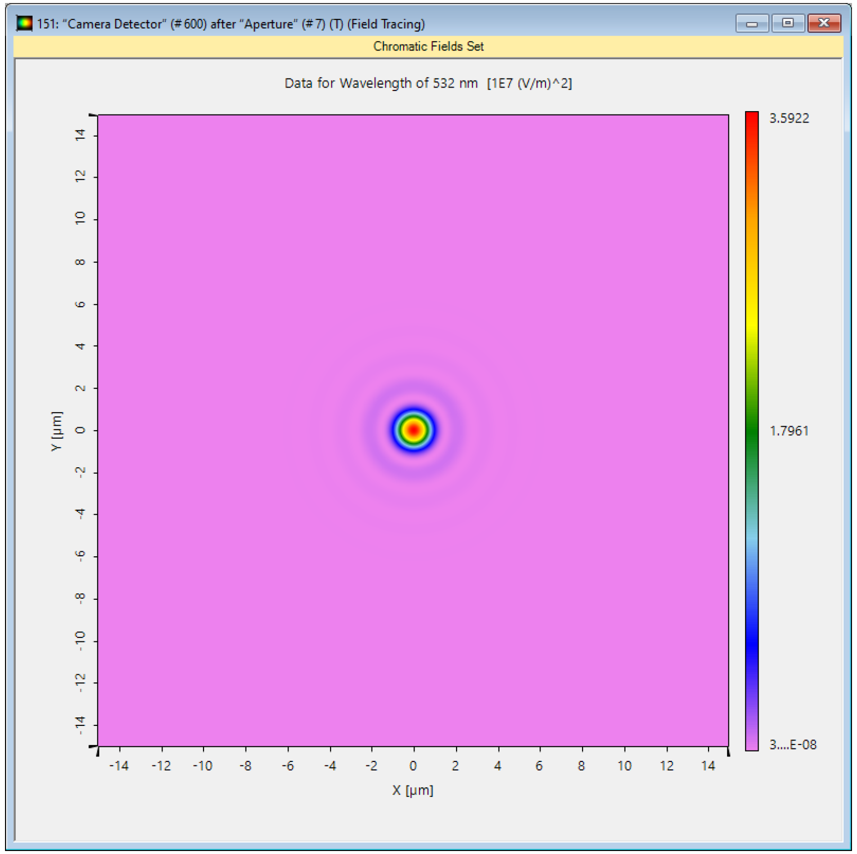
Structural Design Focusing (NA = 0.2): Lens



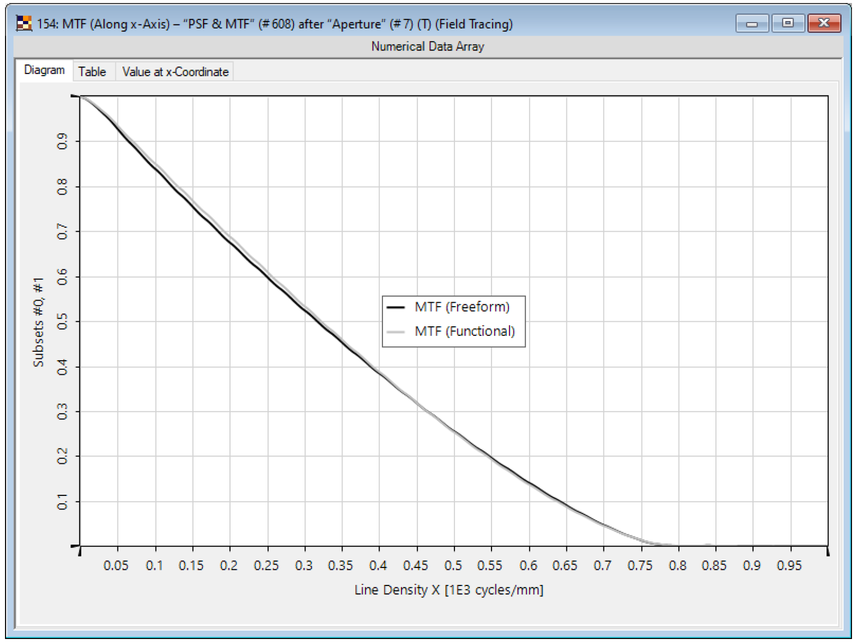
Focusing (NA = 0.2) Lens: Ray Tracing



Focusing (NA = 0.2) Lens: Field Tracing



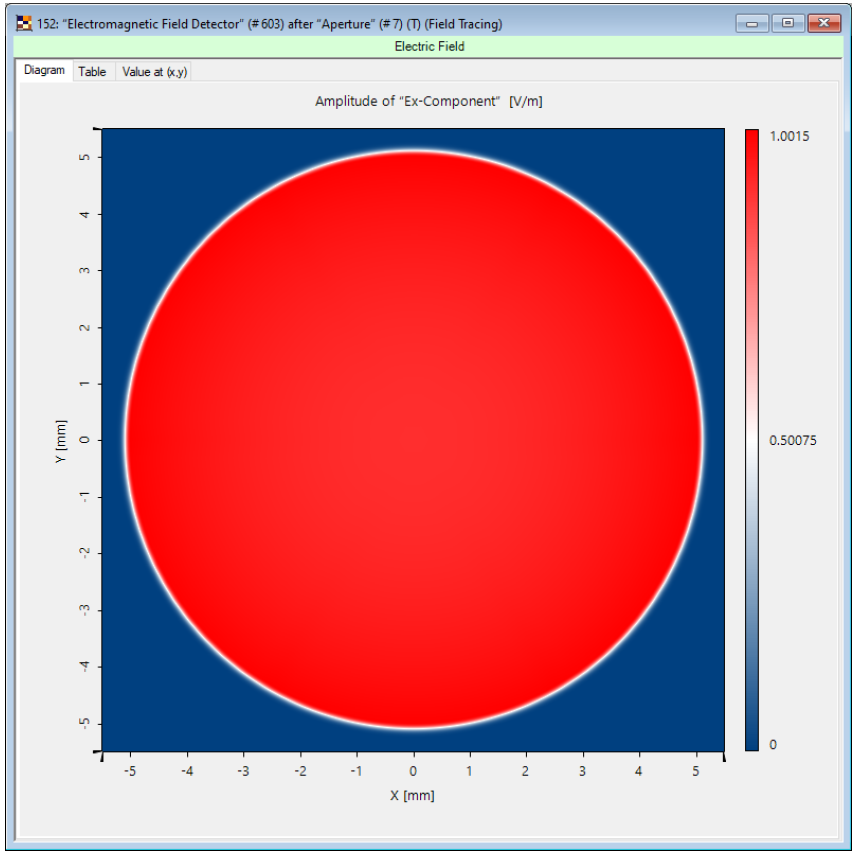
Energy Density in Focus (False Color)



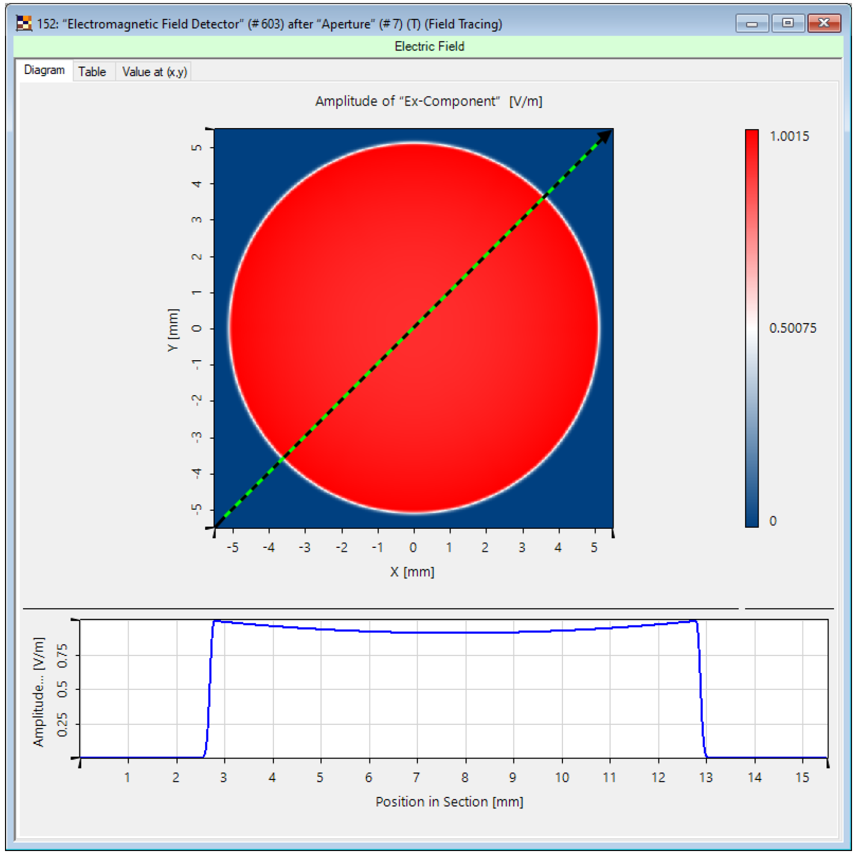
MTF

Efficiency: 91.1% (efficiency after first plane: 96.5%)

Focusing (NA = 0.2) Lens: Field Tracing

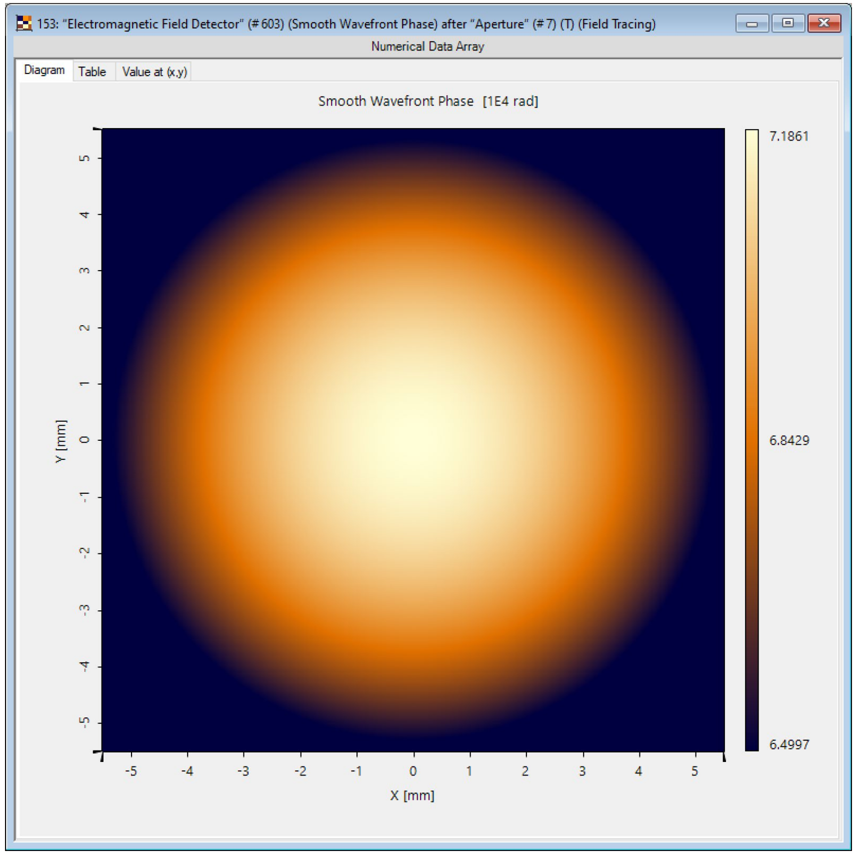


Amplitude after lens

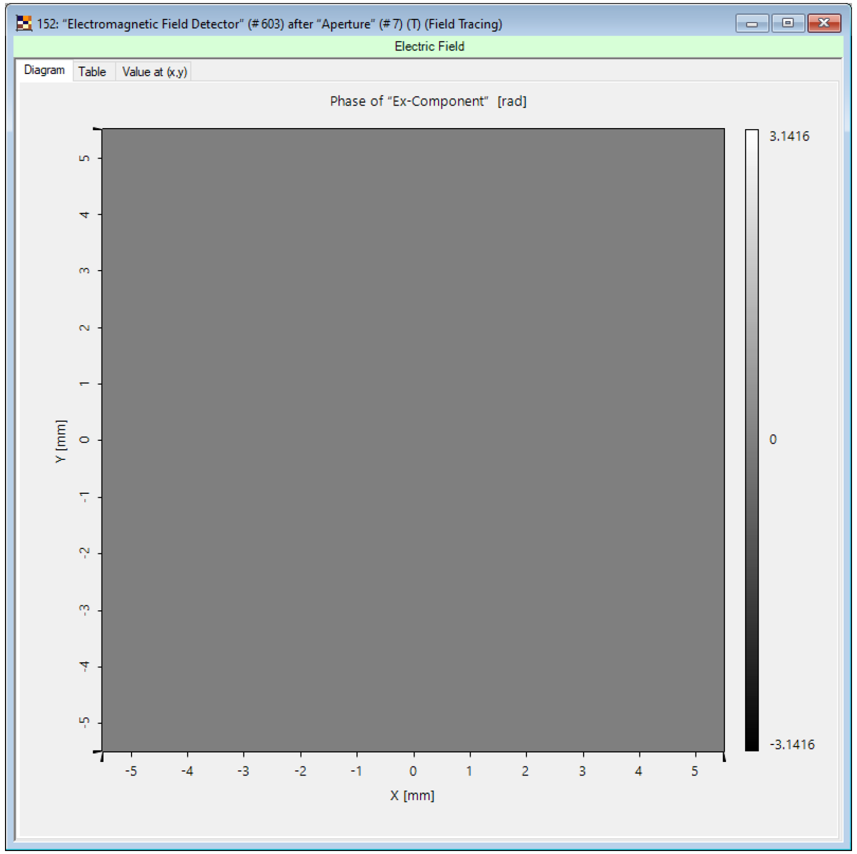


Amplitude after lens

Focusing (NA = 0.2) Lens: Field Tracing

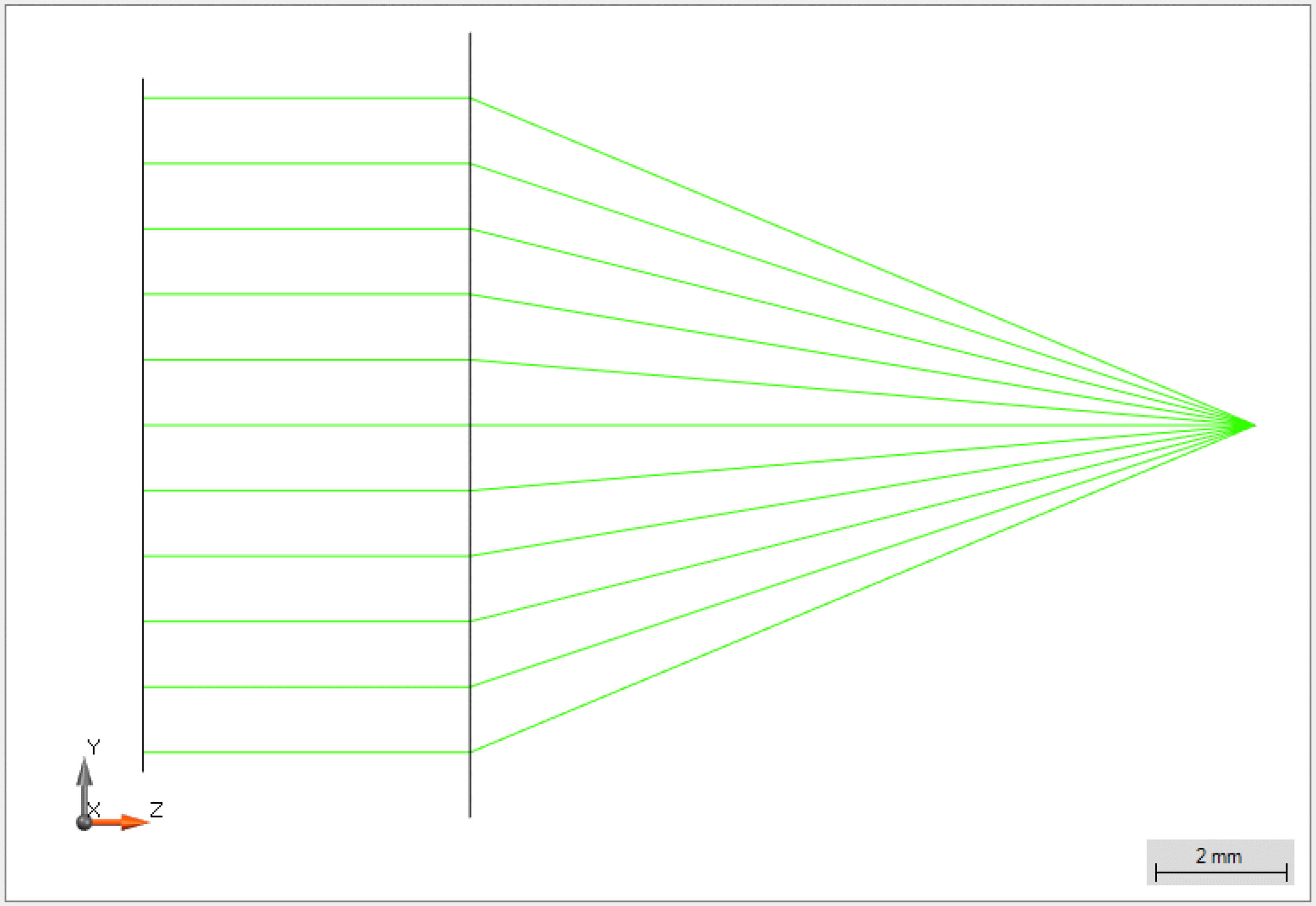


Wavefront phase after lens

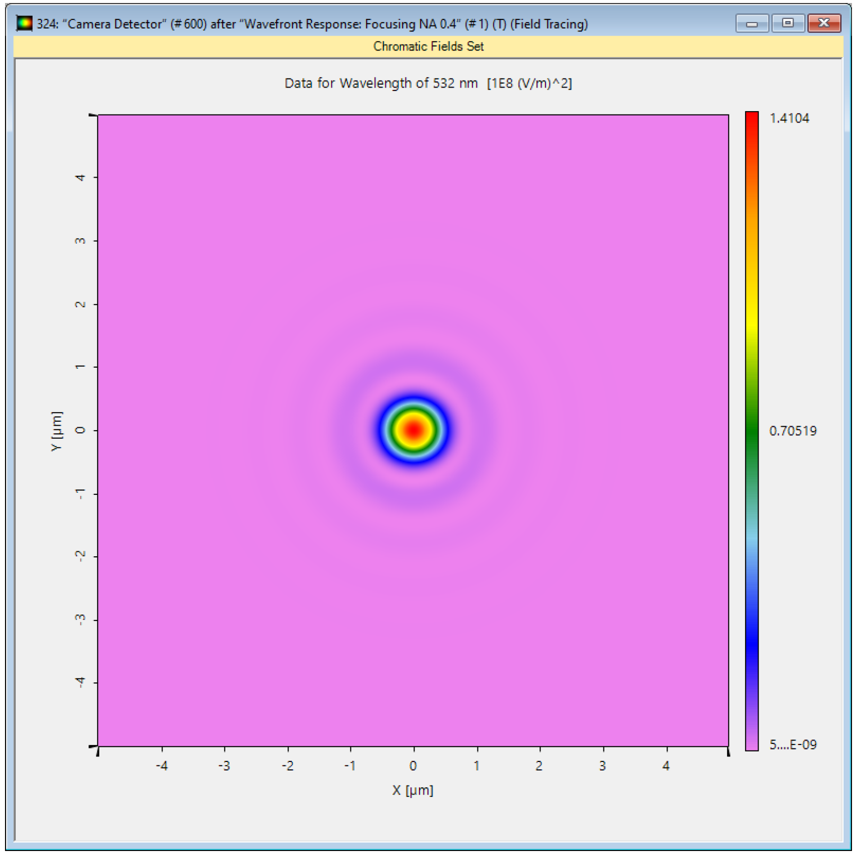


Wavefront phase error after lens

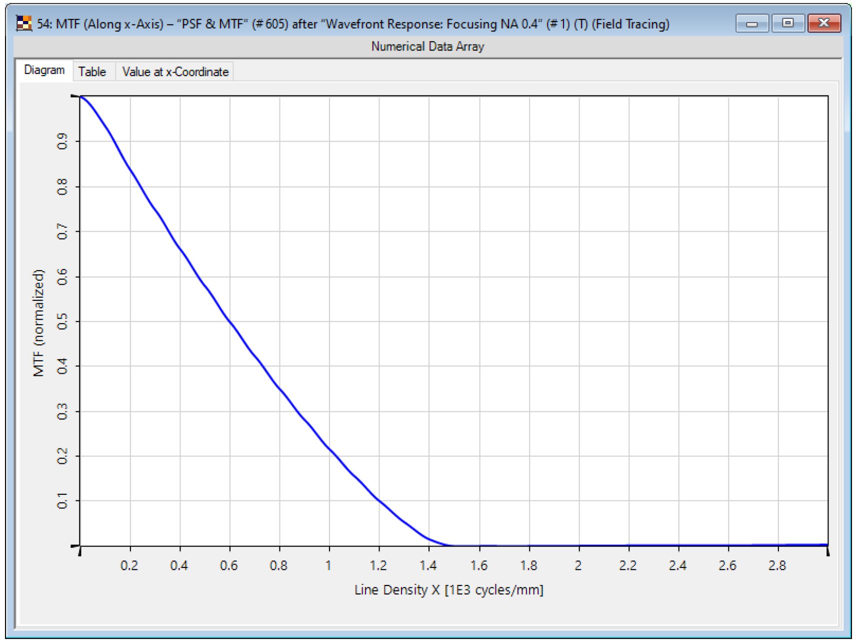
Functional Design: Focusing (NA = 0.4) – Ray Tracing



Functional Design: Focusing (NA = 0.4) – Field Tracing

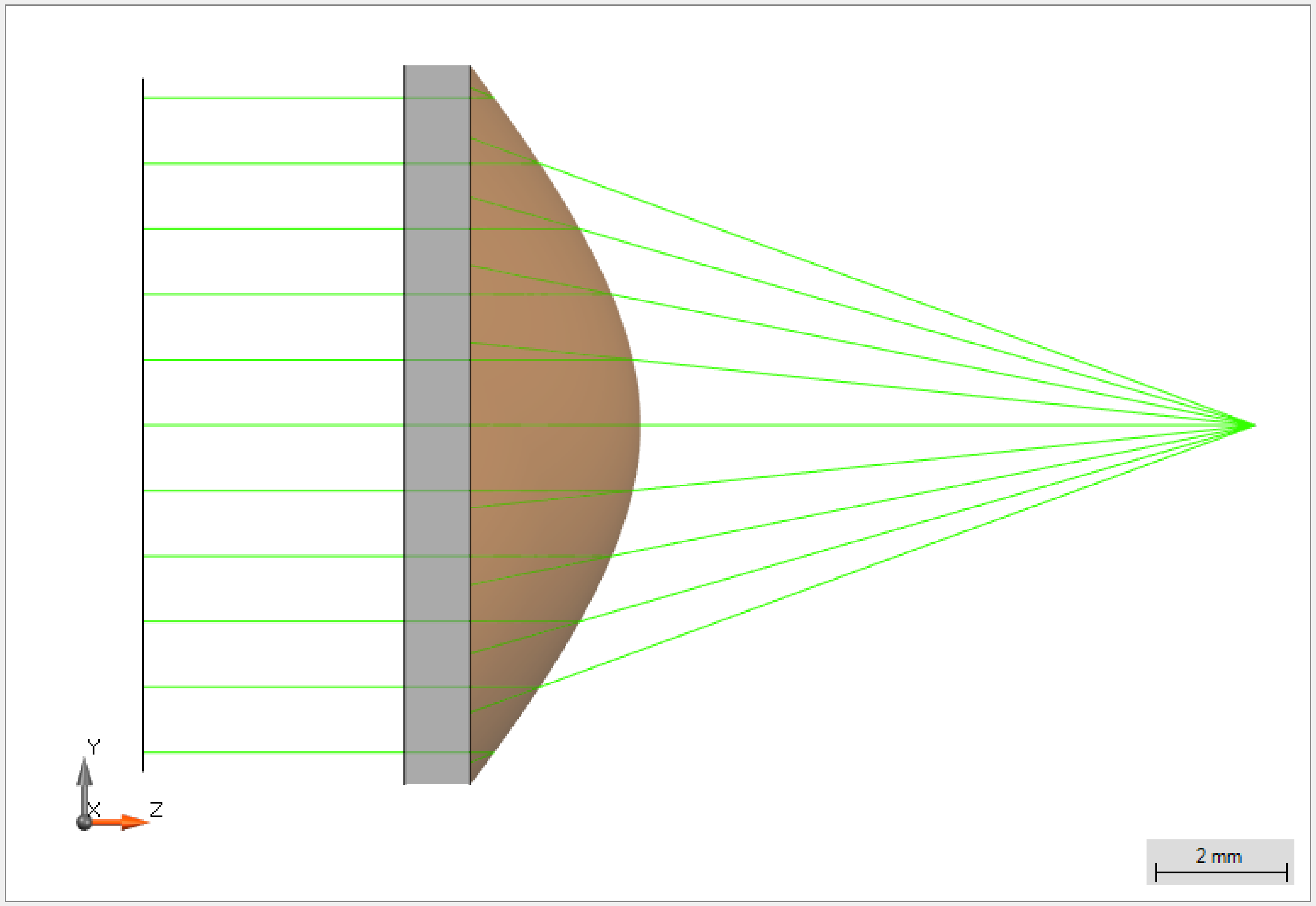


Energy Density in Focus (False Color)

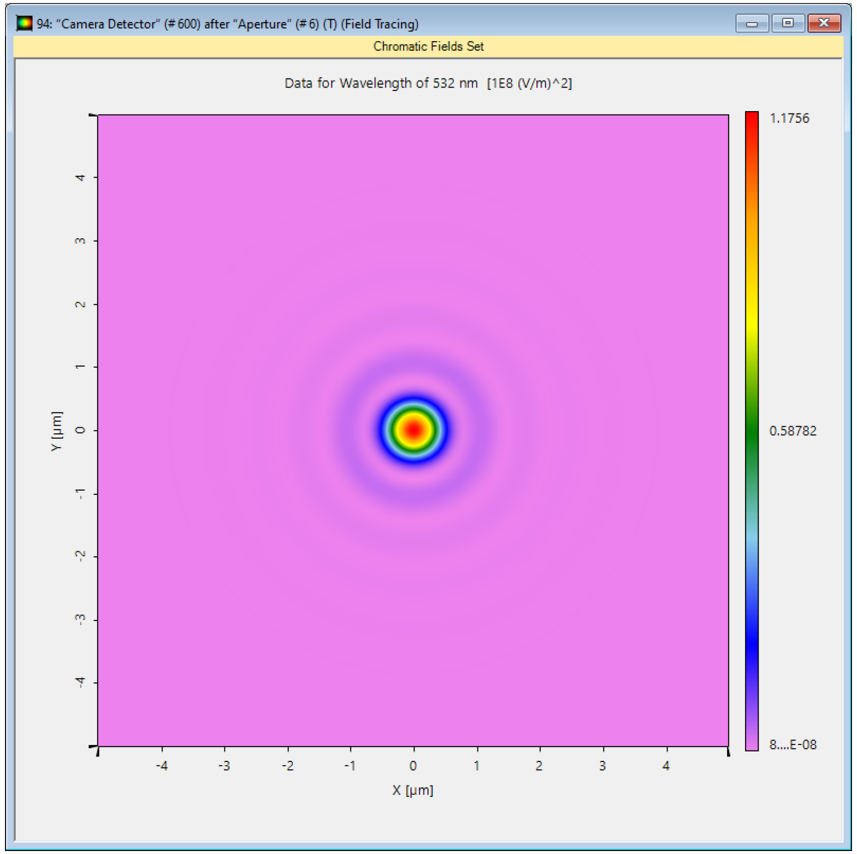


MTF

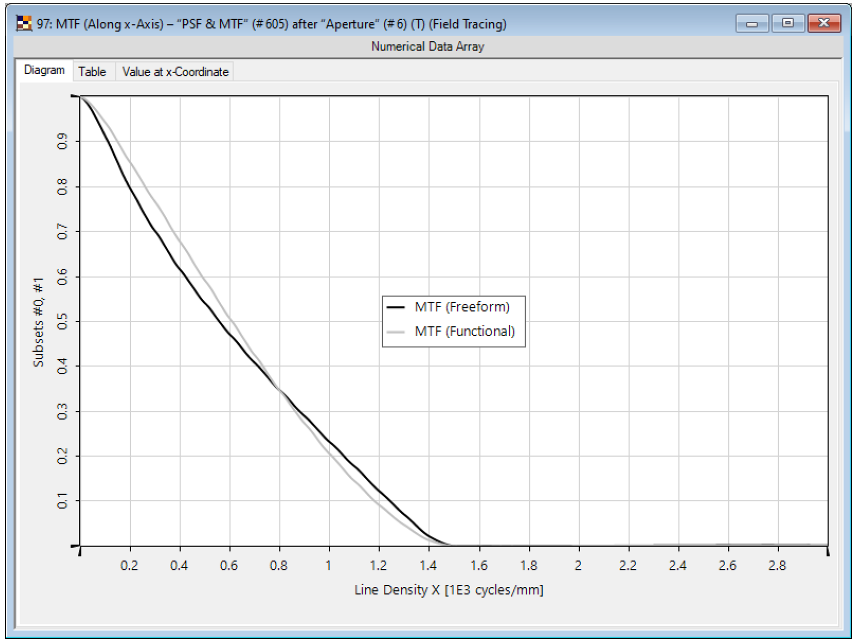
Focusing (NA = 0.4) Lens: Ray Tracing



Focusing (NA = 0.4) Lens: Field Tracing



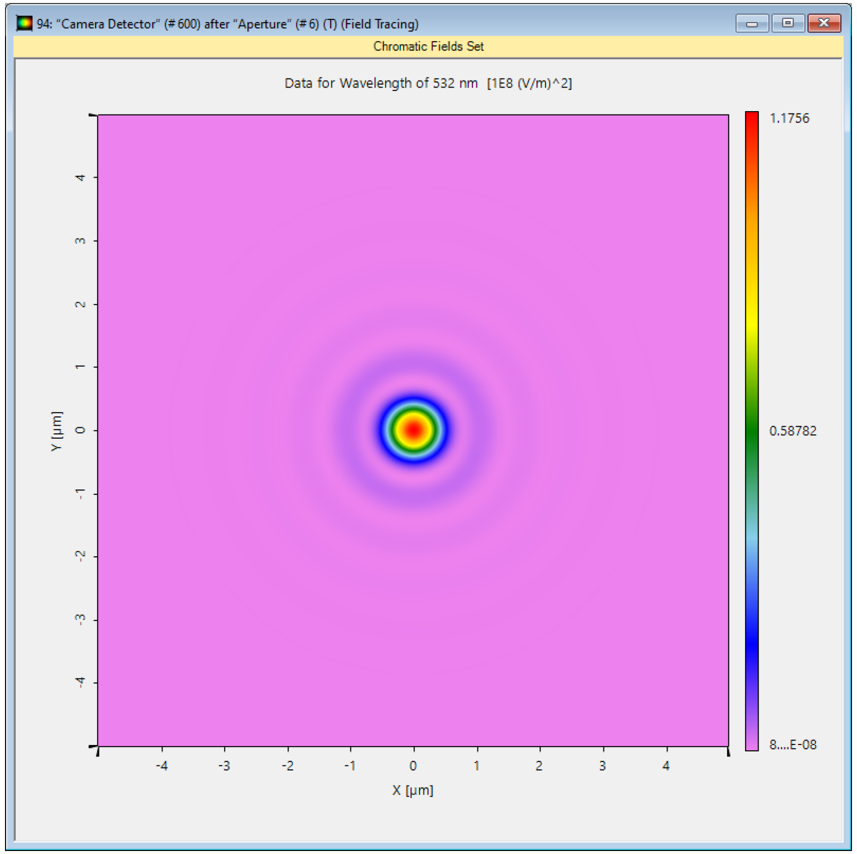
Energy Density in Focus (False Color)



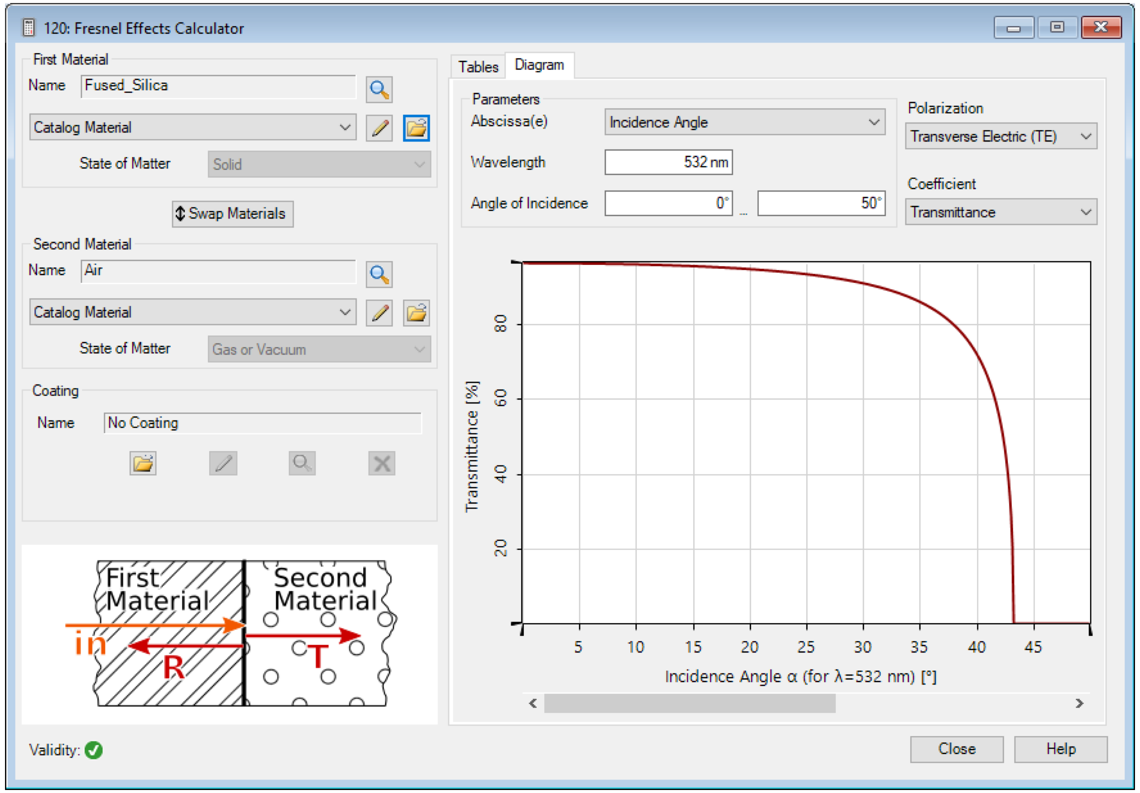
MTF

Efficiency: 84.98% (efficiency after first plane: 96.5%)

Focusing (NA = 0.4) Lens: Field Tracing



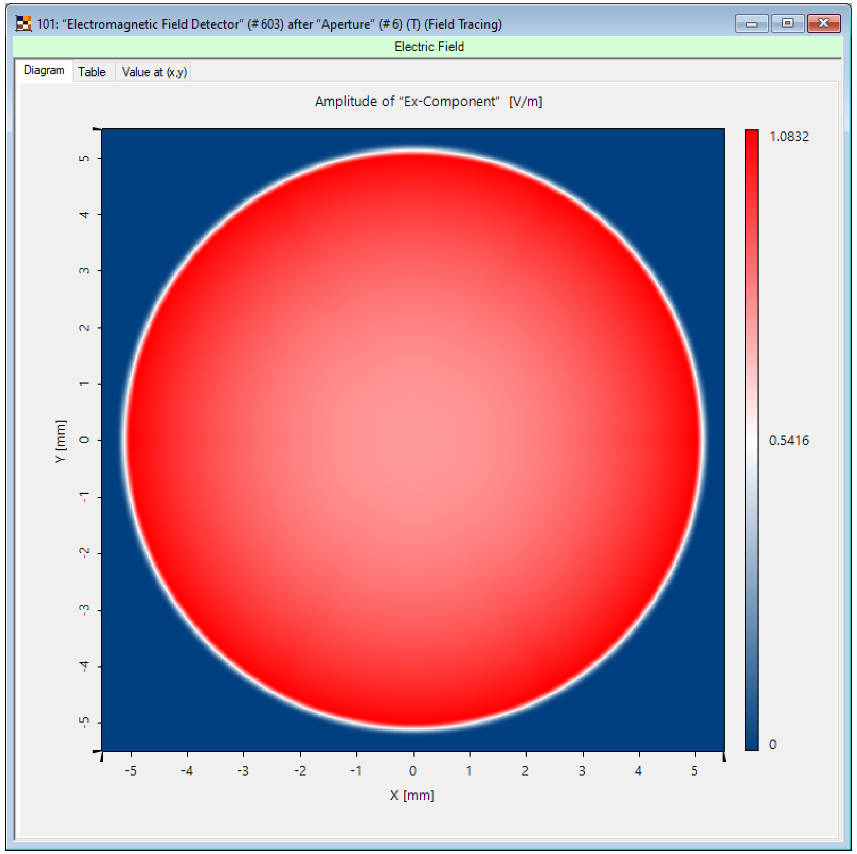
Energy Density in Focus (False Color)



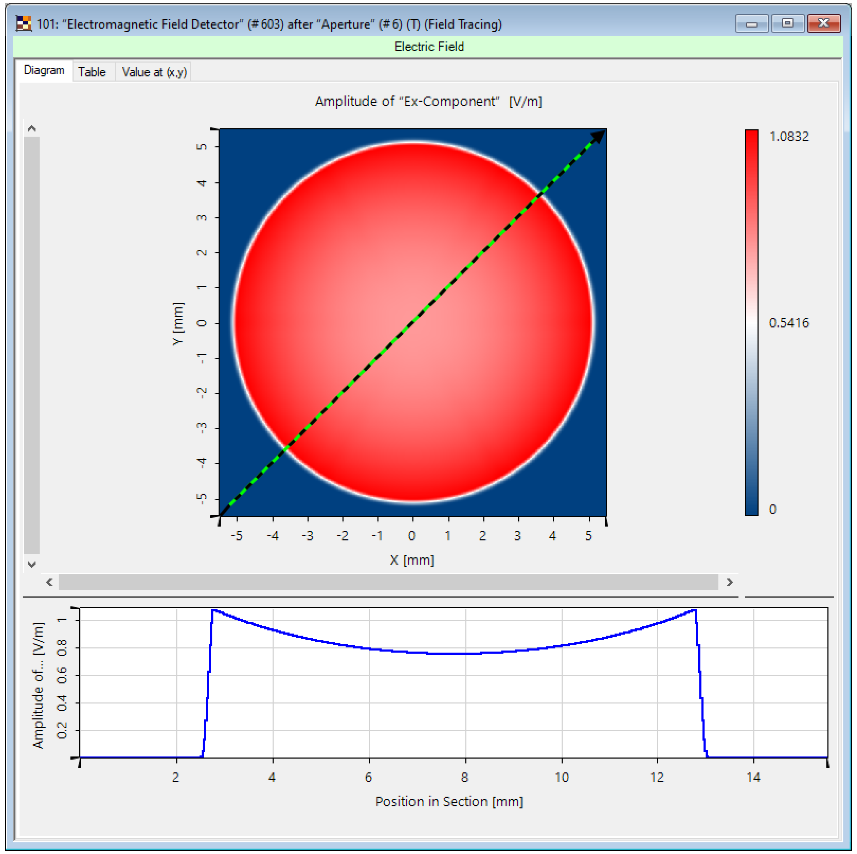
Fresnel effect at surface

Efficiency: 84.98% (efficiency after first plane: 96.5%)

Focusing (NA = 0.4) Lens: Field Tracing



Amplitude after lens



Amplitude after lens

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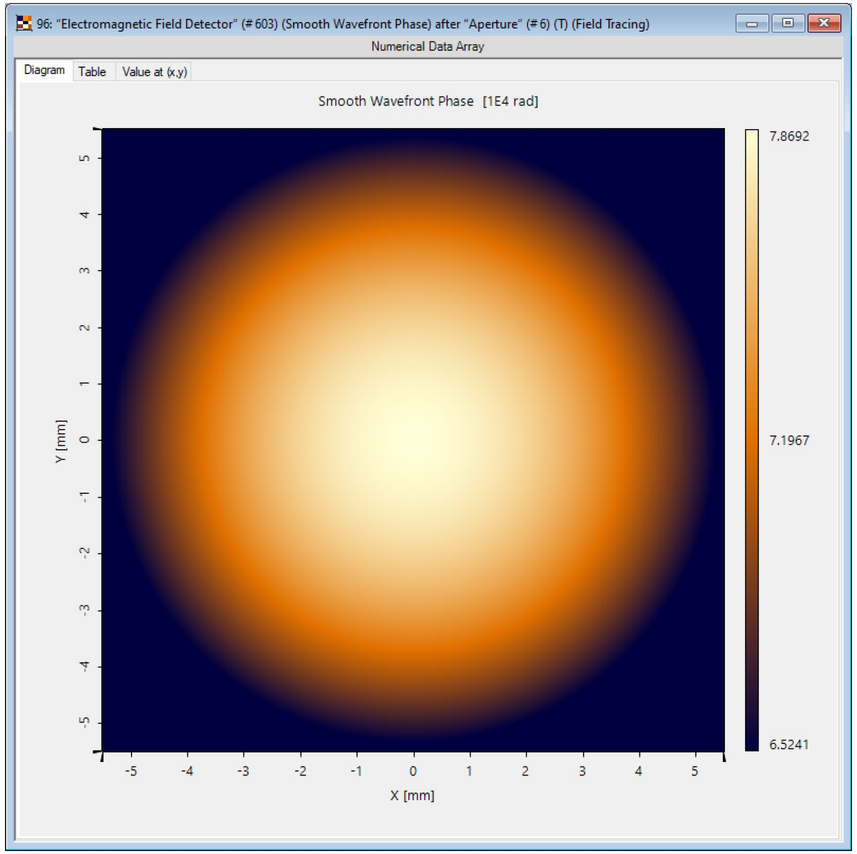
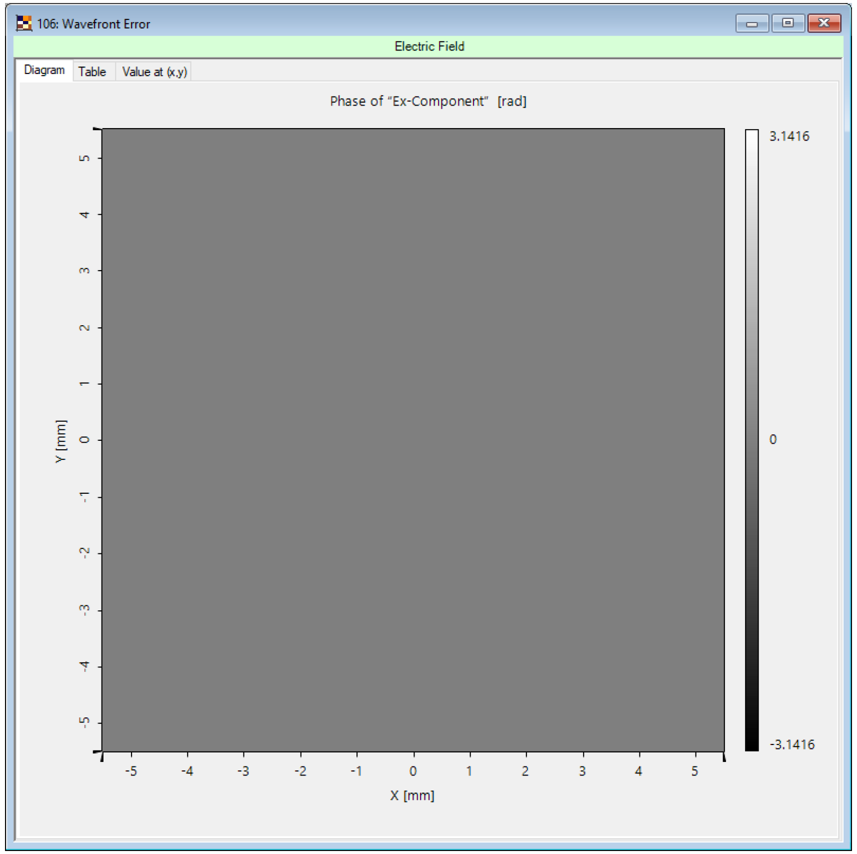


Wavefront phase after lens

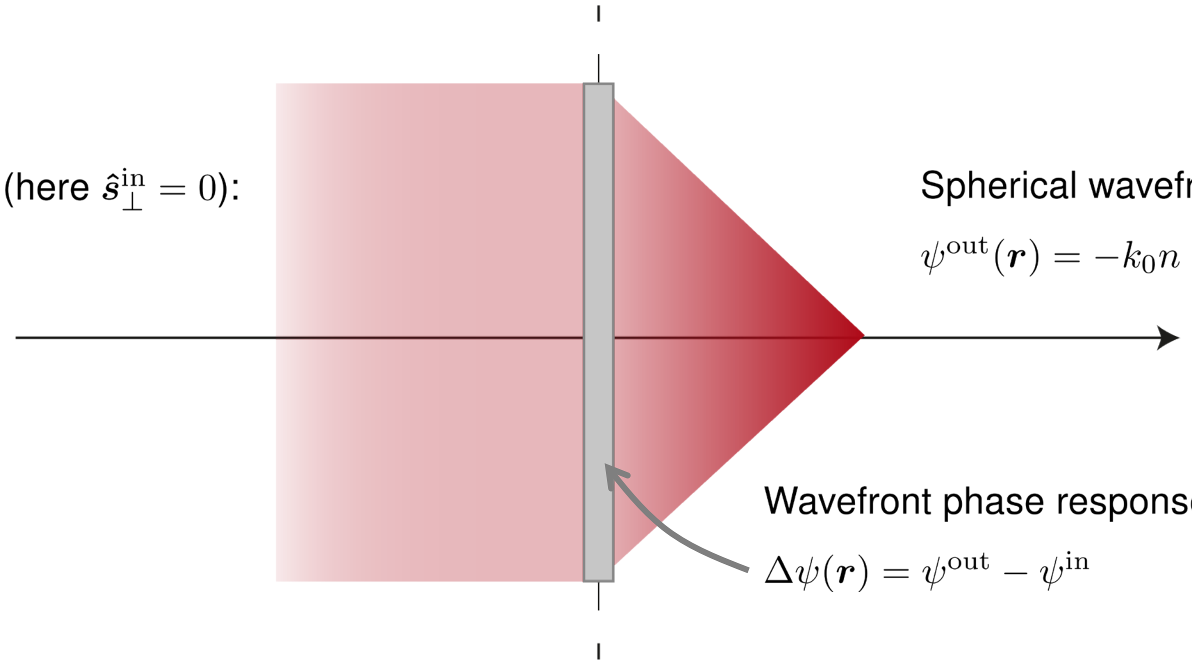


Wavefront phase error after lens

Focusing Lens: Flat Optics Structural Design

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_{\perp}^{\text{in}} = 0$):

$$\psi^{\text{in}}(\boldsymbol{r}) = k_0 n \, \hat{\boldsymbol{s}}_{\perp}^{\text{in}}(\alpha) \cdot \boldsymbol{\rho}$$



Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

$$\psi^{\text{out}}(\boldsymbol{r}) = -k_0 n \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{out}}(\alpha)\|^2 + f^2}$$

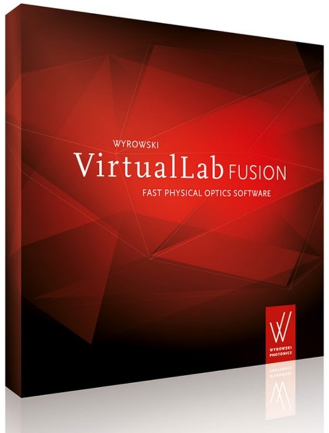
Wavefront phase response function:

$$\Delta\psi(\boldsymbol{r}) = \psi^{\text{out}} - \psi^{\text{in}}$$

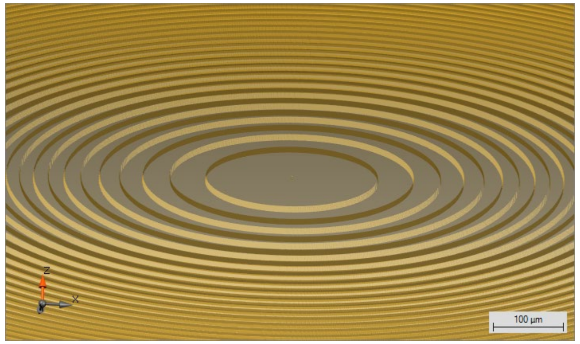
Flat Optics?

Structure of Webinar

- Why physical optics in design?
- Optical design in physical optics terms
- Diffractive Optical Elements (DOE)
  - Design
  - Modeling
  - Fabrication data
- Design examples



VirtualLab Fusion 2021



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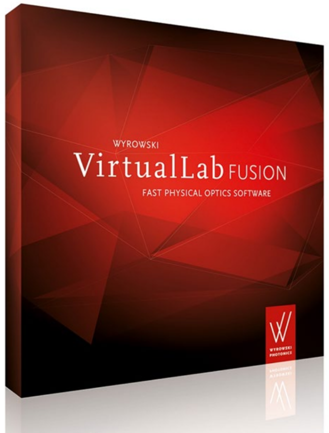
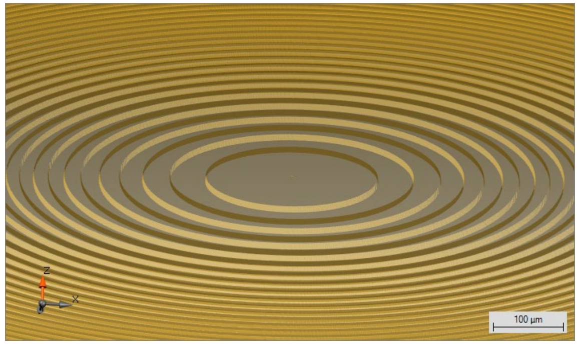
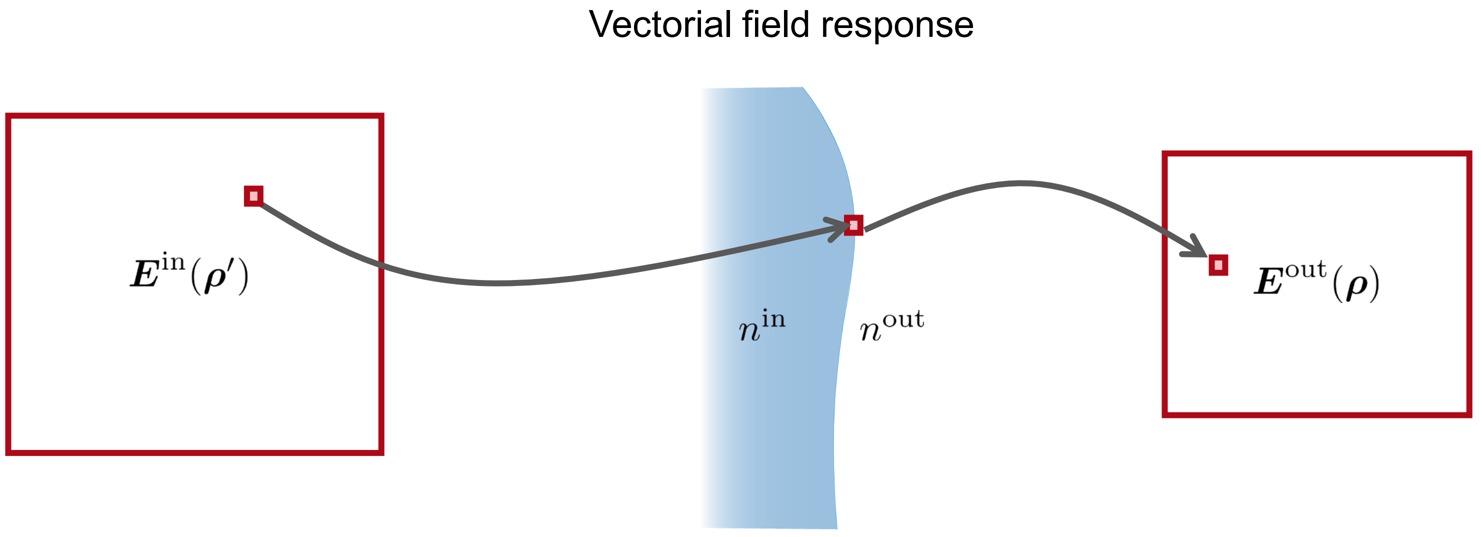


VirtualLab Fusion 2021



Field Response Operator: Freeform Surfaces



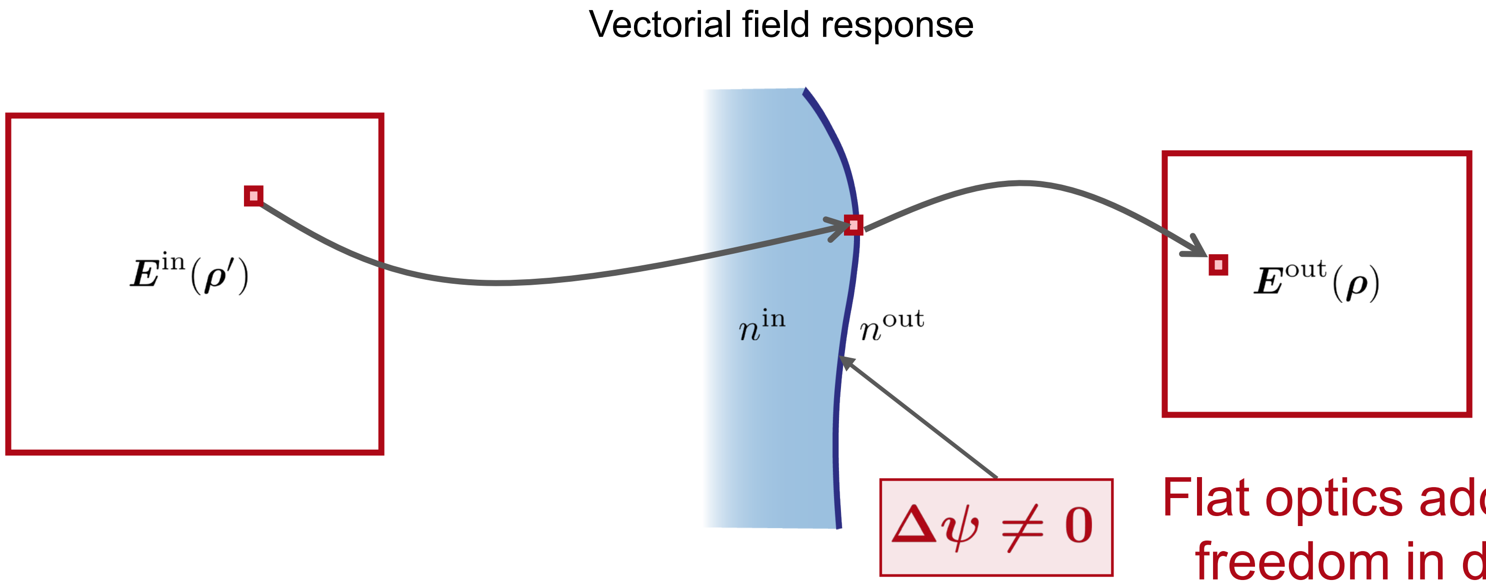
U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

U-field response by Fresnel equations (S-matrix): TE and TM

Wavefront phase response: $\psi^{\text{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\text{out}}(\boldsymbol{\rho})$

Wavefront response by Fresnel equations (S-matrix): $\Delta\psi \overset{!}{=} 0$

Field Response Operator: Flat Optics



Flat optics adds extra freedom in design!

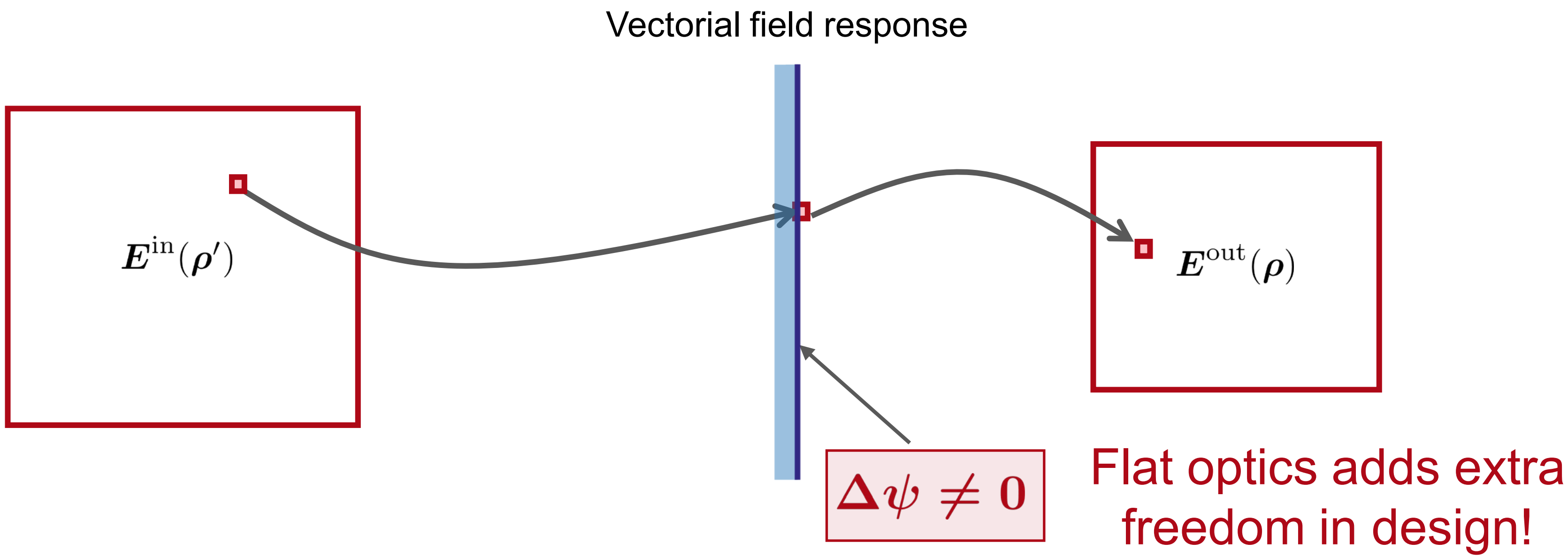
U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

U-field response dependent on type of flat optics

Wavefront phase response: $\psi^{\text{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}') \mapsto \psi^{\text{out}}(\boldsymbol{\rho})$

Wavefront response by different effects: $\boldsymbol{\Delta\psi \overset{!}{\neq} 0}$

Field Response Operator: Flat Optics



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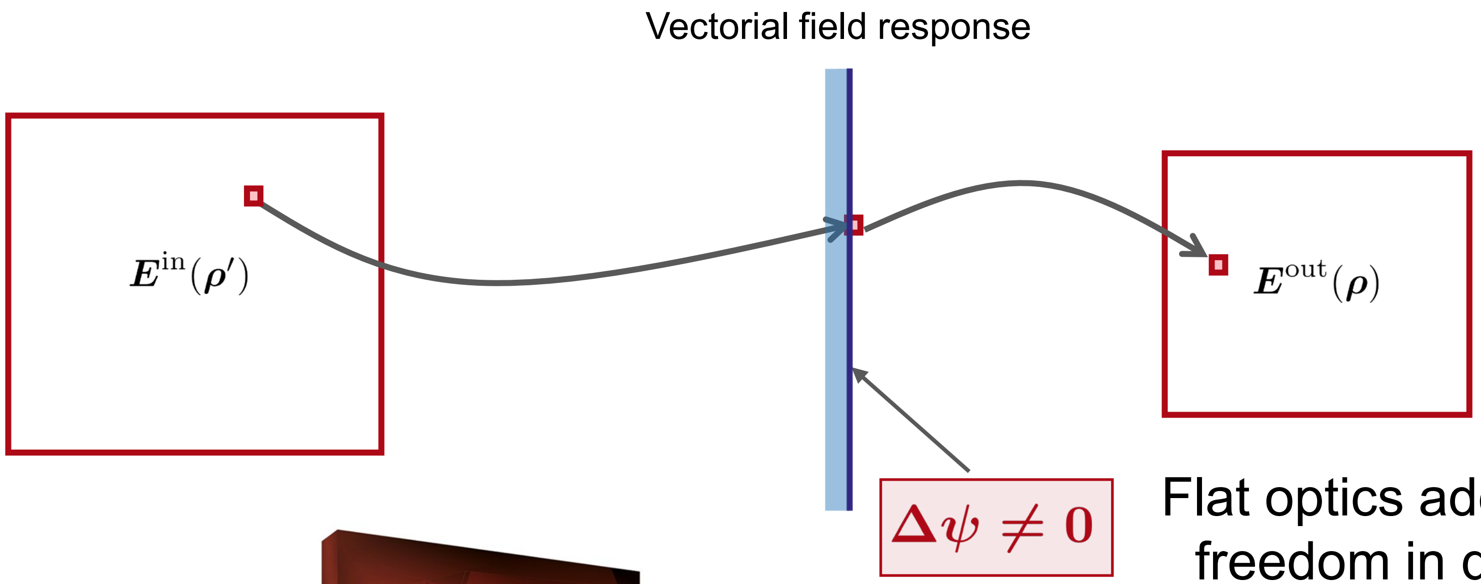

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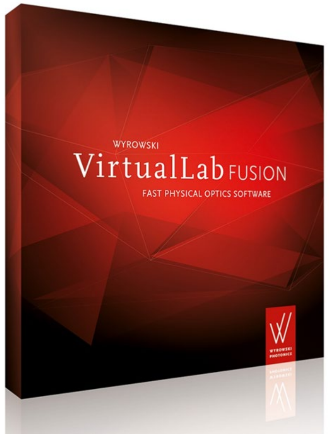
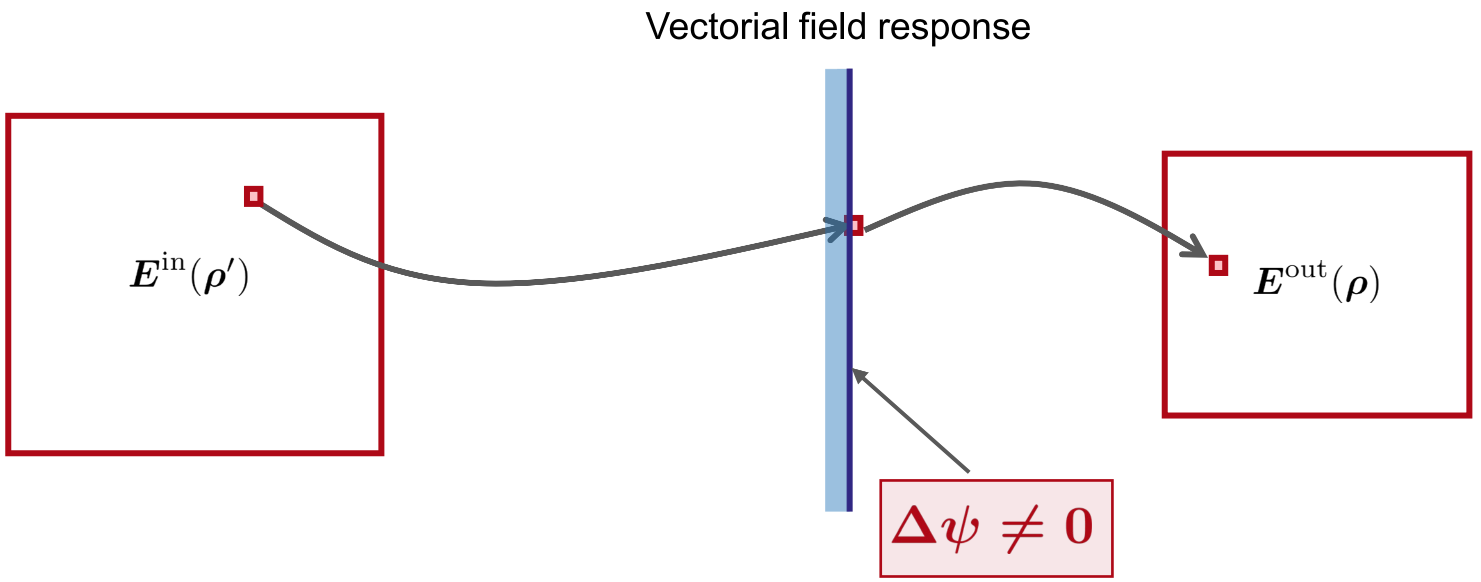


VirtualLab Fusion 2021

VirtualLab Fusion provides tools to investigate and exploit the potential of flat and freeform optics!

Field Response Operator: Flat Optics



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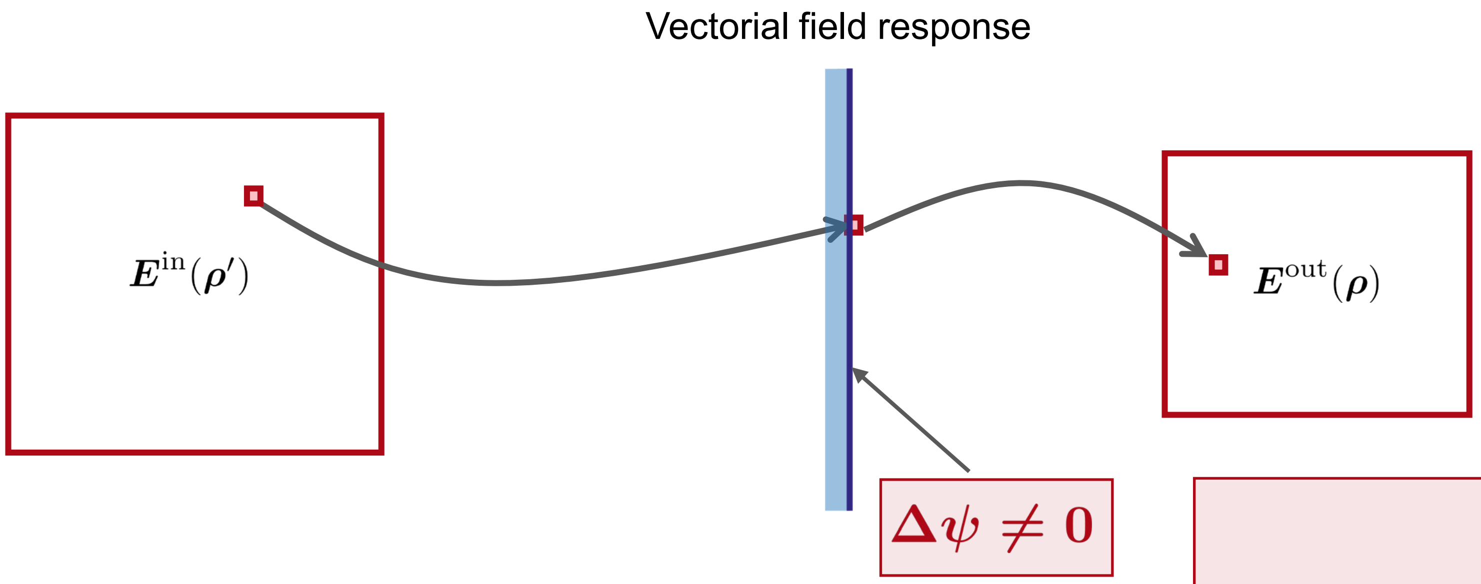

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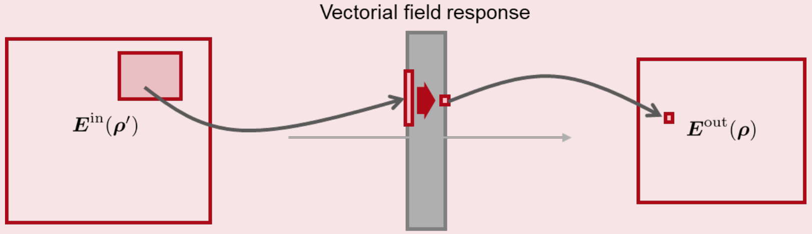
Integral effects?

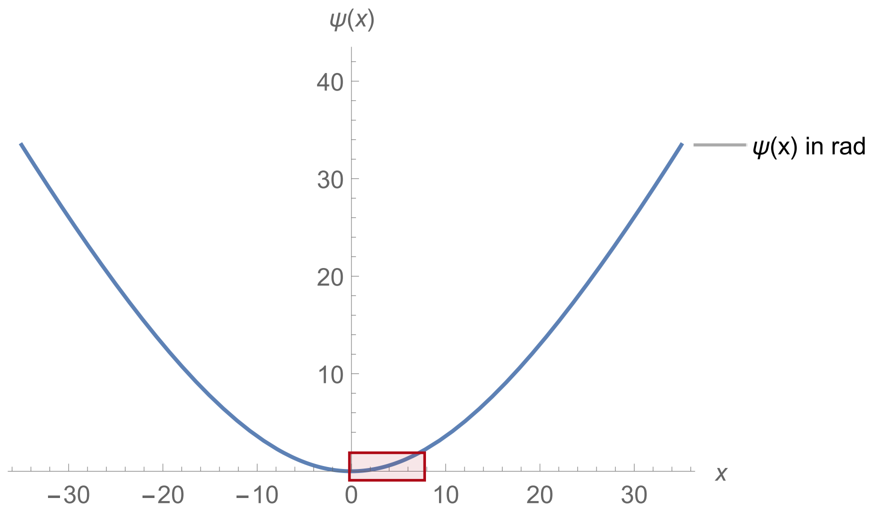


$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}) = \mathcal{B}(\boldsymbol{\rho}' \mapsto \boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}'))(\boldsymbol{\rho}) = \int\int_{X \subset X^{\text{in}}} \mathbf{B}(\boldsymbol{\rho}, \boldsymbol{\rho}')\boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\,\mathrm{d}x'\,\mathrm{d}y'$$

with the matrix integral kernel $\mathbf{B}(\boldsymbol{\rho}, \boldsymbol{\rho}') : \mathbb{R}^2 \times \mathbb{R}^2 \to \mathbb{C}^{3\times 3}$

What Allows Flat Optics to Work?

Example 1D wavefront phase



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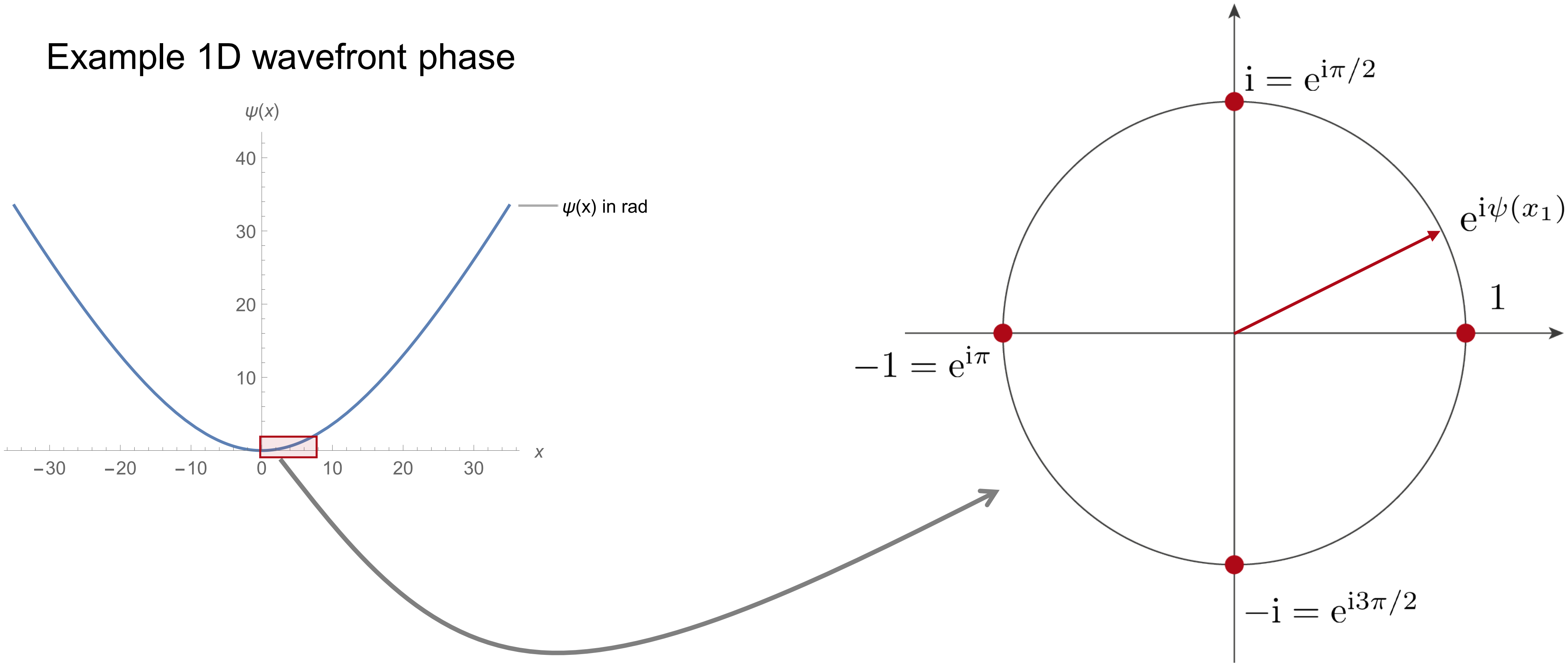
Example 1D wavefront phase



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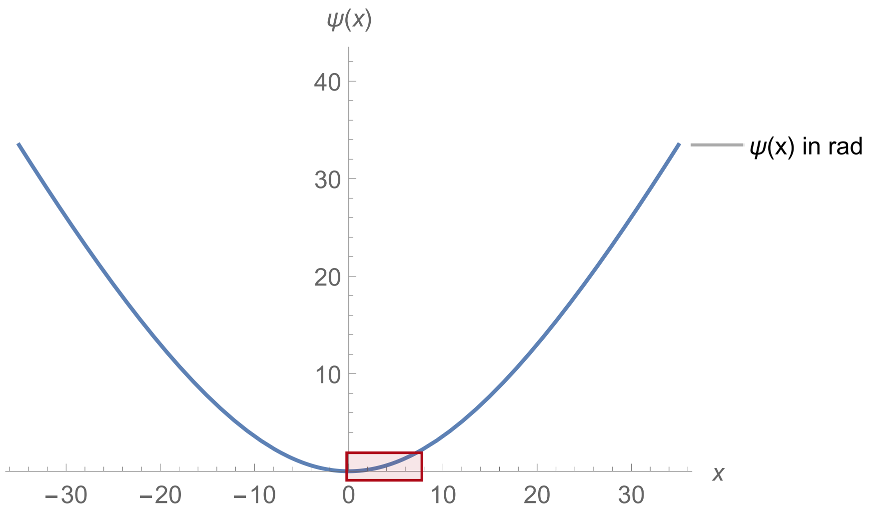

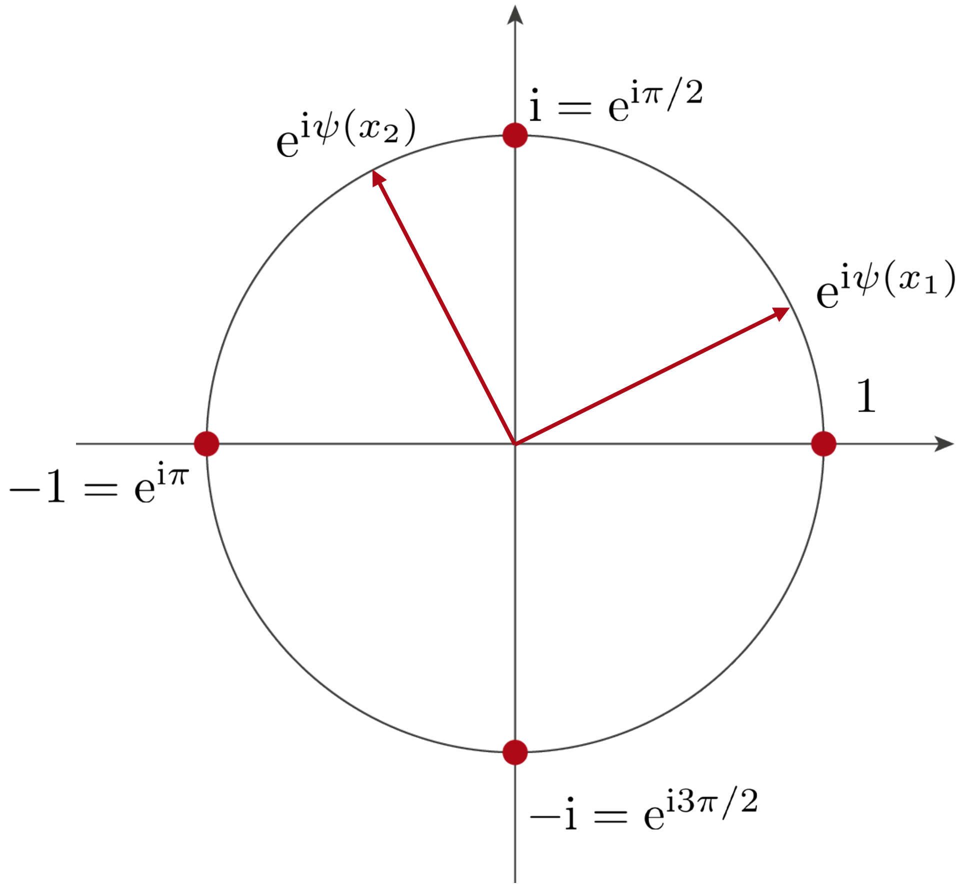

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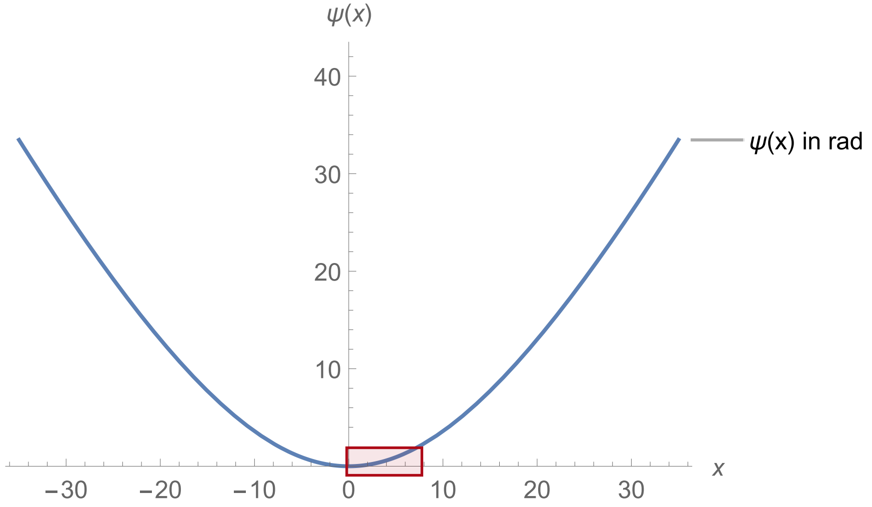

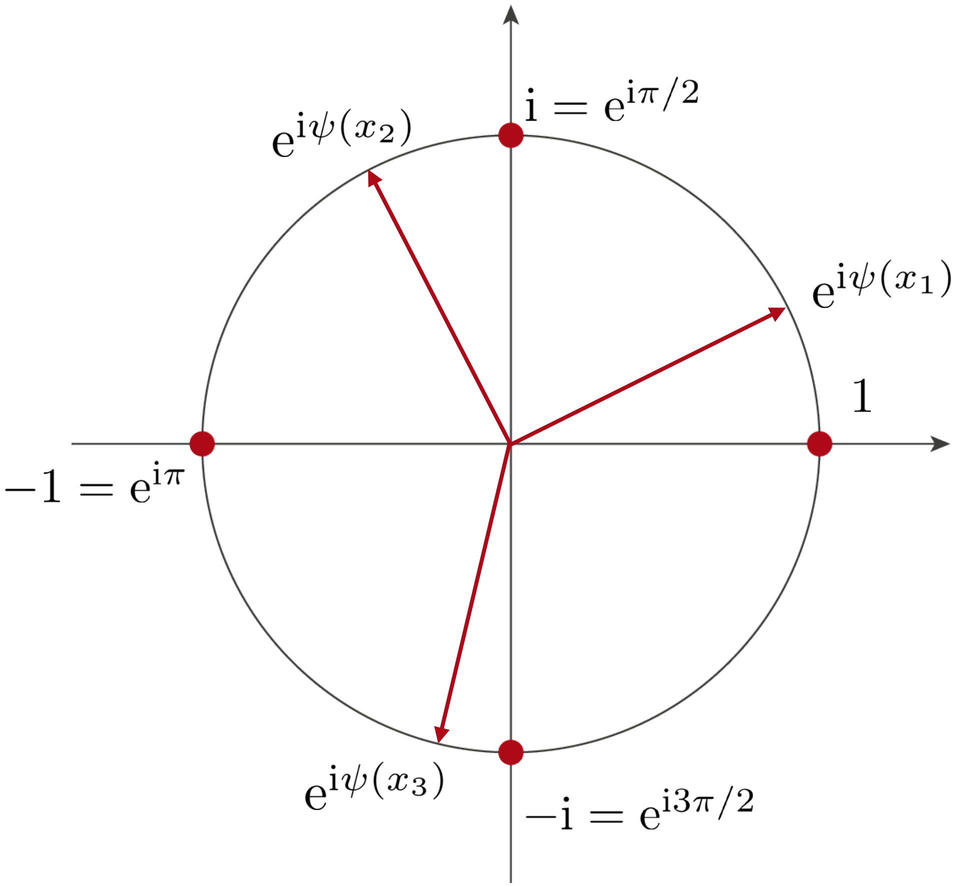

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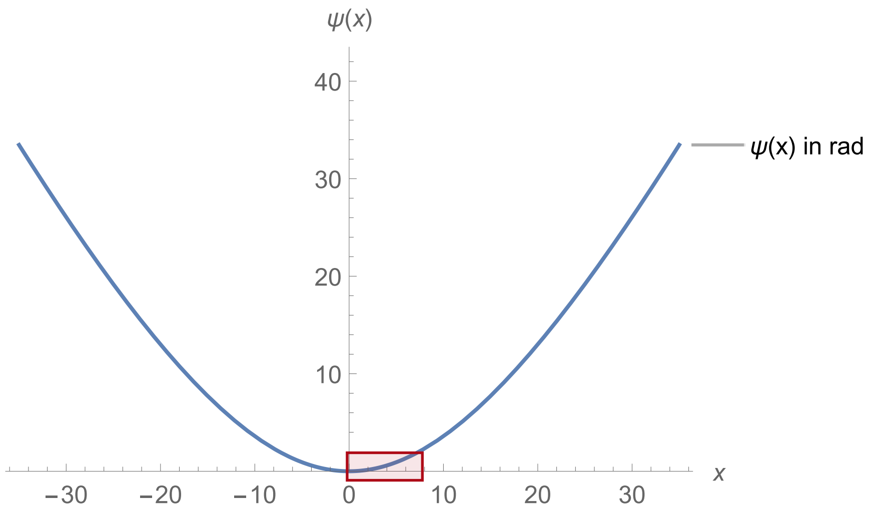

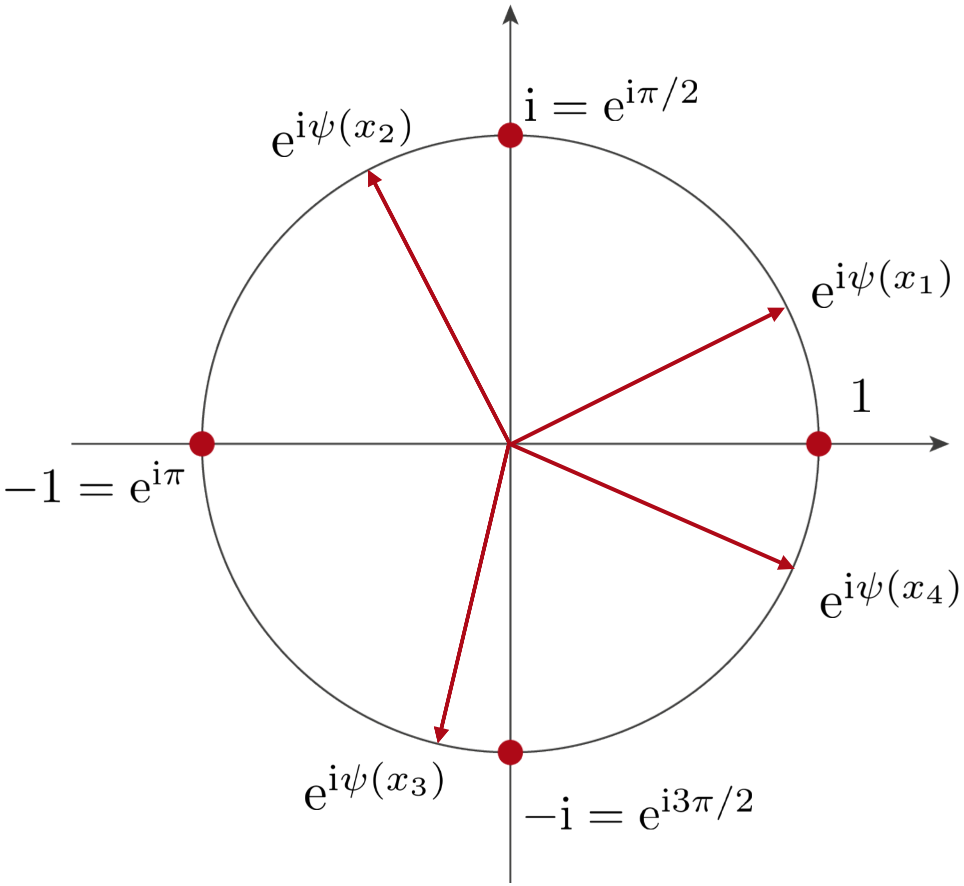

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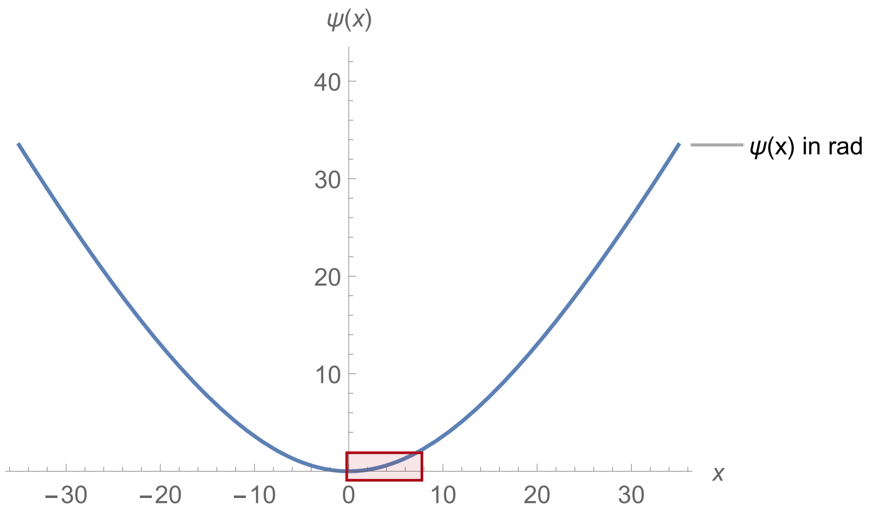

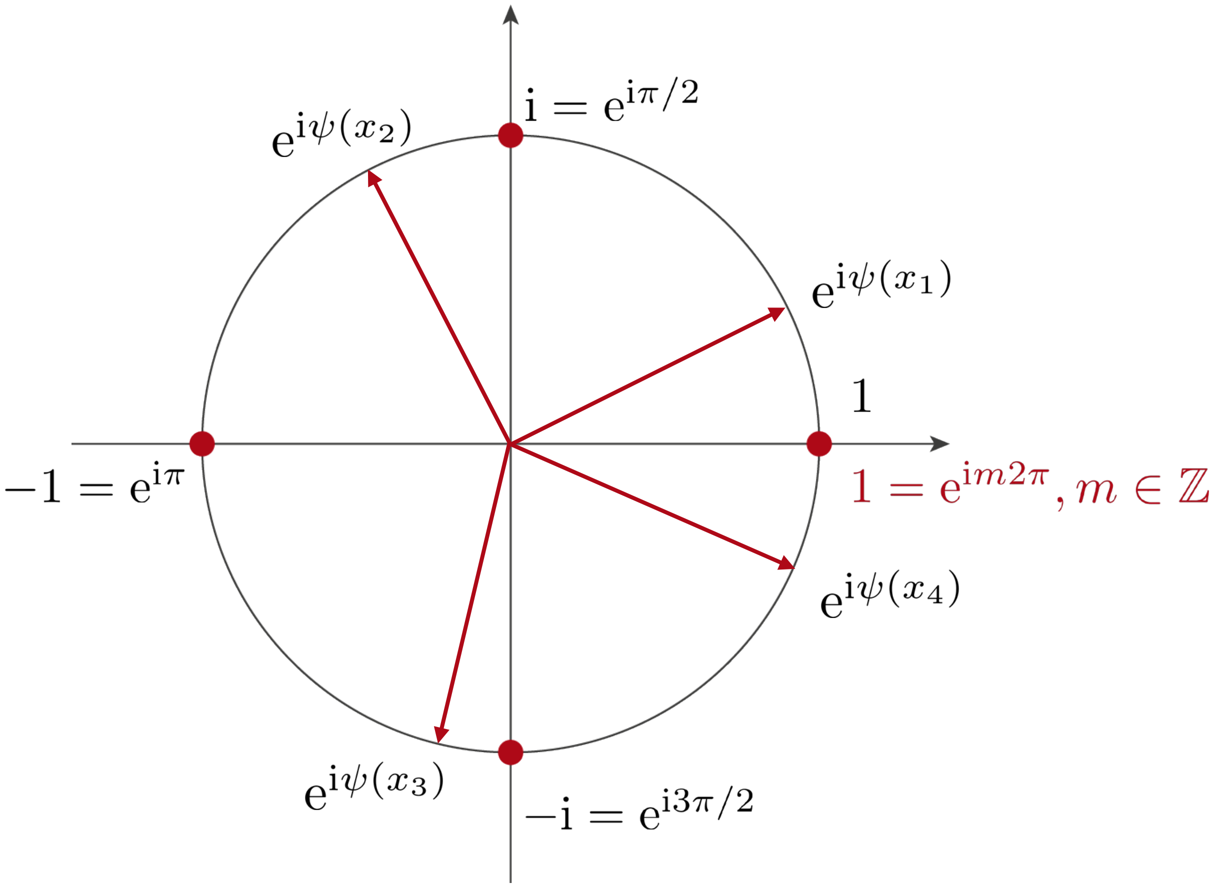

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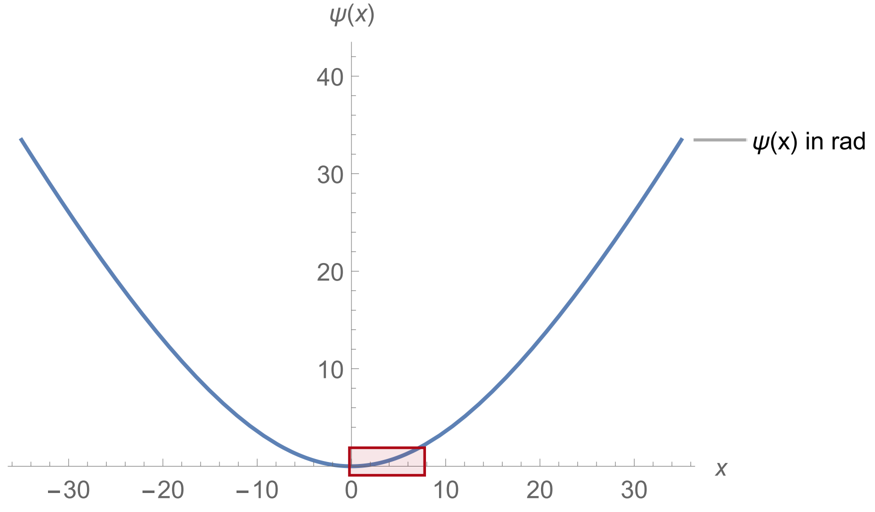
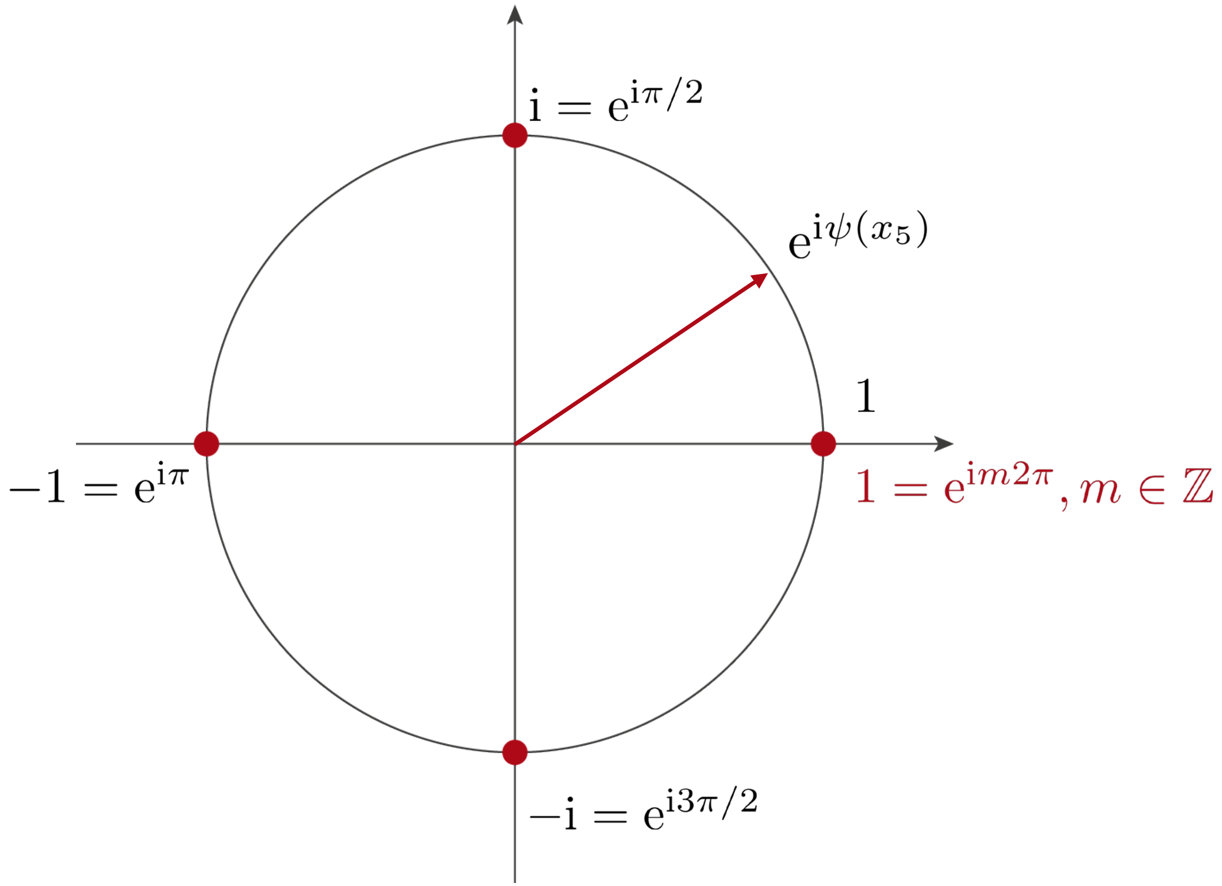
Example 1D wavefront phase





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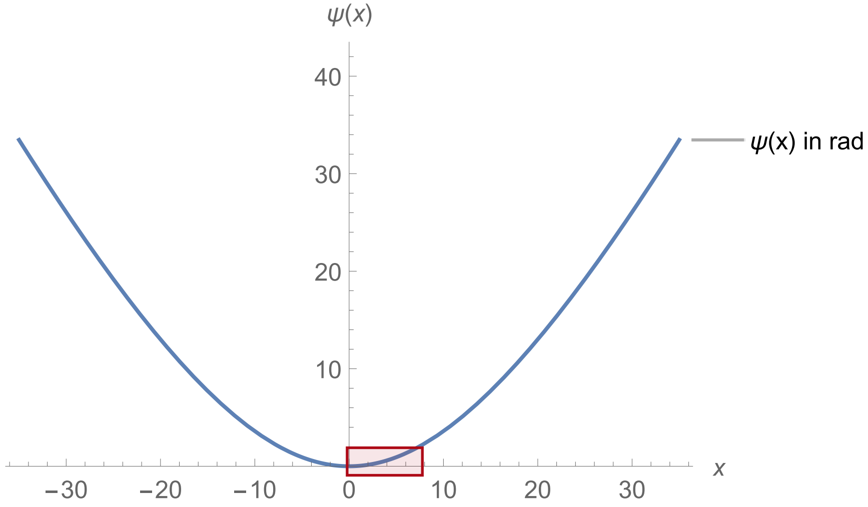

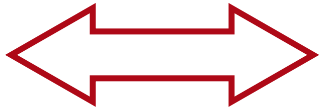

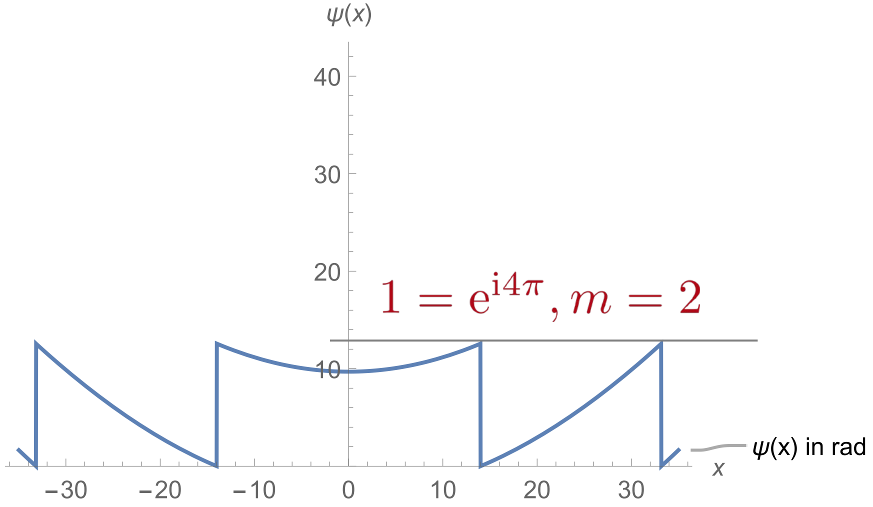

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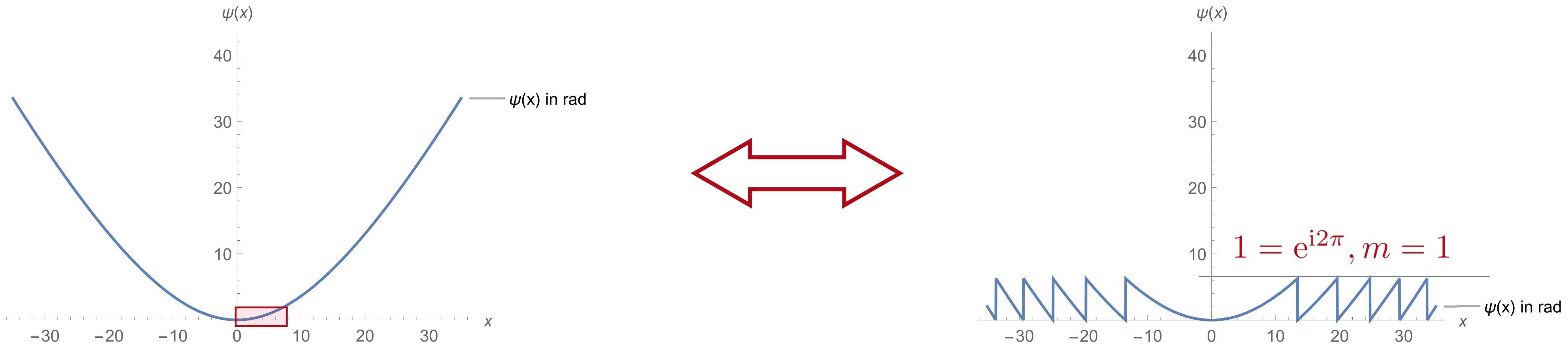
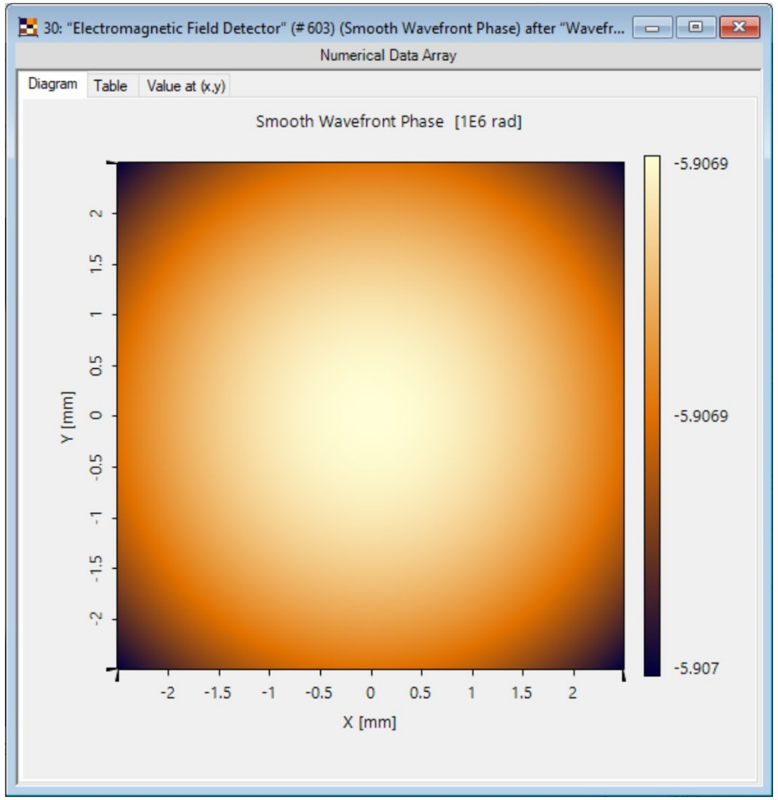
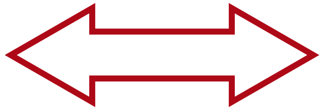
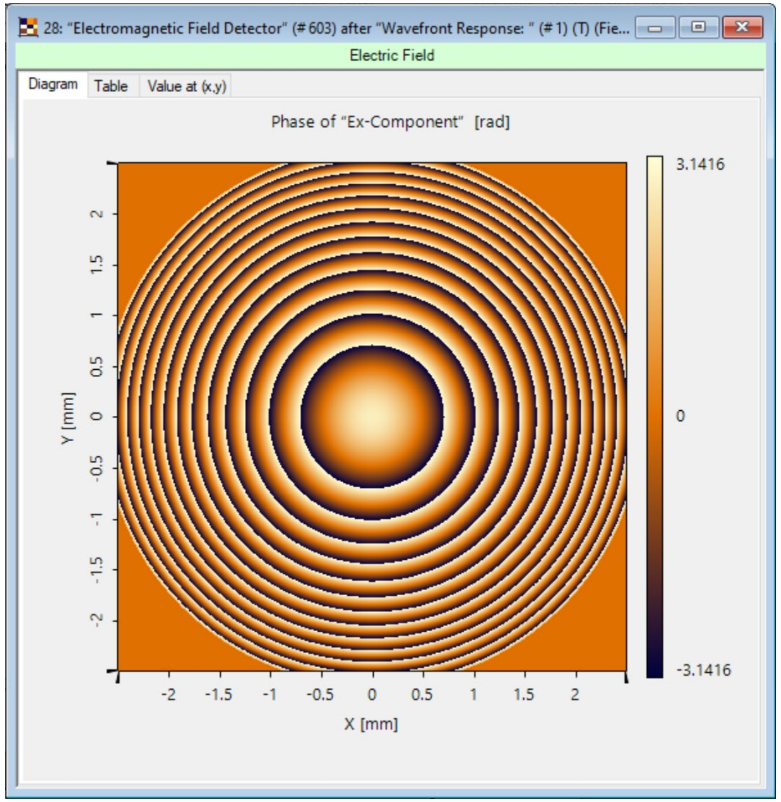


What Allows Flat Optics to Work?

$$1 = e^{i2\pi}, m = 1$$







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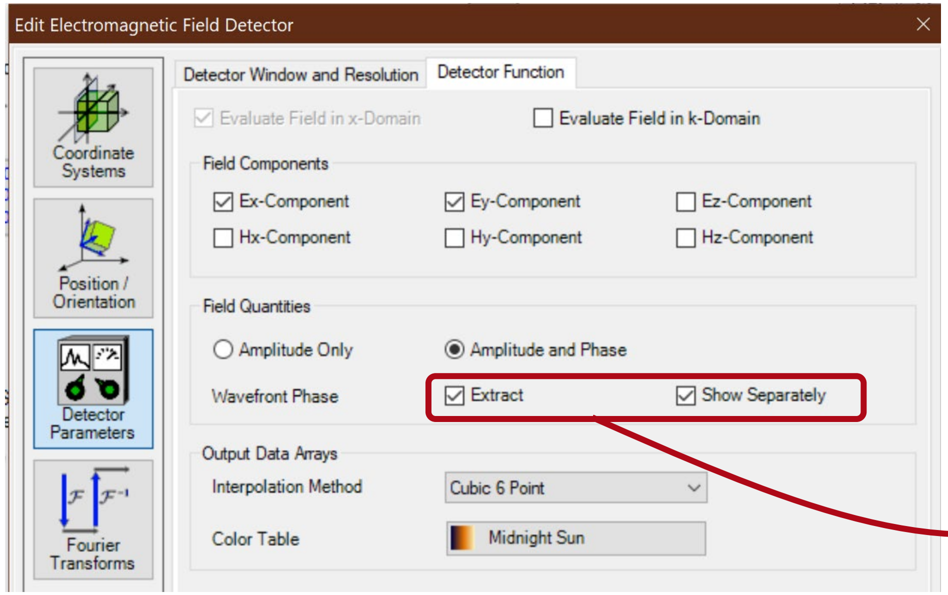

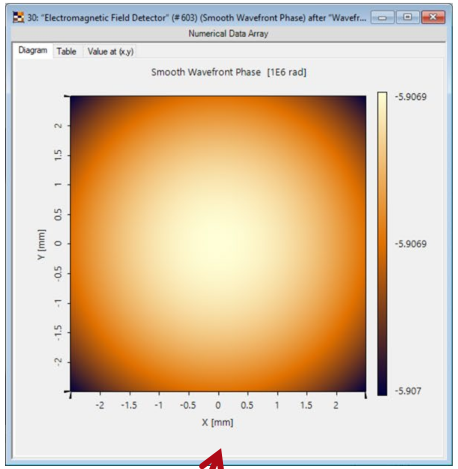

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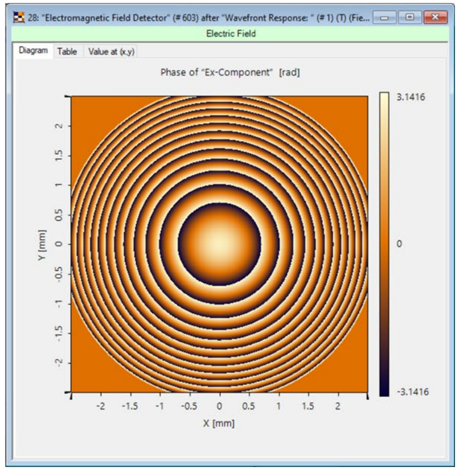
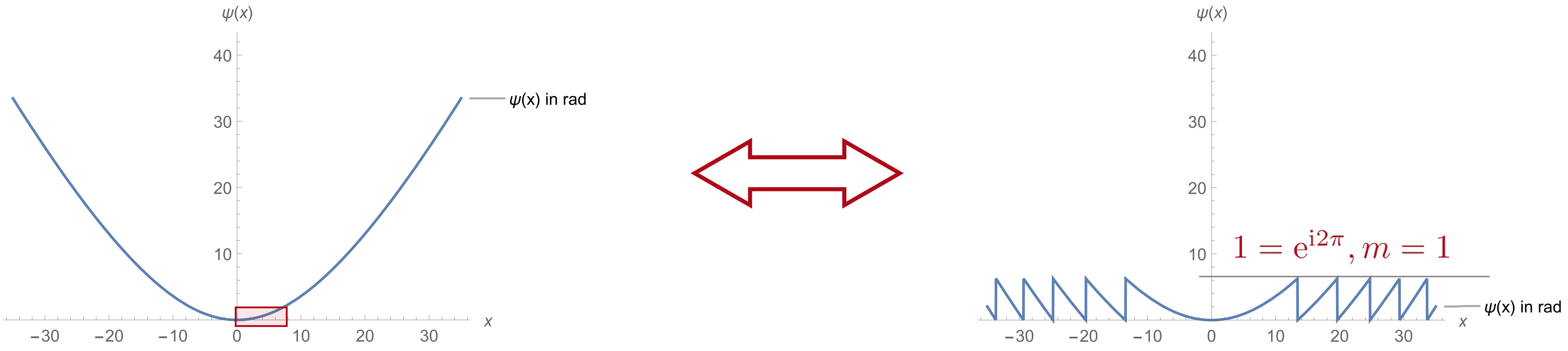


In algorithms of VirtualLab Fusion wavefront phase separated from sampling of complex field amplitudes wherever possible.

One important reason for FAST physical optics modeling.

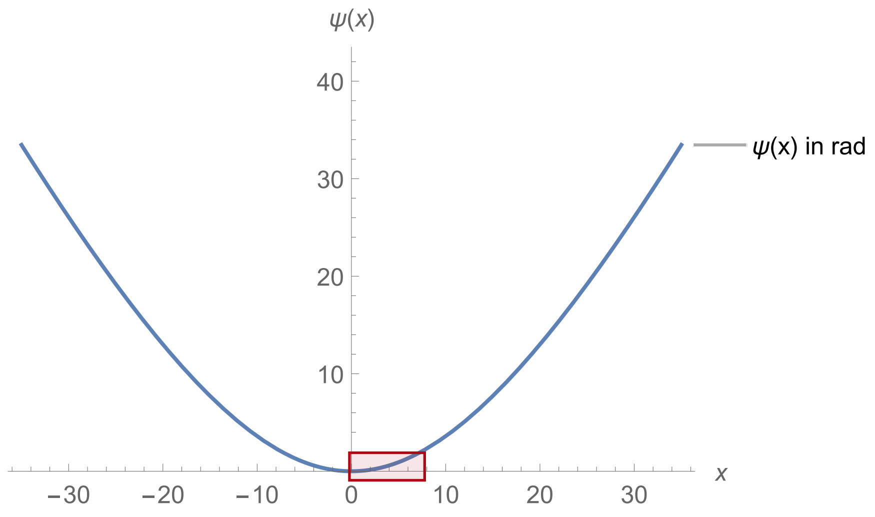
What Allows Flat Optics to Work?

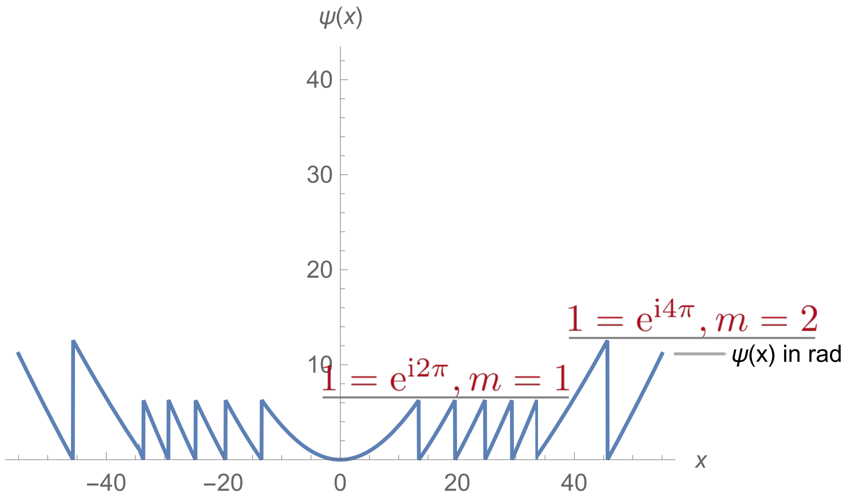
Example 1D wavefront phase



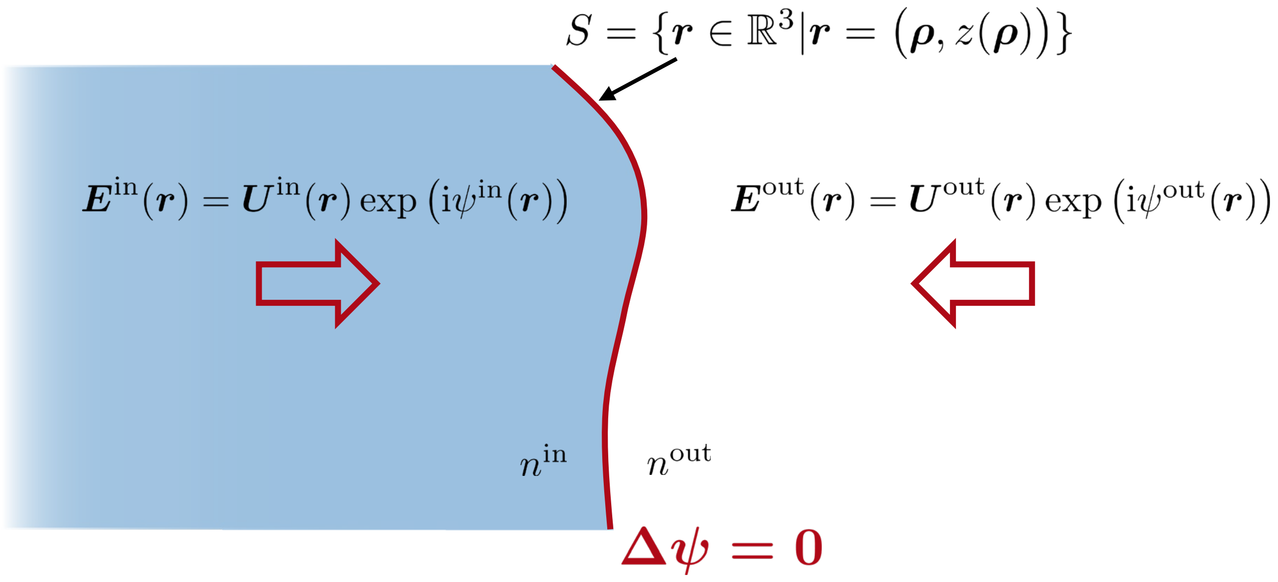
Segmented Phase Manipulation

Example 1D wavefront phase





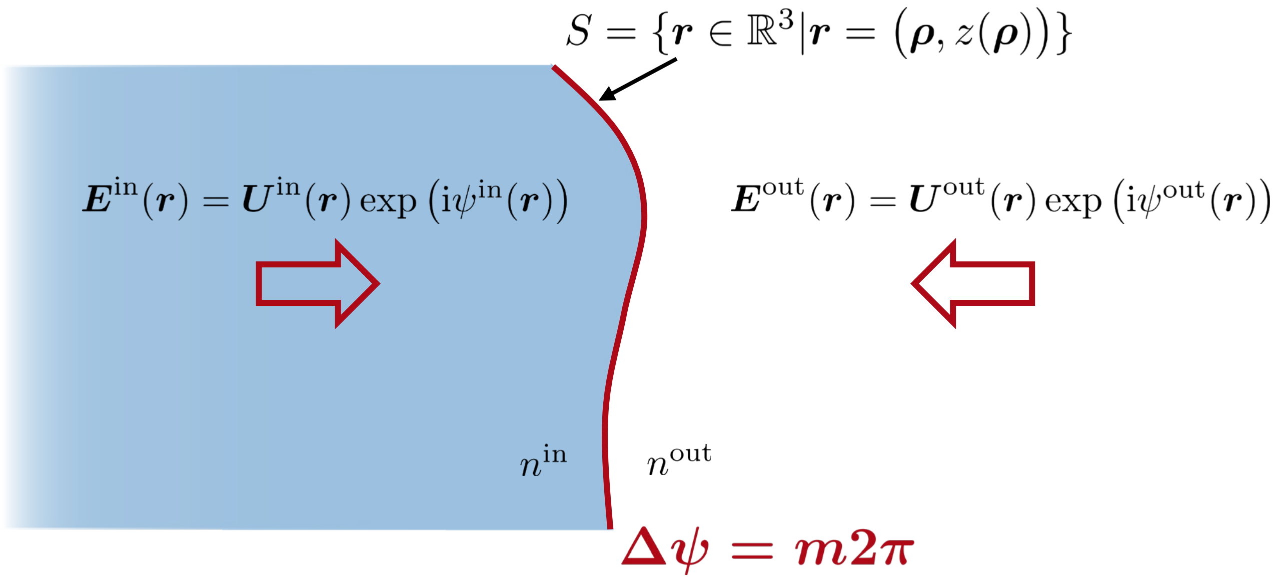
Freeform Surface Design: Inverse Propagation



Calculate the surface $S \subset \mathbb{R}^3$ on which:

$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \boxed{\Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} 0}$$

Segmented Surface Design: Inverse Propagation



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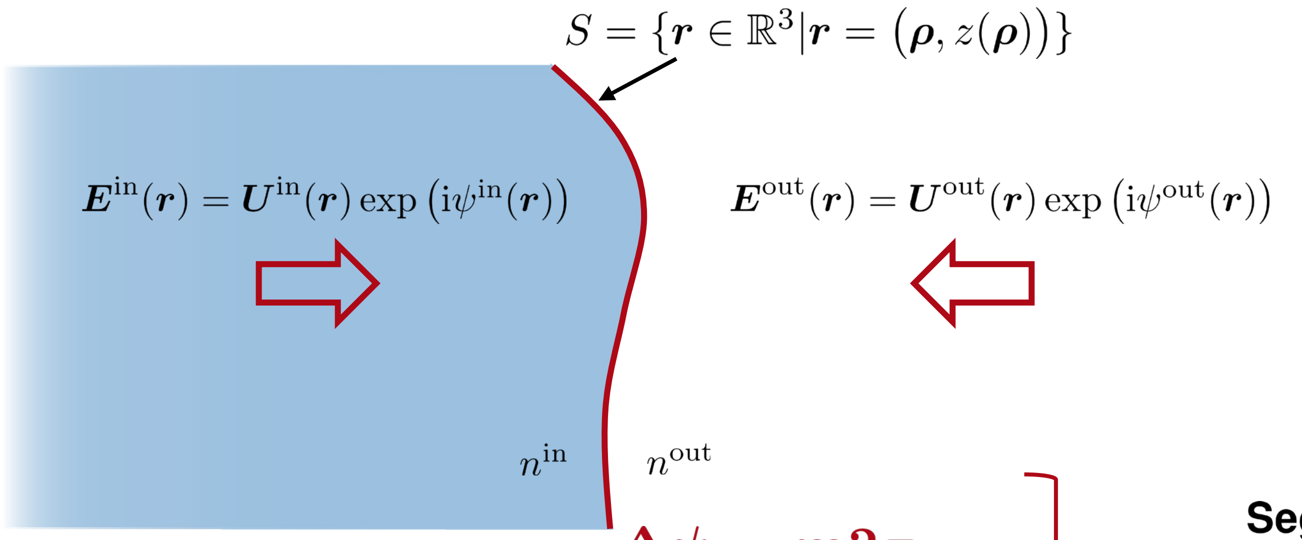

$$\boldsymbol{\Delta\psi = m2\pi}$$

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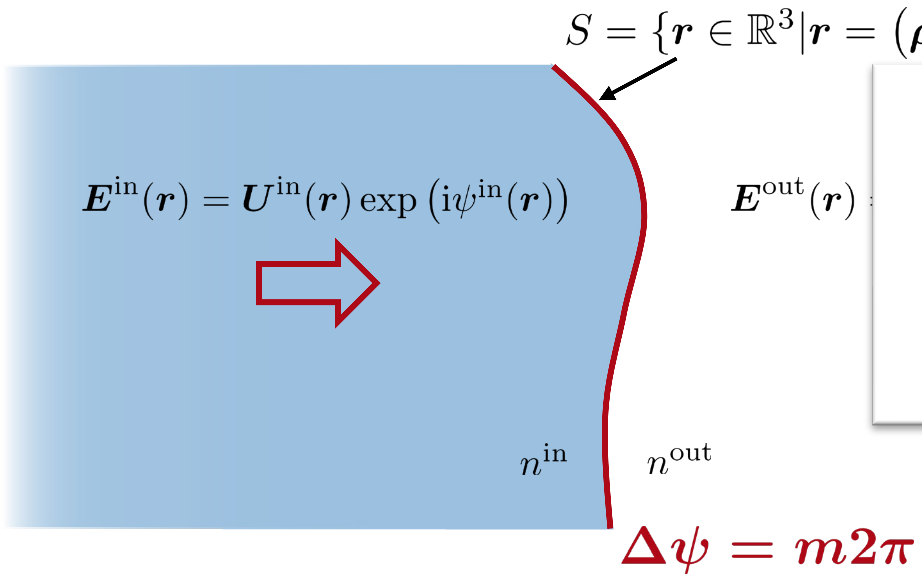
Segmented Elements:

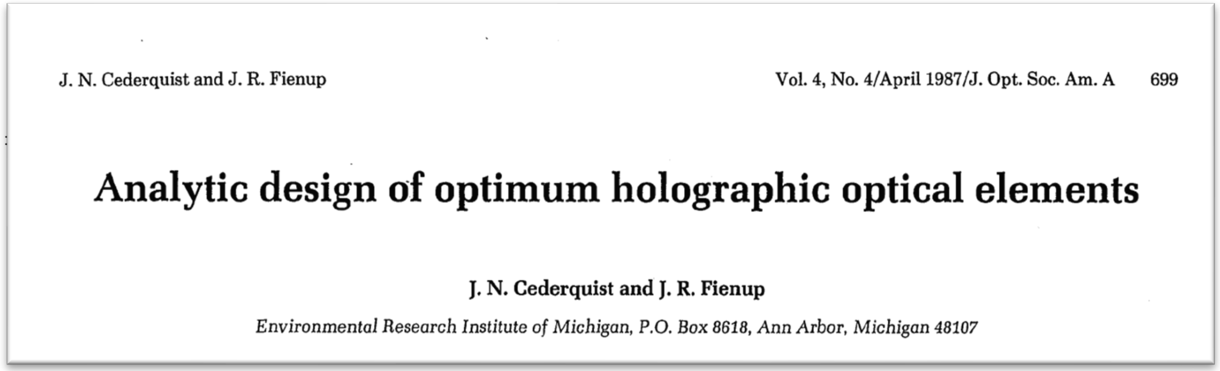
Surface designs with different m can be done in different regions of the element.

Holographic Optical Elements (HOE):

2π-modulo operation on wavefront phase and surface design per resulting zone.

Segmented Surface Design: Inverse Propagation





J. N. Cederquist and J. R. Fienup — Vol. 4, No. 4/April 1987/J. Opt. Soc. Am. A — 699

Analytic design of optimum holographic optical elements

J. N. Cederquist and J. R. Fienup

Environmental Research Institute of Michigan, P.O. Box 8618, Ann Arbor, Michigan 48107

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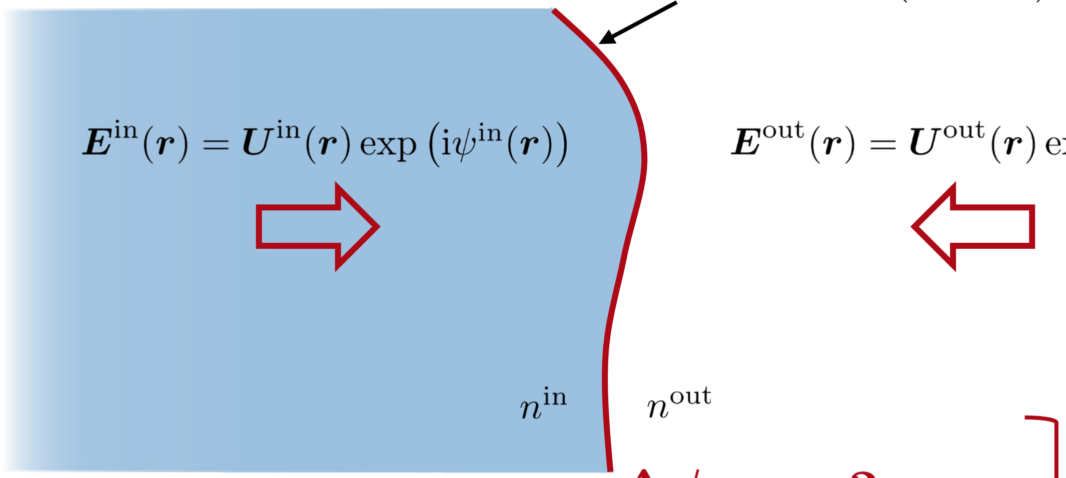
Segmented Surface Design: Inverse Propagation

$$S = \{\boldsymbol{r} \in \mathbb{R}^3 | \boldsymbol{r} = (\boldsymbol{\rho}, z(\boldsymbol{\rho}))\}$$



$$\boldsymbol{E}^{\text{in}}(\boldsymbol{r}) = \boldsymbol{U}^{\text{in}}(\boldsymbol{r}) \exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{r})\right)$$

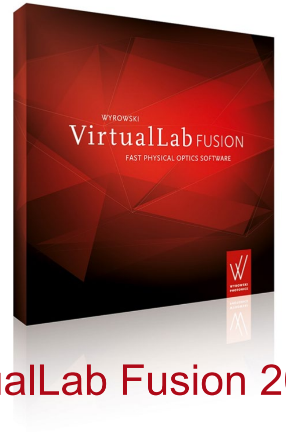
$$\boldsymbol{E}^{\text{out}}(\boldsymbol{r}) = \boldsymbol{U}^{\text{out}}(\boldsymbol{r}) \exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{r})\right)$$

n^{in} n^{out}

$$\boldsymbol{\Delta\psi = m2\pi}$$

Calculate the surface $S \subset \mathbb{R}^3$ on which:

$$\psi^{\text{out}}(\boldsymbol{r} \in S) - \psi^{\text{in}}(\boldsymbol{r} \in S) = \boxed{\Delta\psi(\boldsymbol{r} \in S) \overset{!}{=} m2\pi}$$



VirtualLab Fusion 2021

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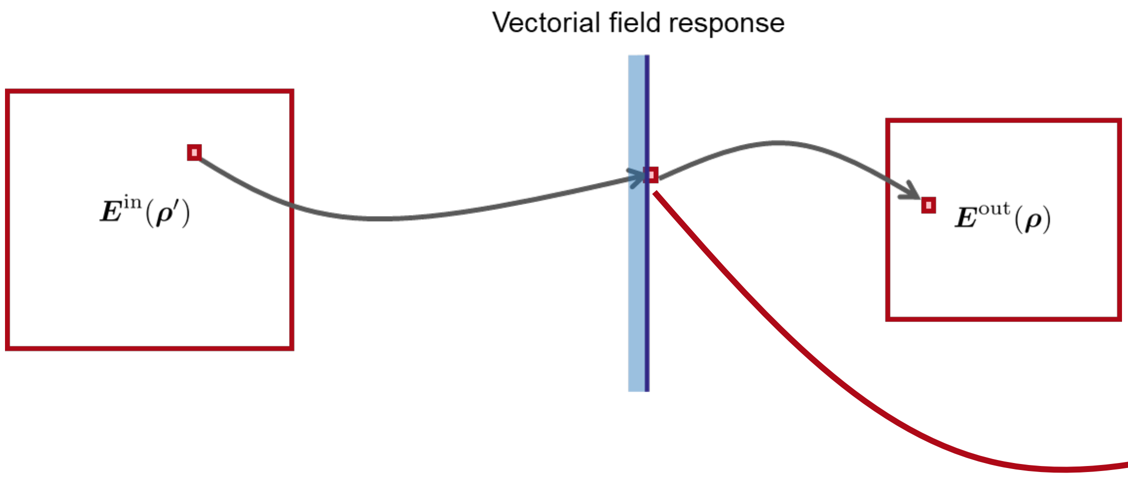
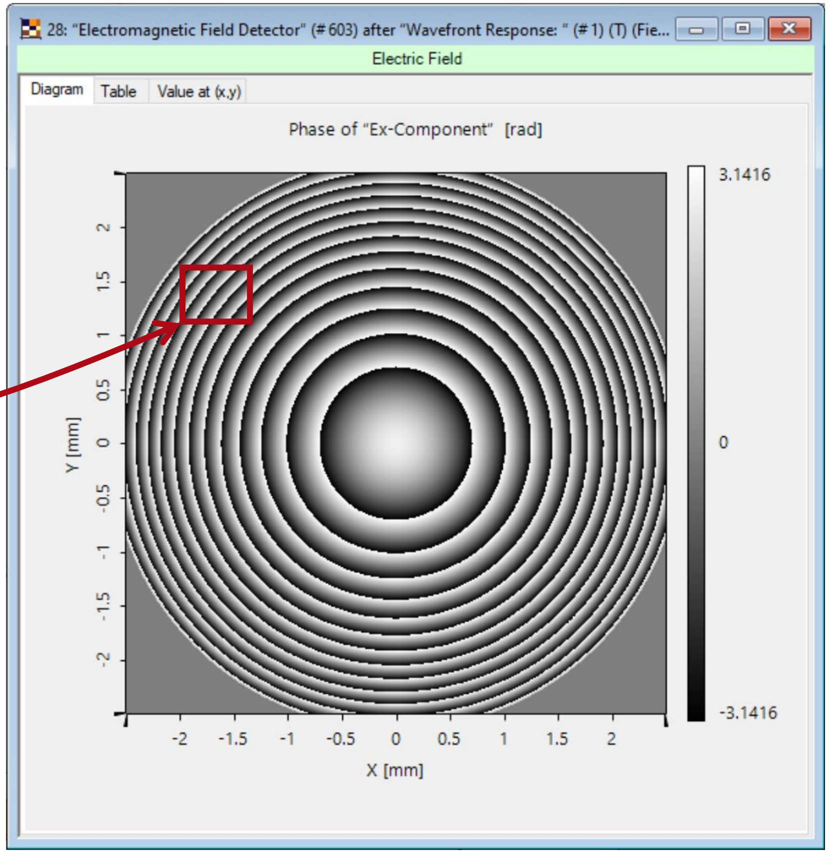
Field Response HOE

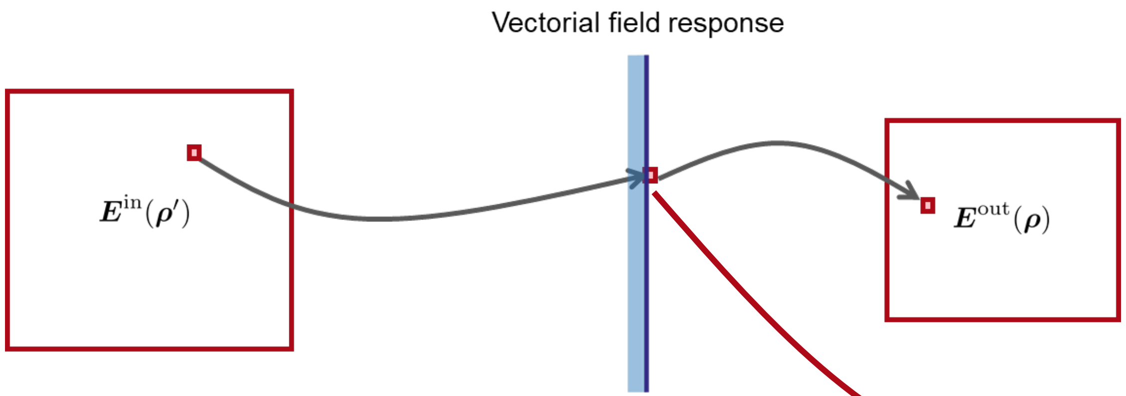


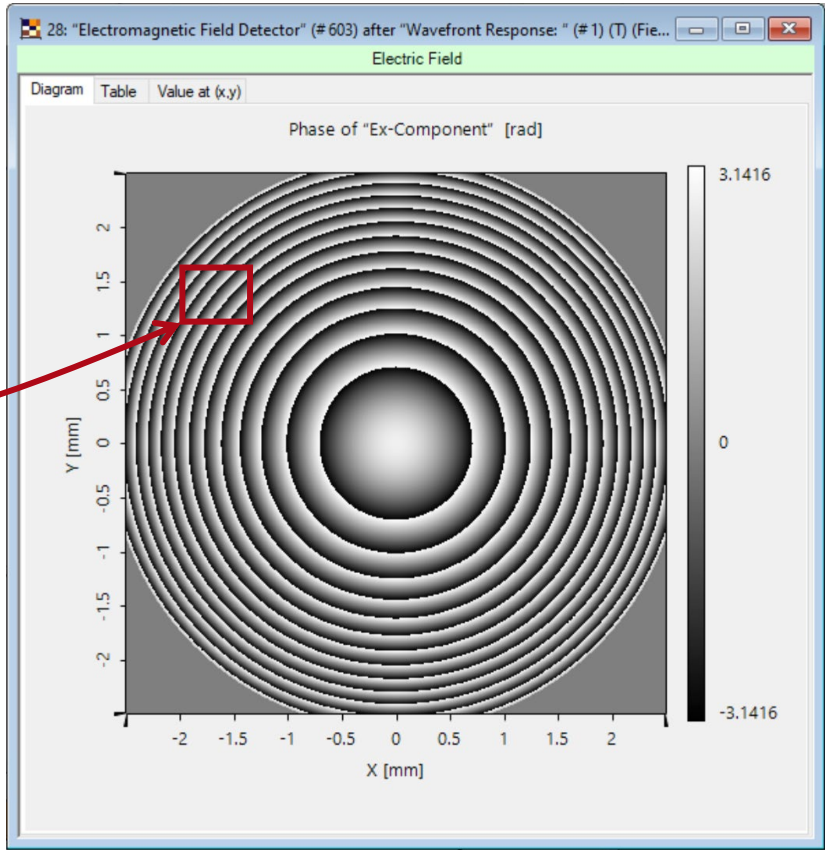


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')U^{\text{in}}(\boldsymbol{\rho}') \mapsto U^{\text{out}}(\boldsymbol{\rho})$

U-field response dependent on type of flat optics

Field Response HOE

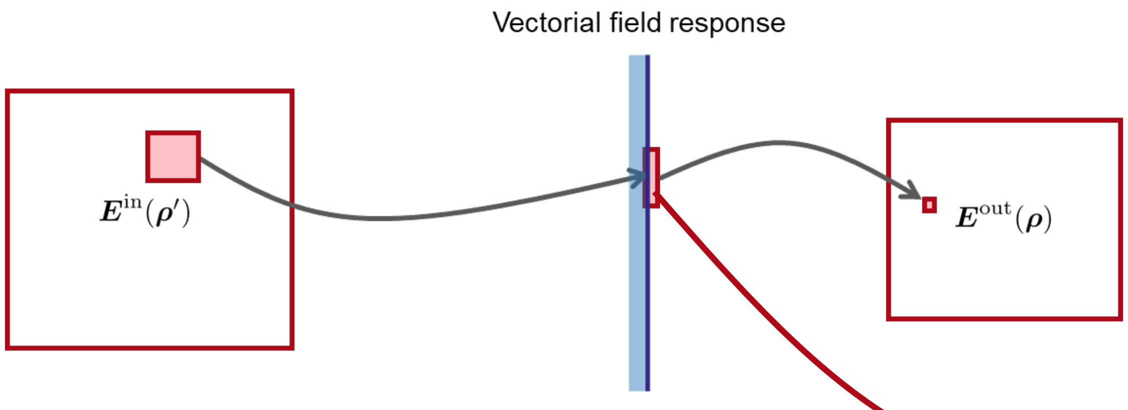




U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')U^{\text{in}}(\boldsymbol{\rho}') \mapsto U^{\text{out}}(\boldsymbol{\rho})$

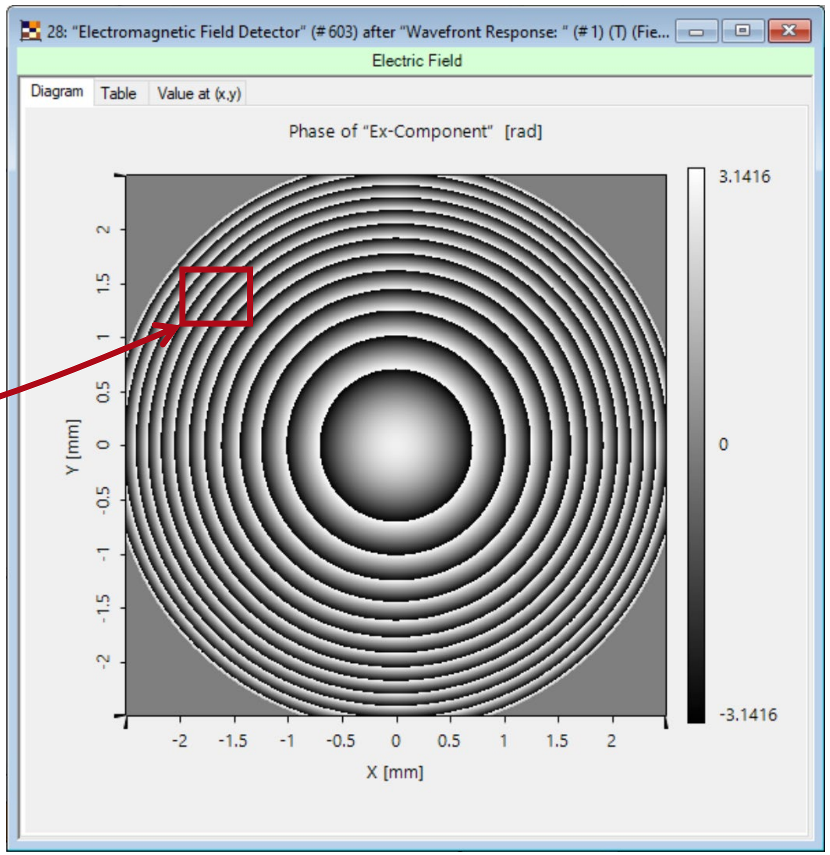
Jumps between zones introduce diffraction effects.

Field Response HOE

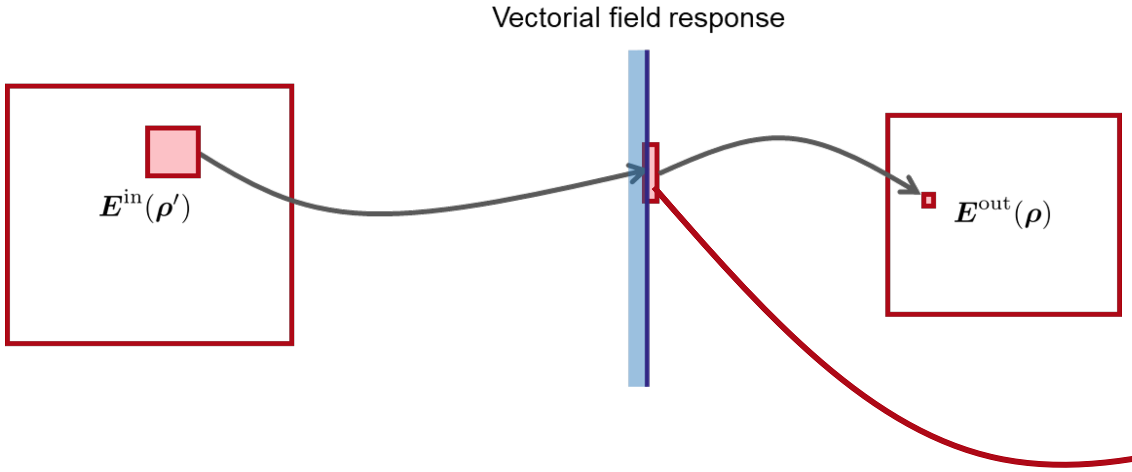


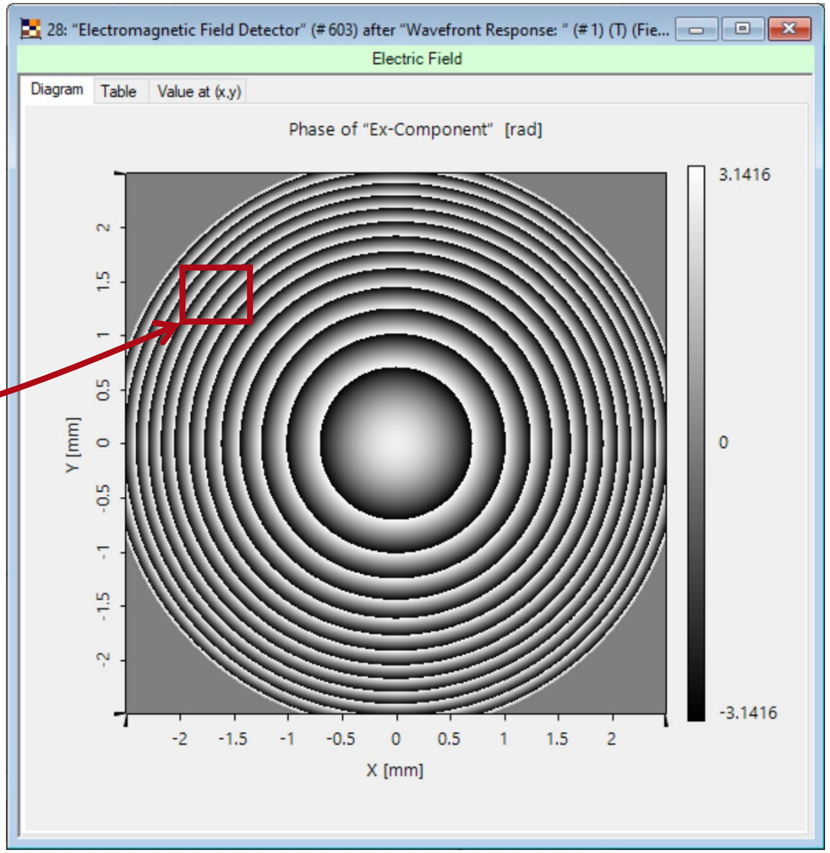
U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')U^{in}(\boldsymbol{\rho}') \mapsto U^{out}(\boldsymbol{\rho})$

Jumps between zones introduce diffraction effects.



Field Response HOE: LLGA



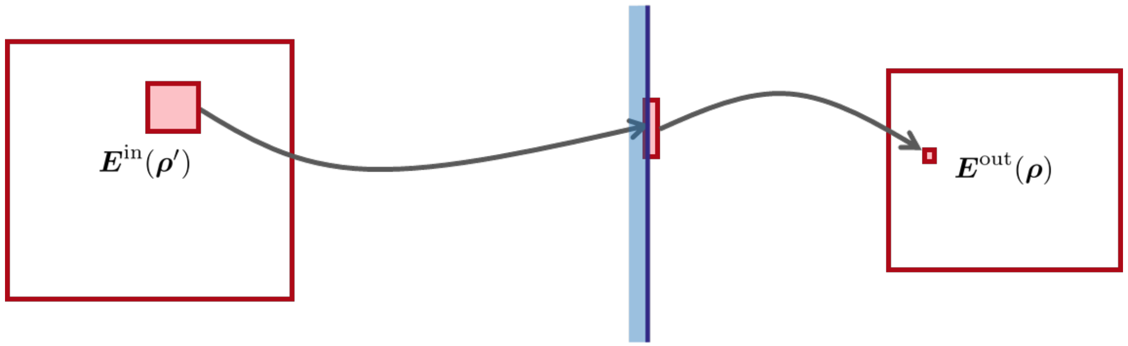


U-field response: $\underline{\mathbf{b}}(\rho')U^{\mathrm{in}}(\rho') \mapsto U^{\mathrm{out}}(\rho)$

U-field response in outer zones is affected by the neighborhood in structure: **local grating**

Field response must be calculated by local application of the rigorous Fourier Modal Method (FMM) to include all effects:
Local Linear Grating Approach (LLGA)

Field Response HOE: LLGA



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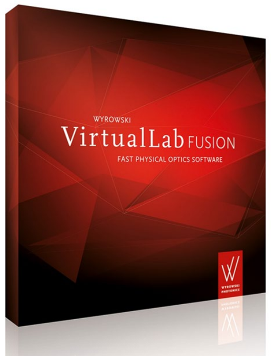
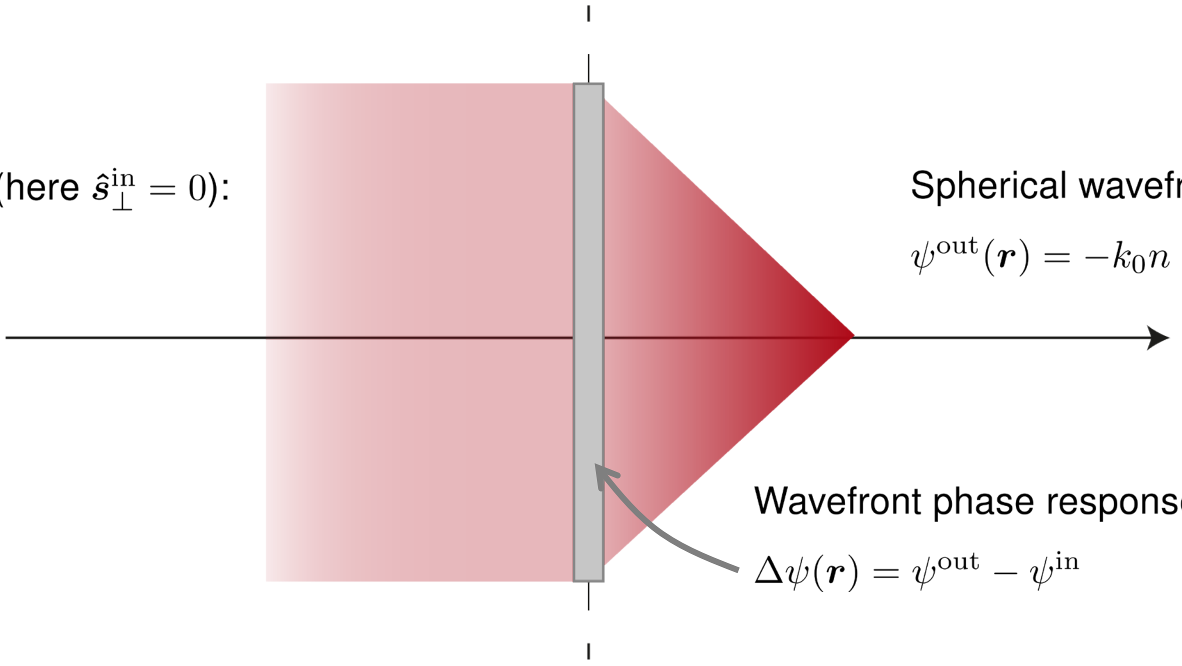


VirtualLab Fusion 2021

Diffractive Focusing Lens: Structural Design

Planar input wavefront phase (here $\hat{\boldsymbol{s}}_\perp^{\text{in}} = 0$):

$\psi^{\text{in}}(\boldsymbol{r}) = k_0 n\, \hat{\boldsymbol{s}}_\perp^{\text{in}}(\alpha) \cdot \boldsymbol{\rho}$

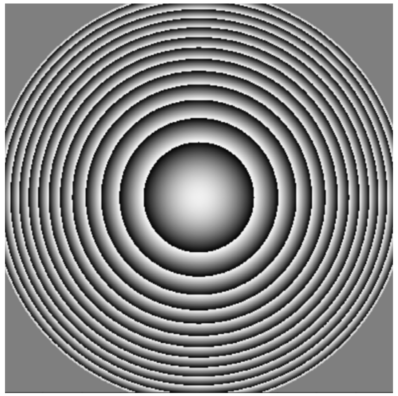


Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

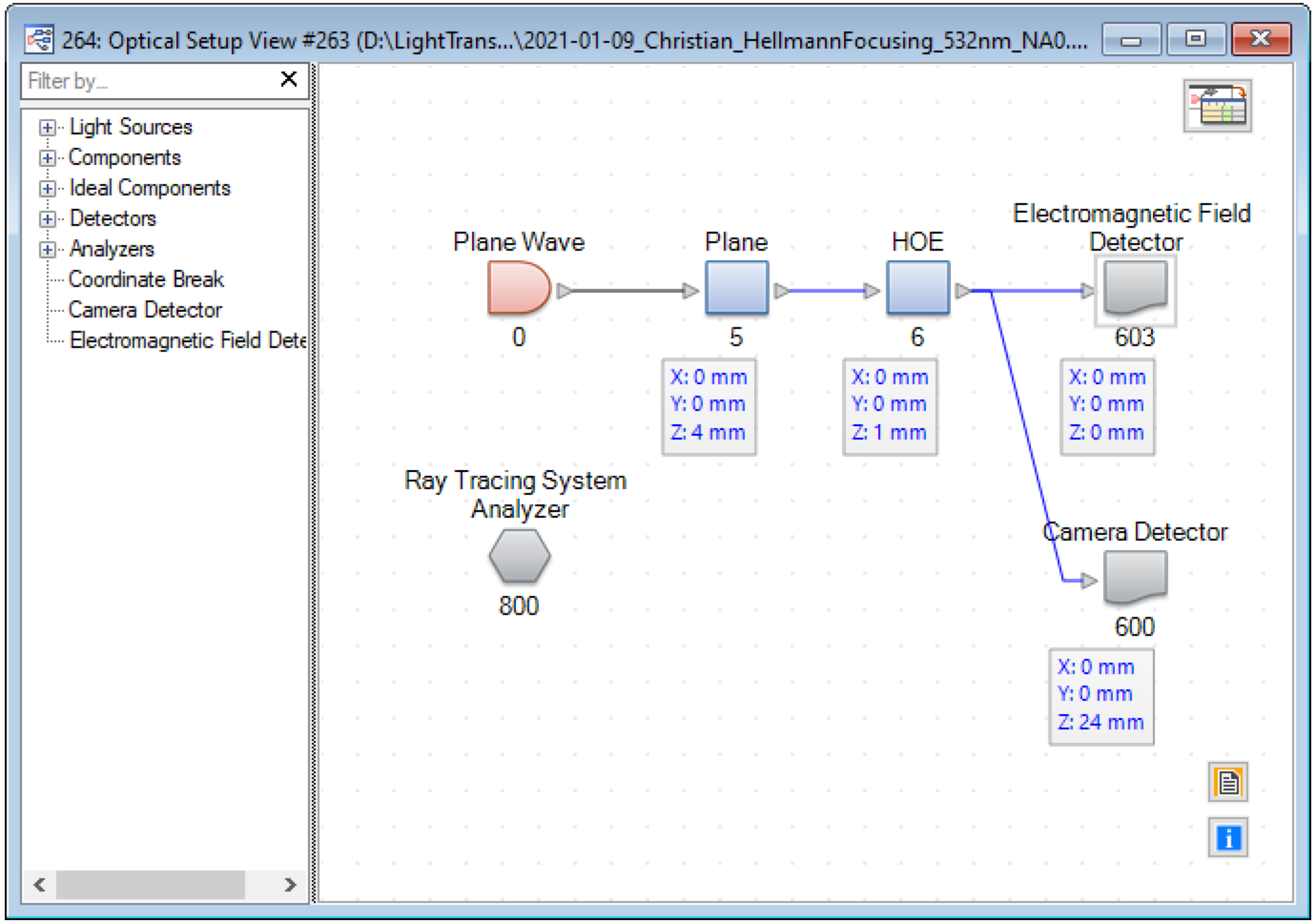
$\psi^{\text{out}}(\boldsymbol{r}) = -k_0 n \sqrt{\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{out}}(\alpha)\|^2 + f^2}$

Wavefront phase response function:

$\Delta\psi(\boldsymbol{r}) = \psi^{\text{out}} - \psi^{\text{in}}$

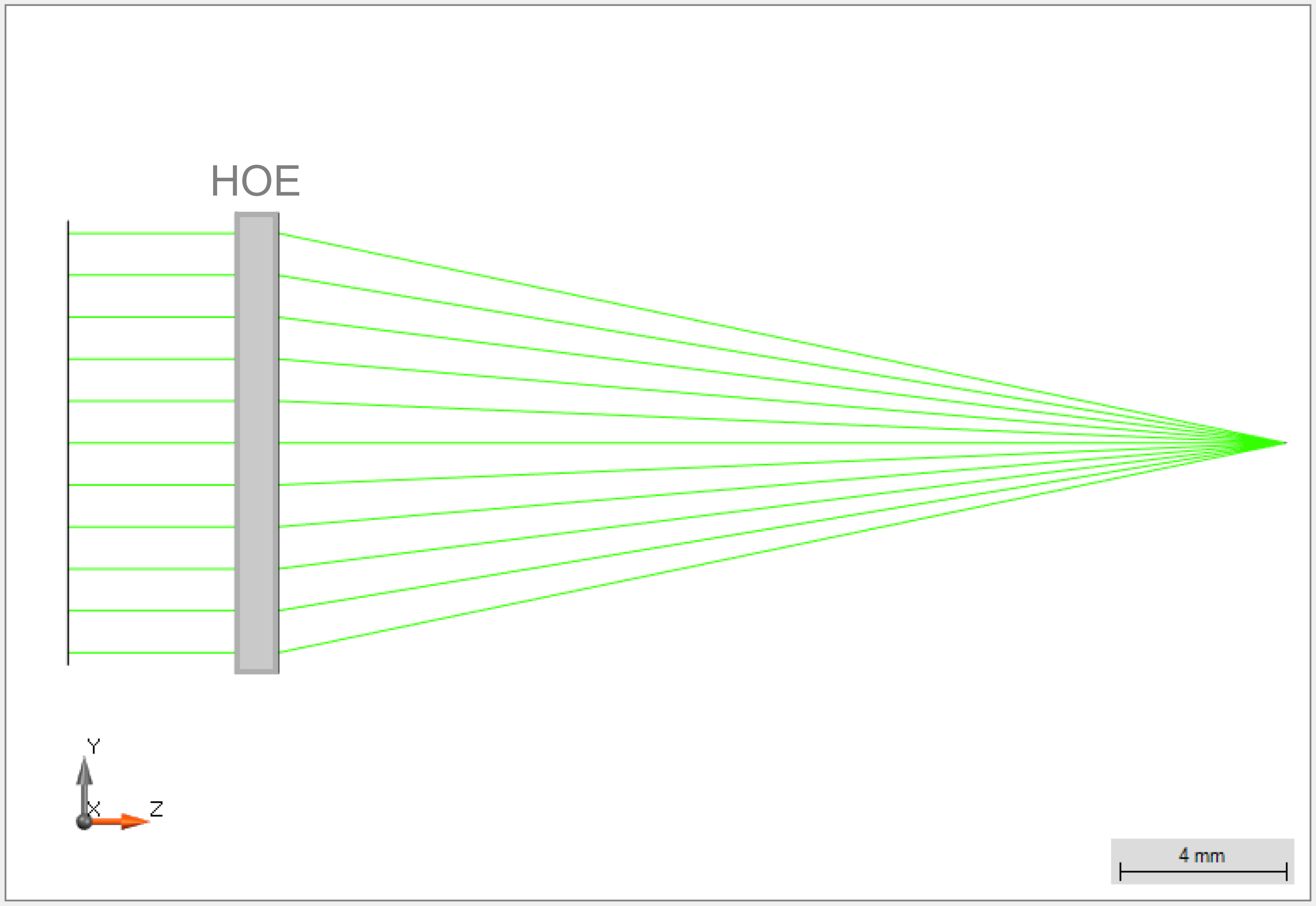


Structural Design Focusing (NA = 0.2): HOE

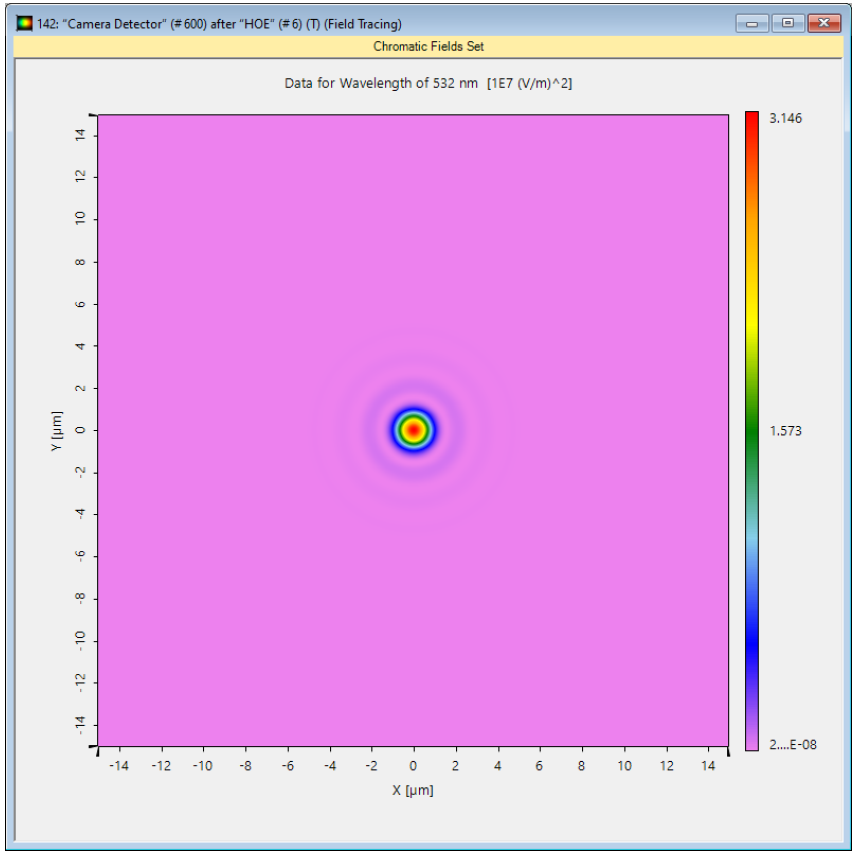


HOE surface: 8 Levels

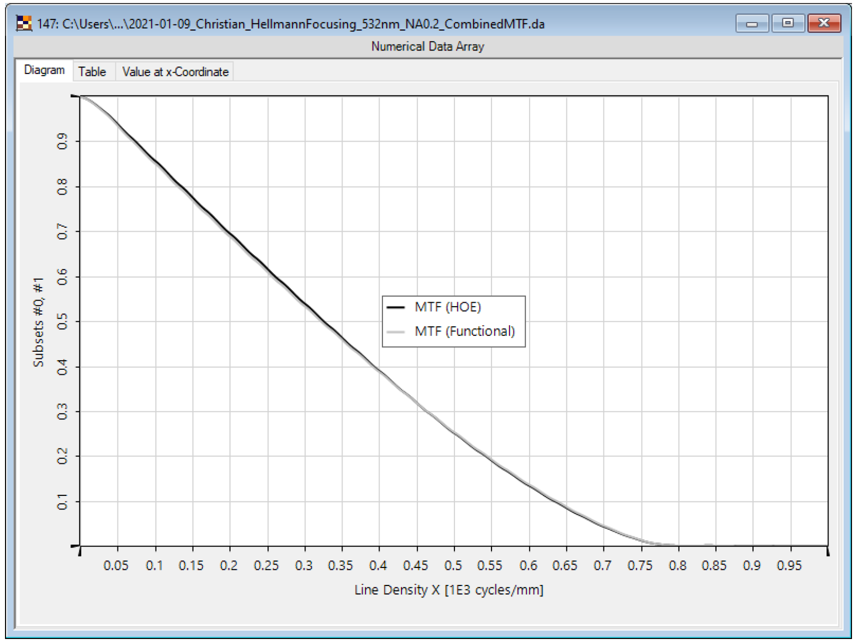
Focusing (NA = 0.2) HOE: Ray Tracing



Focusing (NA = 0.2) HOE: Field Tracing



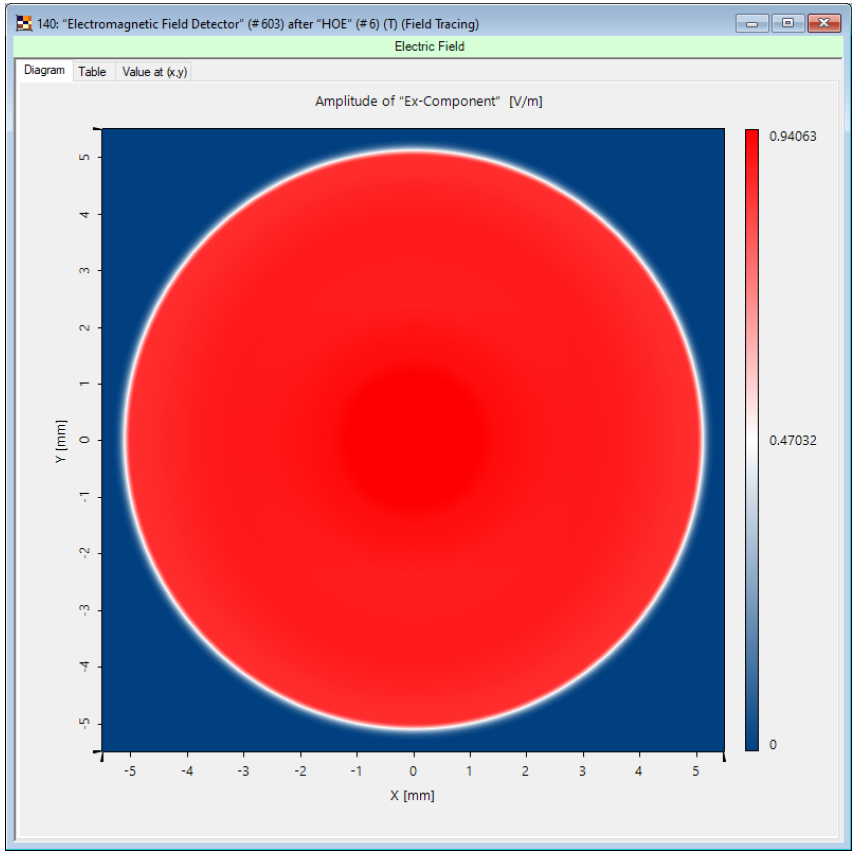
Field in Focus (False Color)



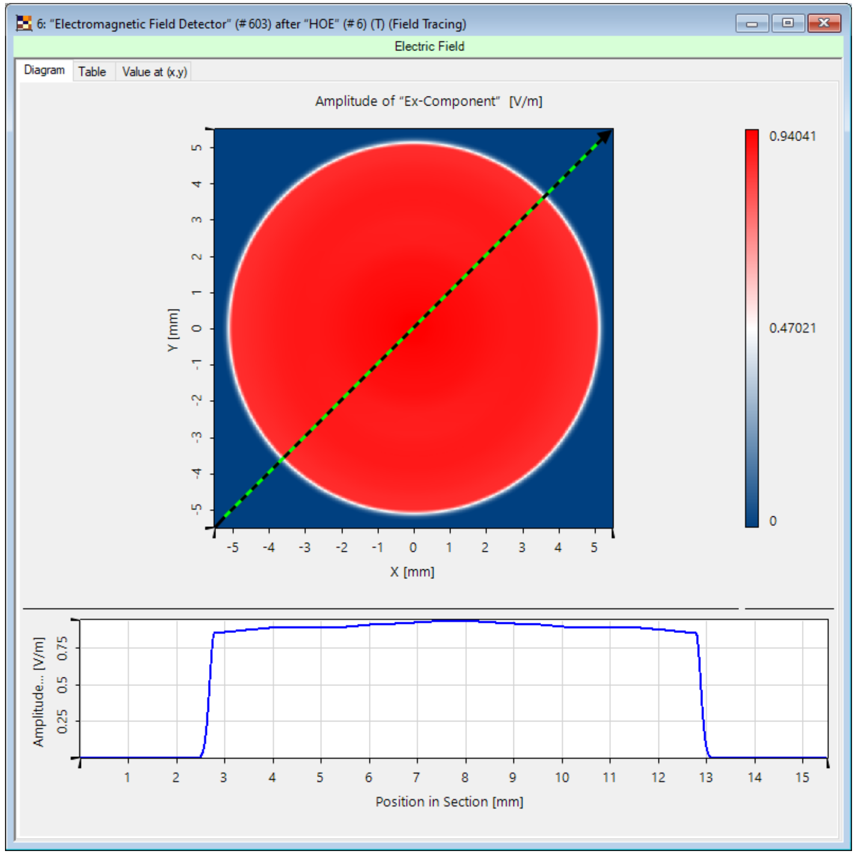
MTF

Efficiency: 78.99% (Efficiency after First Plane: 96.5%)

Focusing (NA = 0.2) HOE: Field Tracing

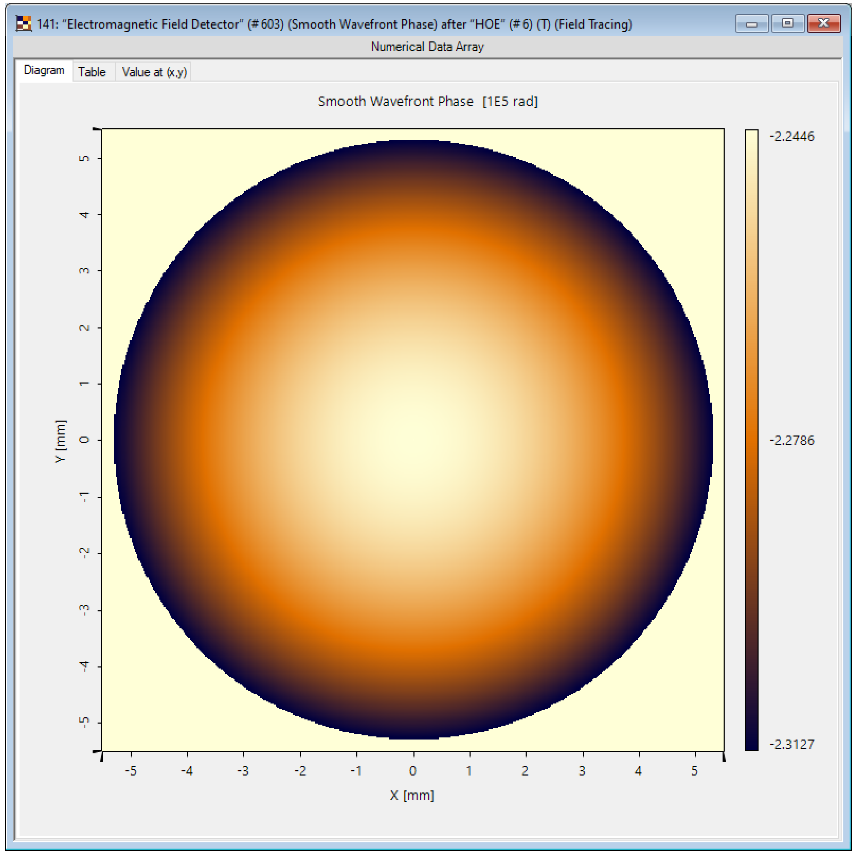


Amplitude after HOE

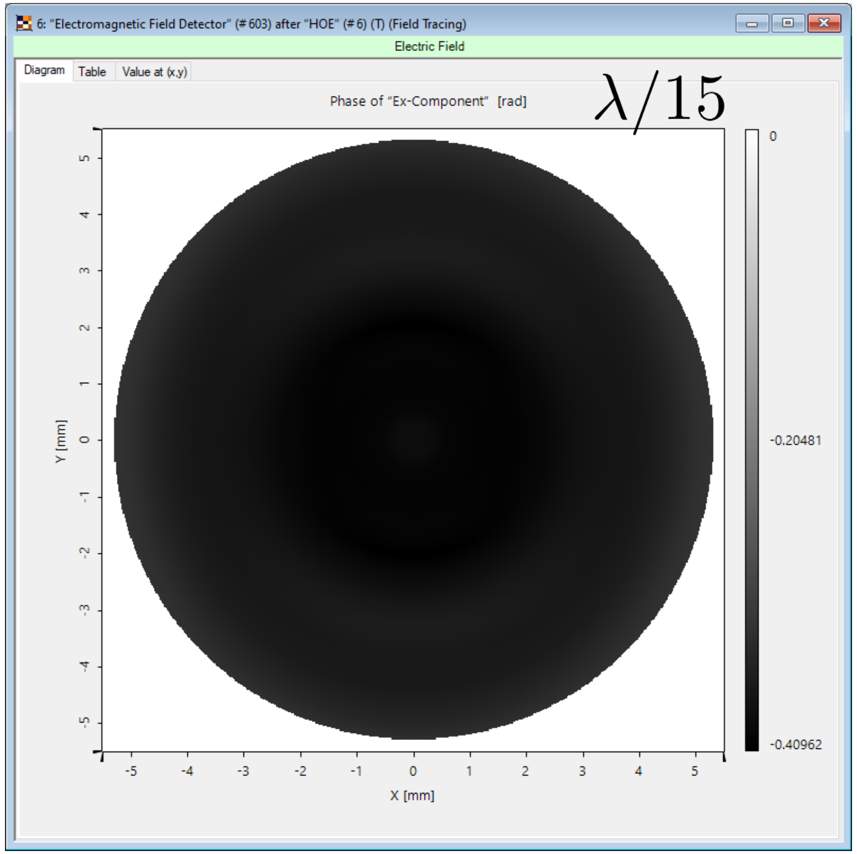


Amplitude after HOE

Focusing (NA = 0.2) HOE: Ray Tracing

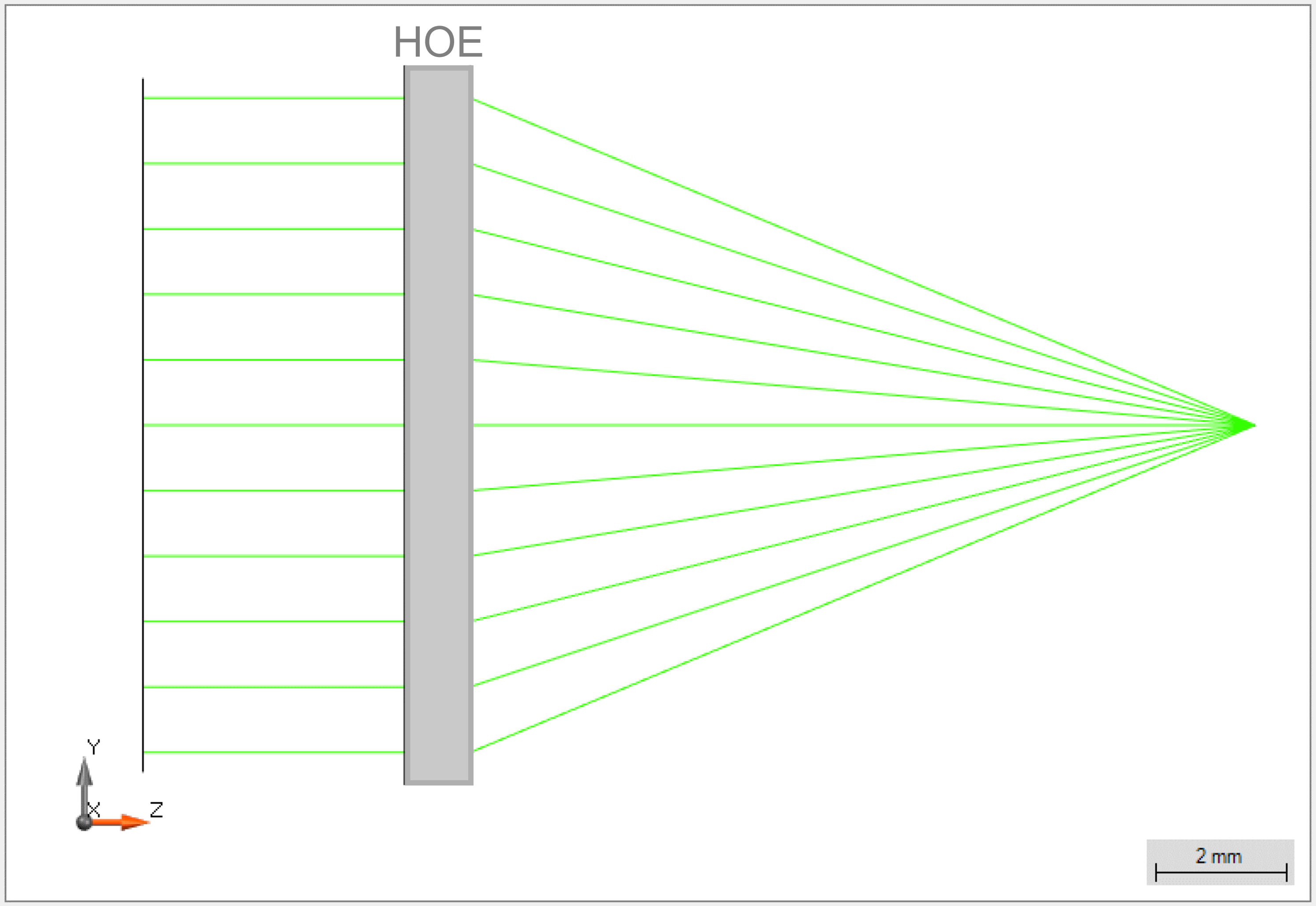


Wavefront after HOE

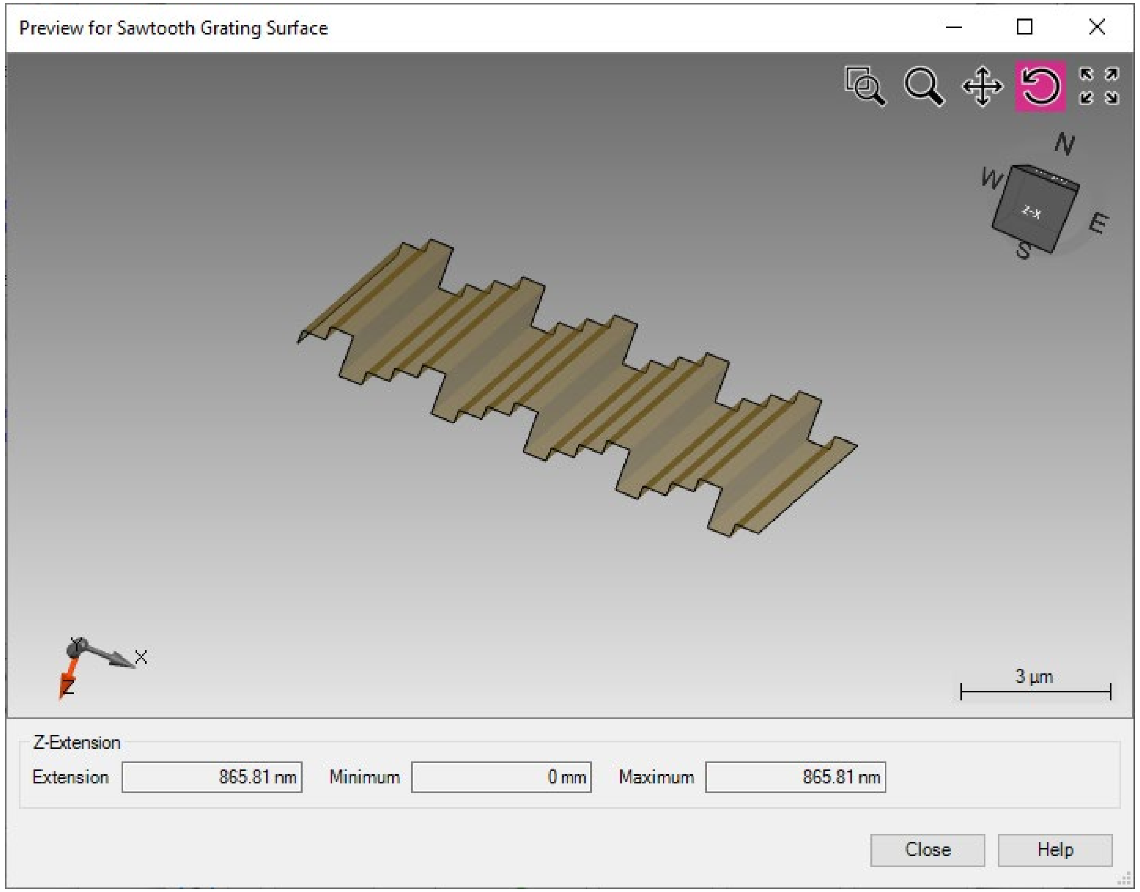


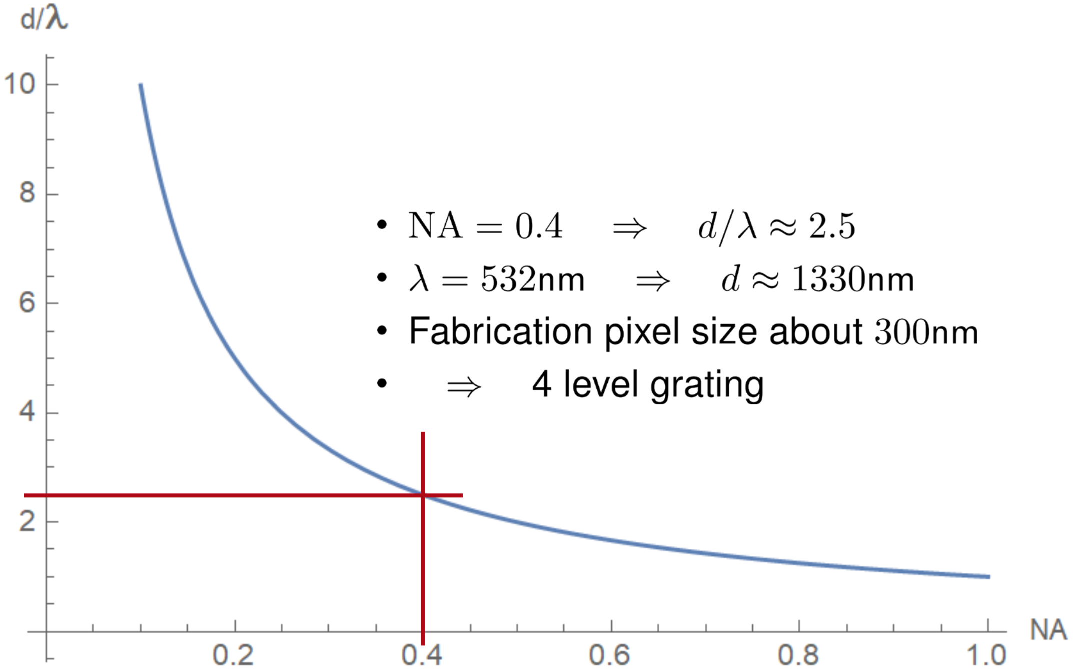
Wavefront Error after HOE

Focusing (NA = 0.4) HOE: Ray Tracing



Grating Profile for HOE: Four Level

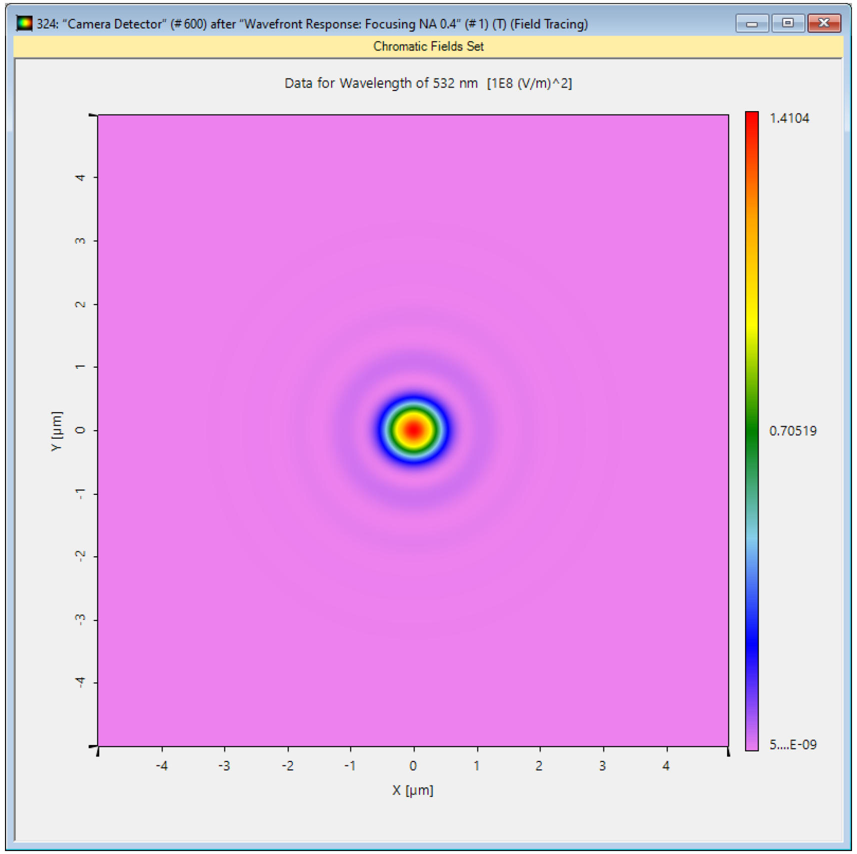




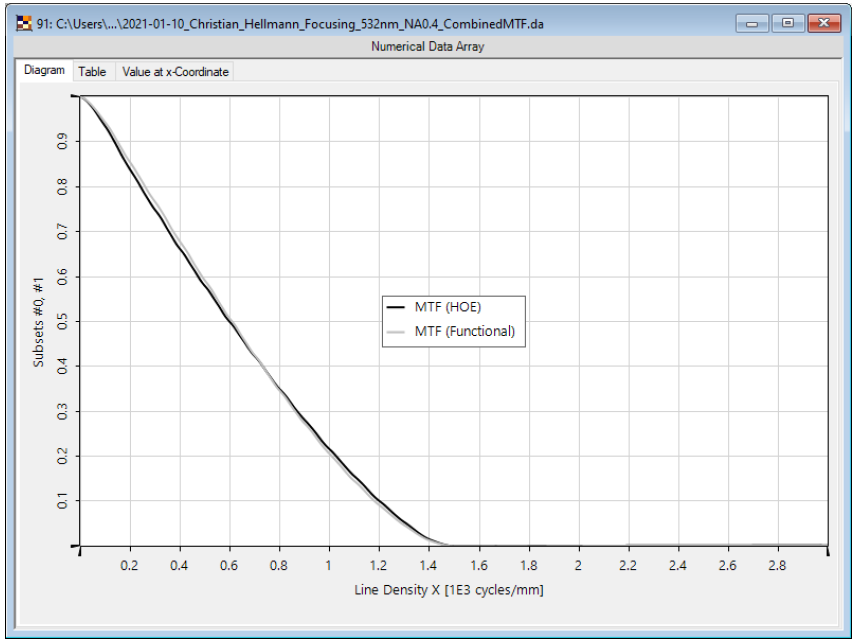
- $\mathrm{NA} = 0.4 \quad \Rightarrow \quad d/\lambda \approx 2.5$
- $\lambda = 532\mathrm{nm} \quad \Rightarrow \quad d \approx 1330\mathrm{nm}$
- Fabrication pixel size about $300\mathrm{nm}$
- $\Rightarrow$ 4 level grating

$\frac{\text{grating period at margin of lens}}{\lambda}$ vs. NA

Focusing (NA = 0.4) HOE: Field Tracing



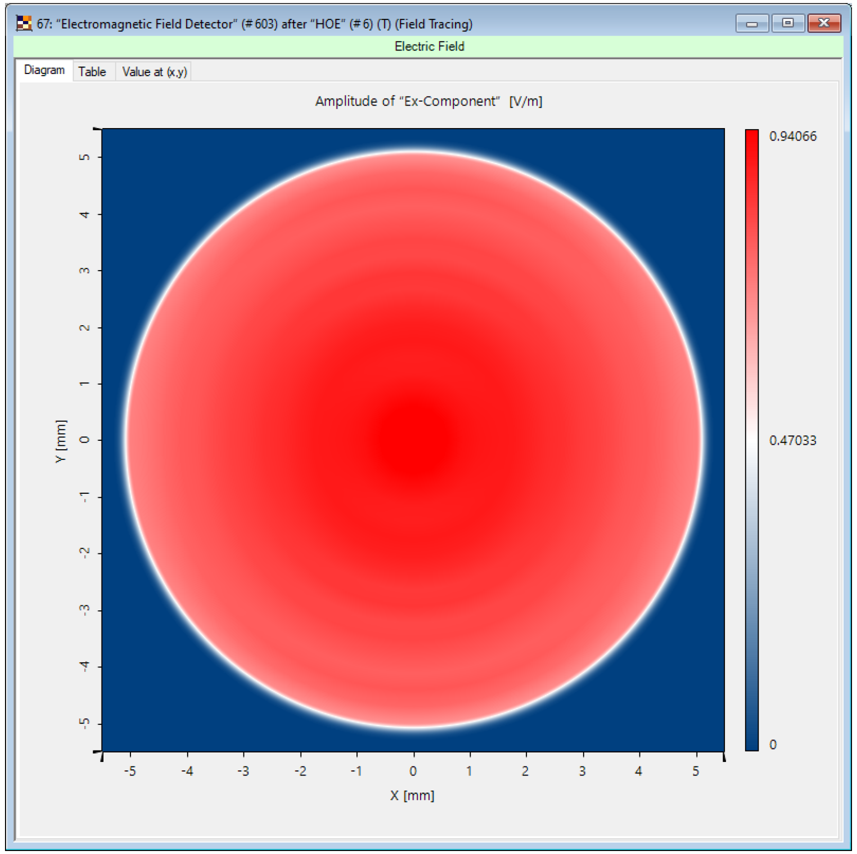
Energy Density in Focus (False Color)



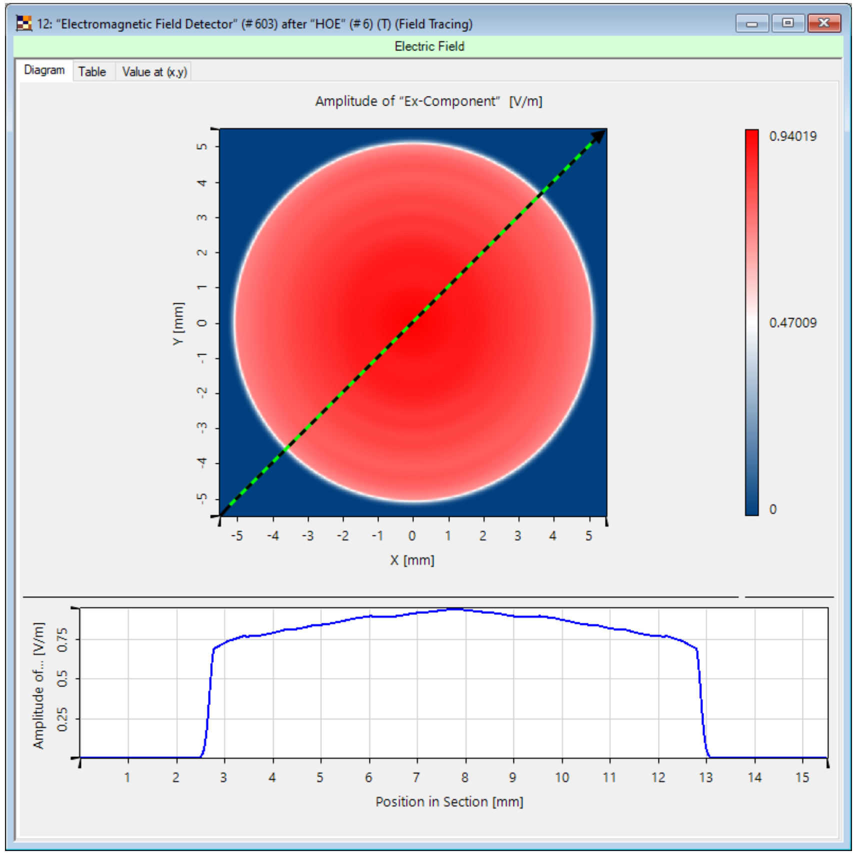
MTF

Efficiency: 65.17% (efficiency after first plane: 96.5%)

Focusing (NA = 0.4) HOE: Field Tracing

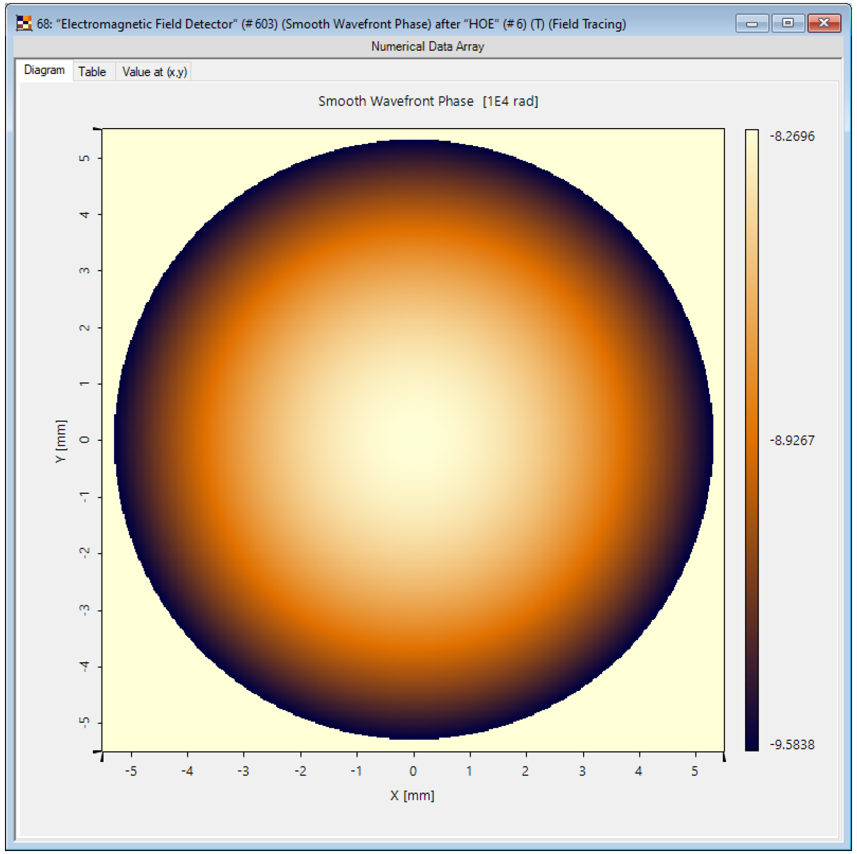


Amplitude after HOE

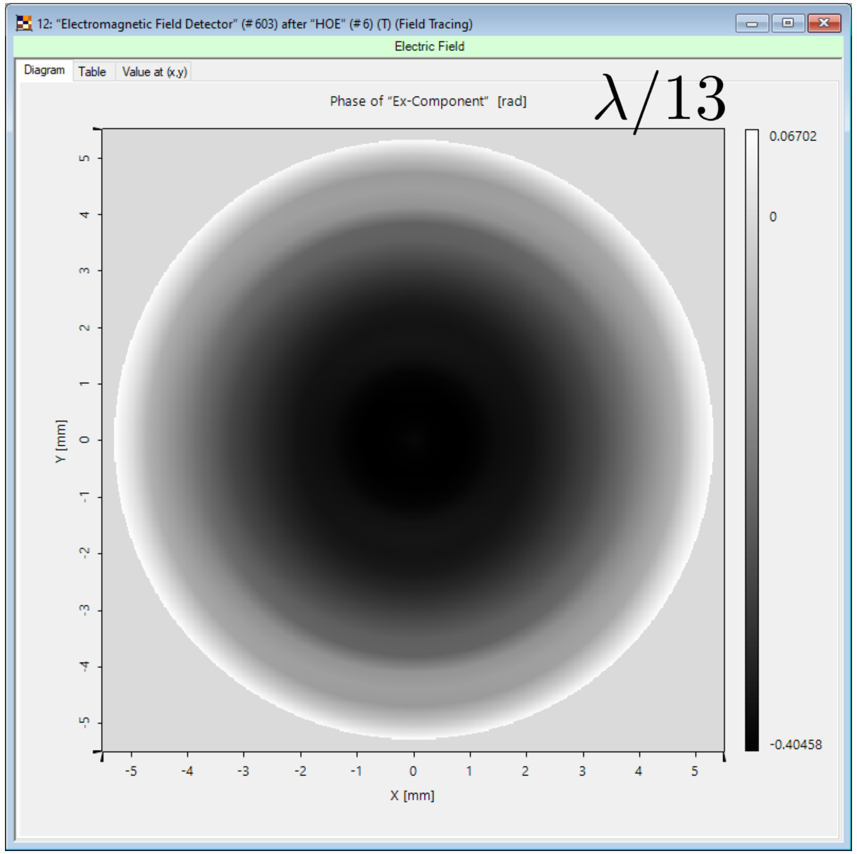


Amplitude after HOE

Focusing (NA = 0.4) HOE: Field Tracing

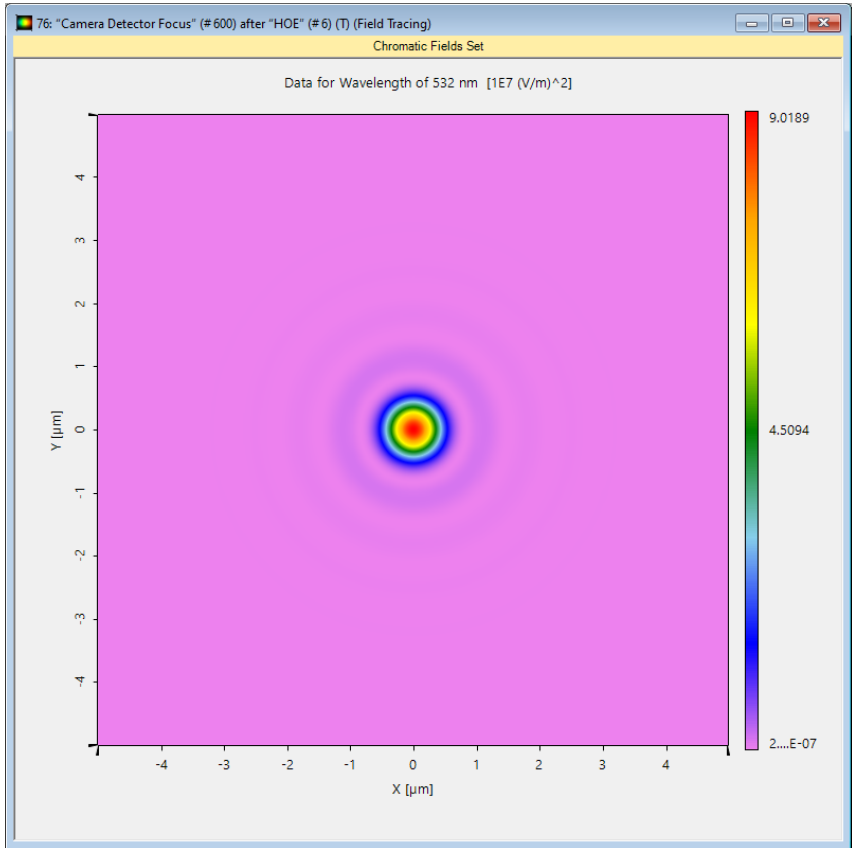


Wavefront after HOE



Wavefront Error after HOE

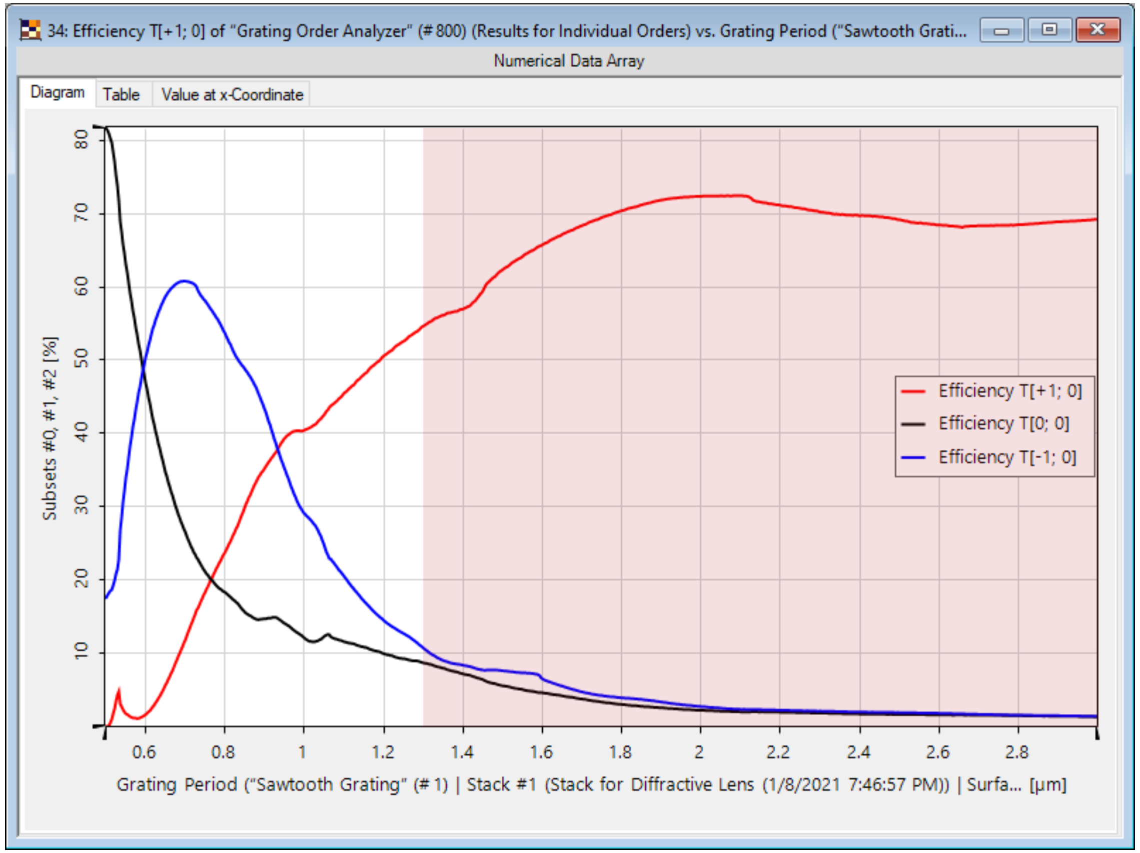
Focusing (NA = 0.4) HOE: Field Tracing → -1st, 0th, +1st



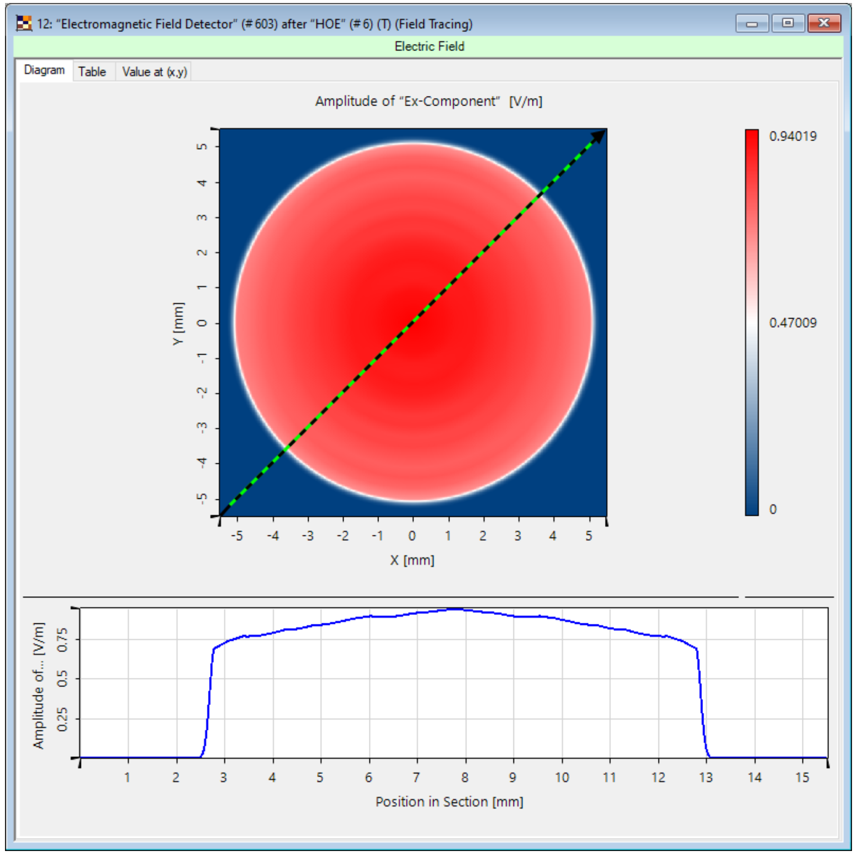
Energy Density in Focus (False Color)

Order HOE	Efficiency after HOE
-3	0.98%
-2	3.51%
-1	5.31%
0	3.46%
1	65.17%
2	6.17%
3	0.31%

Focusing (NA = 0.4) HOE: Field Tracing

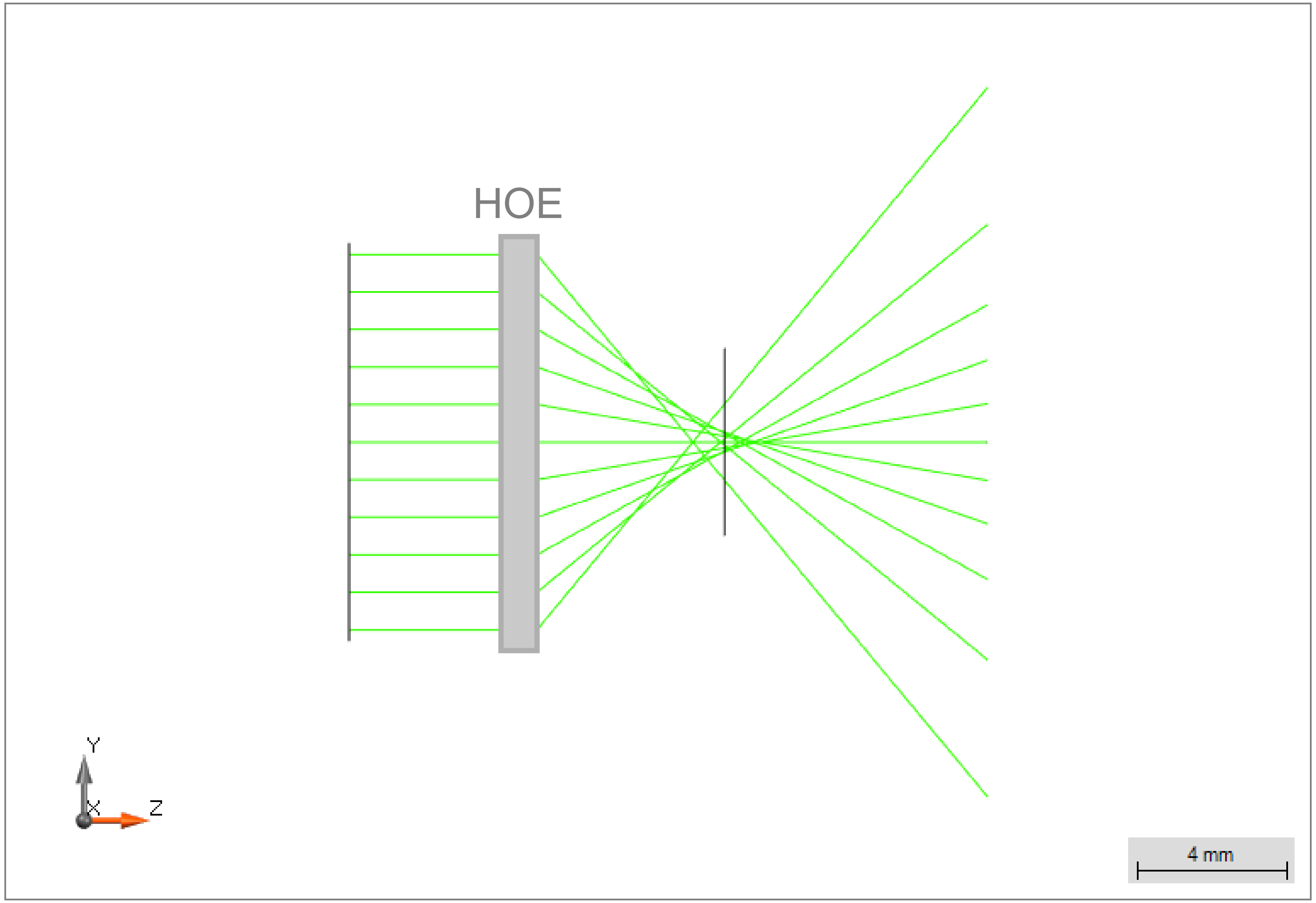


Efficiencies vs. Period



Amplitude after HOE

Focusing (NA = 0.4) HOE: Ray Tracing → 2nd Order



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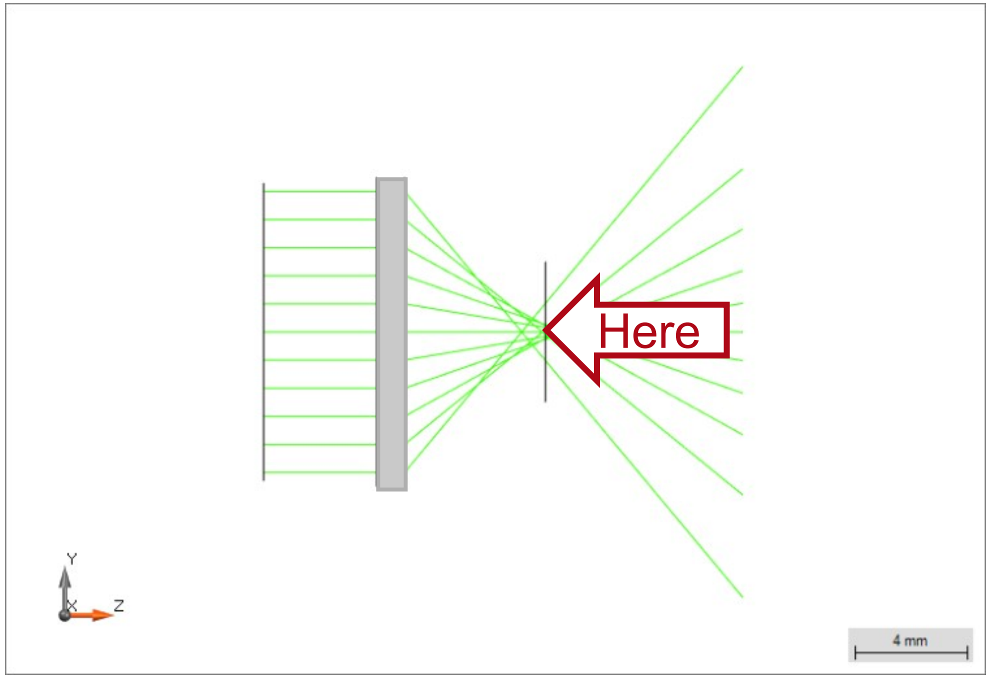
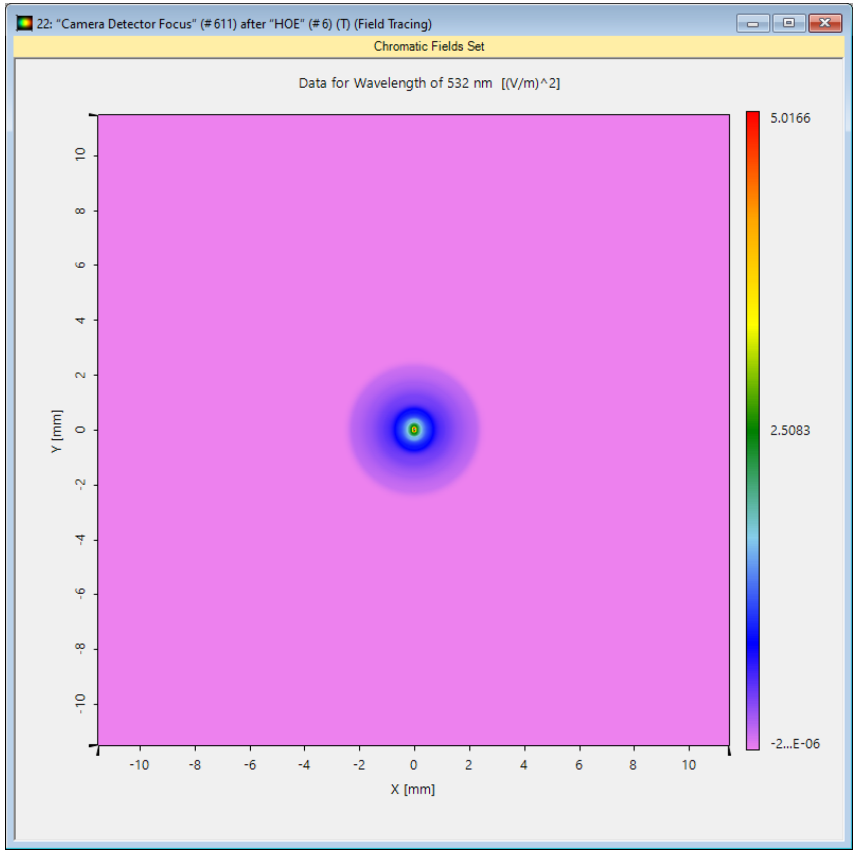
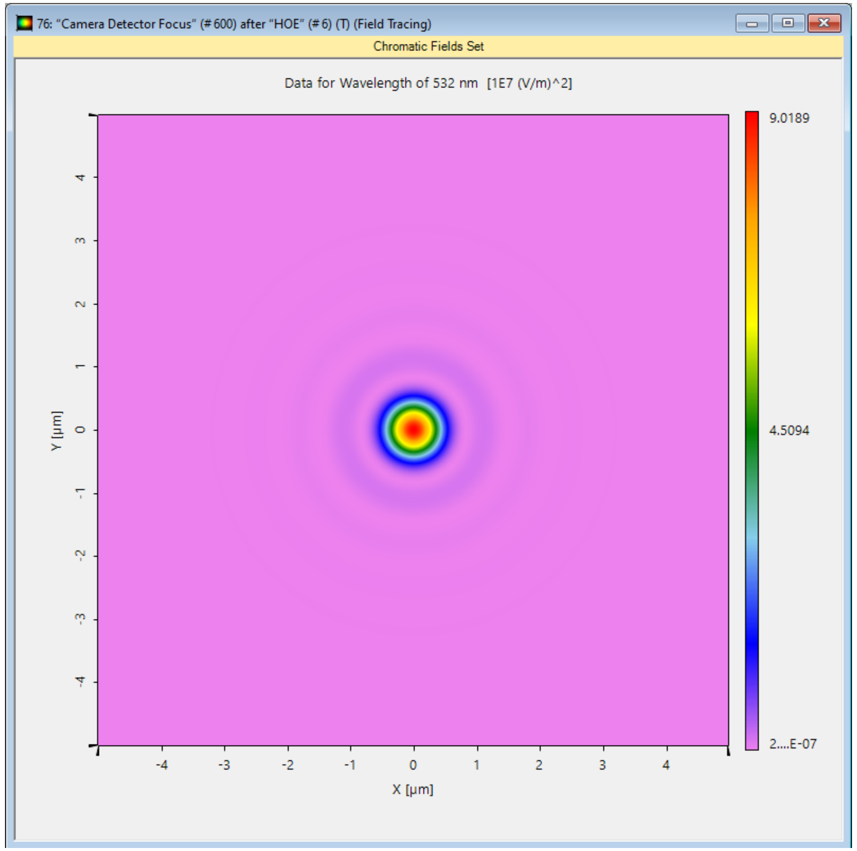




Intermediate focus after 5mm

Focusing (NA = 0.4) HOE: Field Tracing → -1st, 0th, +1st



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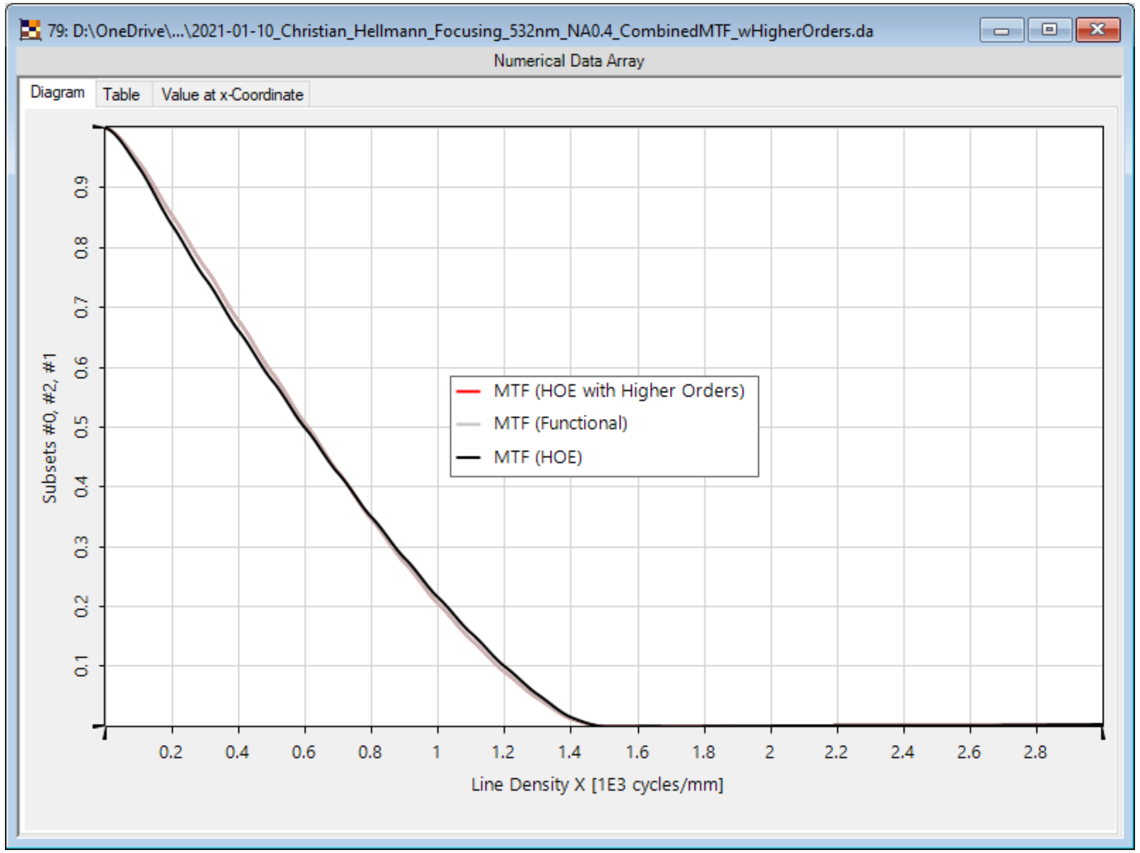

MTF

Design Workflow in VirtualLab Fusion

Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN

Design the system by introducing functional components to achieve the demanded system functionality.

STRUCTURAL DESIGN

Replace functional components by smooth surface or flat optics components.

MODELING & EVALUATION

Model the system with ray tracing and physical optics. Evaluate the performance by suitable detectors and merit functions.

FURTHER OPTIMIZATION

Use the modeling techniques to further optimize the system by, e.g., parametric optimization.

SYSTEM TOLERANCING

Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

FABRICATION DATA

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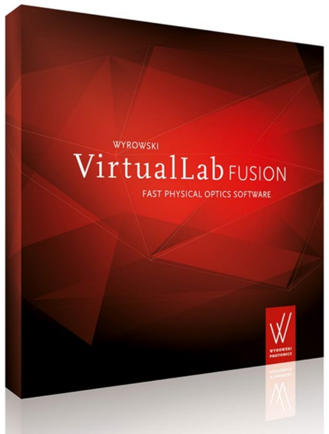
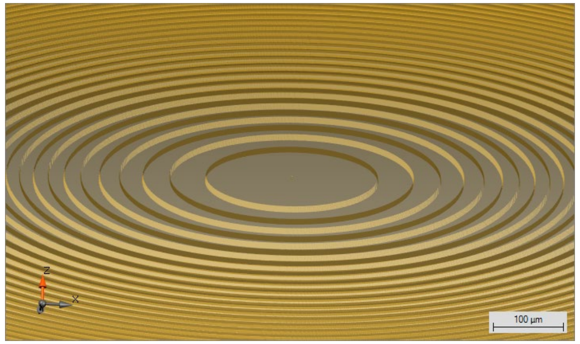
Structure of Webinar

- Why physical optics?
- Optical design in physical optics terms
- Diffractive Optical Elements (DOE)
  - Design
  - Modeling
  - Fabrication data
- Design examples



VirtualLab Fusion 2021



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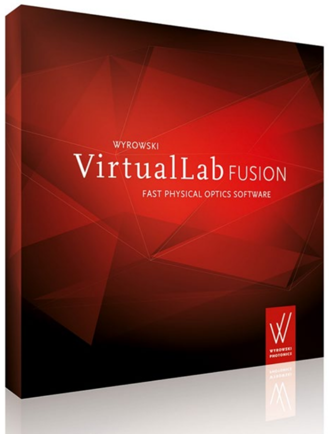
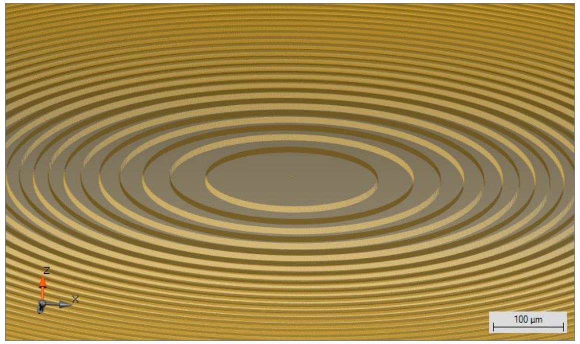
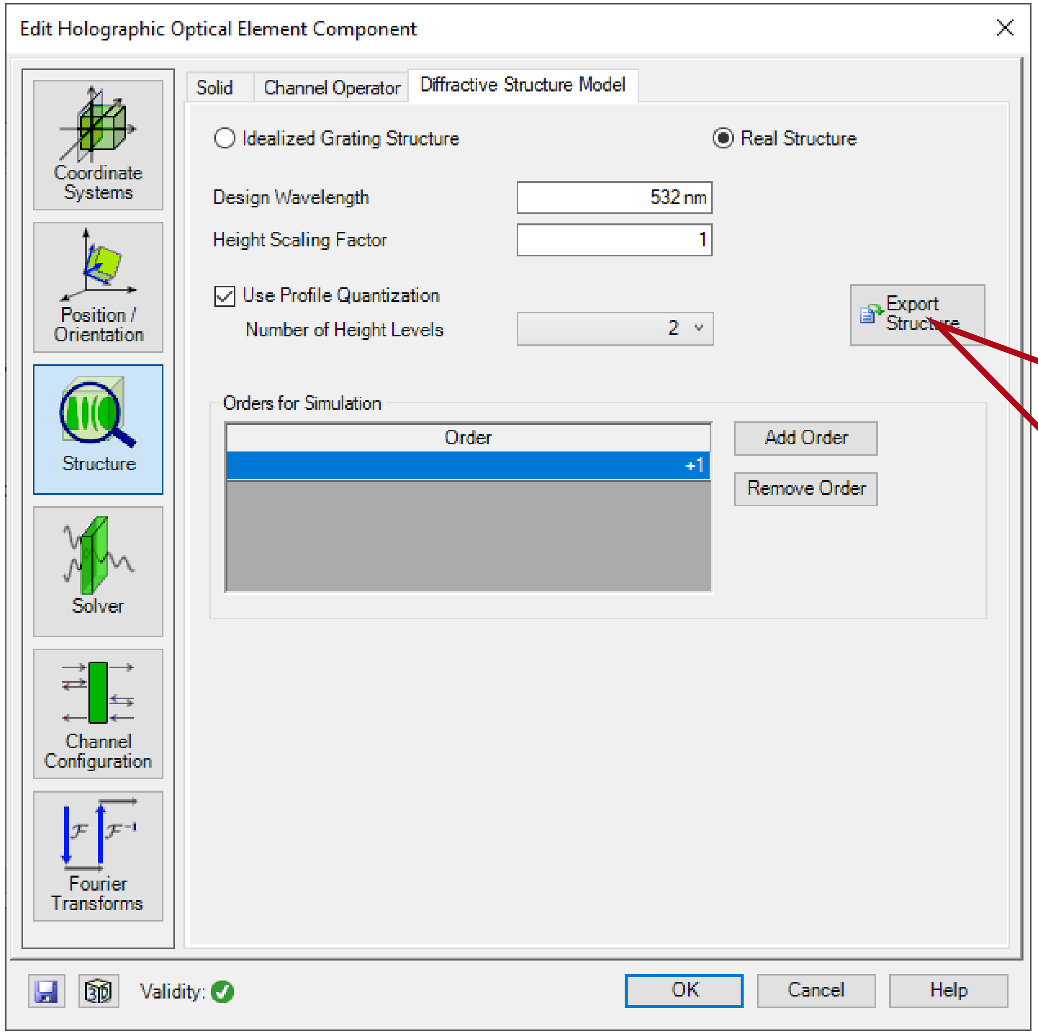


VirtualLab Fusion 2021

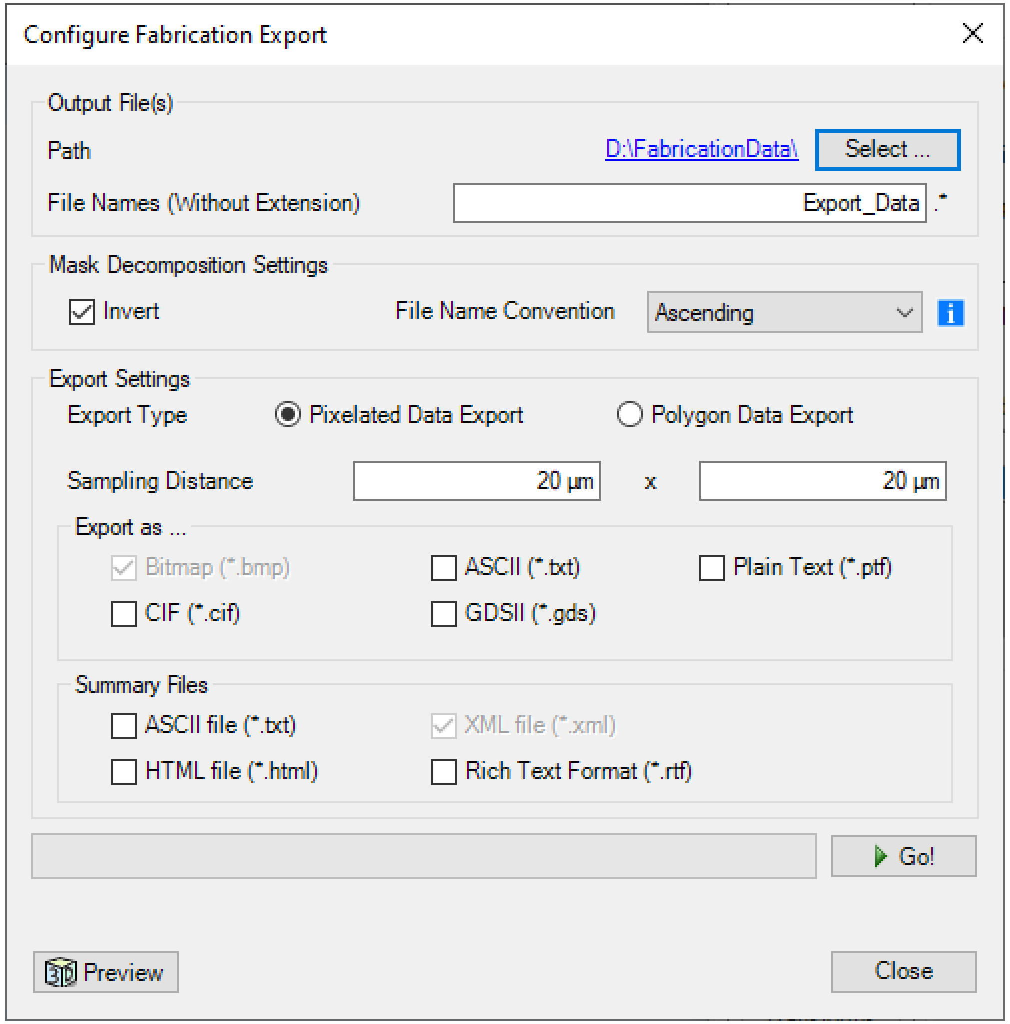


HOE Fabrication Data Export



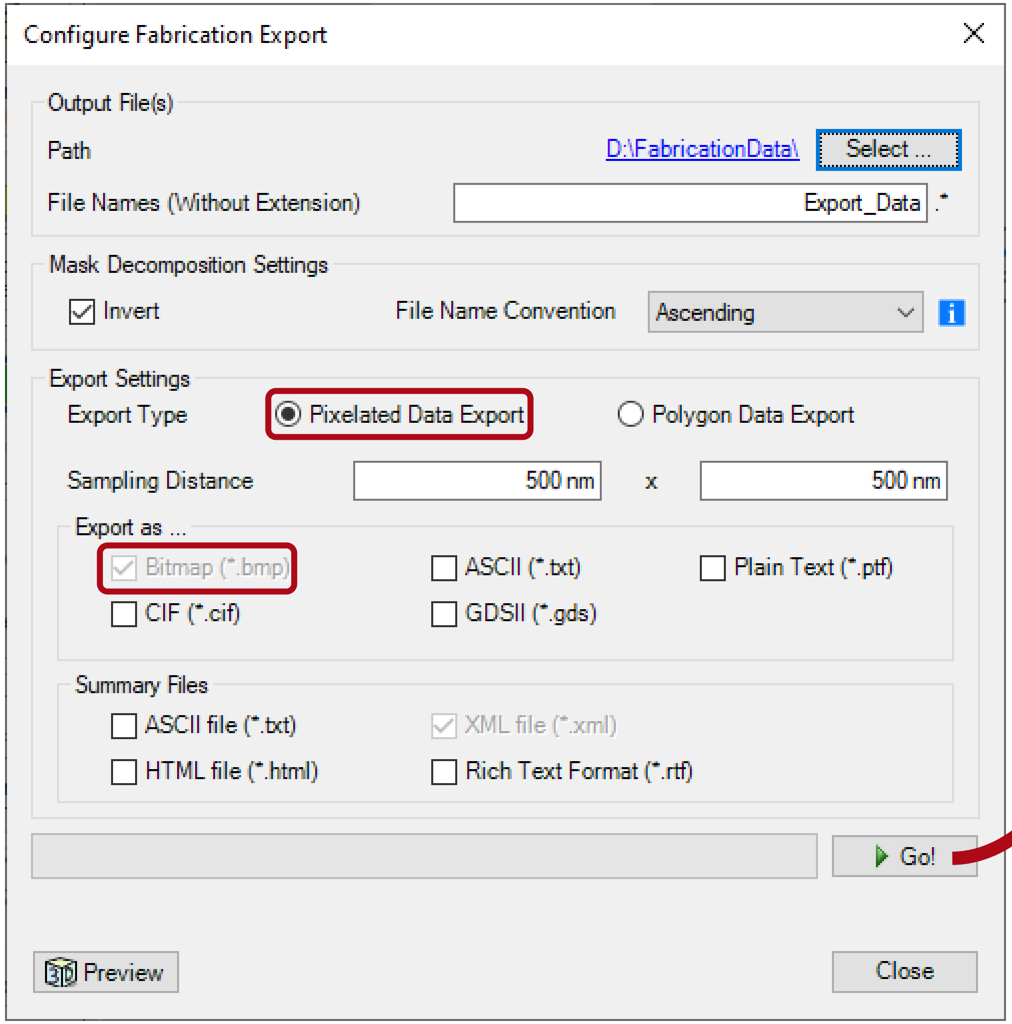
Structure export for quantized height structures can be performed by clicking on the corresponding button in the edit dialog of the HOE.

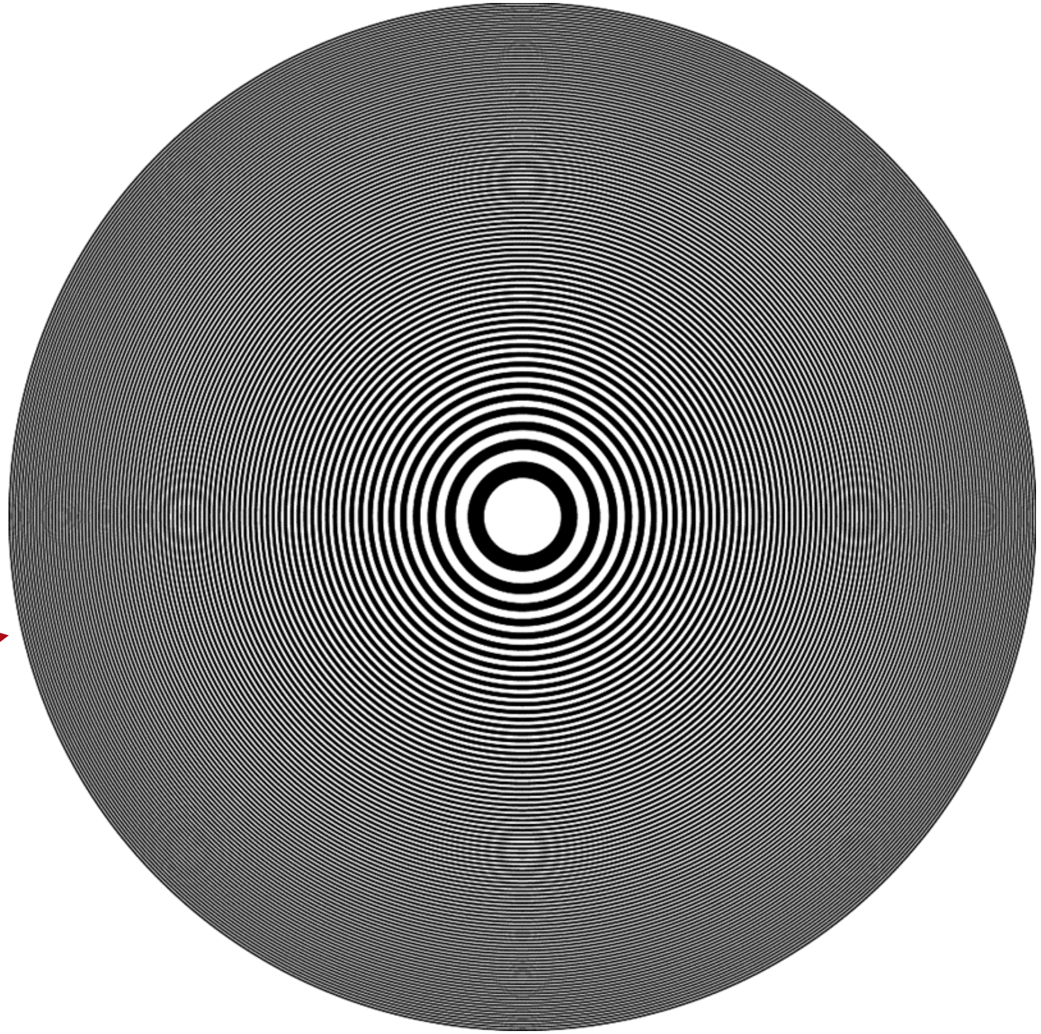
HOE Fabrication Data Export



- Fabrication export supports specification of
  - Target directory
  - Parameters for mask decomposition
  - Pixelated or polygon data export (+ export accuracy parameters)
  - File format (supported formats: bitmap, text files, GDISII or CIF)

HOE Fabrication Data Export – Sample Data Pixelated Bitmap





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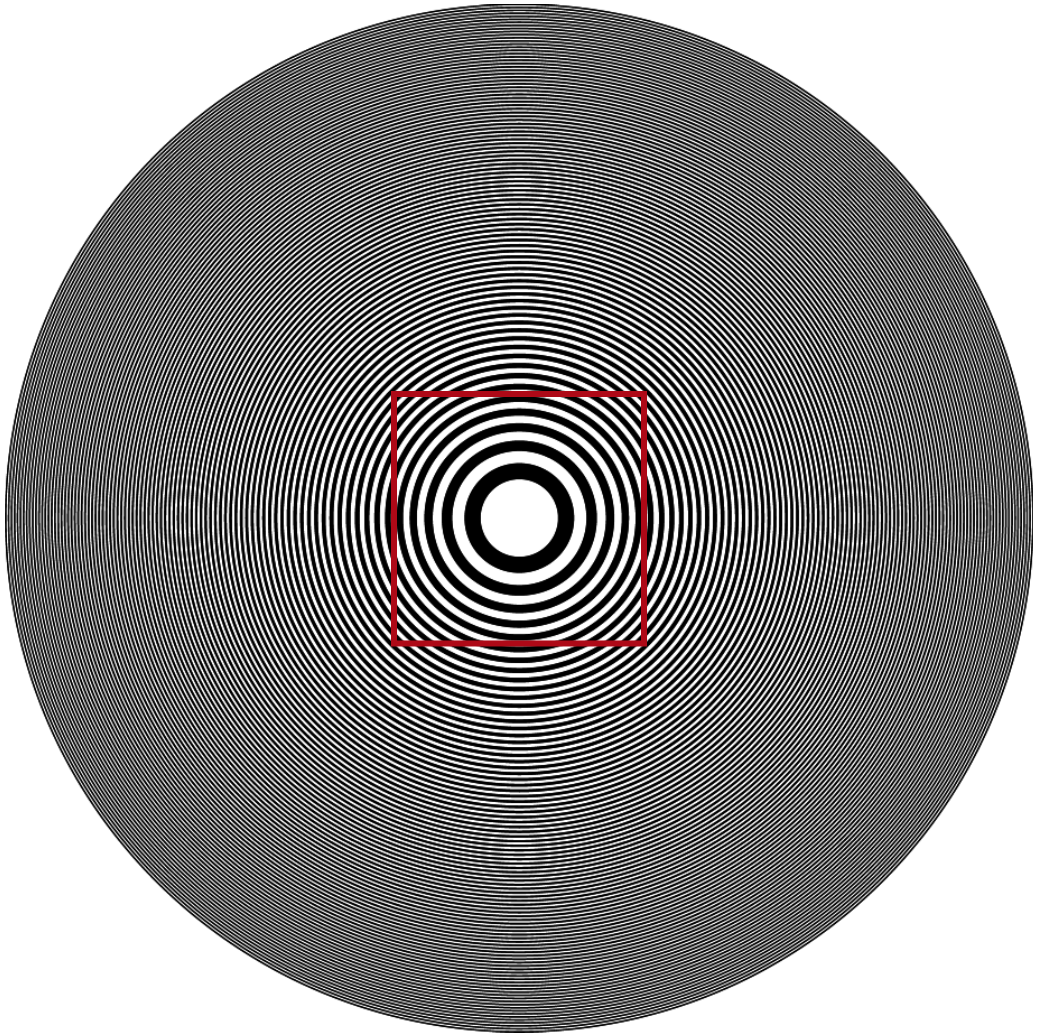

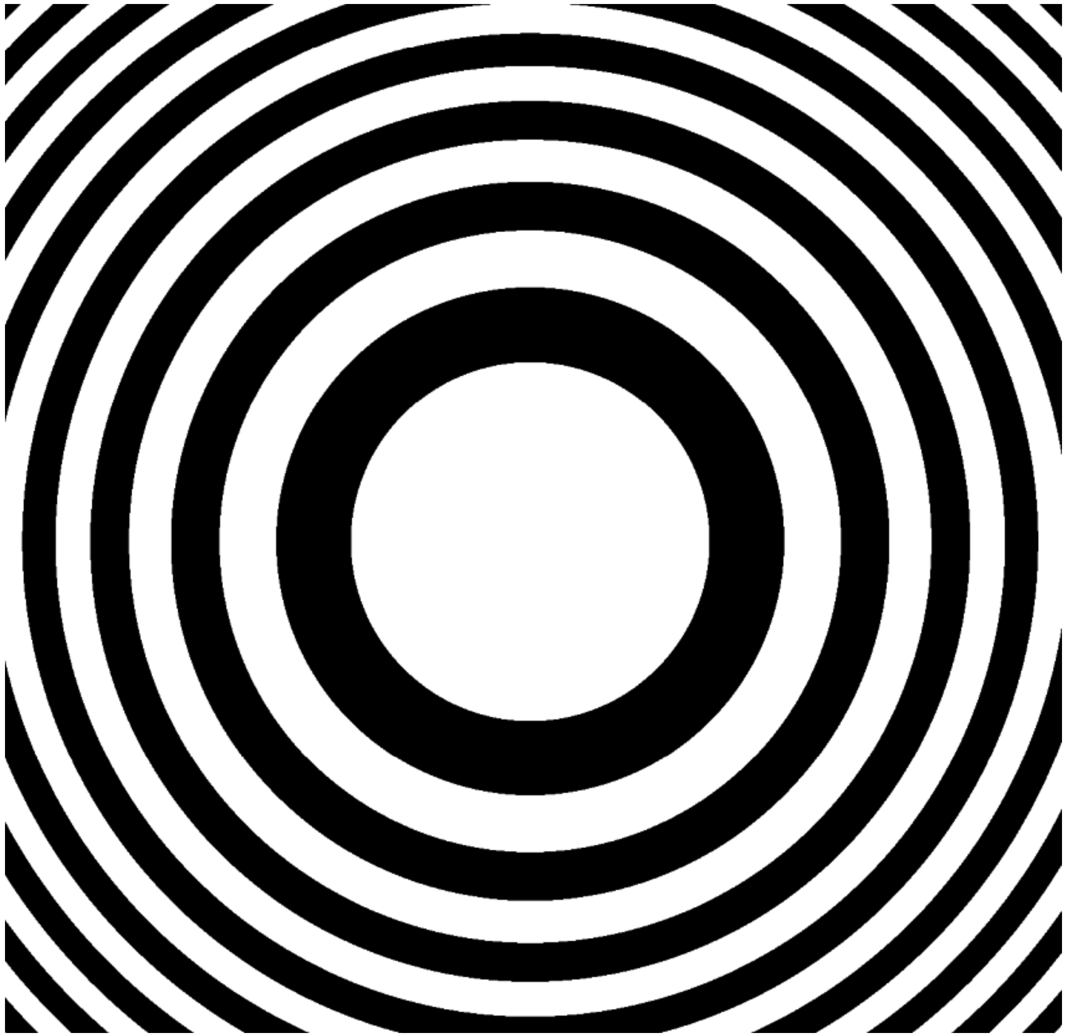

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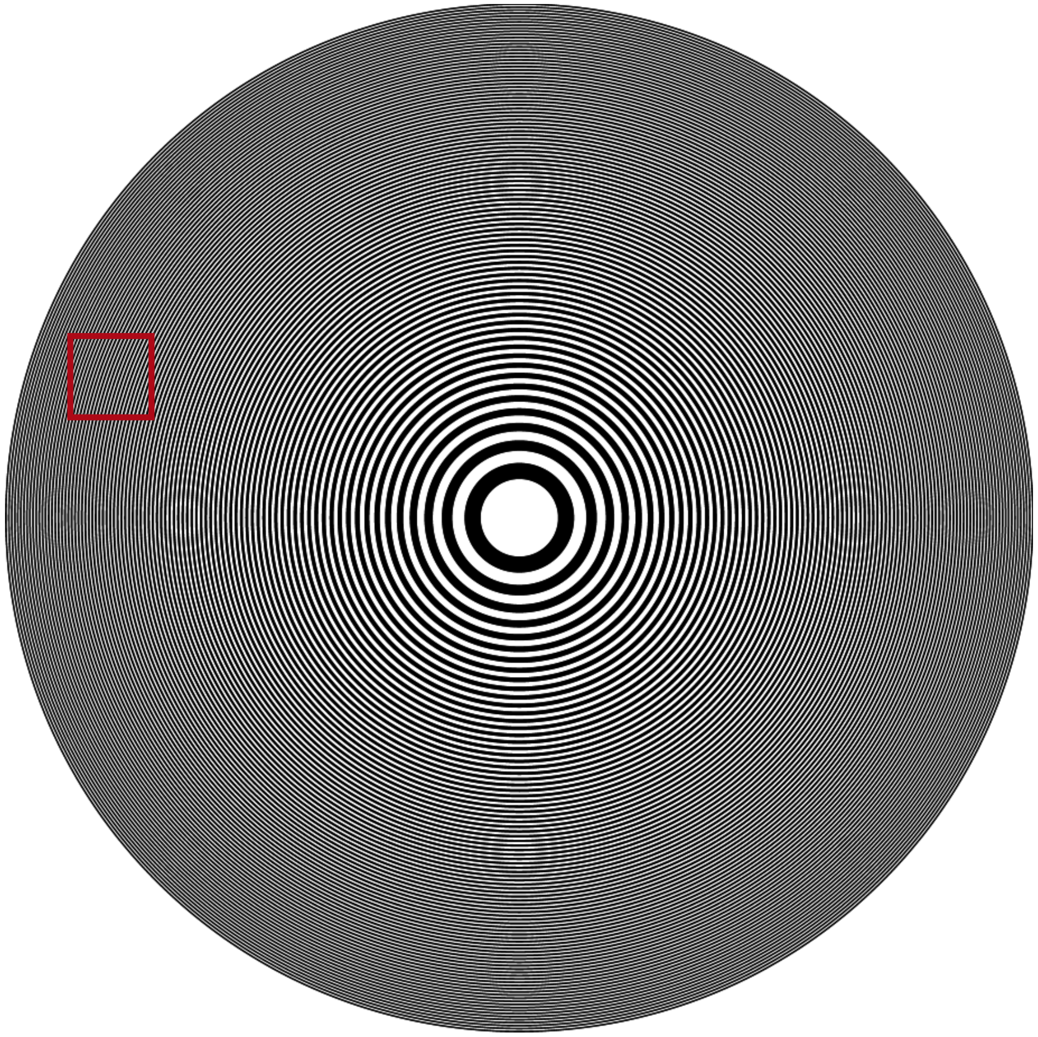
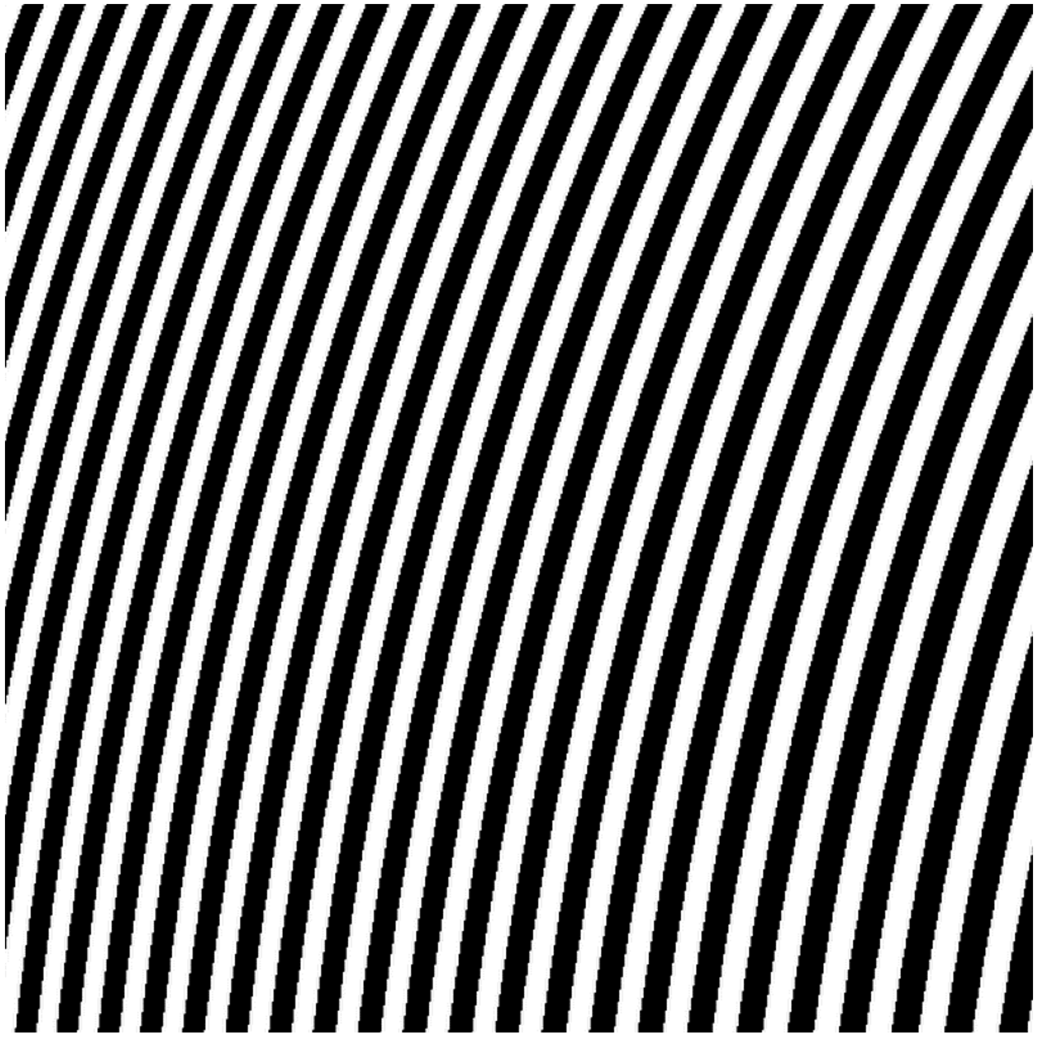
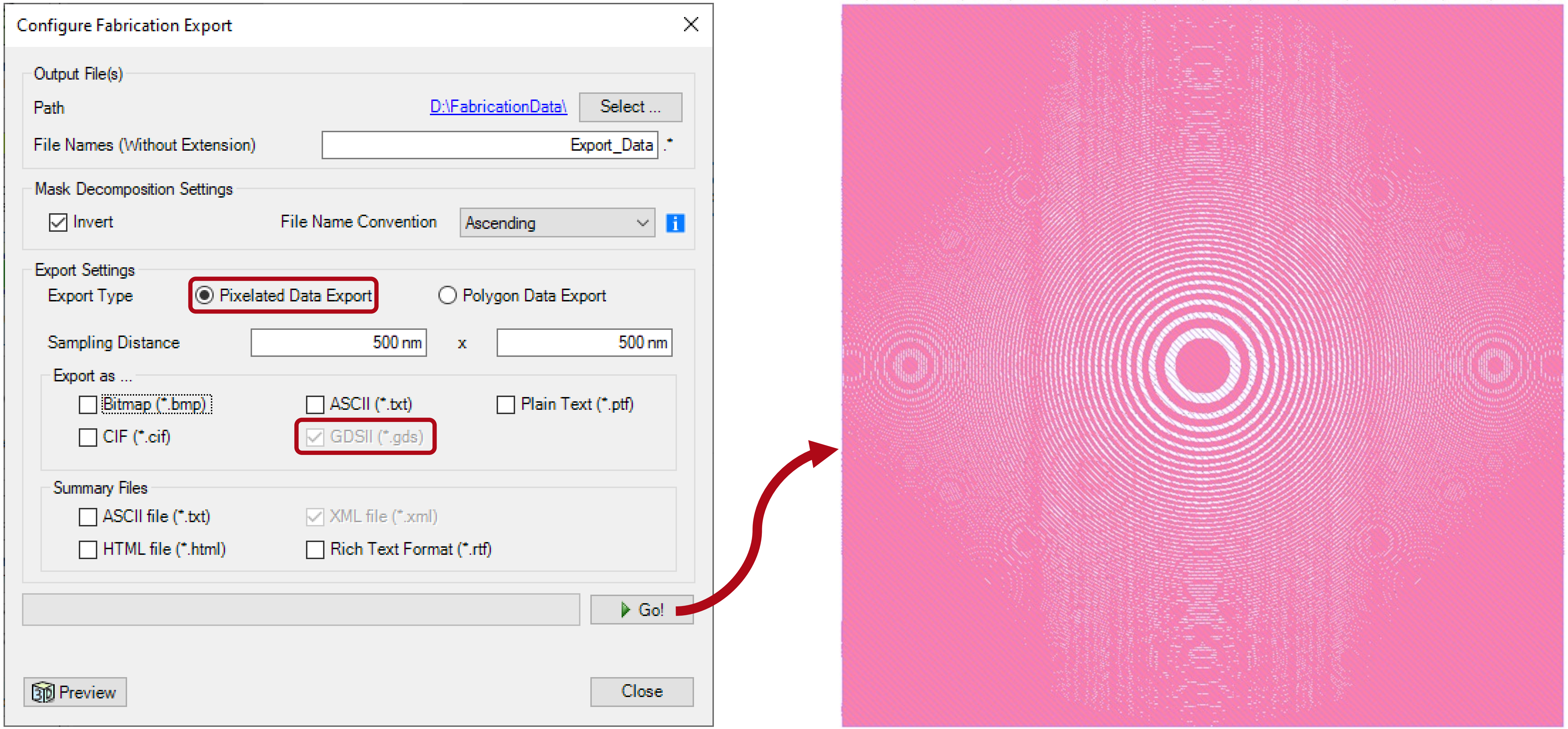
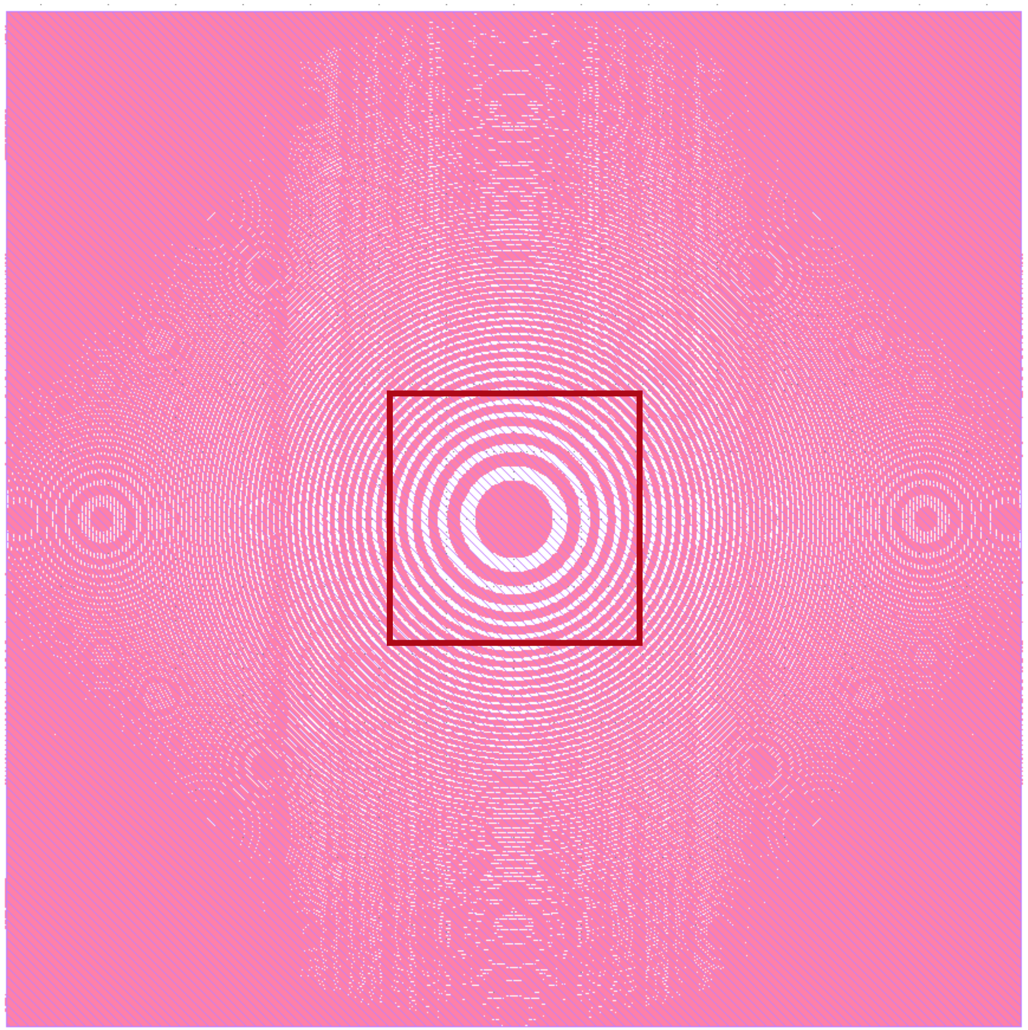


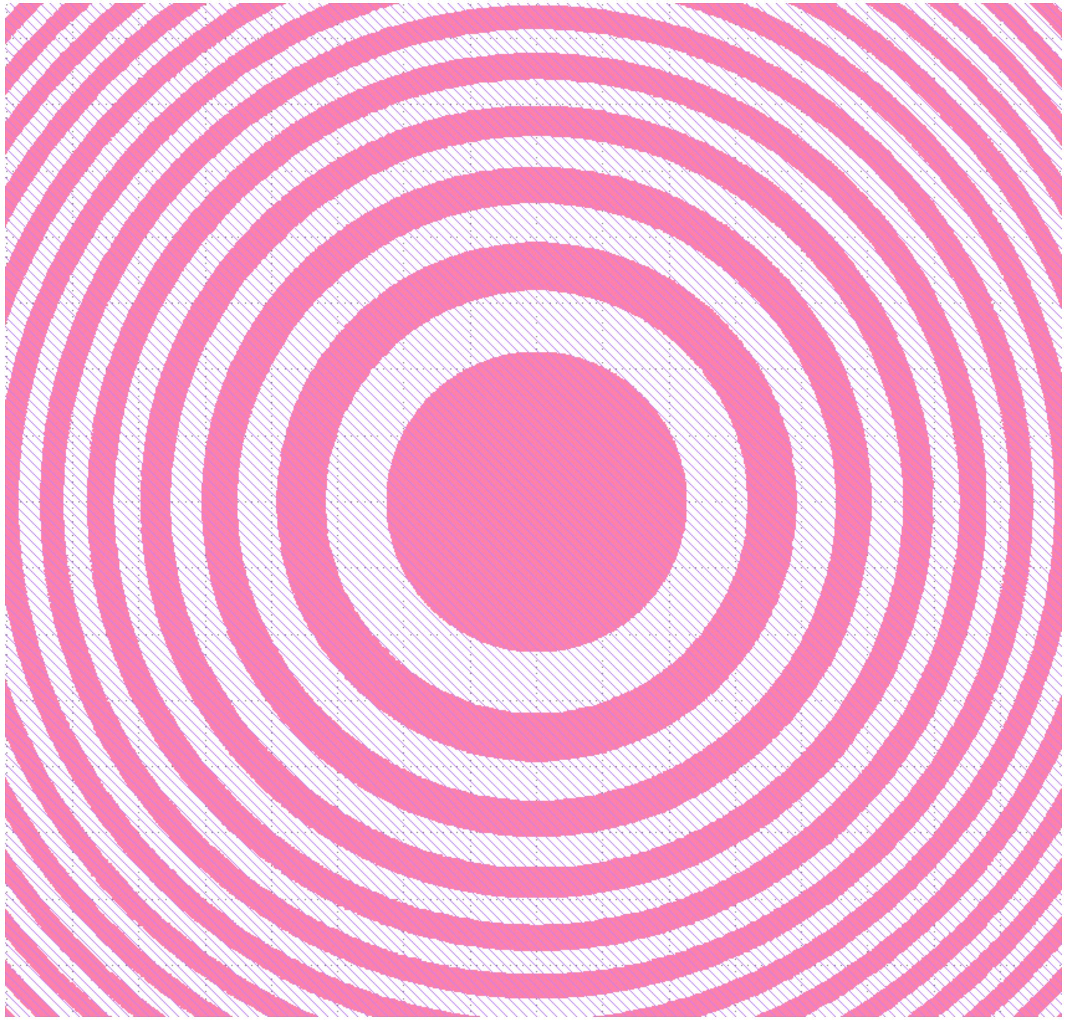


HOE Fabrication Data Export – Sample Data Pixelated GDSII

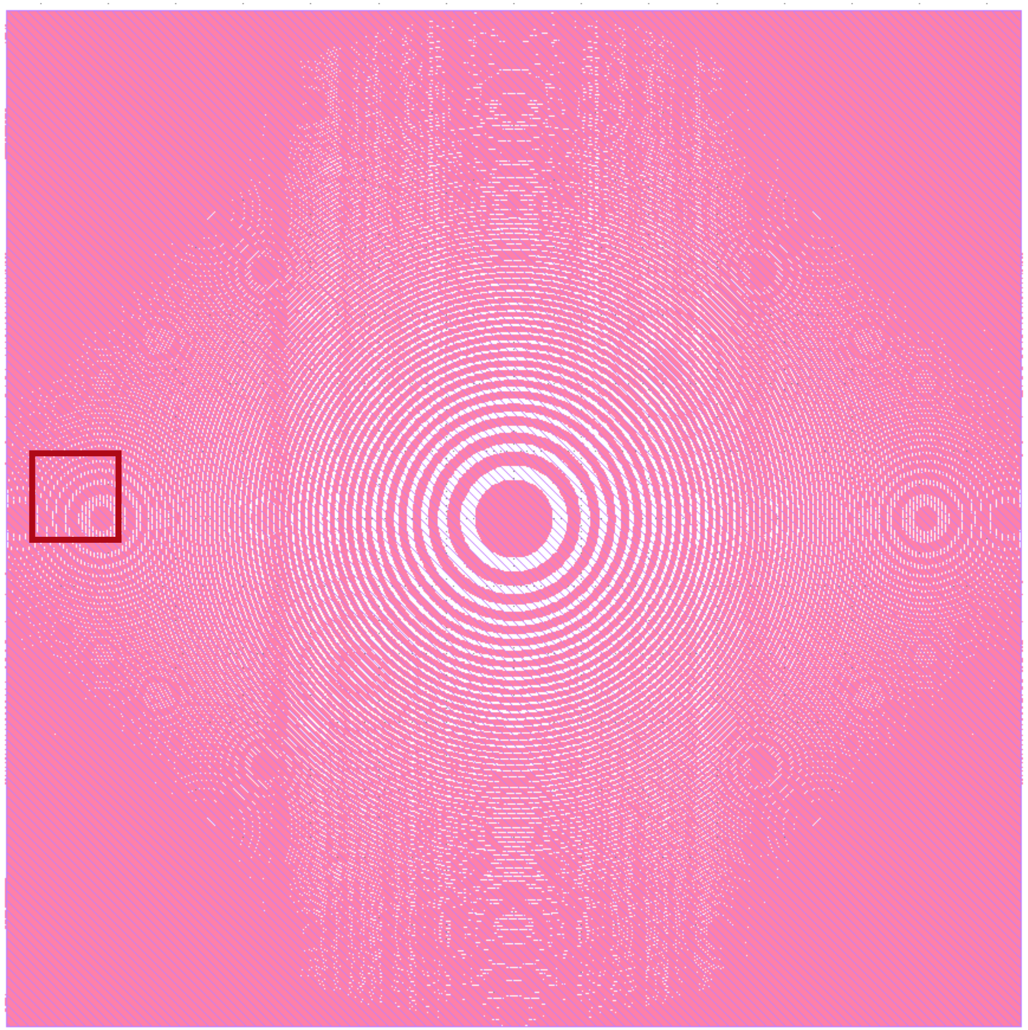


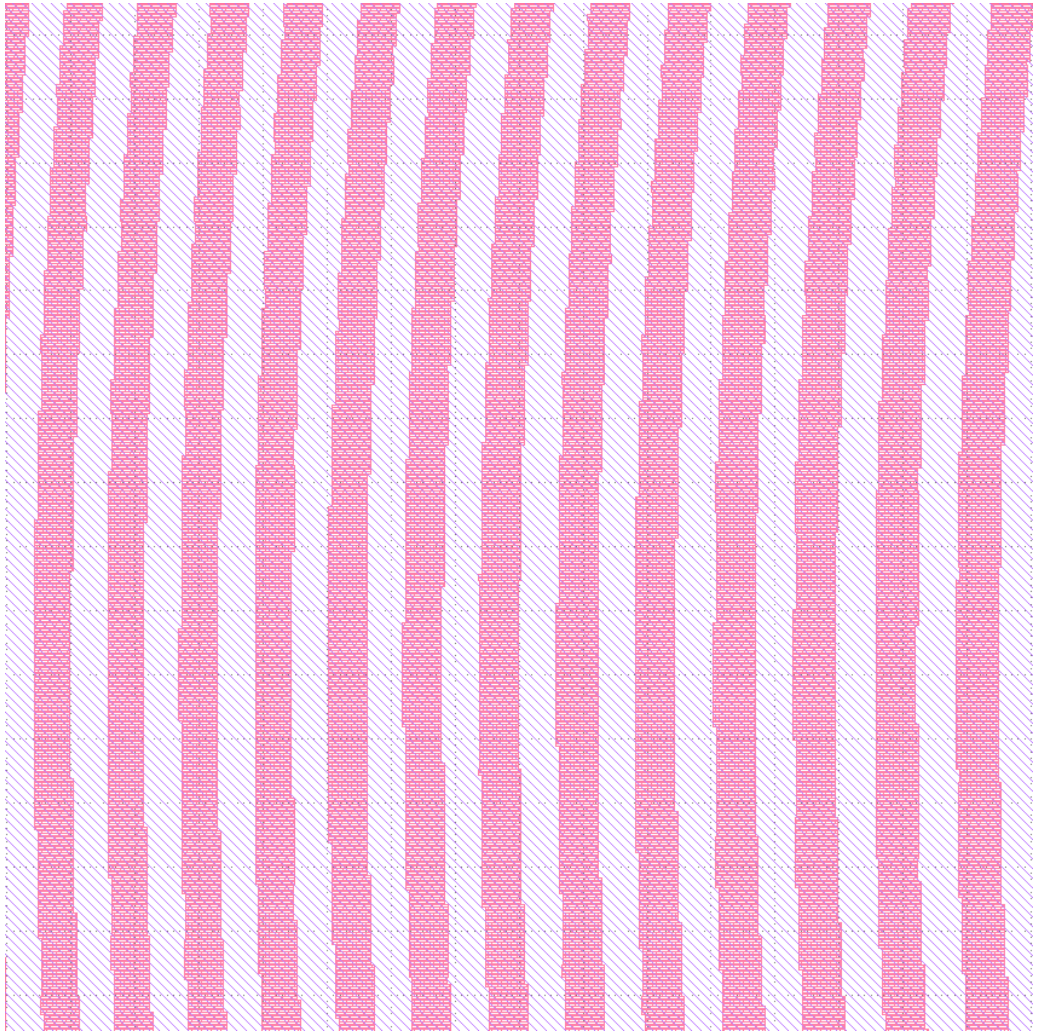
HOE Fabrication Data Export – Sample Data Pixelated GDSII



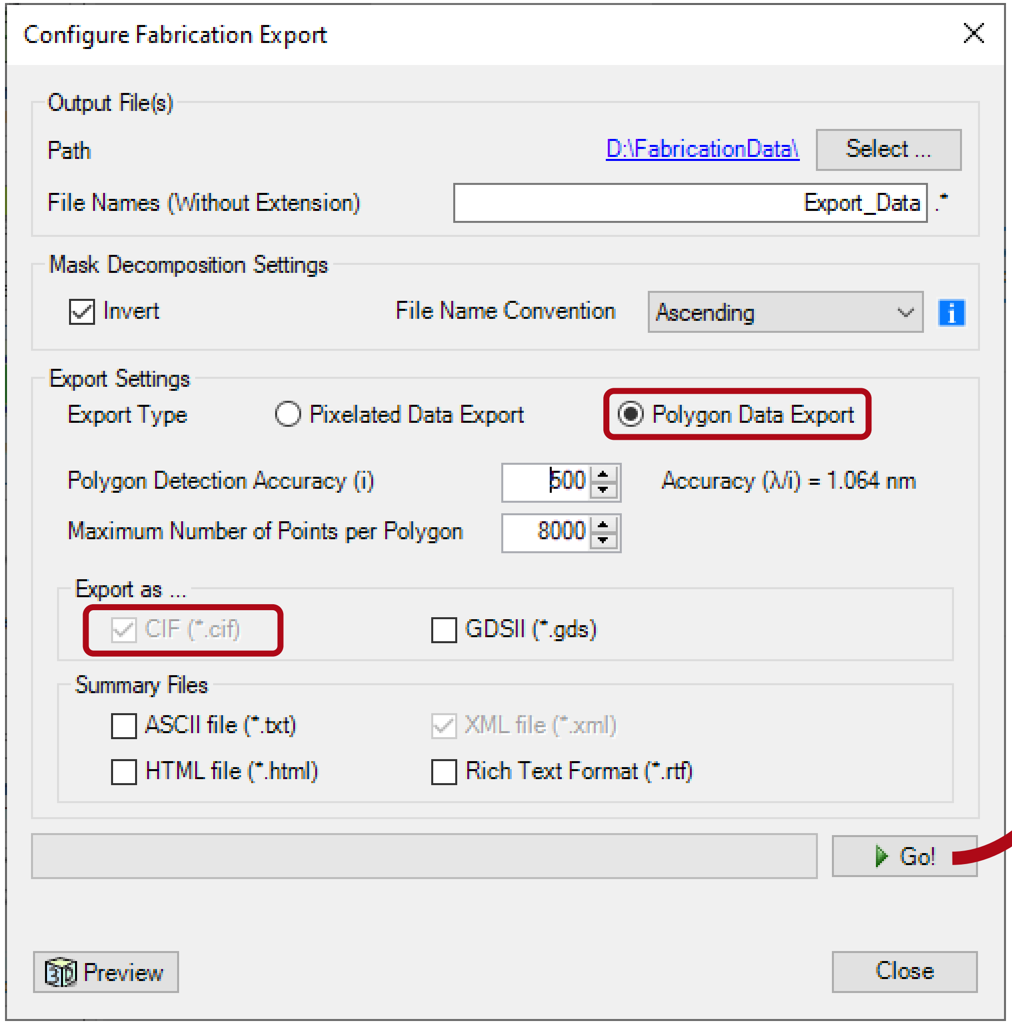


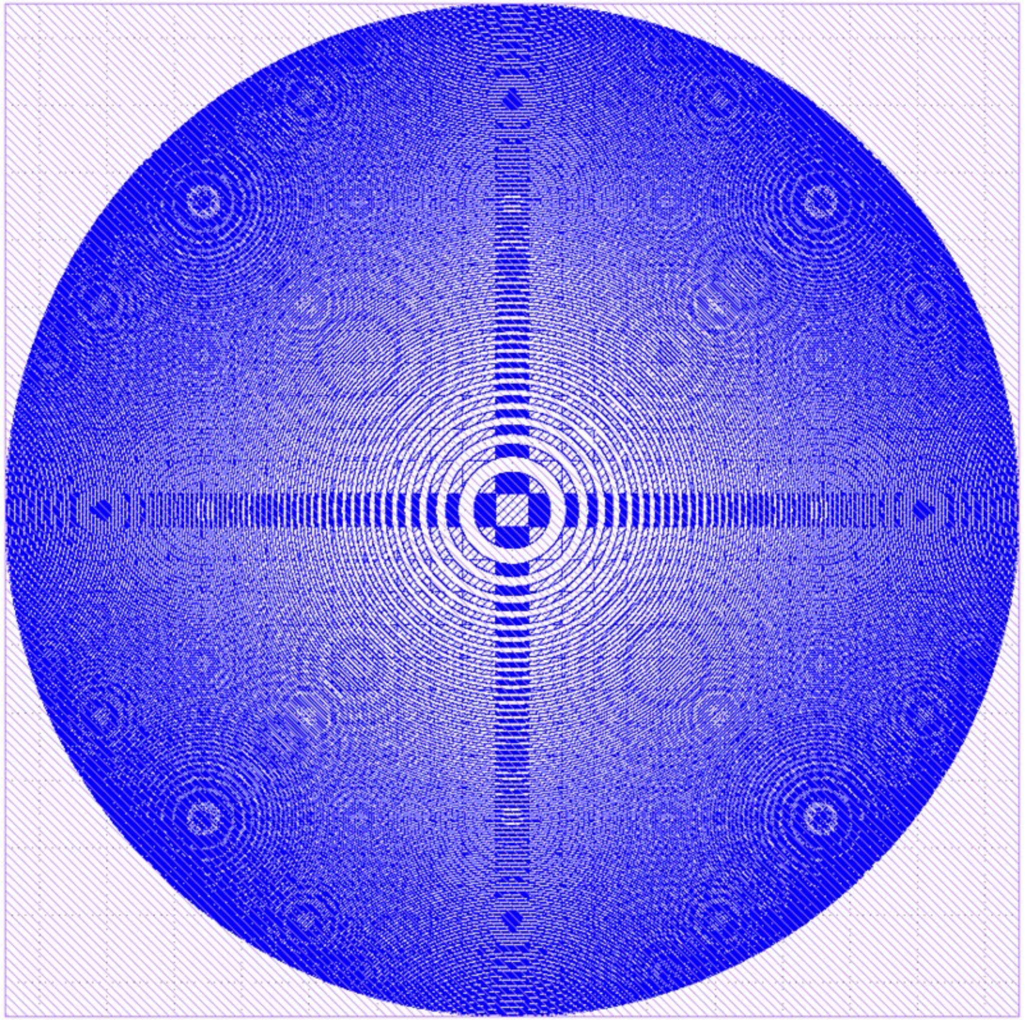
HOE Fabrication Data Export – Sample Data Pixelated GDSII



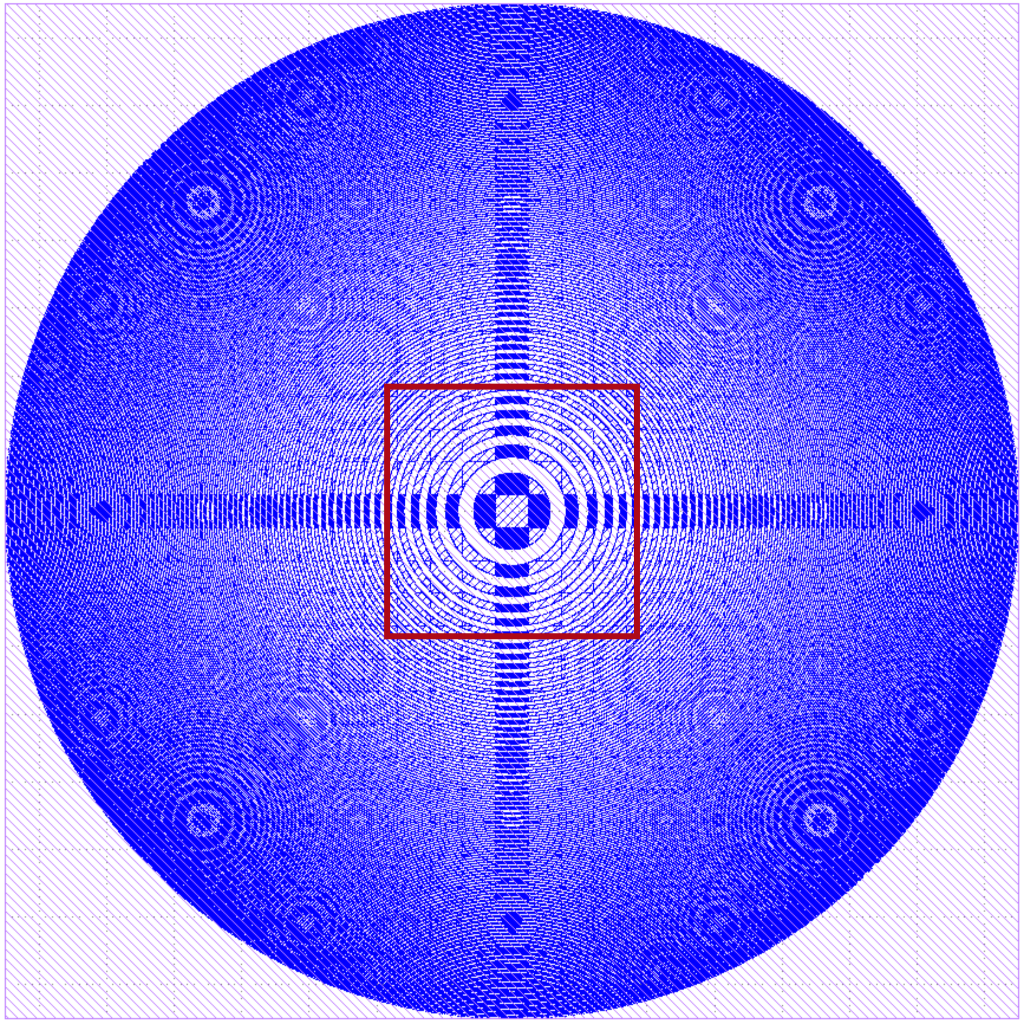


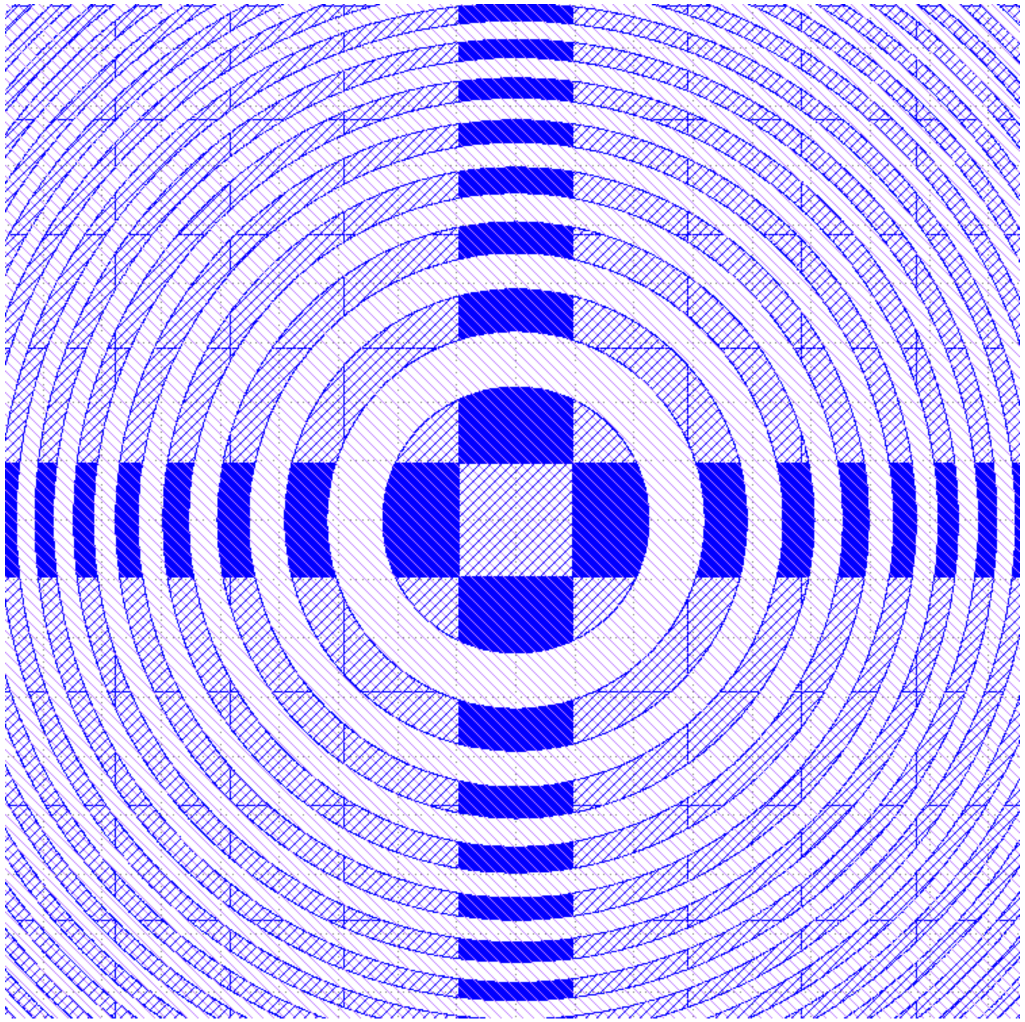
HOE Fabrication Data Export – Sample Data Polygon CIF





HOE Fabrication Data Export – Sample Data Polygon CIF





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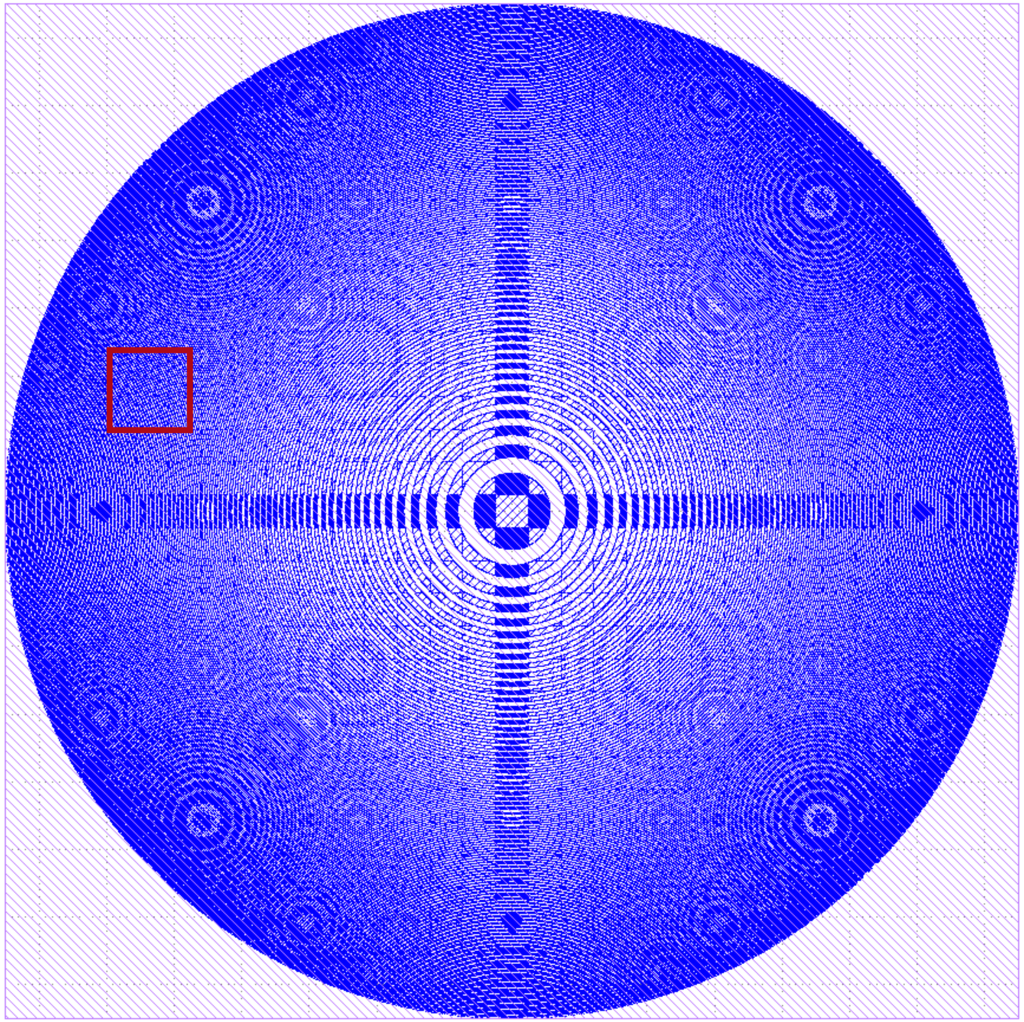
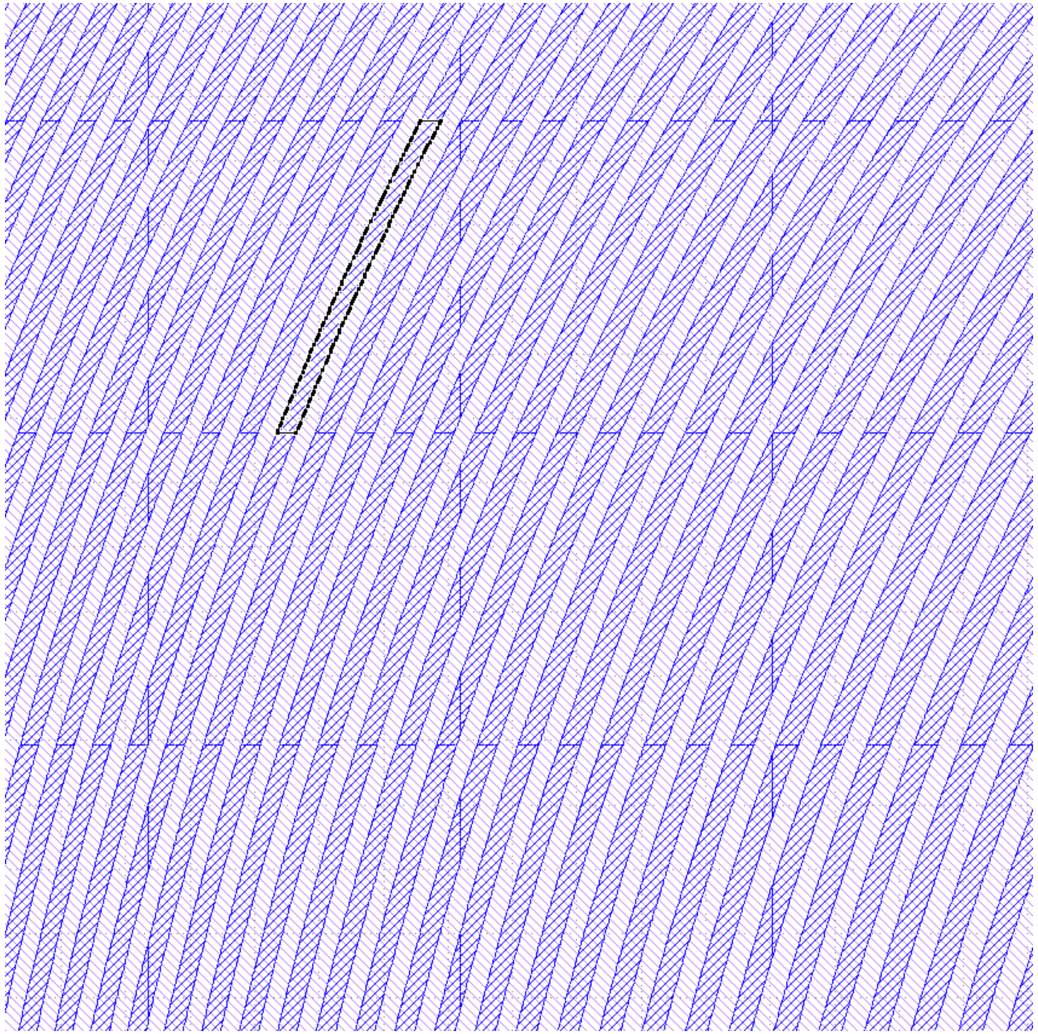
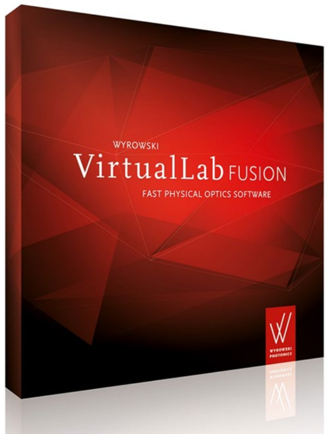


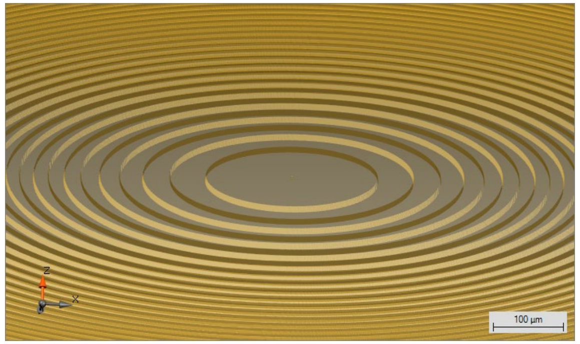


Structure of Webinar

- Why physical optics?
- Optical design in physical optics terms
- Diffractive Optical Elements (DOE)
  - Design
  - Modeling
  - Fabrication data
- Design examples



VirtualLab Fusion 2021



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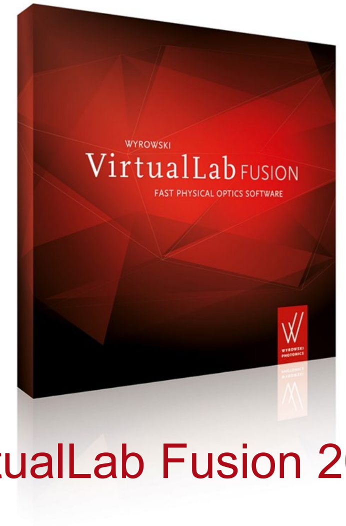

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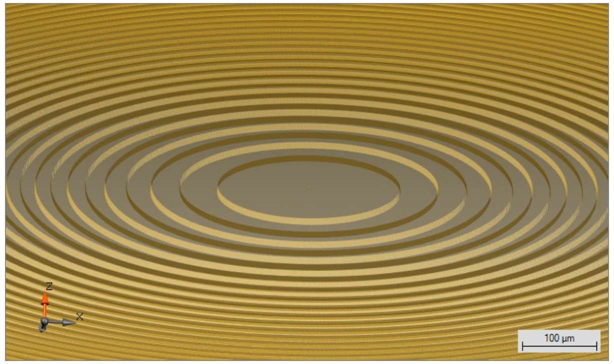
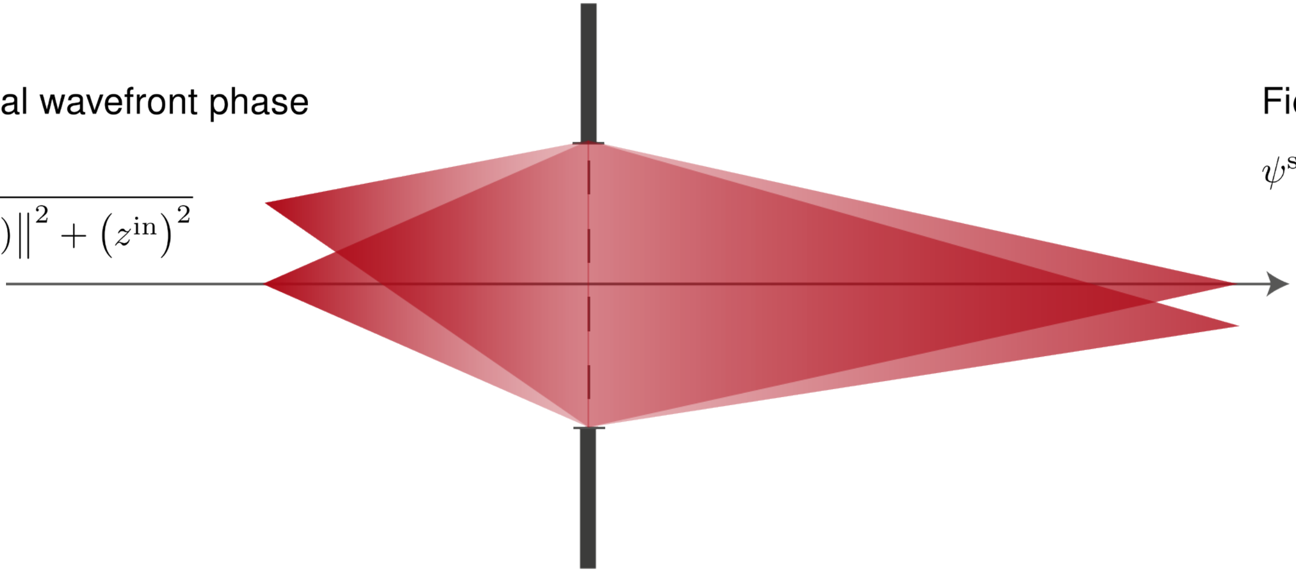


Imaging with one component

Imaging with One Component: Scenario

Input fields with spherical wavefront phase

$$\psi^{\mathrm{sph,in}}(\boldsymbol{\rho},\omega,\alpha) = k_0 n^{\mathrm{in}} \sqrt{\left\|\boldsymbol{\rho}-\boldsymbol{\rho}^{\mathrm{in}}(\alpha)\right\|^2 + \left(z^{\mathrm{in}}\right)^2}$$



Fields with spherical wavefront phase

$$\psi^{\mathrm{sph,out}}(\boldsymbol{r},\omega,\alpha) = -k_0 n^{\mathrm{out}} \sqrt{\left\|\boldsymbol{\rho}-M\boldsymbol{\rho}^{\mathrm{in}}(\alpha)\right\|^2 + \left(z^{\mathrm{out}}\right)^2}$$

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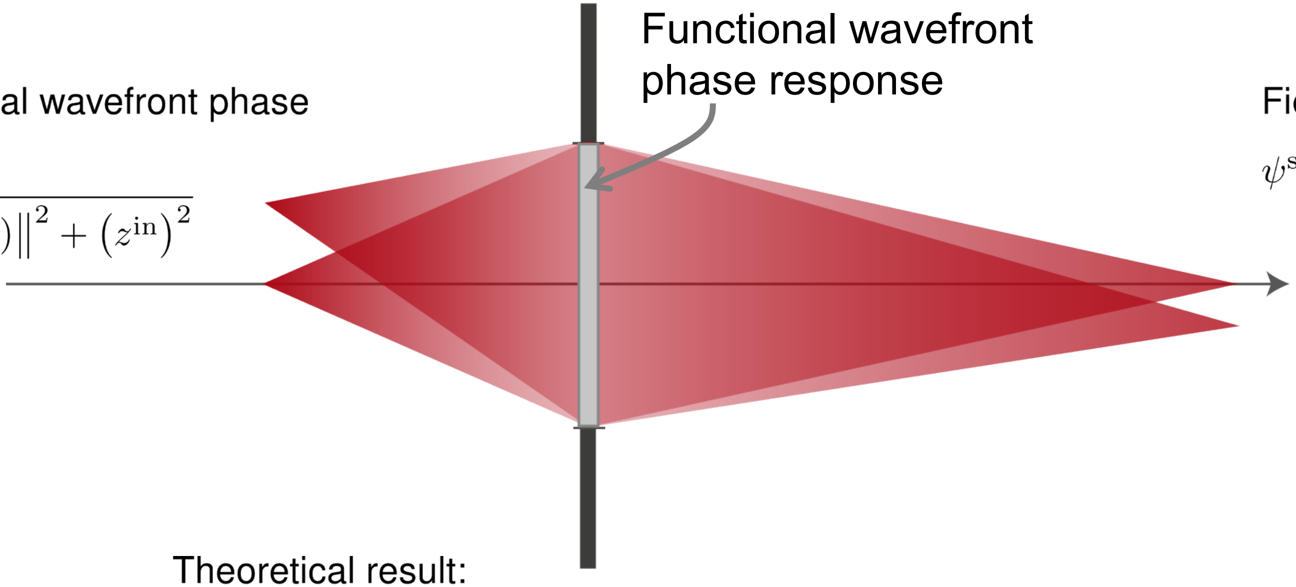

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Theoretical result:

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$$z^{\mathrm{out}} = \sqrt{\left(z^{\mathrm{in}}M\right)^2 + \rho_0^2\left(M^2-1\right)}$$

In paraxial approximation:

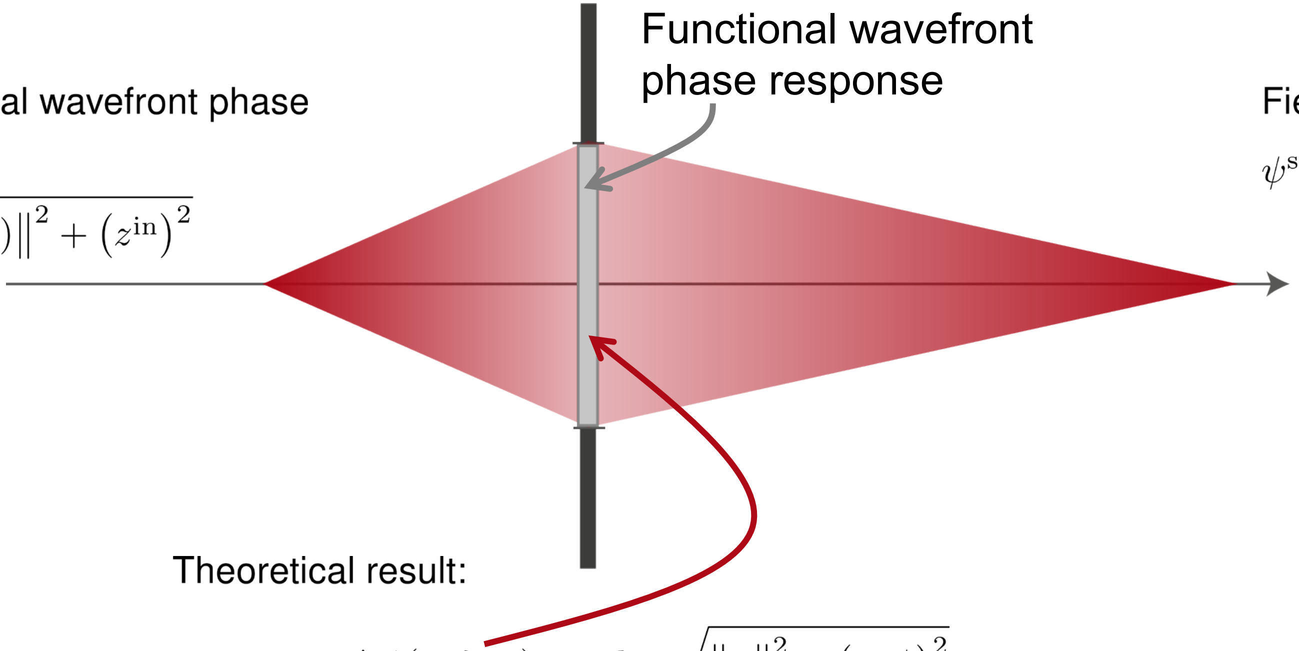
$$\Delta\psi(\boldsymbol{\rho},\lambda,\alpha) \approx \Delta\psi_0 - k_0 n \frac{\|\boldsymbol{\rho}\|^2}{2f}$$

In general dependent of input field

Imaging with One Component: Functional Design

Input fields with spherical wavefront phase

$$\psi^{\mathrm{sph,in}}(\boldsymbol{\rho}, \omega, \alpha) = k_0 n^{\mathrm{in}} \sqrt{\left\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\mathrm{in}}(\alpha)\right\|^2 + \left(z^{\mathrm{in}}\right)^2}$$



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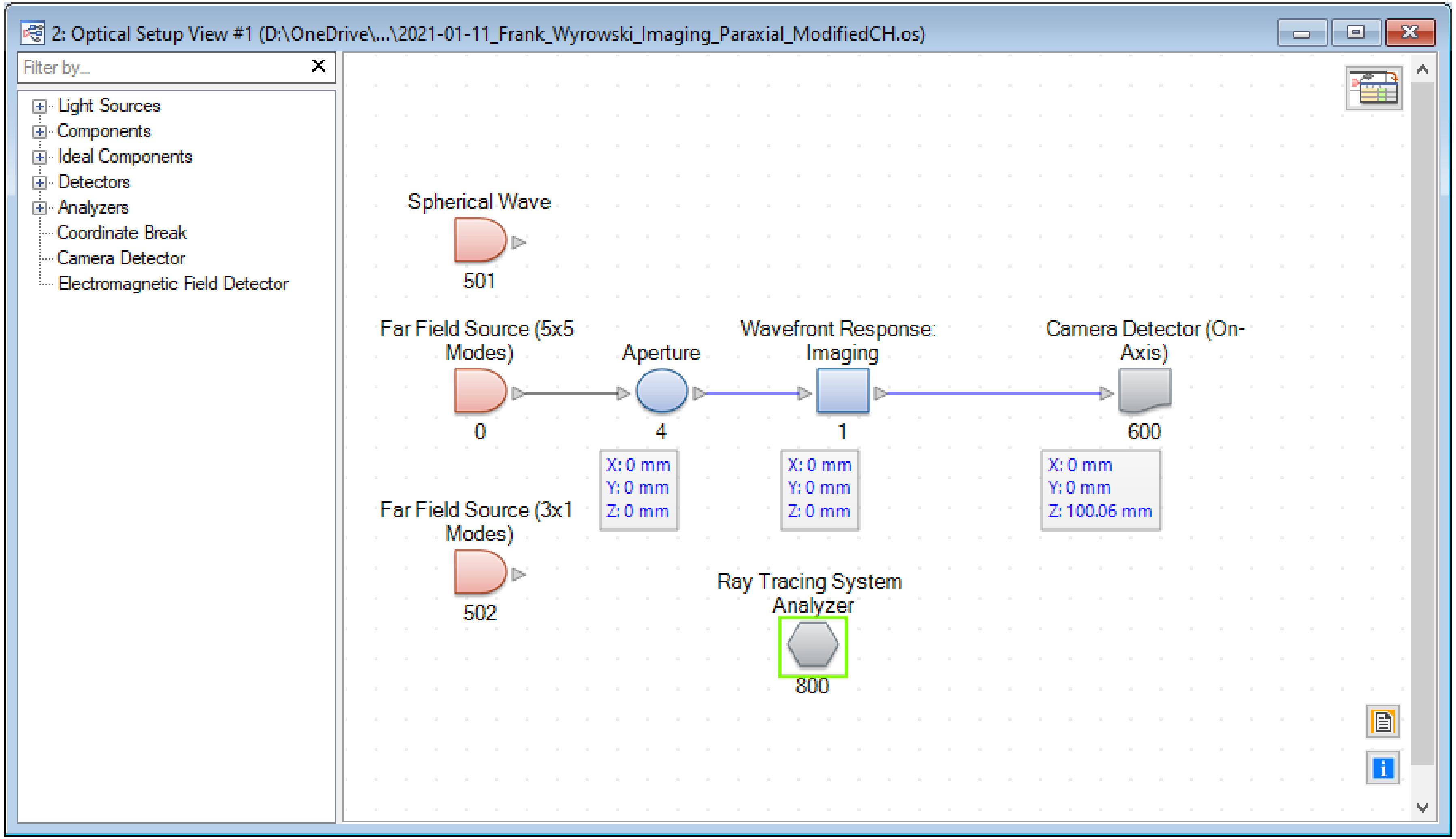
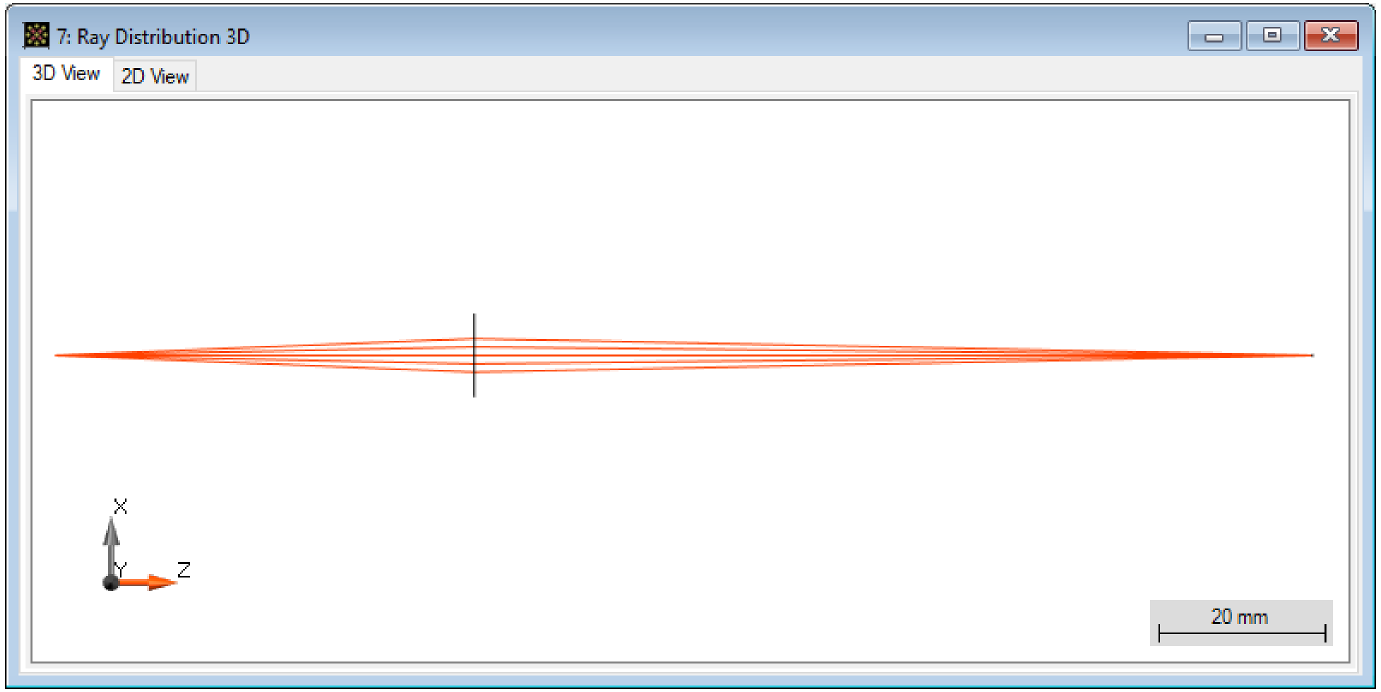
Functional Design for Imaging: NA 0.02



Functional Design for Imaging (NA 0.02): Ray Tracing



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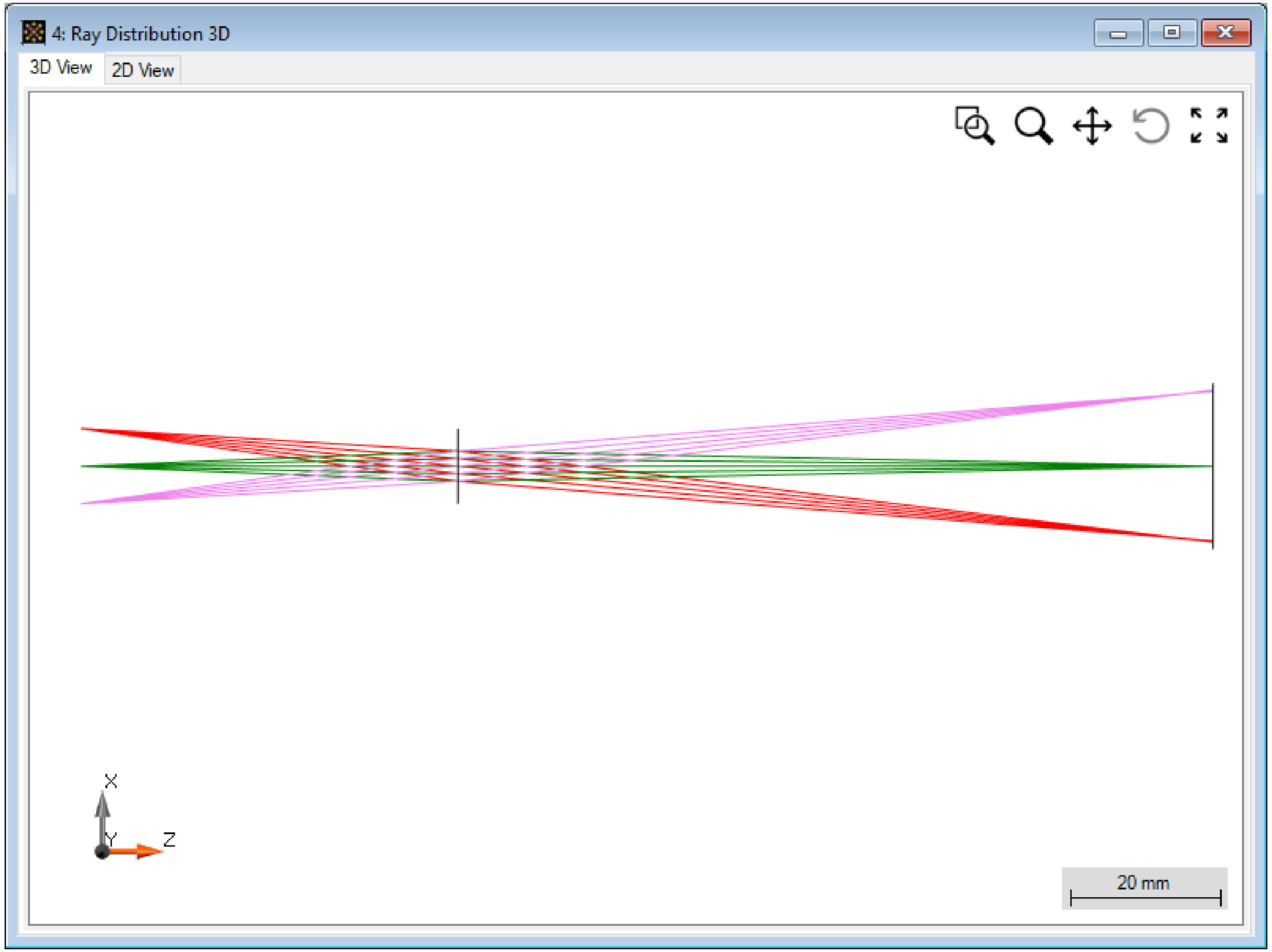

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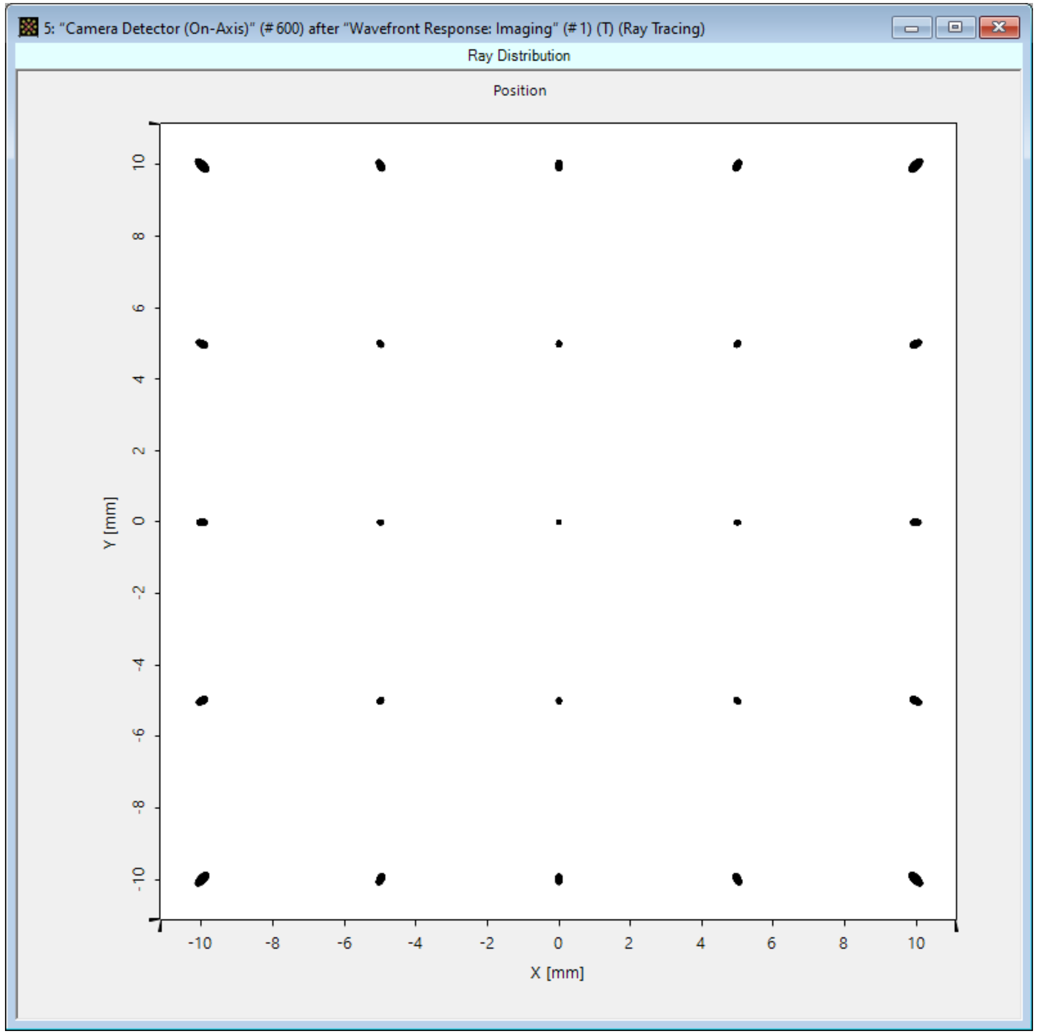
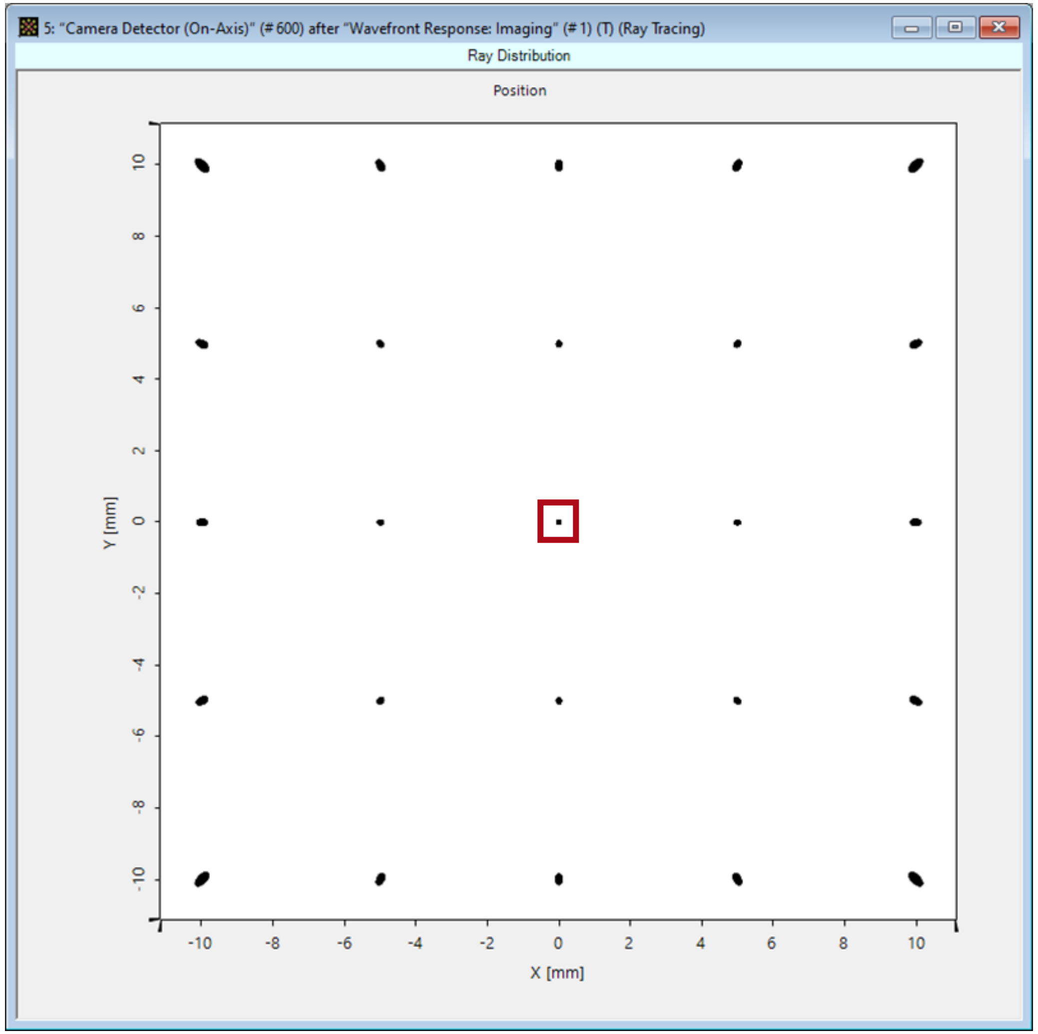
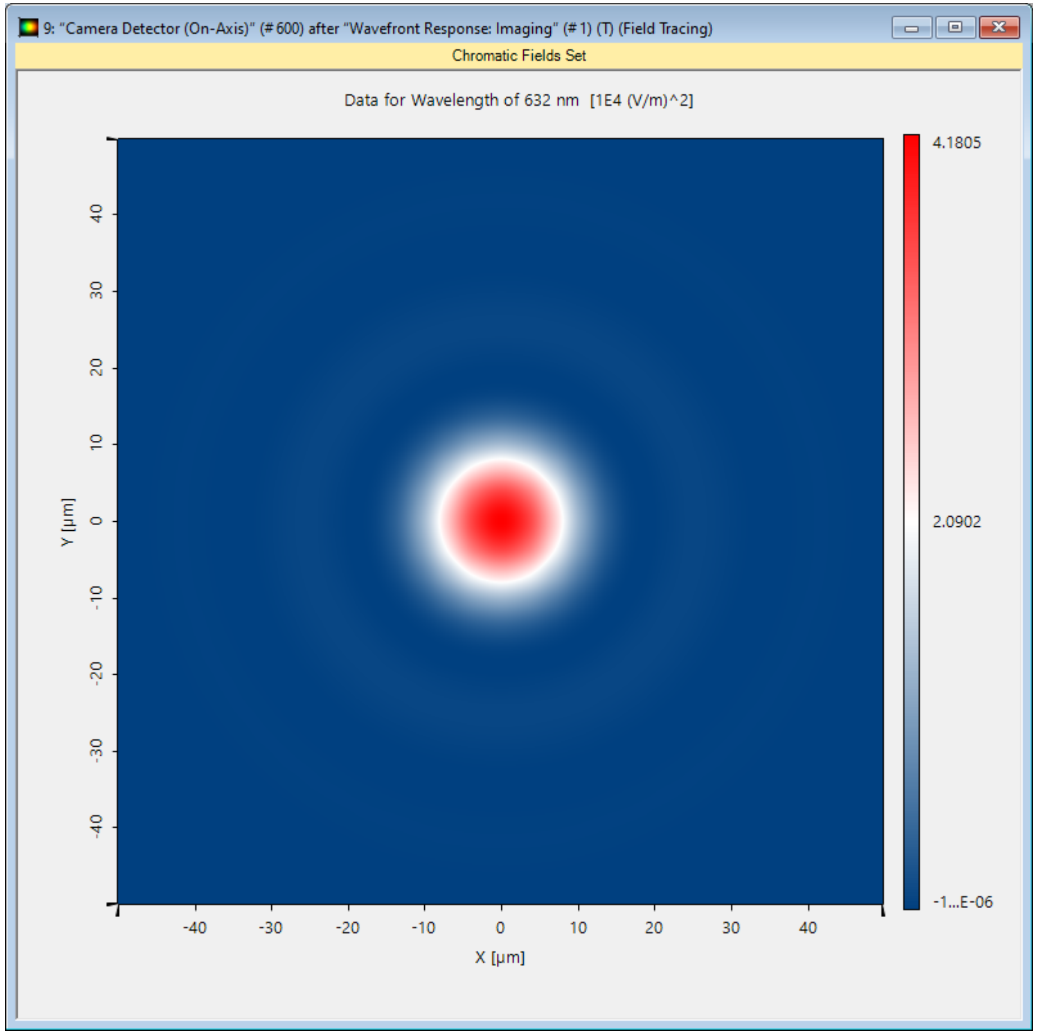


Functional Design for Imaging (NA 0.02): Field Tracing





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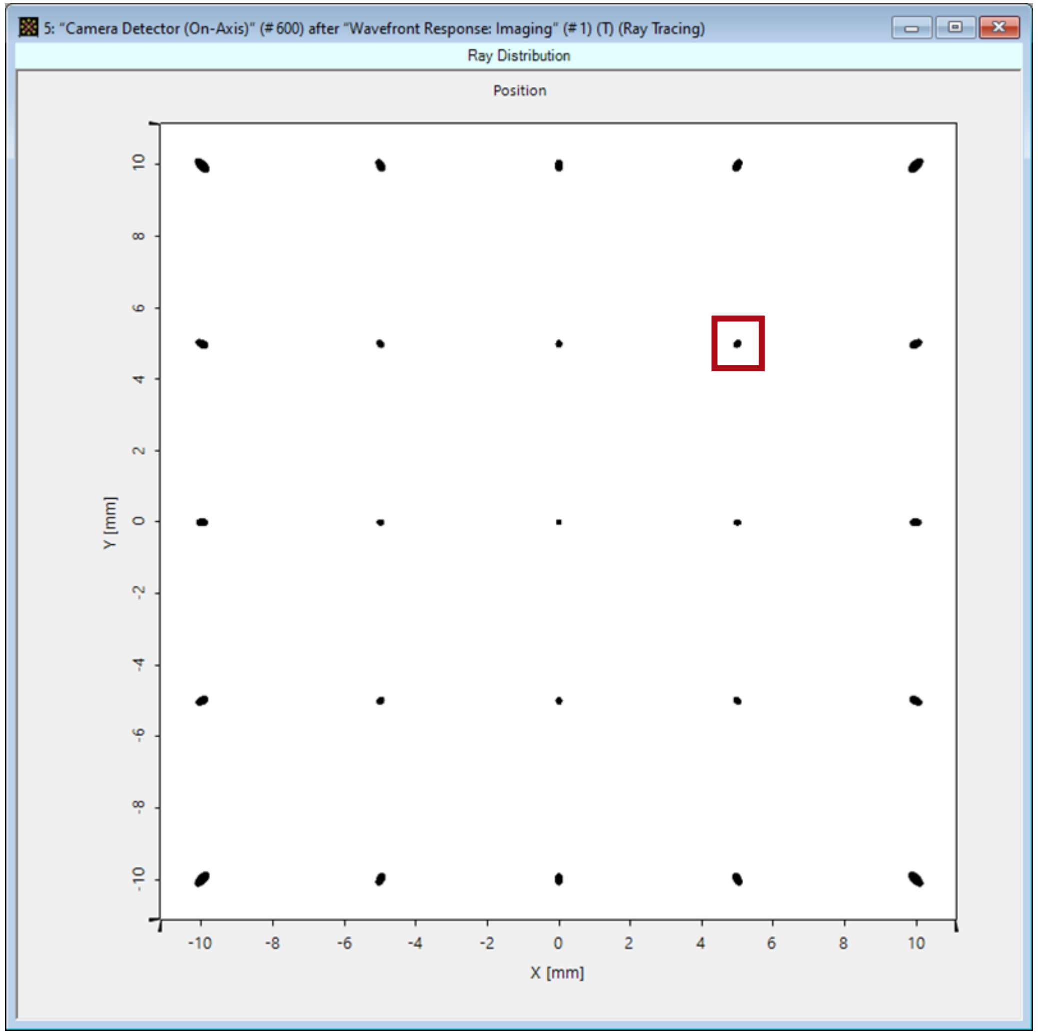
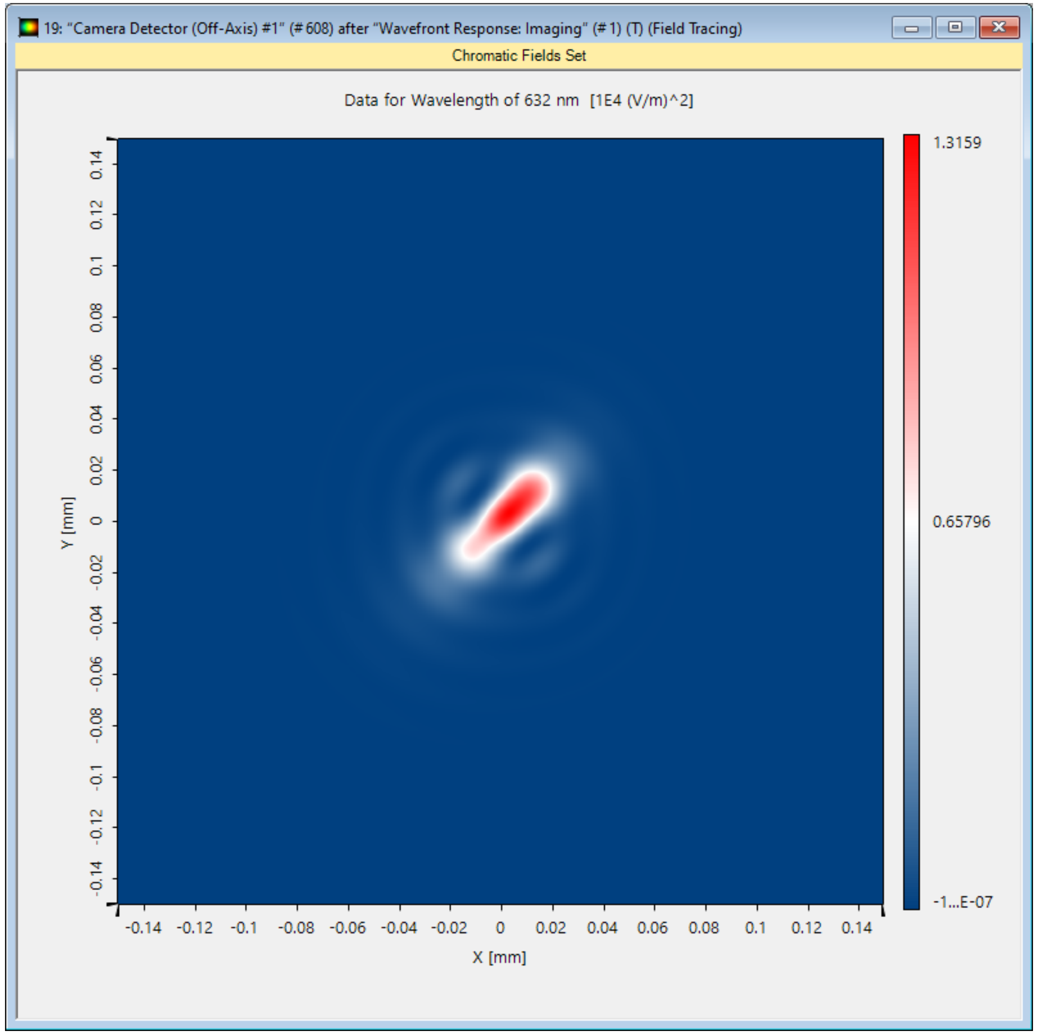
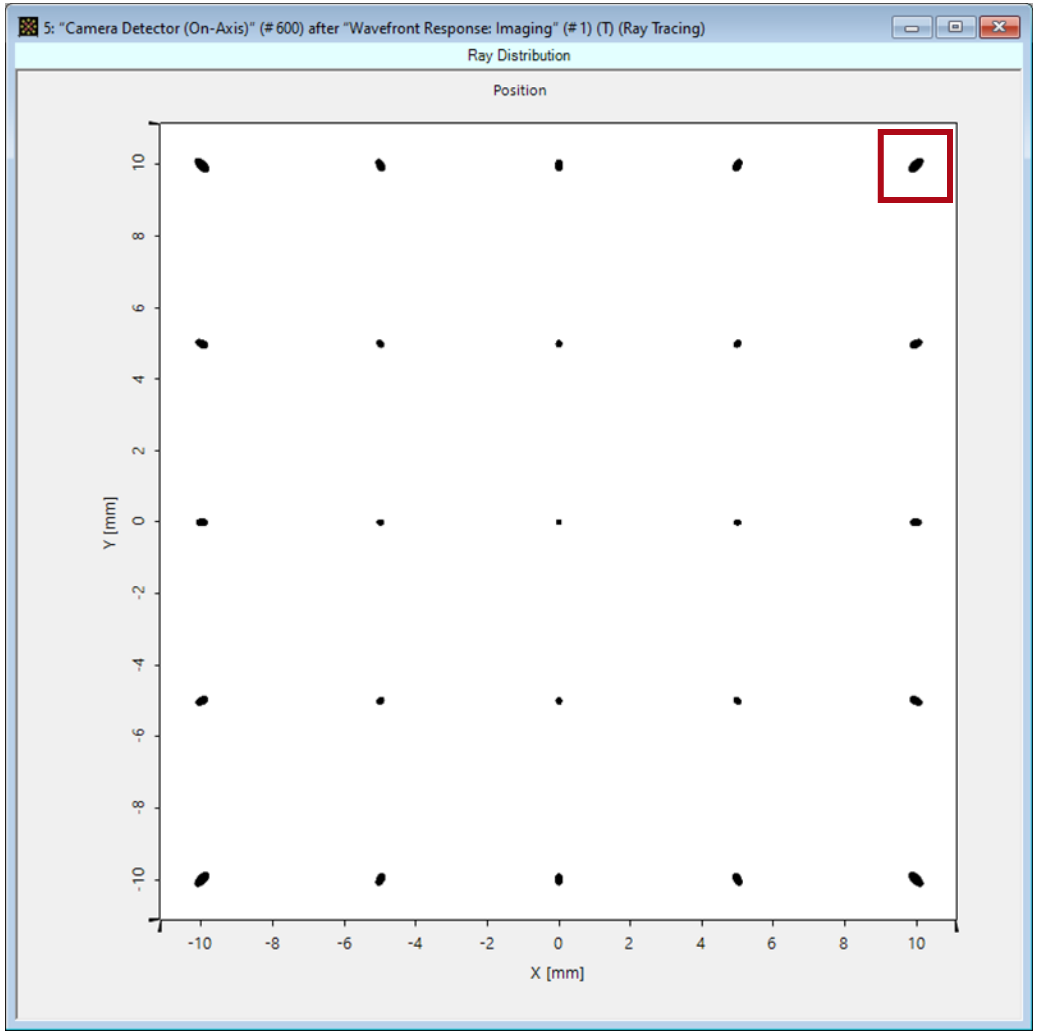
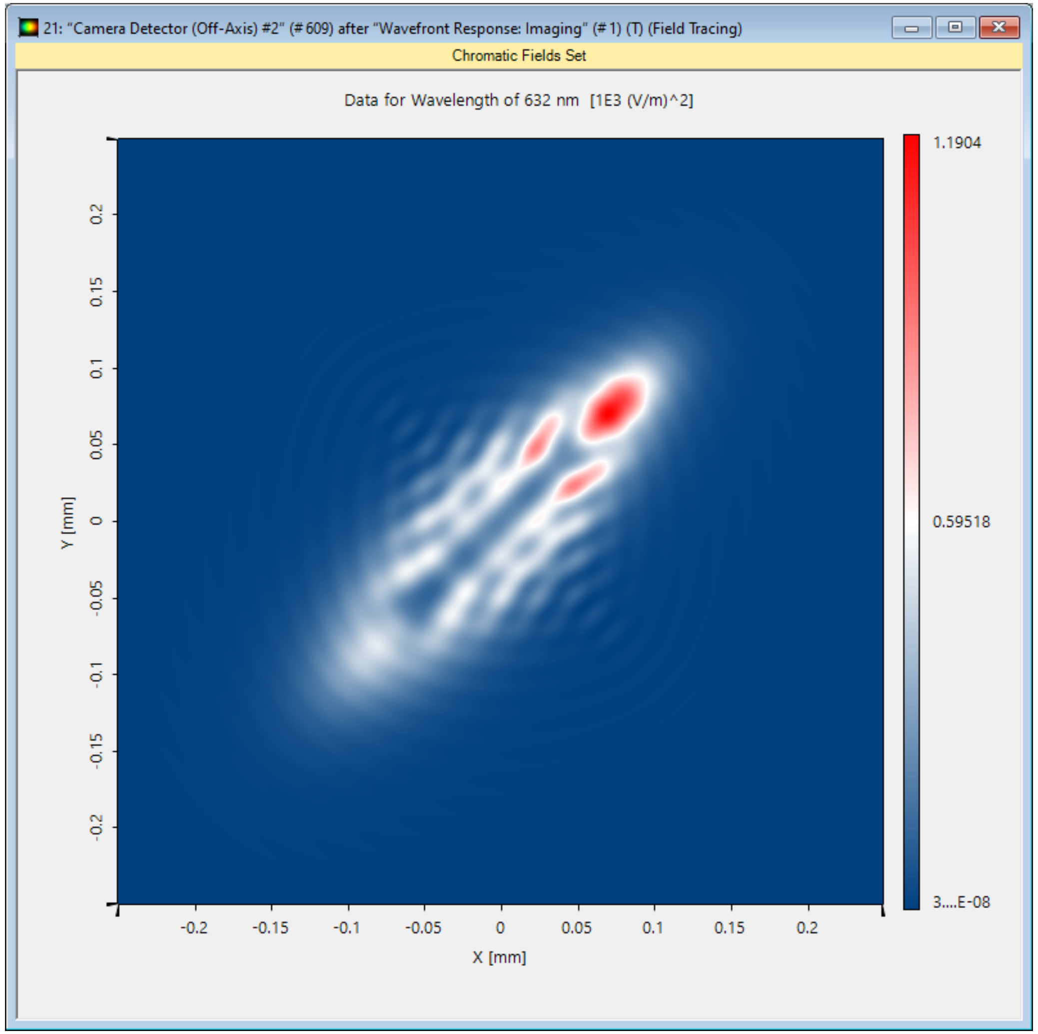




Functional Design for Imaging (NA 0.02): Field Tracing





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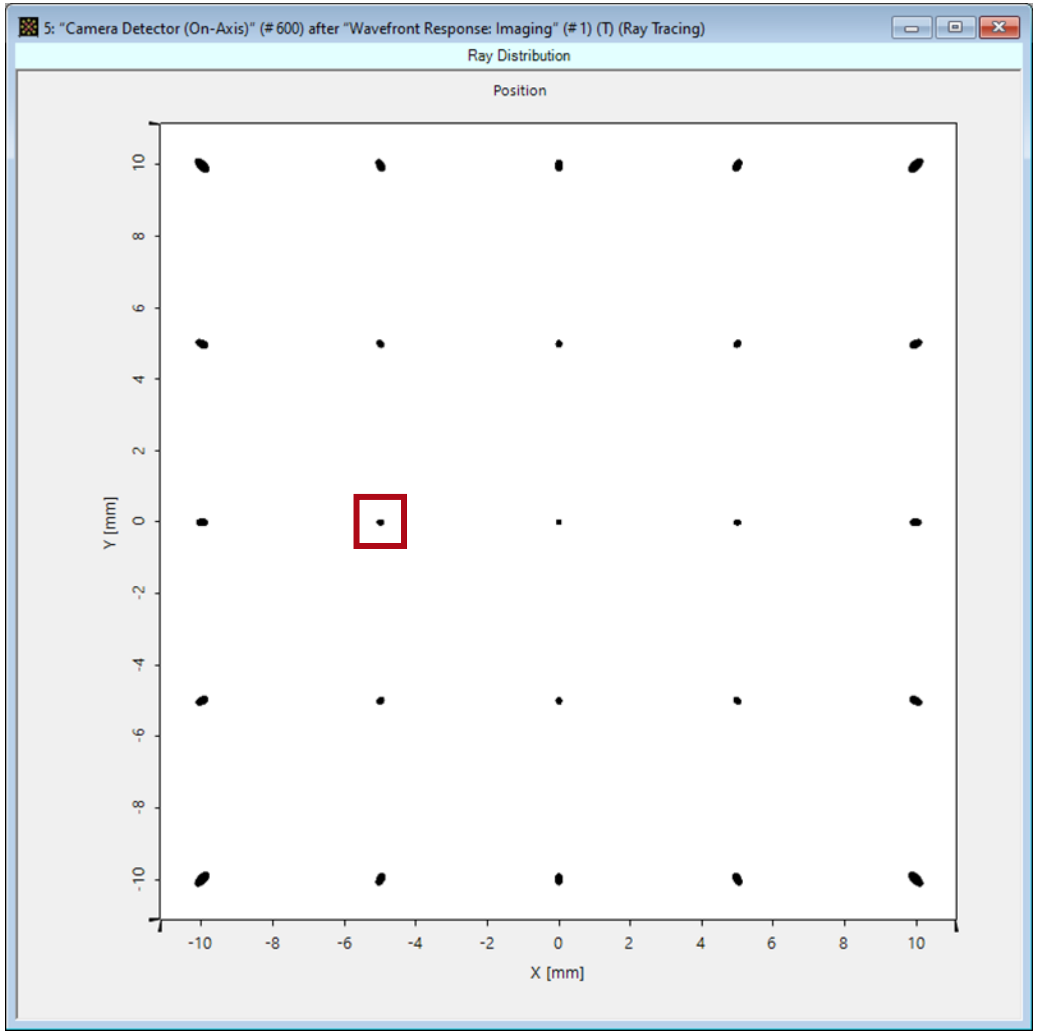
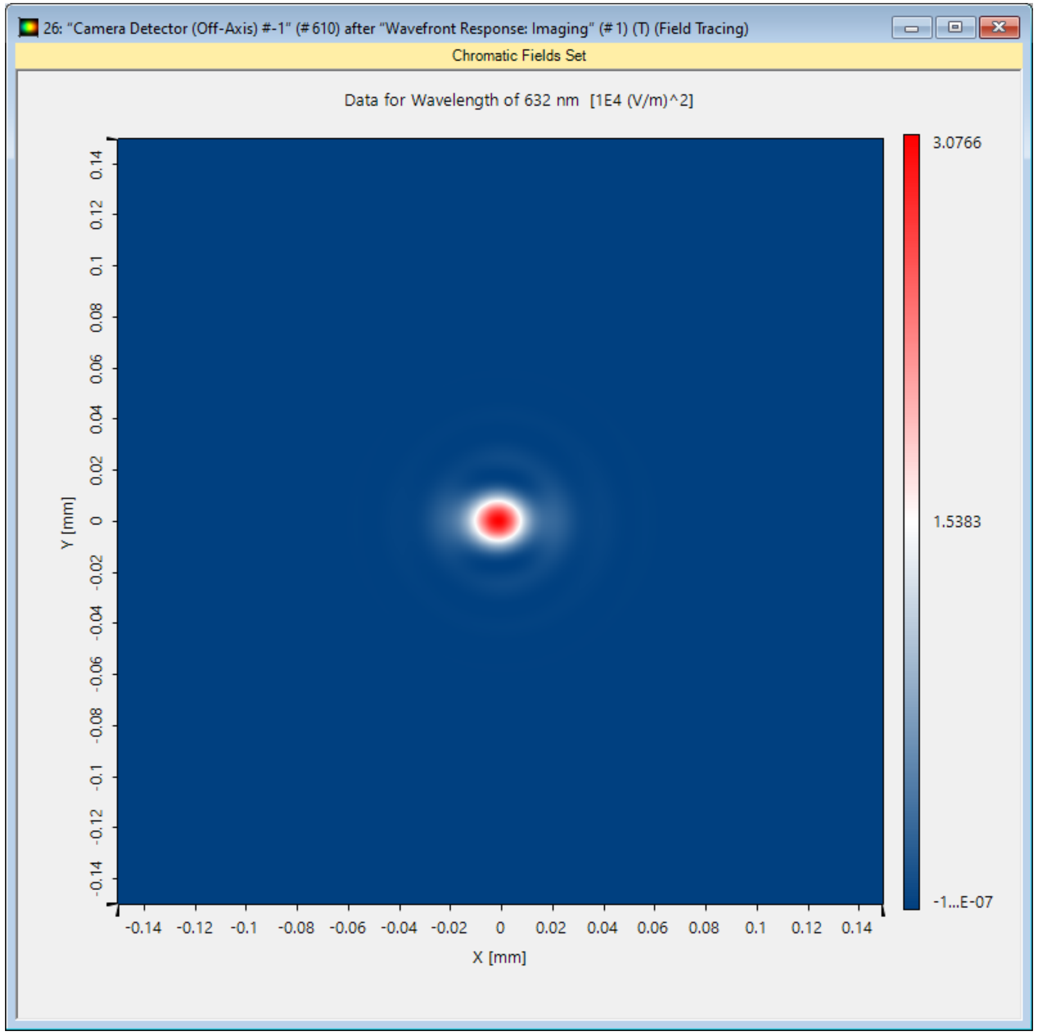
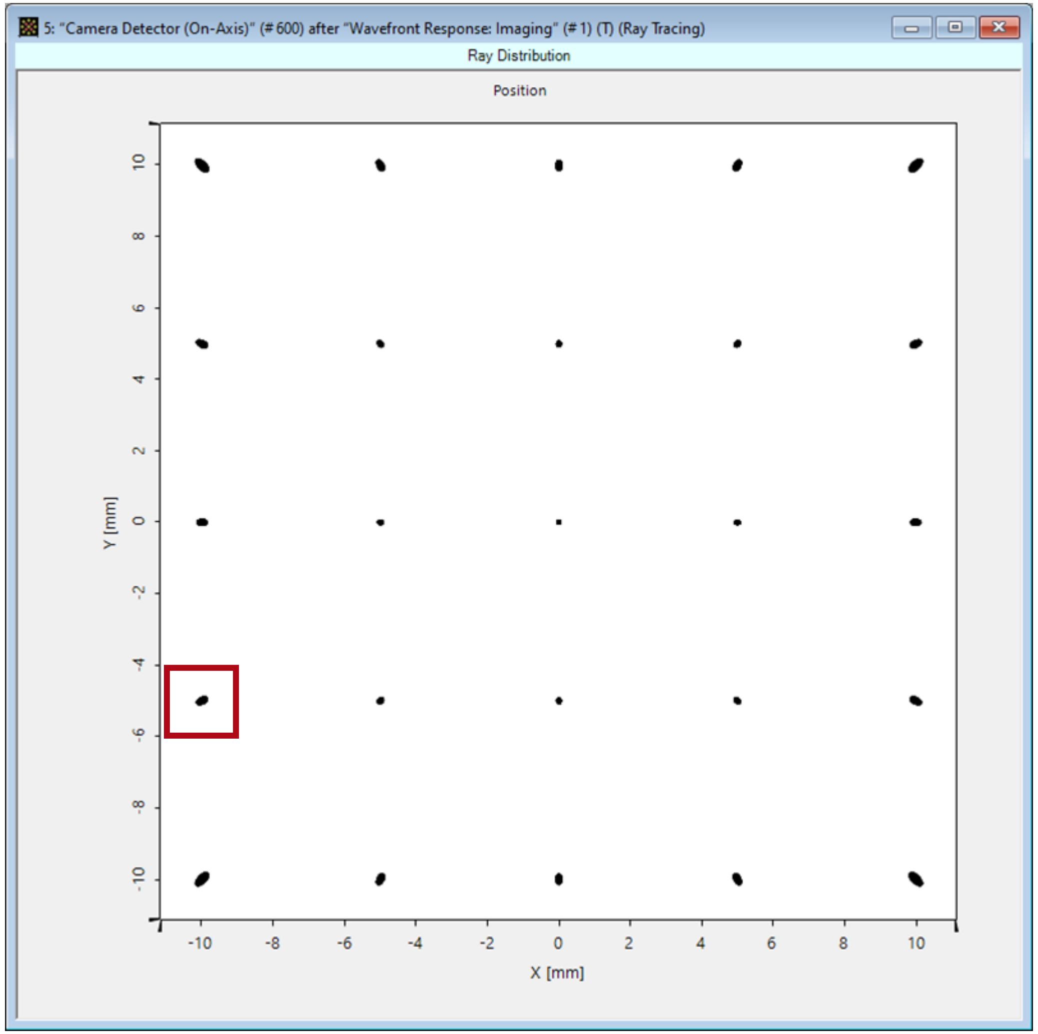
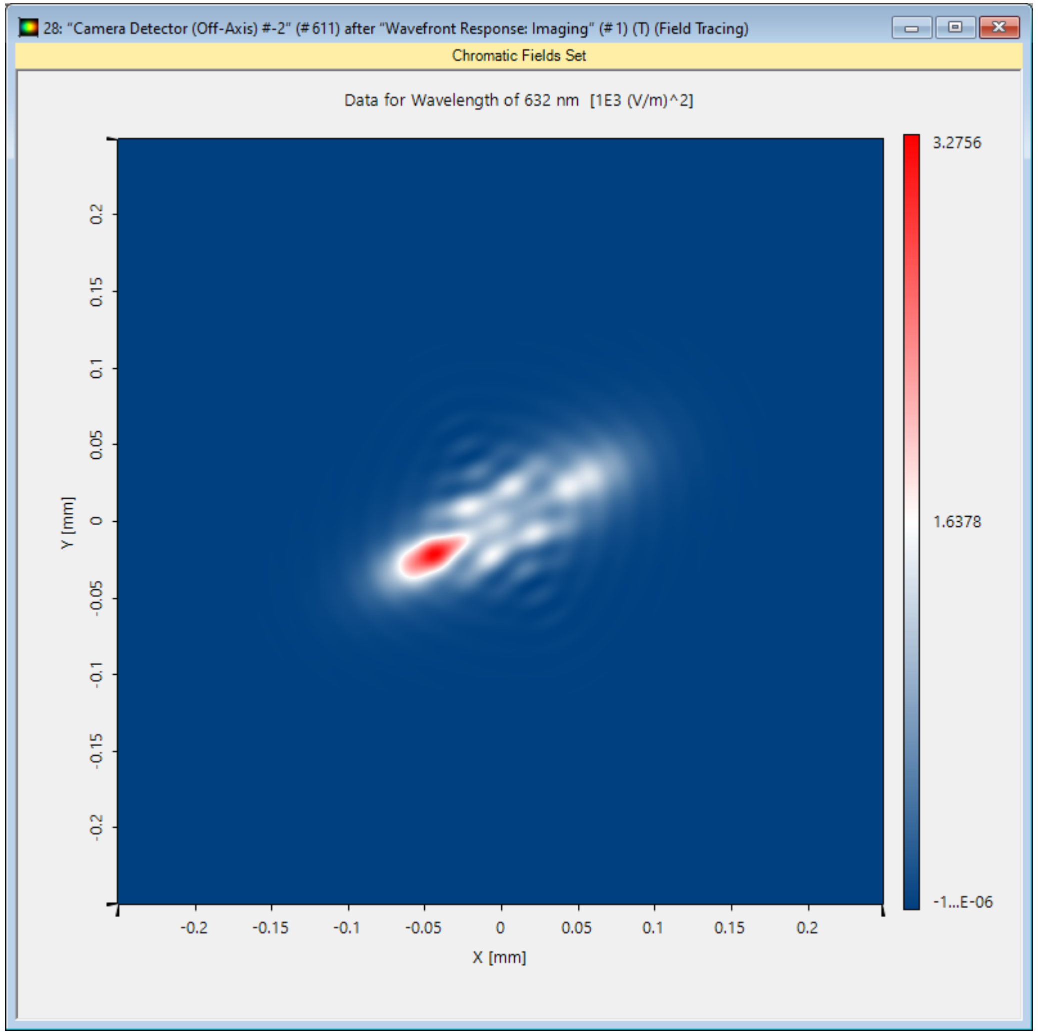


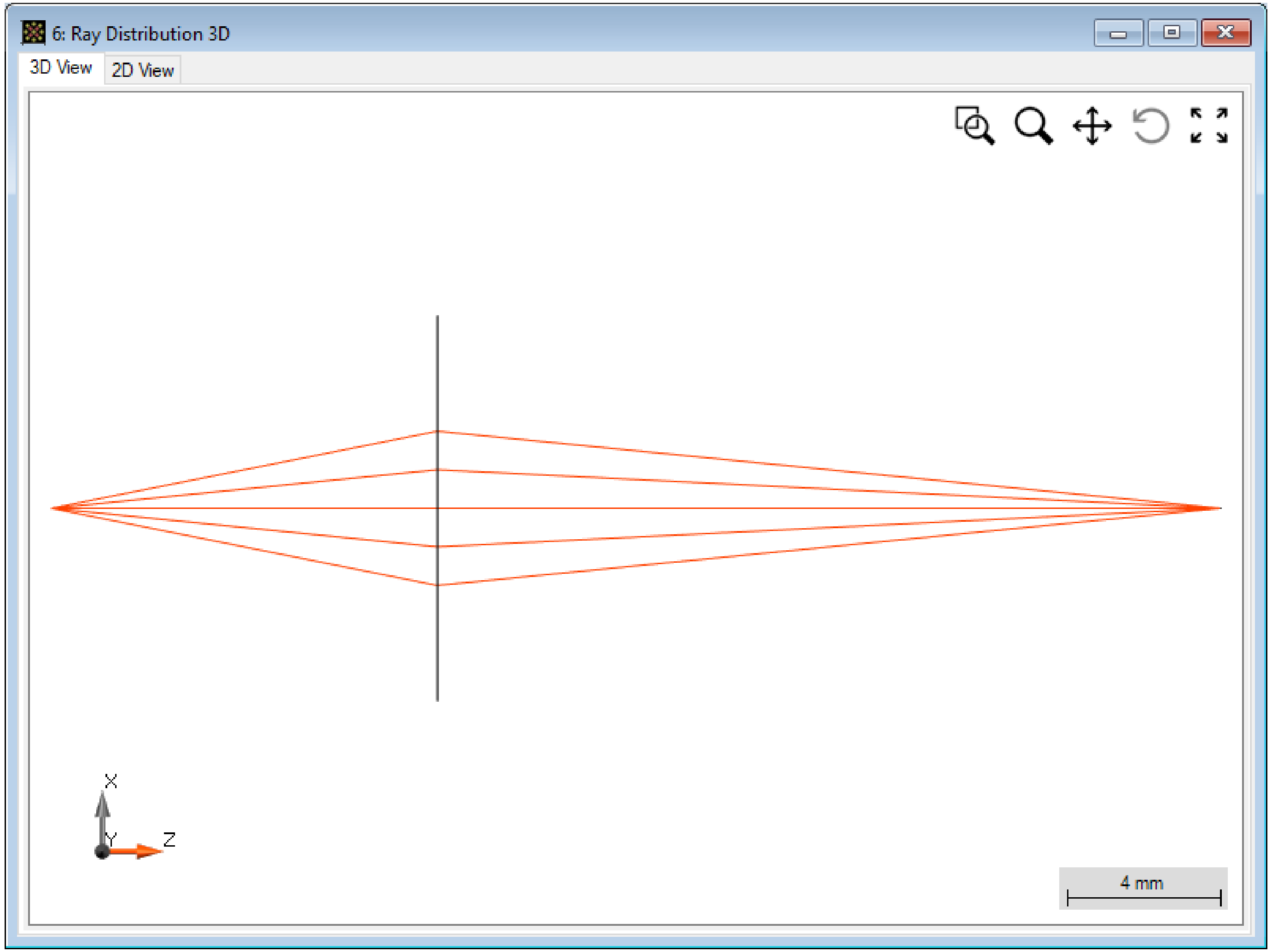


Functional Design for Imaging (NA 0.02): Field Tracing

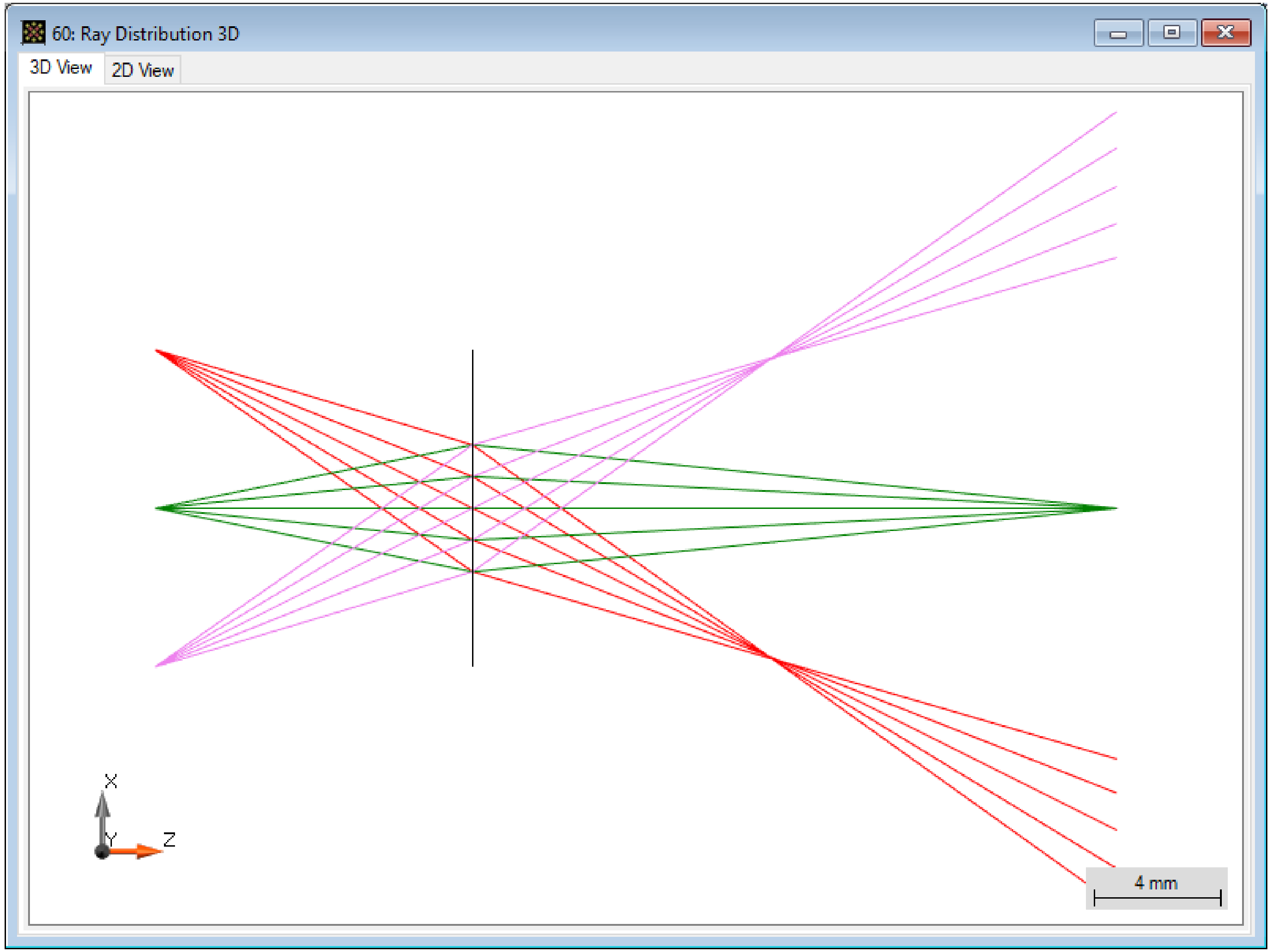




Functional Design for Imaging (NA 0.1): Ray Tracing



Functional Design for Imaging (NA 0.1): Ray Tracing



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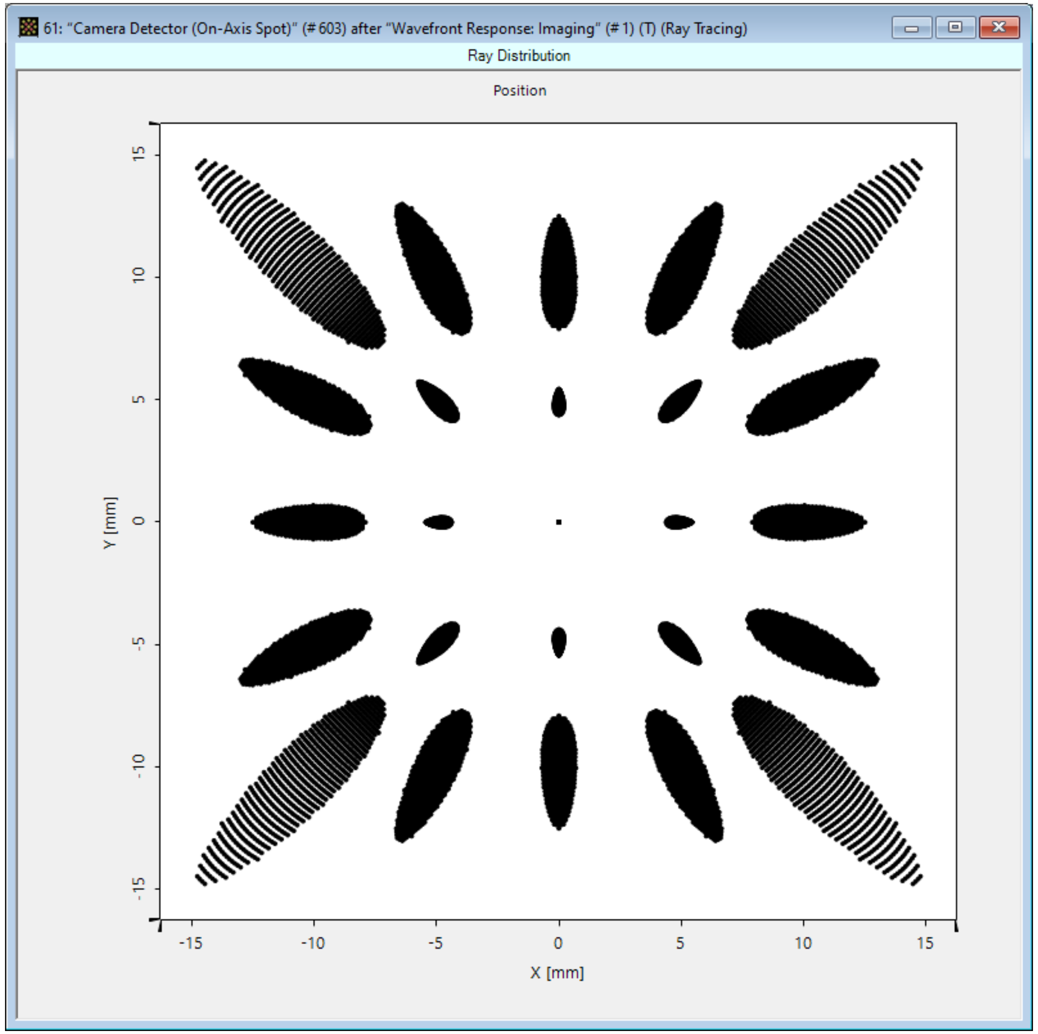
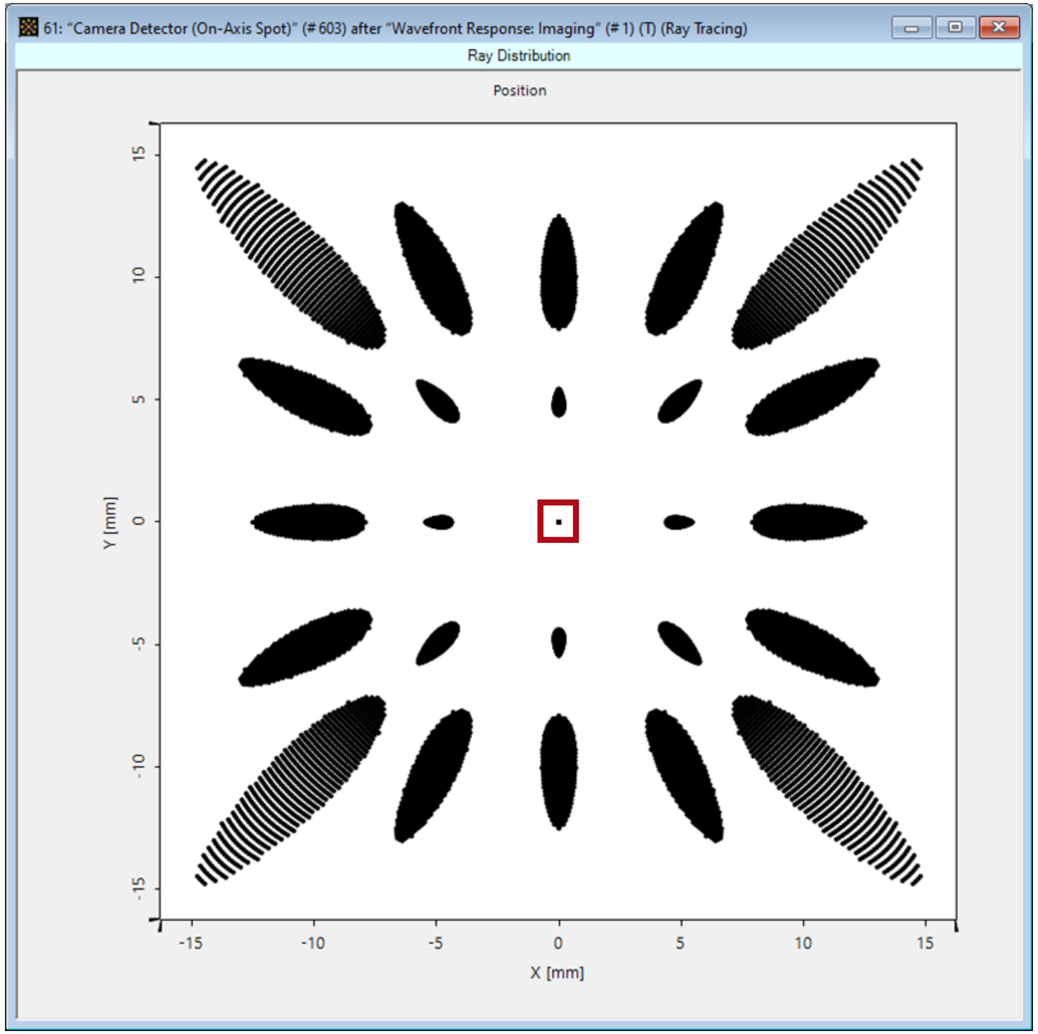
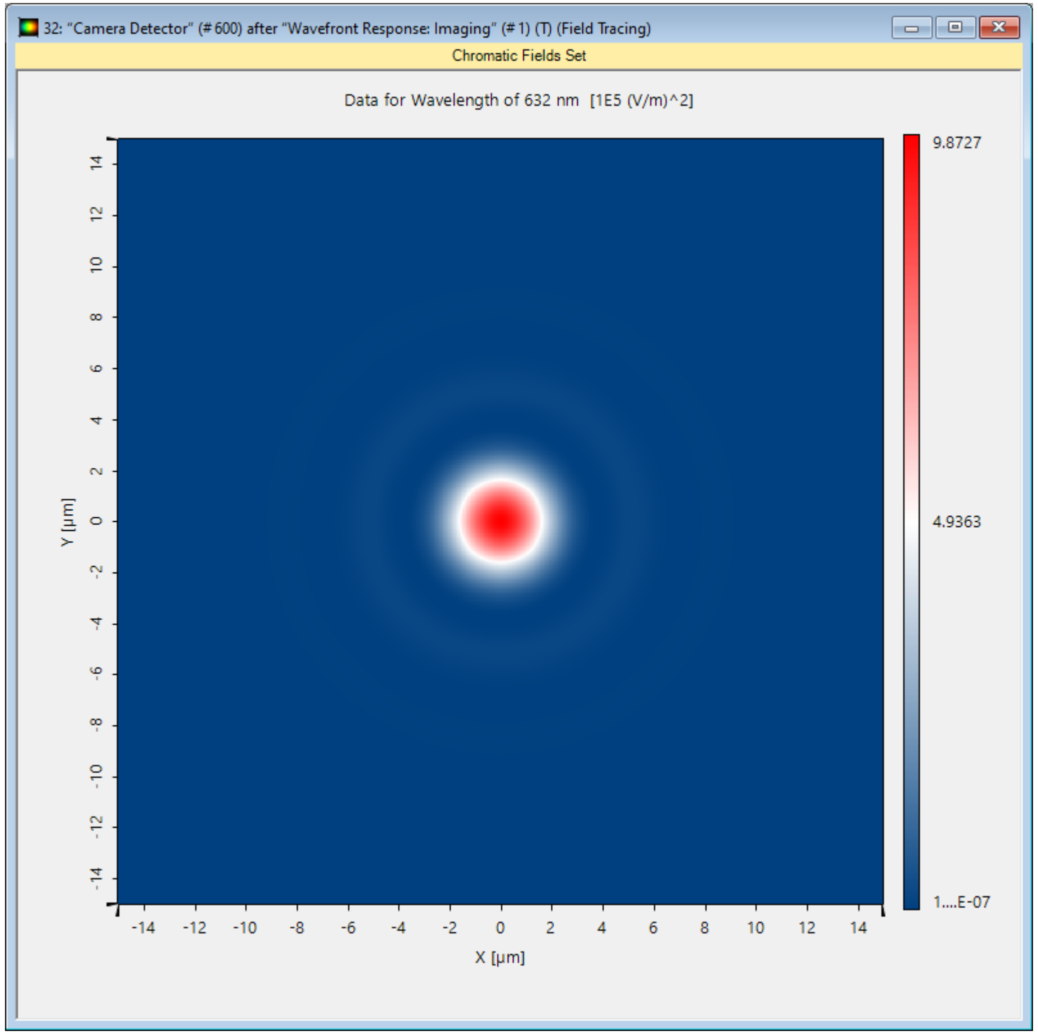


Functional Design for Imaging (NA 0.1): Field Tracing





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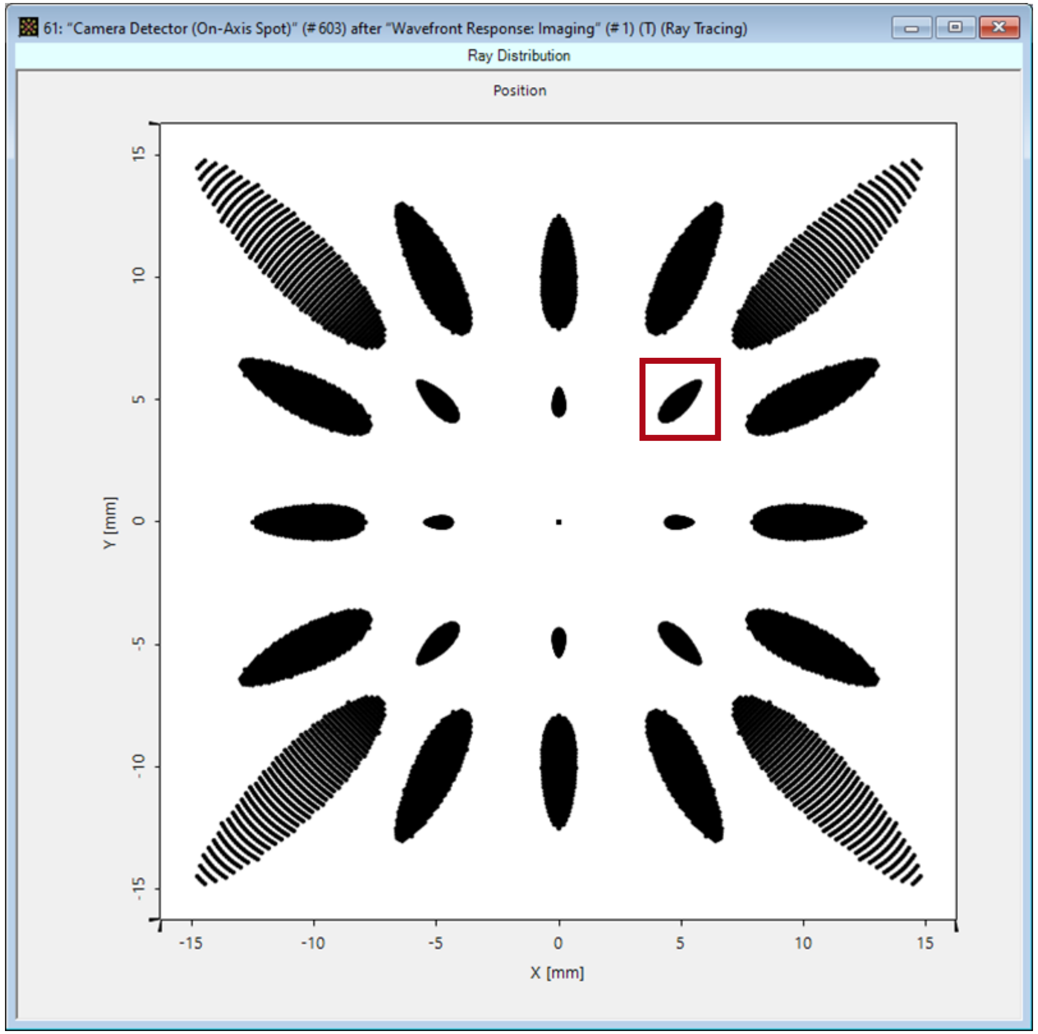

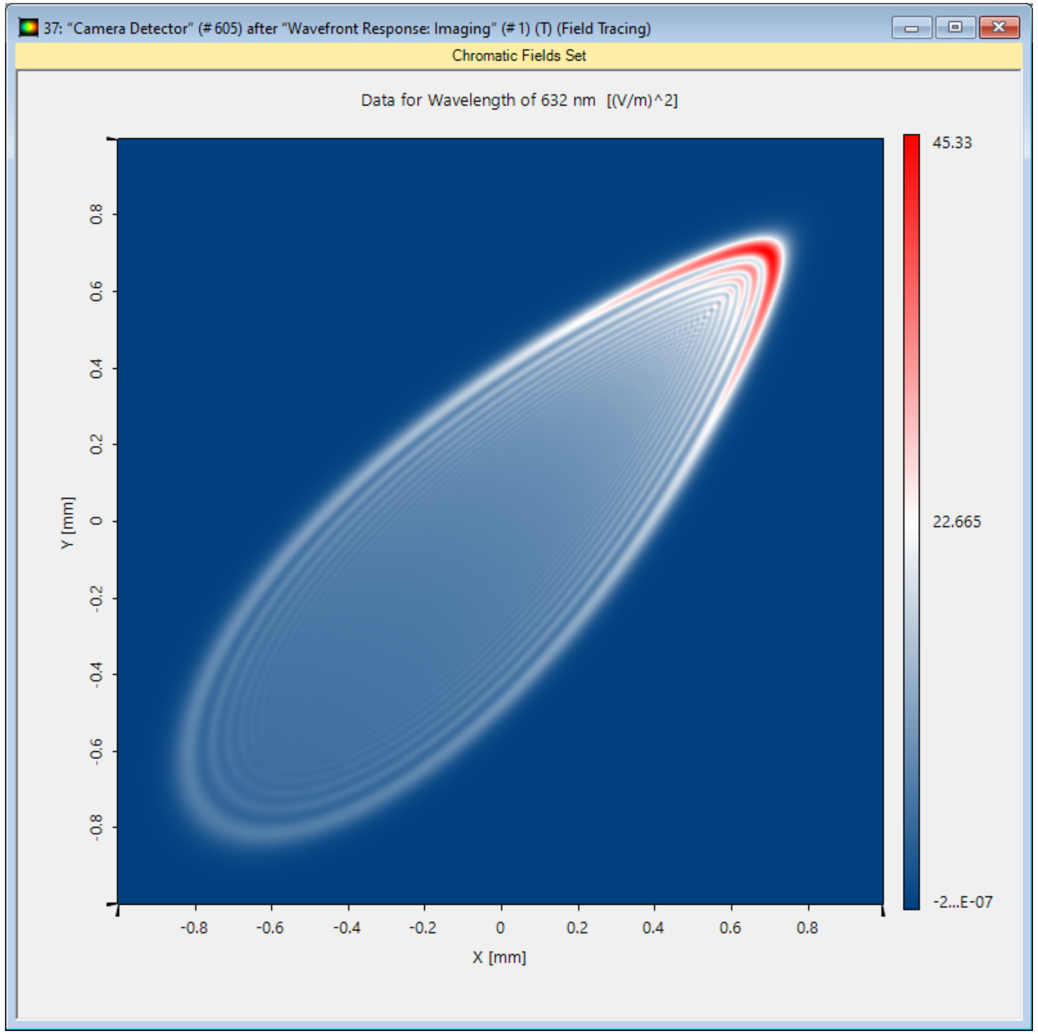

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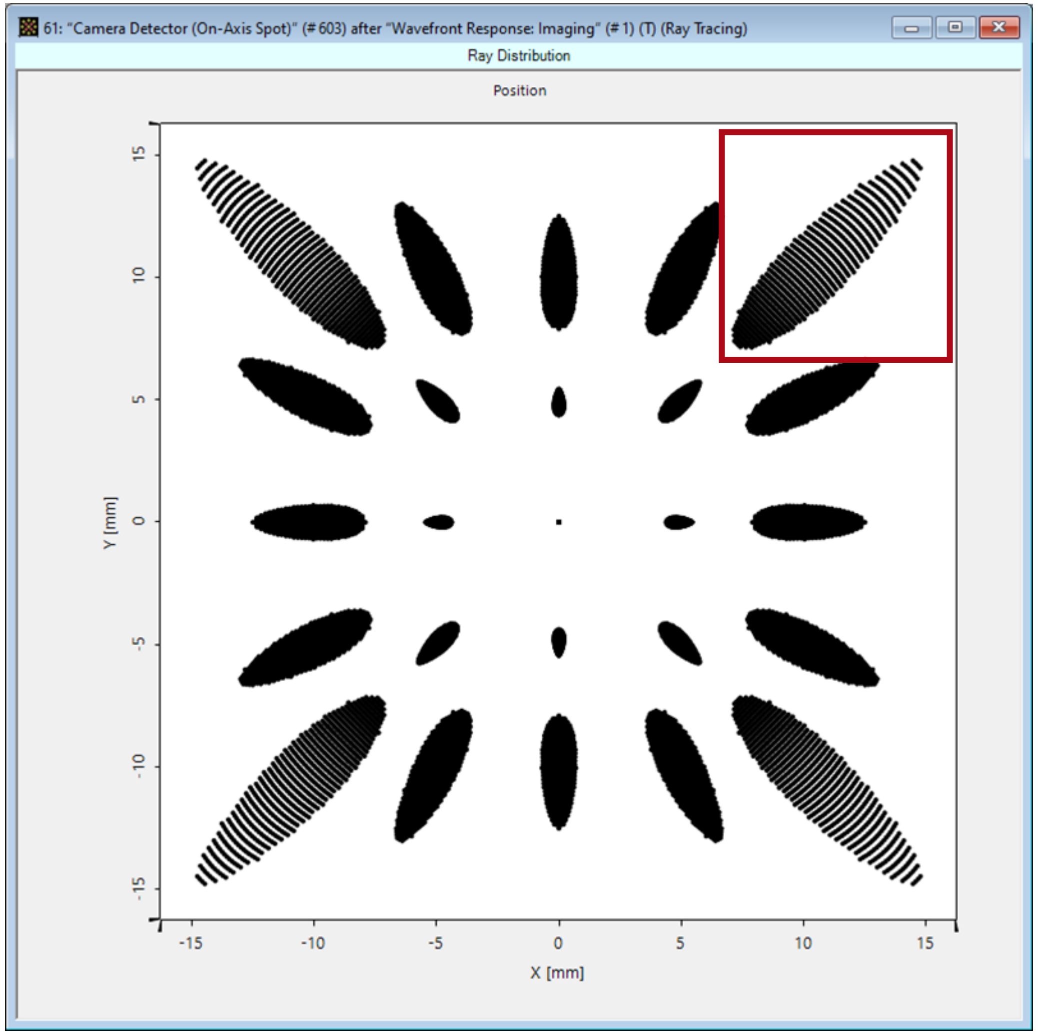

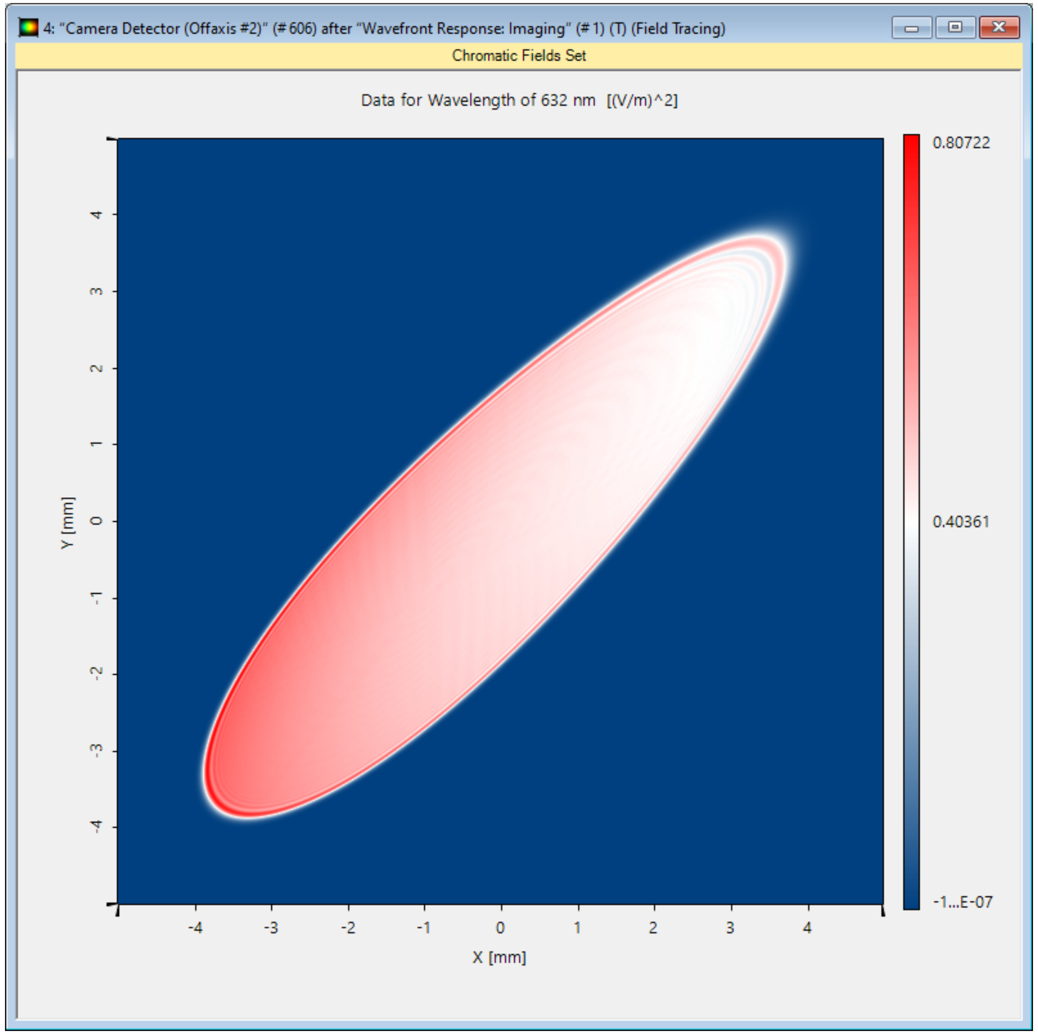

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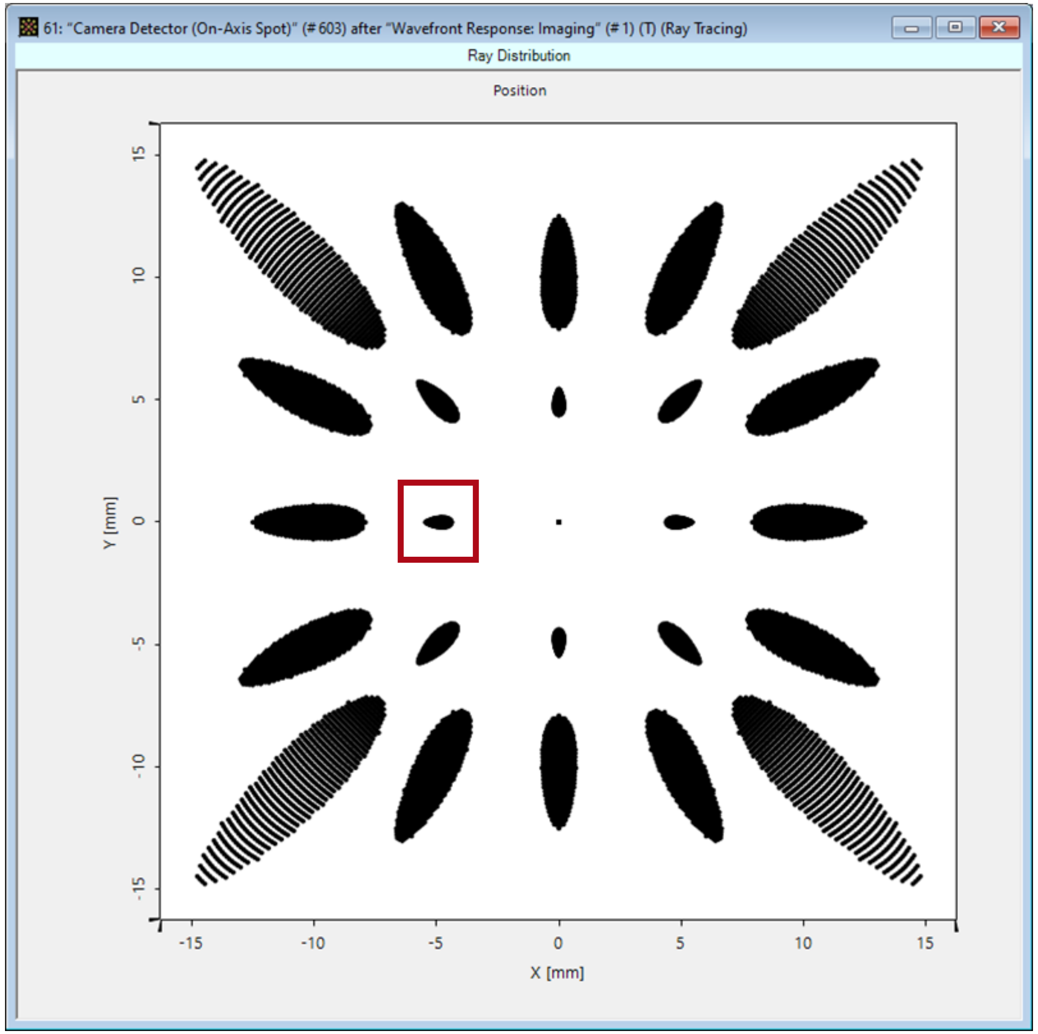

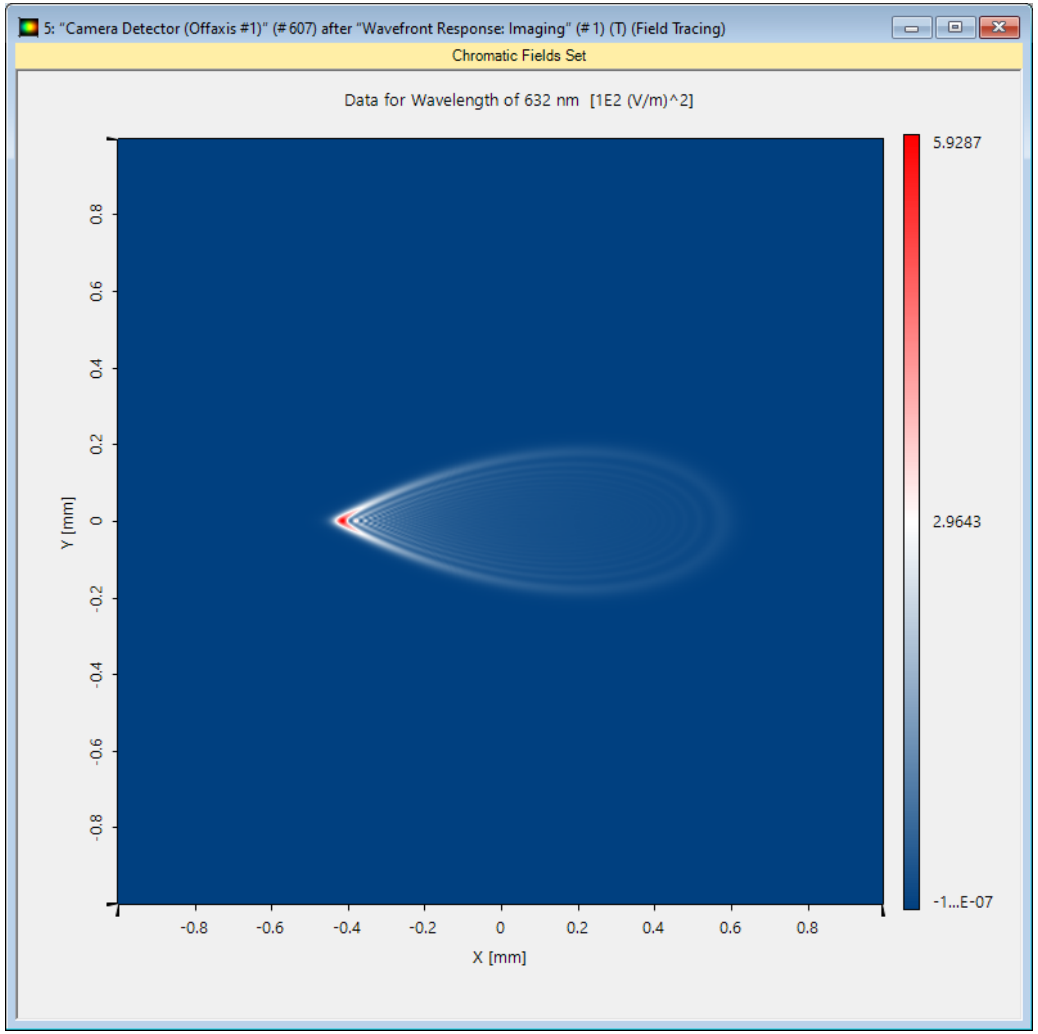

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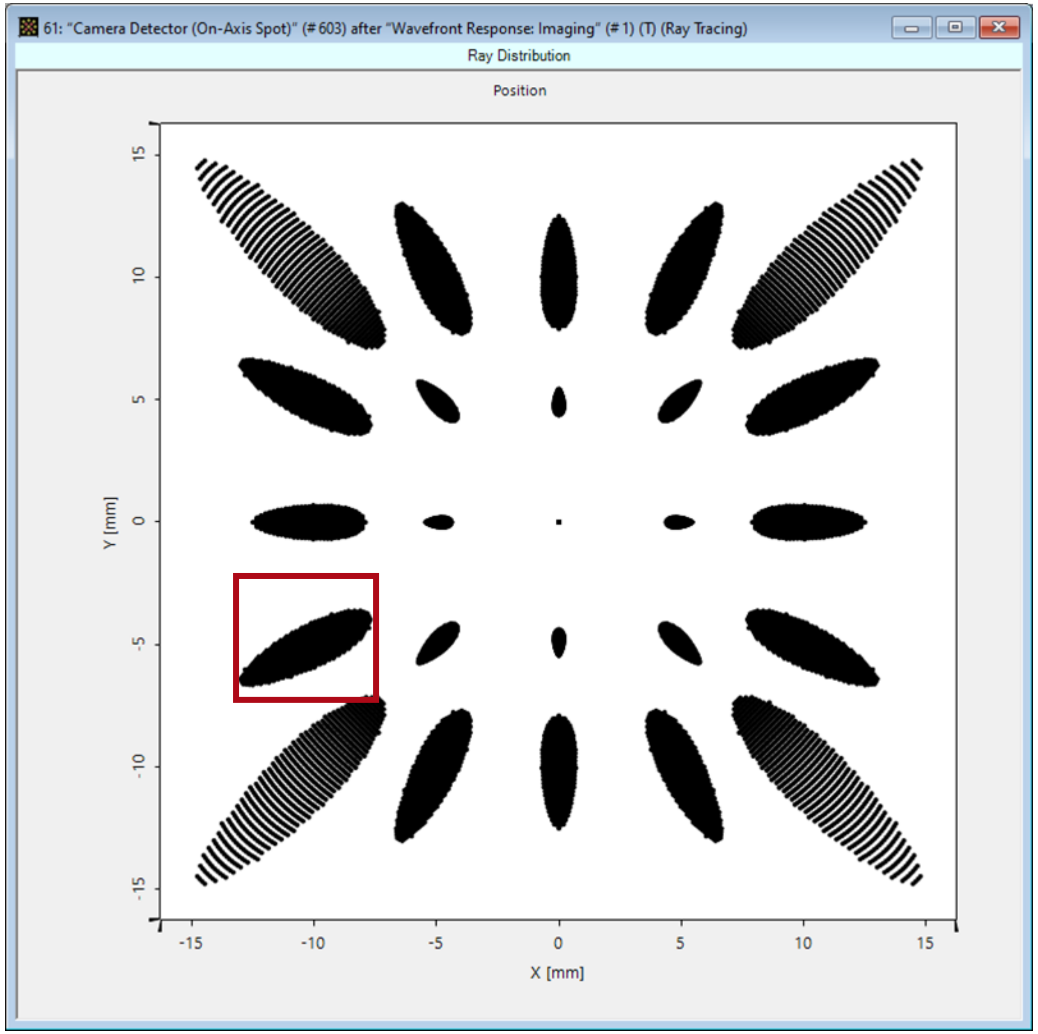

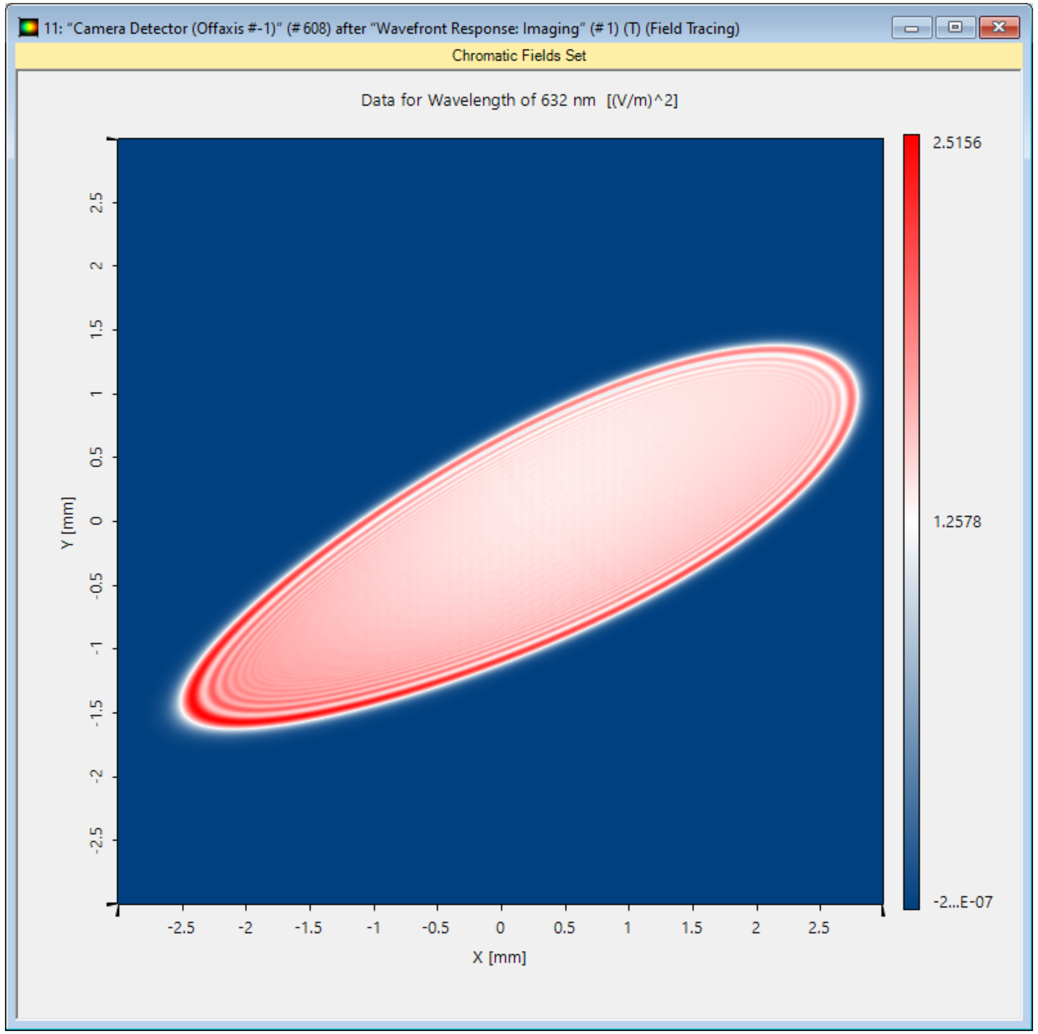

Functional Design for Imaging (NA 0.1): Off-Axis Mode

Theoretical result:

$$\Delta\psi(\boldsymbol{\rho},\lambda,\alpha) = -k_0 n\sqrt{\left\|\boldsymbol{\rho} - M\boldsymbol{\rho}^{\text{in}}(\alpha)\right\|^2 + \left(z^{\text{out}}\right)^2} - k_0 n\sqrt{\left\|\boldsymbol{\rho} - \boldsymbol{\rho}^{\text{in}}(\alpha)\right\|^2 + \left(z^{\text{in}}\right)^2}$$

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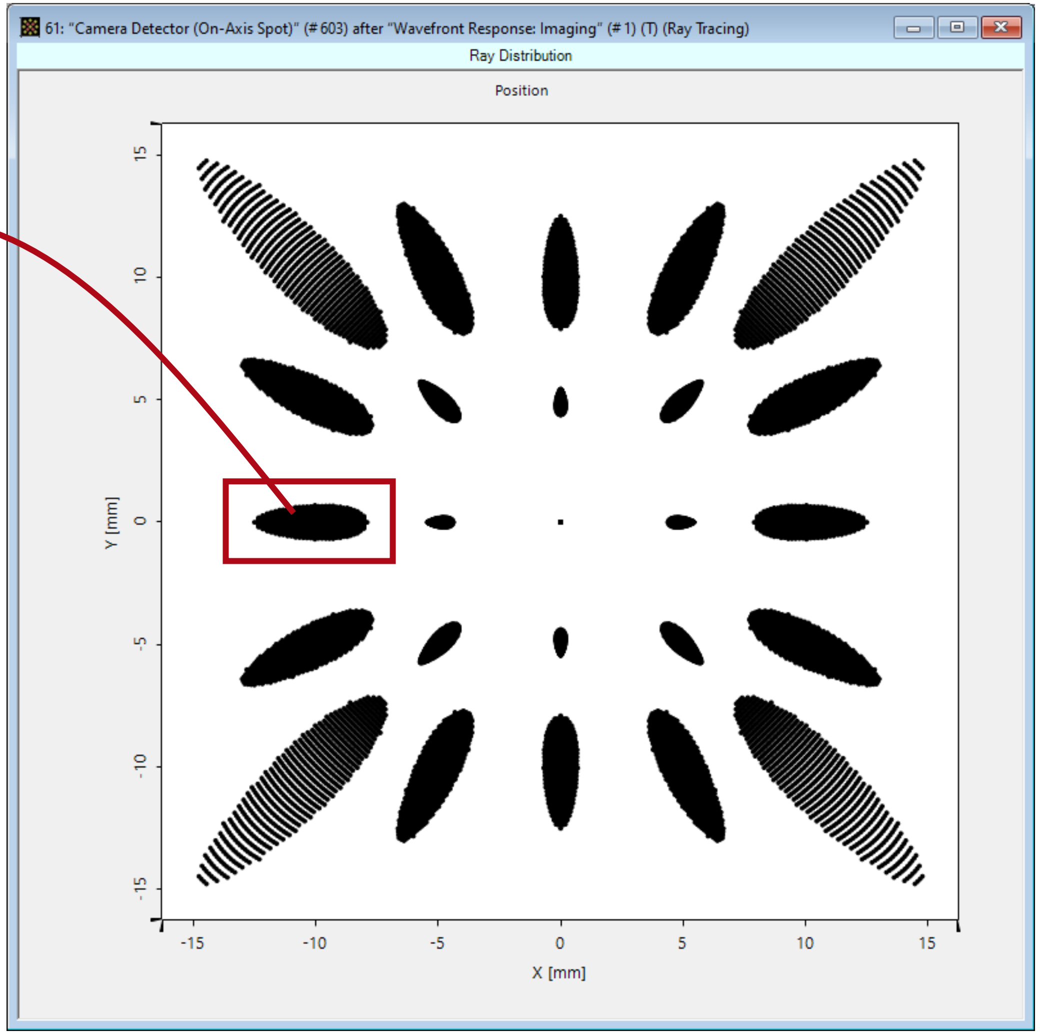

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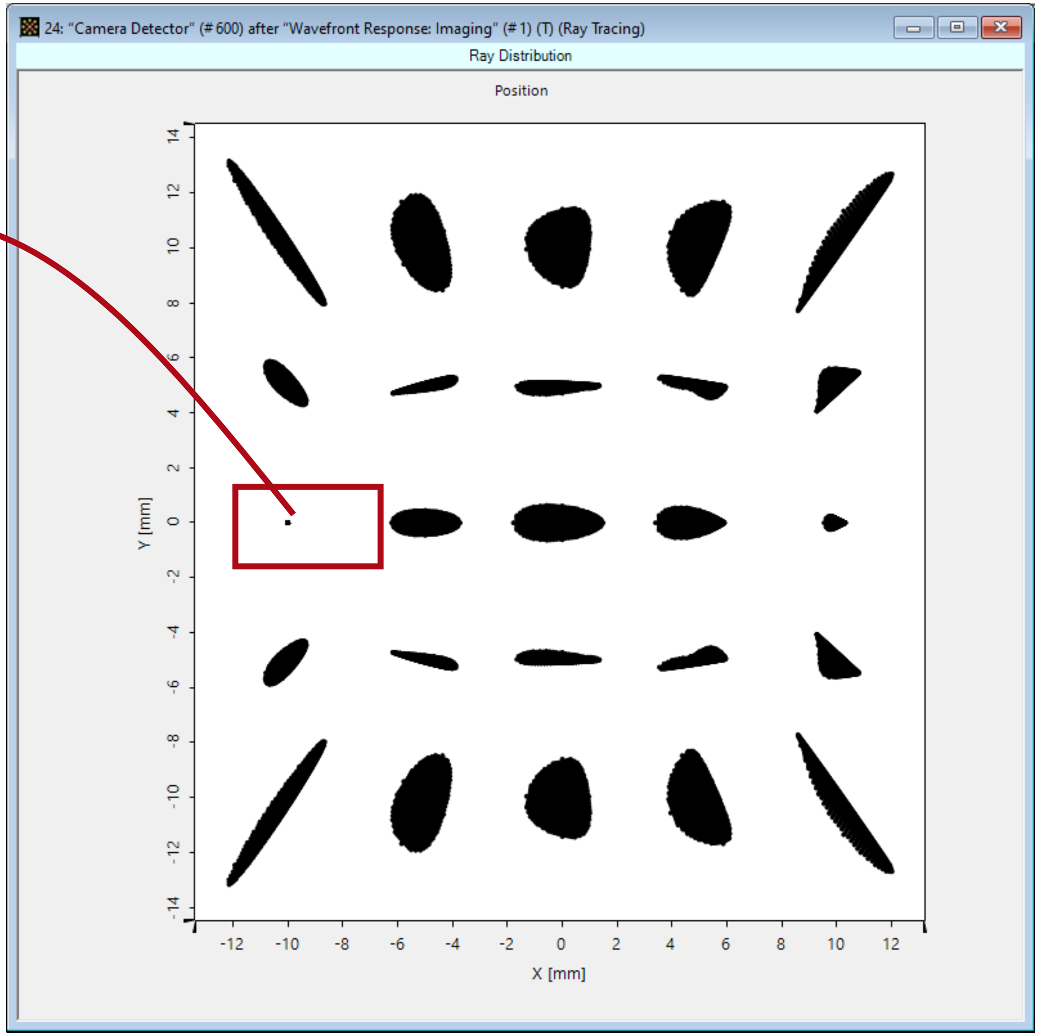
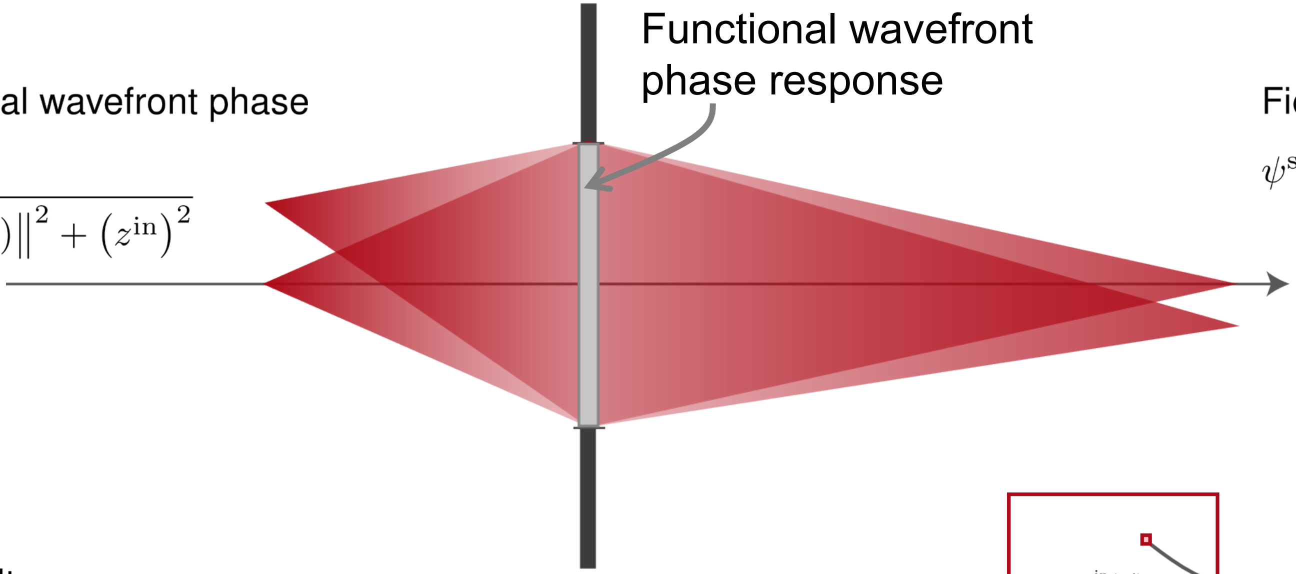


Imaging with One Component: Structural Design

Input fields with spherical wavefront phase

$$\psi^{\mathrm{sph,in}}(\boldsymbol{\rho},\omega,\alpha) = k_0 n^{\mathrm{in}} \sqrt{\left\|\boldsymbol{\rho}-\boldsymbol{\rho}^{\mathrm{in}}(\alpha)\right\|^2 + \left(z^{\mathrm{in}}\right)^2}$$



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$$\psi^{\mathrm{sph,out}}(\boldsymbol{r},\omega,\alpha) = -k_0 n^{\mathrm{out}} \sqrt{\left\|\boldsymbol{\rho}-M\boldsymbol{\rho}^{\mathrm{in}}(\alpha)\right\|^2 + \left(z^{\mathrm{out}}\right)^2}$$

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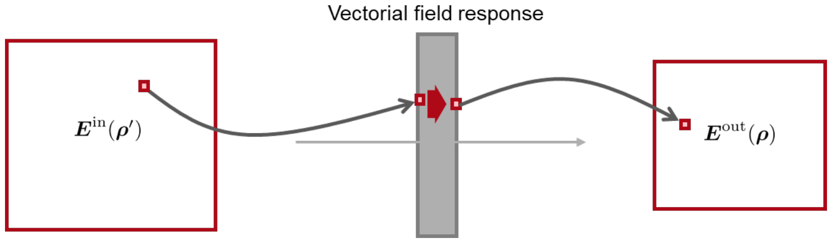

U-field response:

$$\underline{\mathbf{b}}(\boldsymbol{\rho}',\lambda,\alpha)\boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho}',\lambda,\alpha) \mapsto \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho}',\lambda,\alpha)$$

Wavefront phase response:

$$\psi^{\mathrm{in}}(\boldsymbol{\rho}',\lambda,\alpha) + \Delta\psi(\boldsymbol{\rho}',\lambda,\alpha) \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho},\lambda,\alpha)$$

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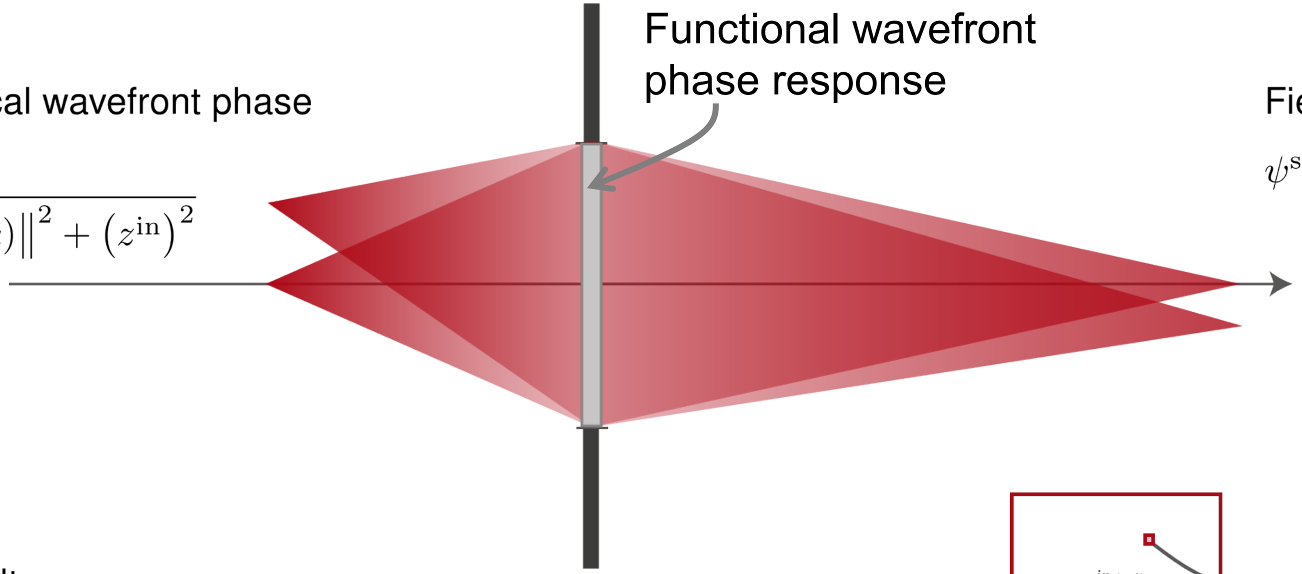

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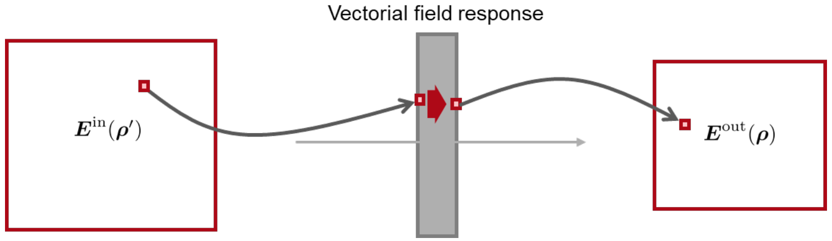

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Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

FABRICATION DATA

Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

Does a **single** surface structure exist, which generates the demanded phase responses in a tailored way per field?

U-field response:

$$\underline{\mathbf{b}}(\boldsymbol{\rho}', \lambda, \alpha)\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho}', \lambda, \alpha)$$

Wavefront phase response:

$$\psi^{\text{in}}(\boldsymbol{\rho}', \lambda, \alpha) + \Delta\psi(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \psi^{\text{out}}(\boldsymbol{\rho}, \lambda, \alpha)$$

Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN

Design the system by introducing functional components to achieve the demanded system functionality.

STRUCTURAL DESIGN

Replace functional components by smooth surface or flat optics components.

MODELING &

de

merit functions.

FURTHER

SYSTEM TOLERANCING

Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

FABRICATION DATA

Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

Meta surfaces may offer a chance for a tailored wavefront phase response to some extent. But still ongoing R&D and final answer not available.

U-field response:

$$\underline{\mathbf{b}}(\boldsymbol{\rho}', \lambda, \alpha)\boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho}', \lambda, \alpha)$$

Wavefront phase response:

$$\psi^{\mathrm{in}}(\boldsymbol{\rho}', \lambda, \alpha) + \Delta\psi(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho}, \lambda, \alpha)$$

Design Workflow in VirtualLab Fusion

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MODELING &

merit functions.

FURTHER

However, we know for sure: A combination of surfaces can solve the problem well. Flat optics adds extra flexibility and options to further improve such solutions!

SYSTEM TOLERANCING

Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

FABRICATION DATA

Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

U-field response:

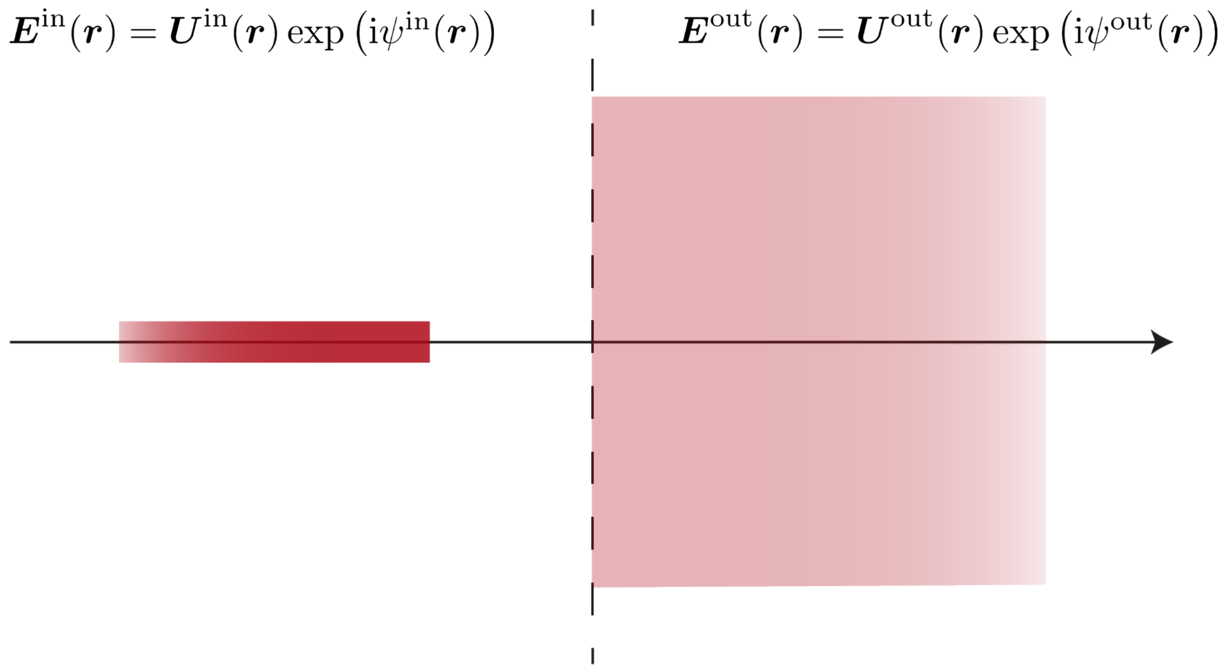
$$\underline{\mathbf{b}}(\boldsymbol{\rho}', \lambda, \alpha)\boldsymbol{U}^{\mathrm{in}}(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \boldsymbol{U}^{\mathrm{out}}(\boldsymbol{\rho}', \lambda, \alpha)$$

Wavefront phase response:

$$\psi^{\mathrm{in}}(\boldsymbol{\rho}', \lambda, \alpha) + \Delta\psi(\boldsymbol{\rho}', \lambda, \alpha) \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho}, \lambda, \alpha)$$

Beam Expander

Beam Expander: Scenario



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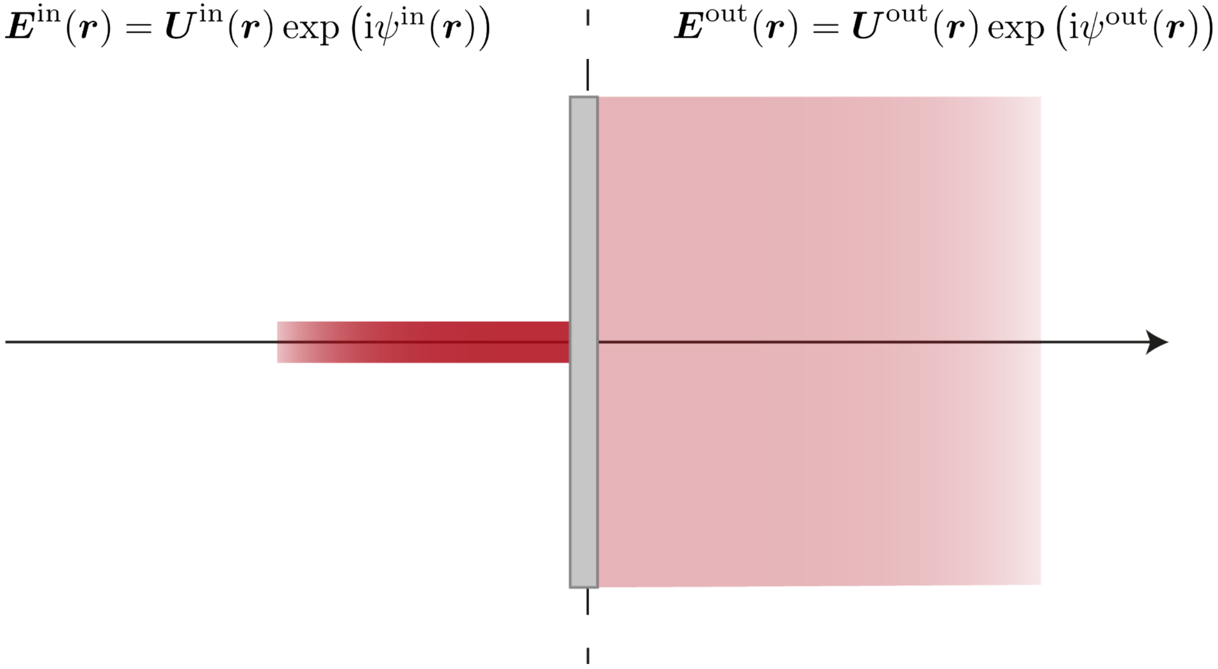
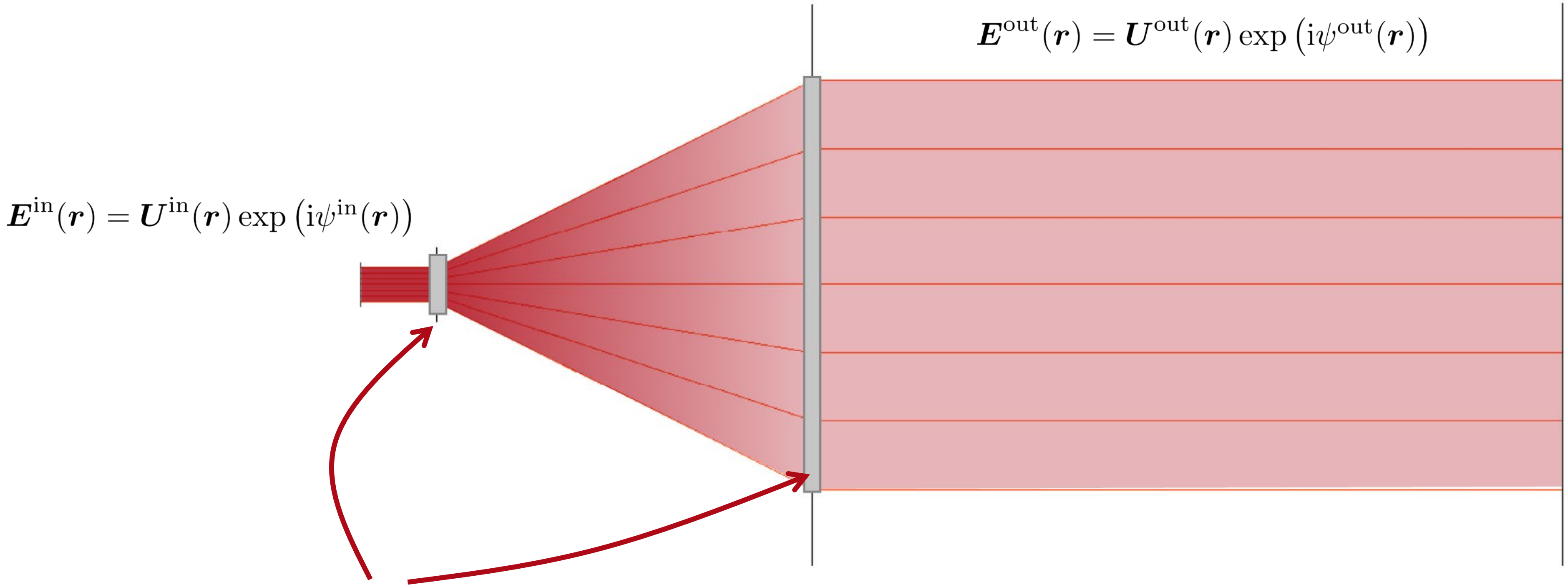
Beam Expander: Functional Design

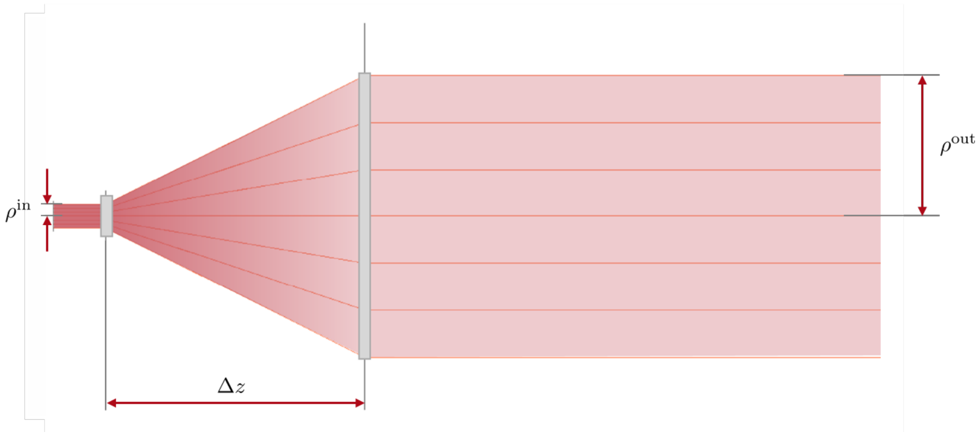


Beam Expander: Functional Design



Two functional components:
Divergent and inverse spherical wavefront phase responses.

Beam Expander: Functional Design



- Let assume the given parameters are the expander ratio $\zeta = \rho^{\text{out}}/\rho^{\text{in}}$ and the distance Δz.
- A straightforward evaluation leads to the equations

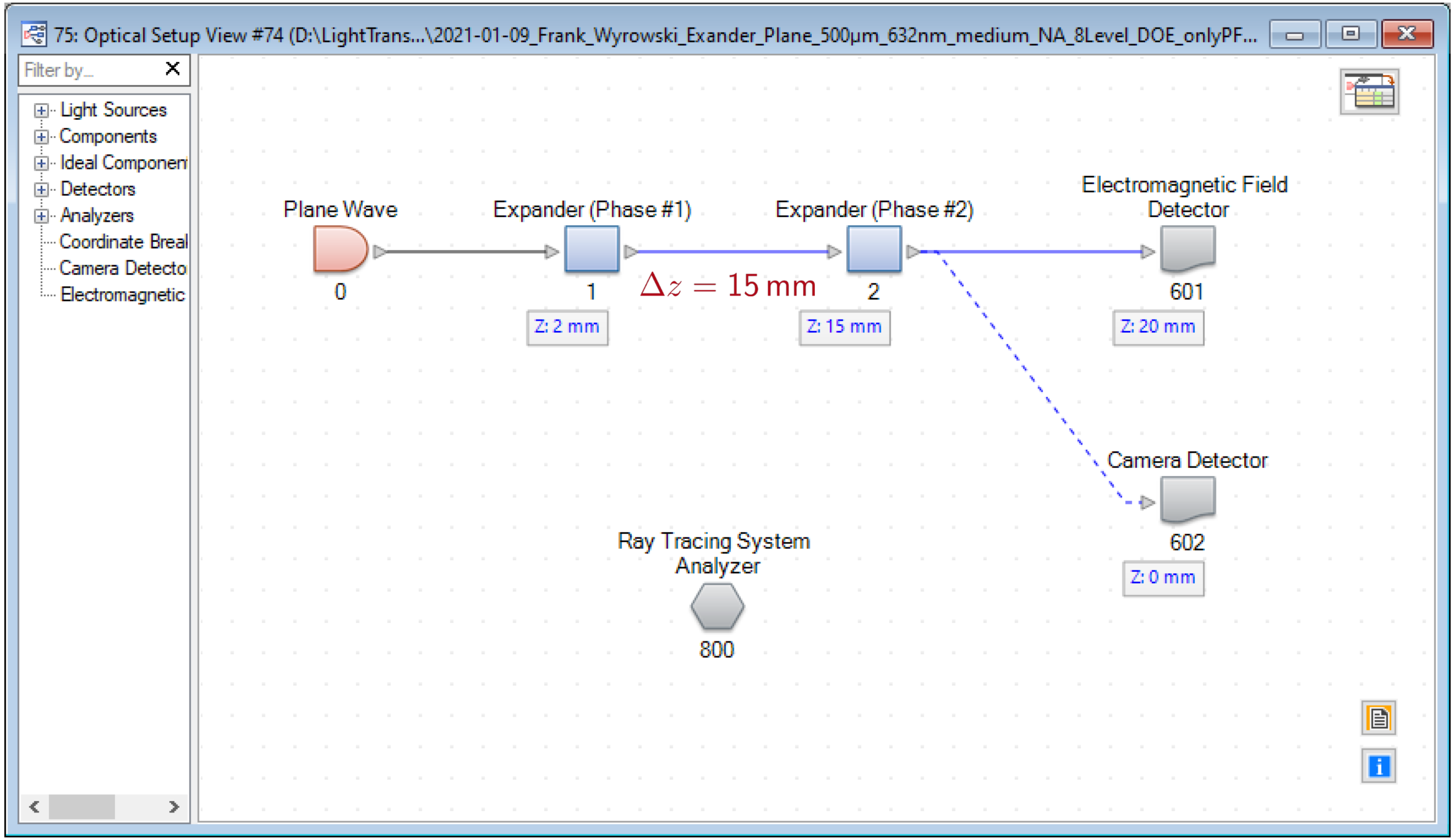
$$R_1 = \frac{\Delta z}{(\zeta - 1)}$$
$$R_2 = -(\Delta z + R_1)$$
$$\text{NA} = \frac{n}{\sqrt{1 + \left(\Delta z/\rho^{\text{out}}\right)^2}}$$

for radii of the first and second spherical wavefront phase response and the related NA .

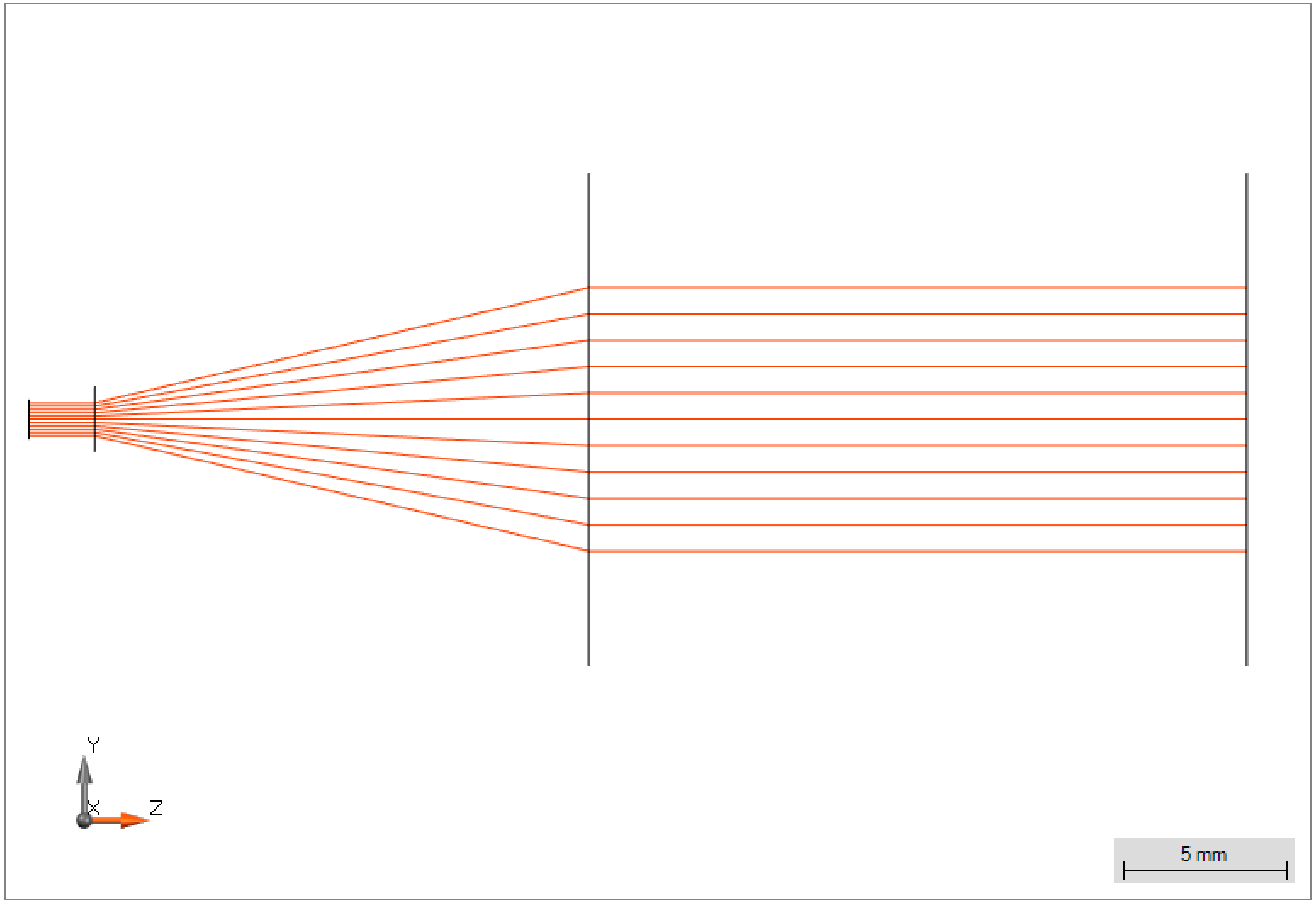
- Thus, the functional design results by analytical considerations to the wavefront phases:

$$\Delta\psi_1(\boldsymbol{\rho}, k_0) = k_0 n \sqrt{\|\boldsymbol{\rho}\|^2 + R_1^2}$$
$$\Delta\psi_2(\boldsymbol{\rho}, k_0) = -k_0 n \sqrt{\|\boldsymbol{\rho}\|^2 + R_2^2}$$

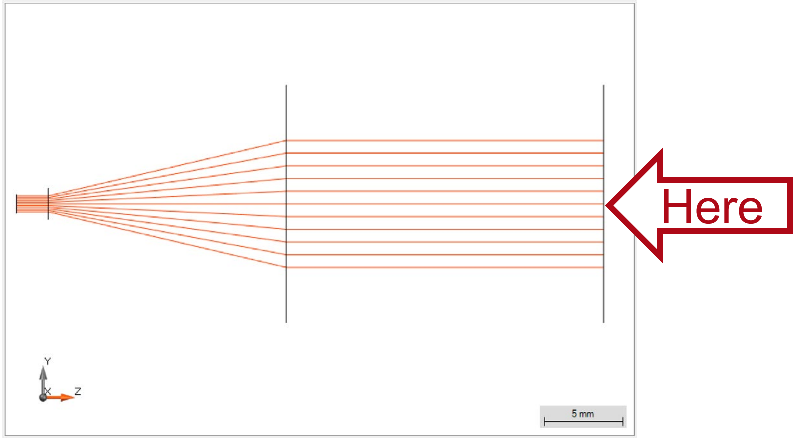
Beam Expander (1:5) – Functional Design

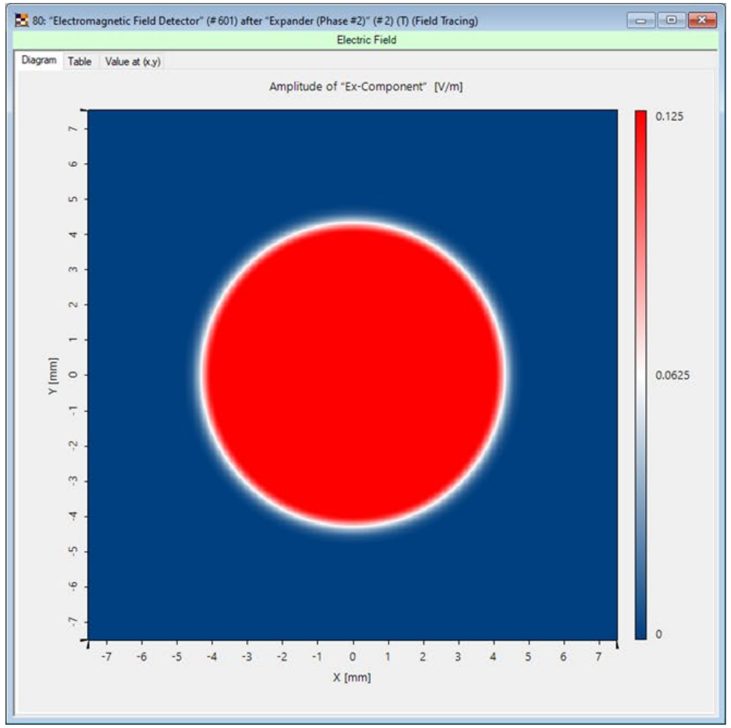


Beam Expander (1:5) – Functional Design: Ray Tracing

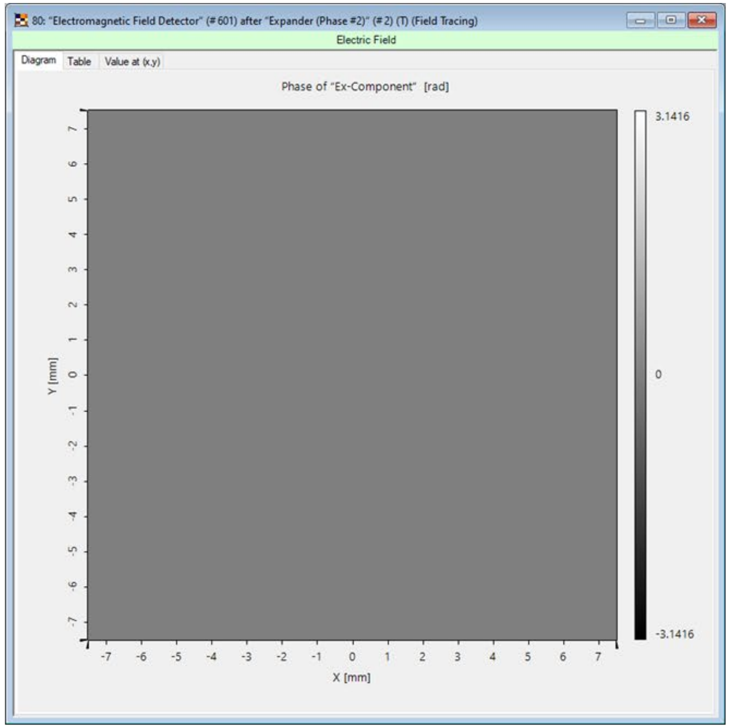


Beam Expander (1:5) – Functional Design: Output Beam





Amplitude after Beam Expander



Phase after Beam Expander

Design Workflow in VirtualLab Fusion

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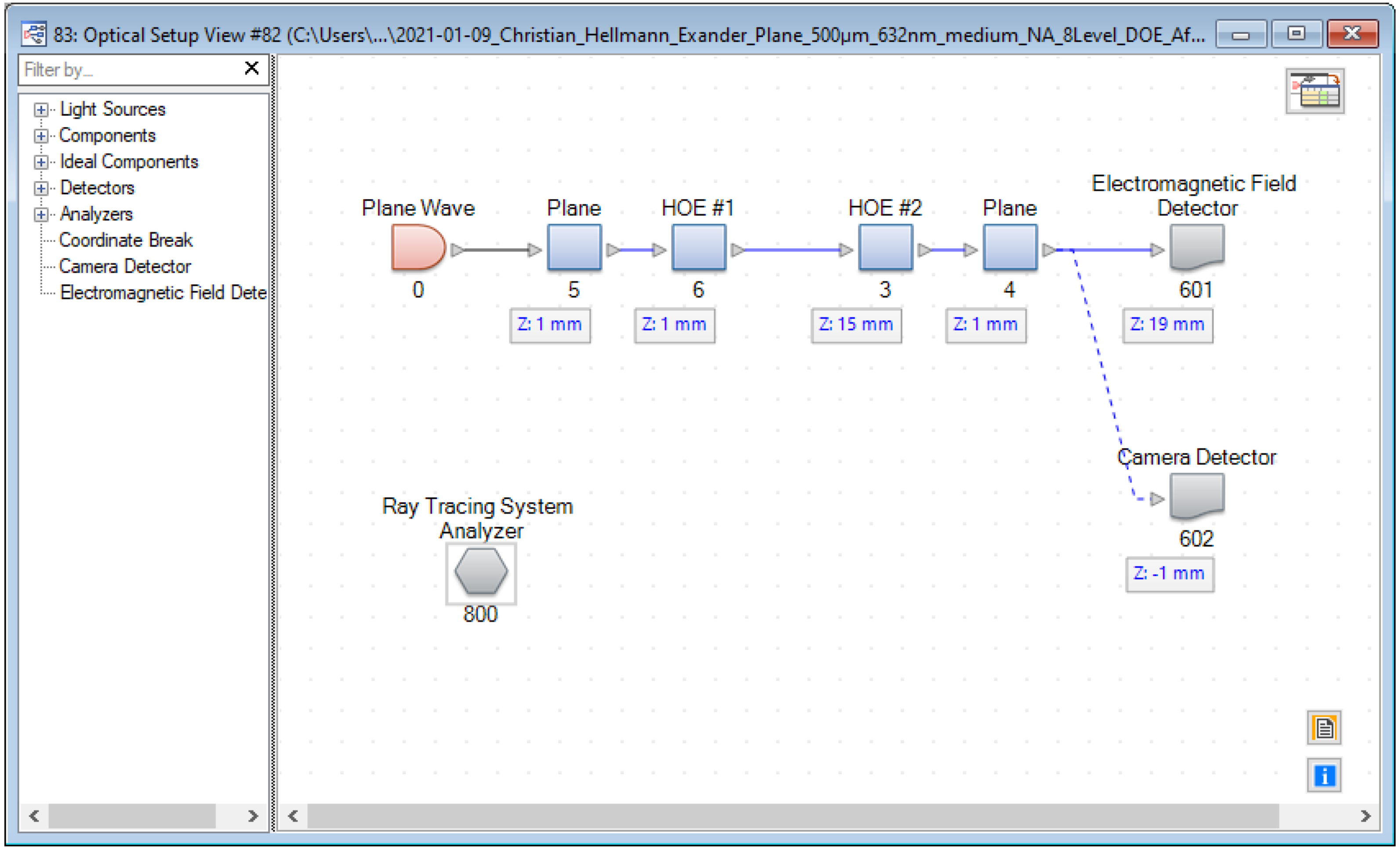
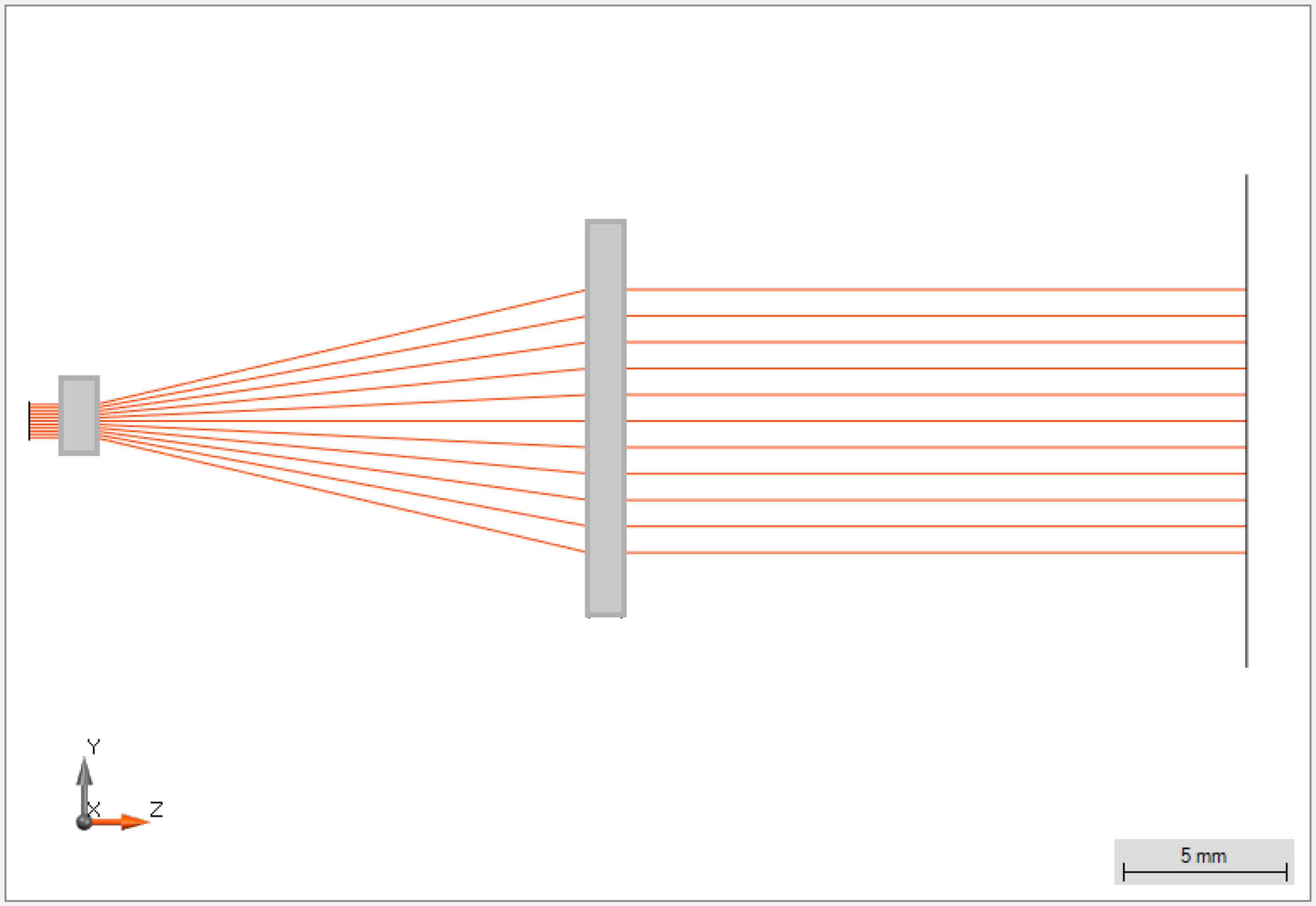
FABRICATION DATA

Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

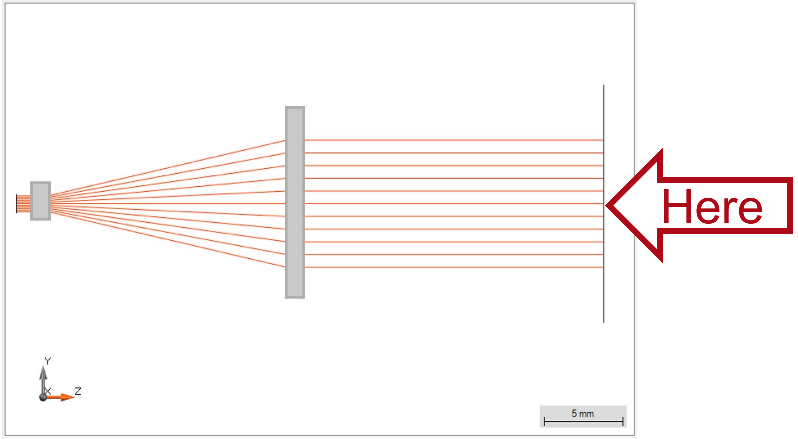
Beam Expander (1:5) – Structural Design: HOEs

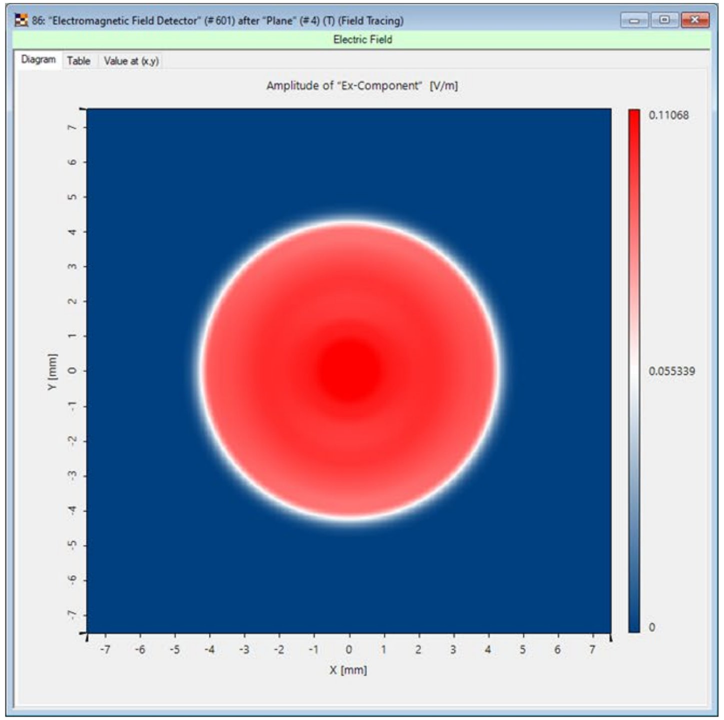


Beam Expander (1:5) – Structural Design: HOEs

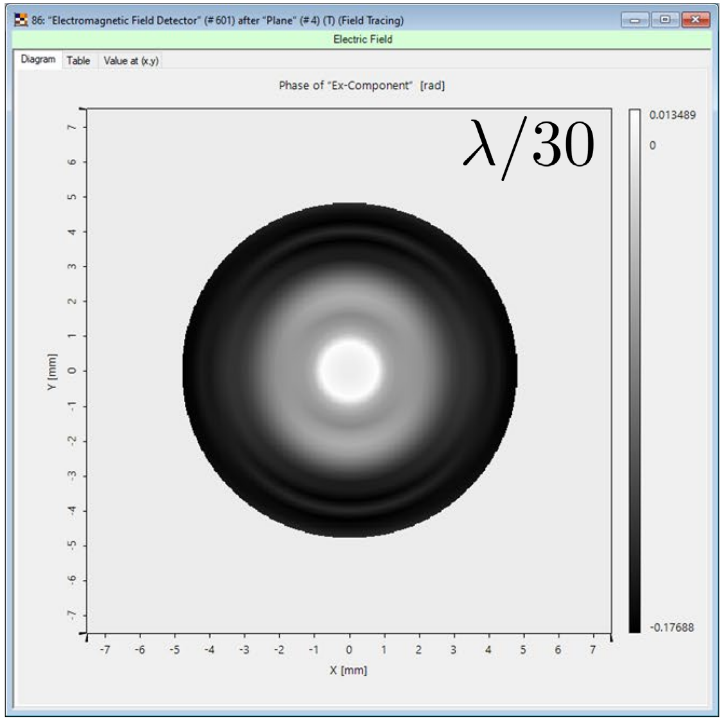


Beam Expander (1:5): Output Beam for HOEs





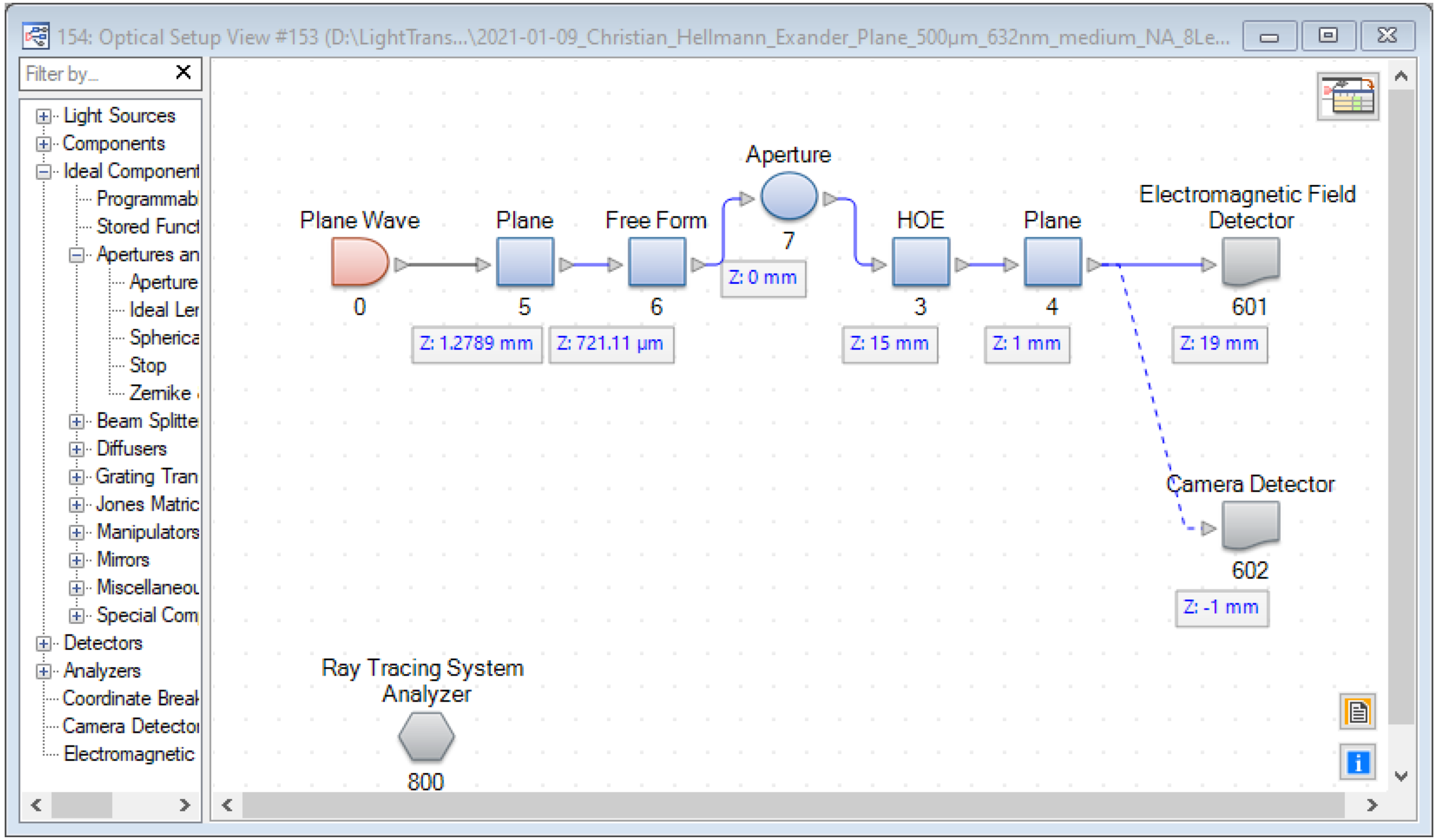
Amplitude after Beam Expander



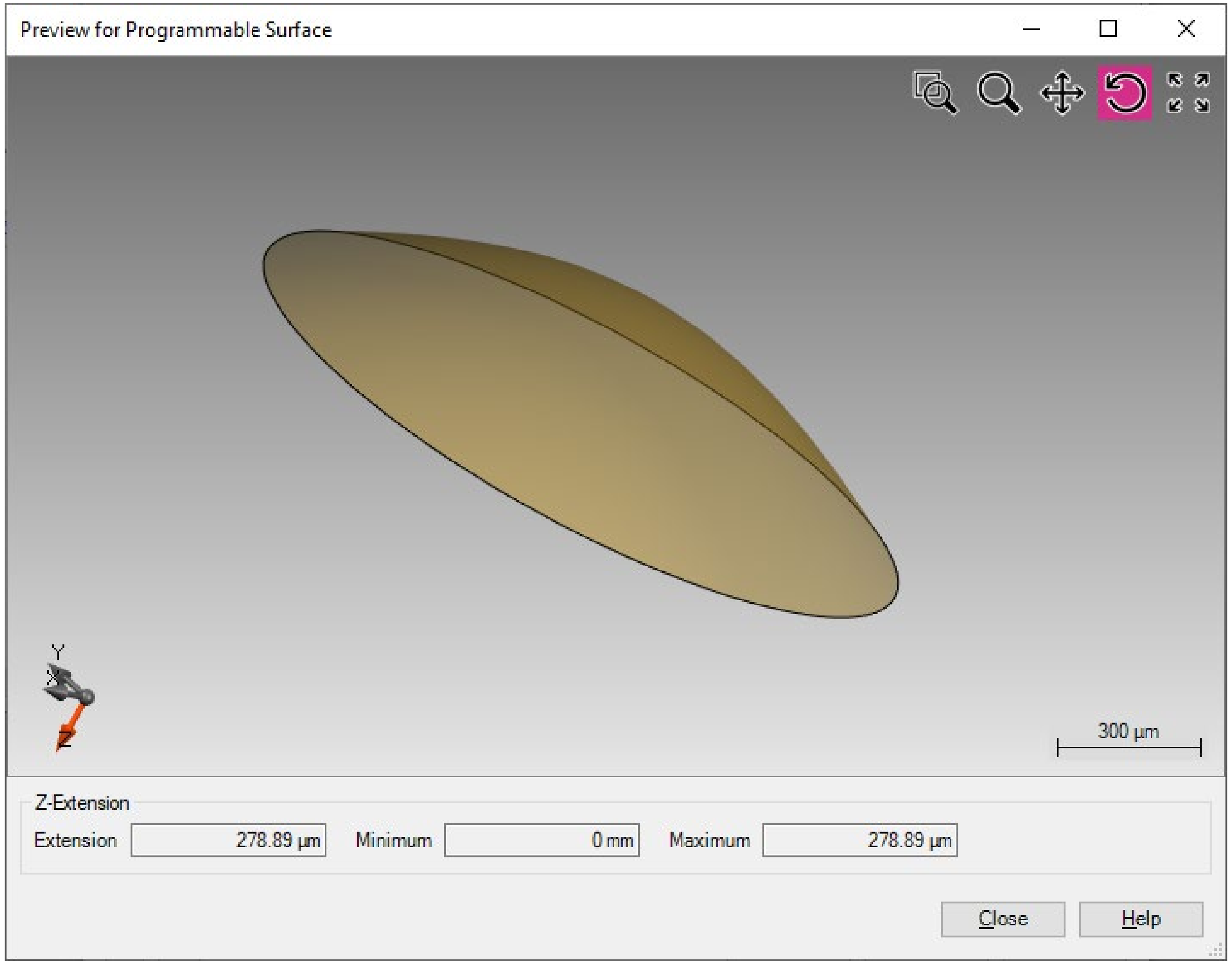
Phase after Beam Expander

Efficiency of HOE #1: 76.82%
Efficiency of HOE #2: 77.15%
System Efficiency: 59.27%

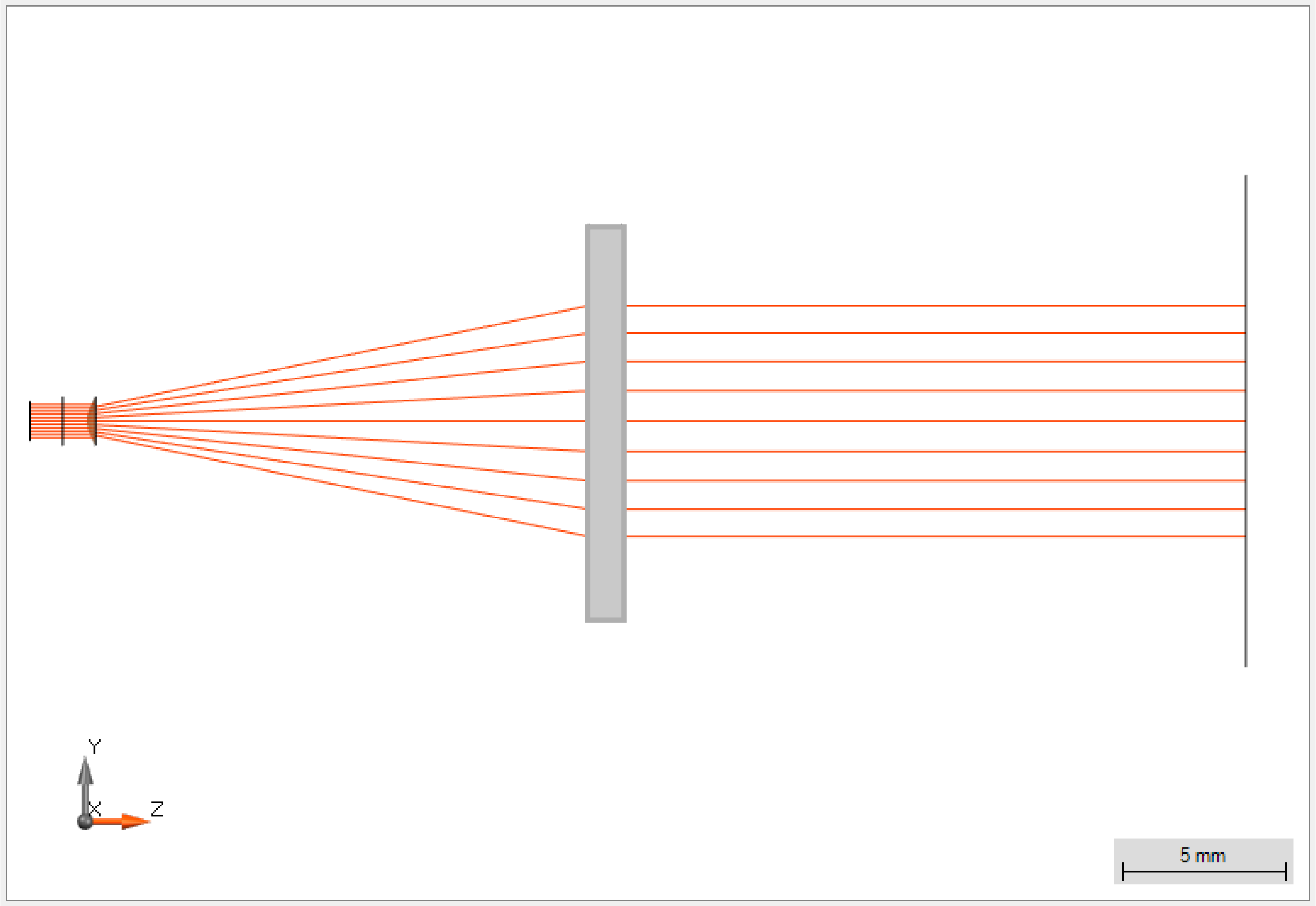
Beam Expander (1:5) – Structural Design: Lens + HOE



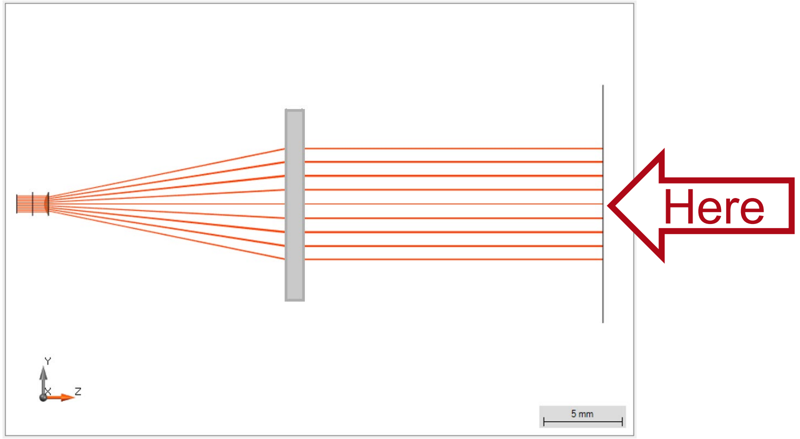
Beam Expander (1:5) – Structural Design: Lens

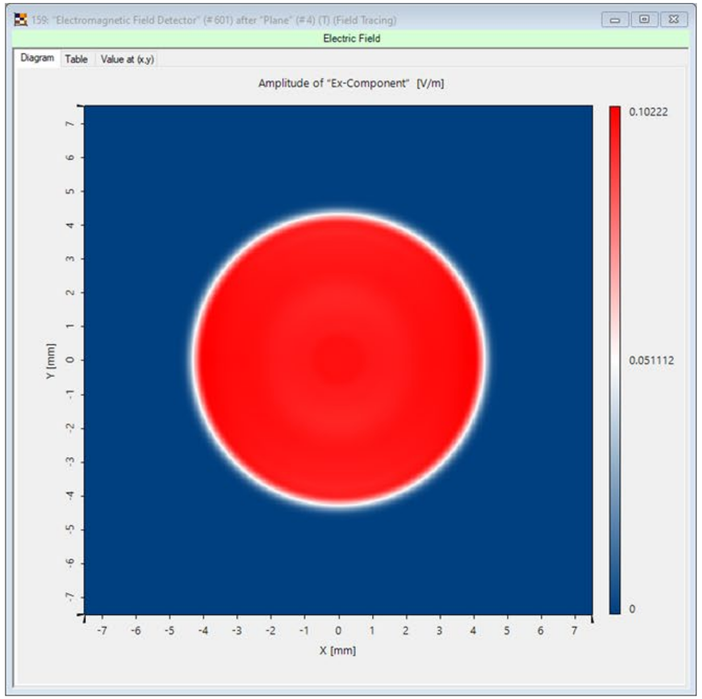


Beam Expander (1:5) – Structural Design: Lens + HOE

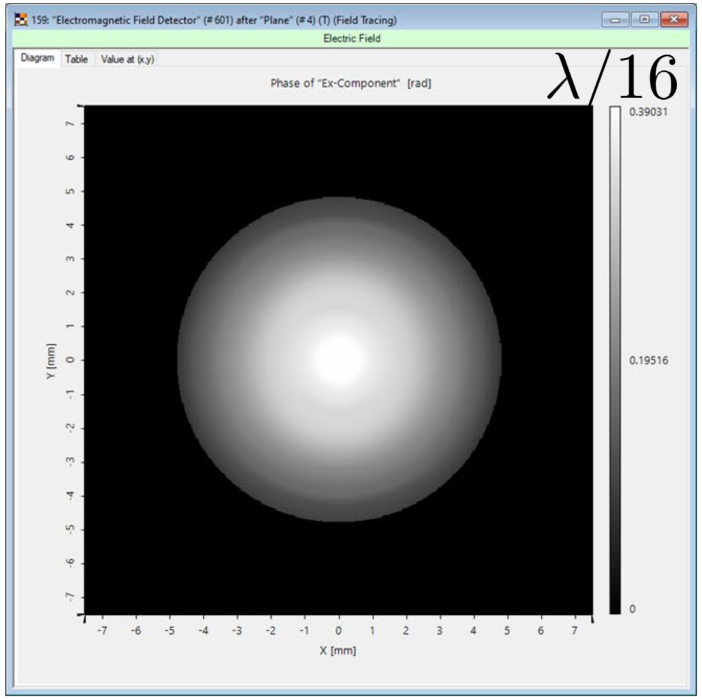


Beam Expander (1:5): Output Beam for Lens + HOE





Amplitude after Beam Expander



Phase after Beam Expander

Efficiency of Freeform: 93.09%
Efficiency of HOE: 77.15%
System Efficiency: 71.82%

Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN

Design the system by introducing functional components to achieve the demanded system functionality.

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MODELING & EVALUATION

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FURTHER OPTIMIZATION

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SYSTEM TOLERANCING

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FABRICATION DATA

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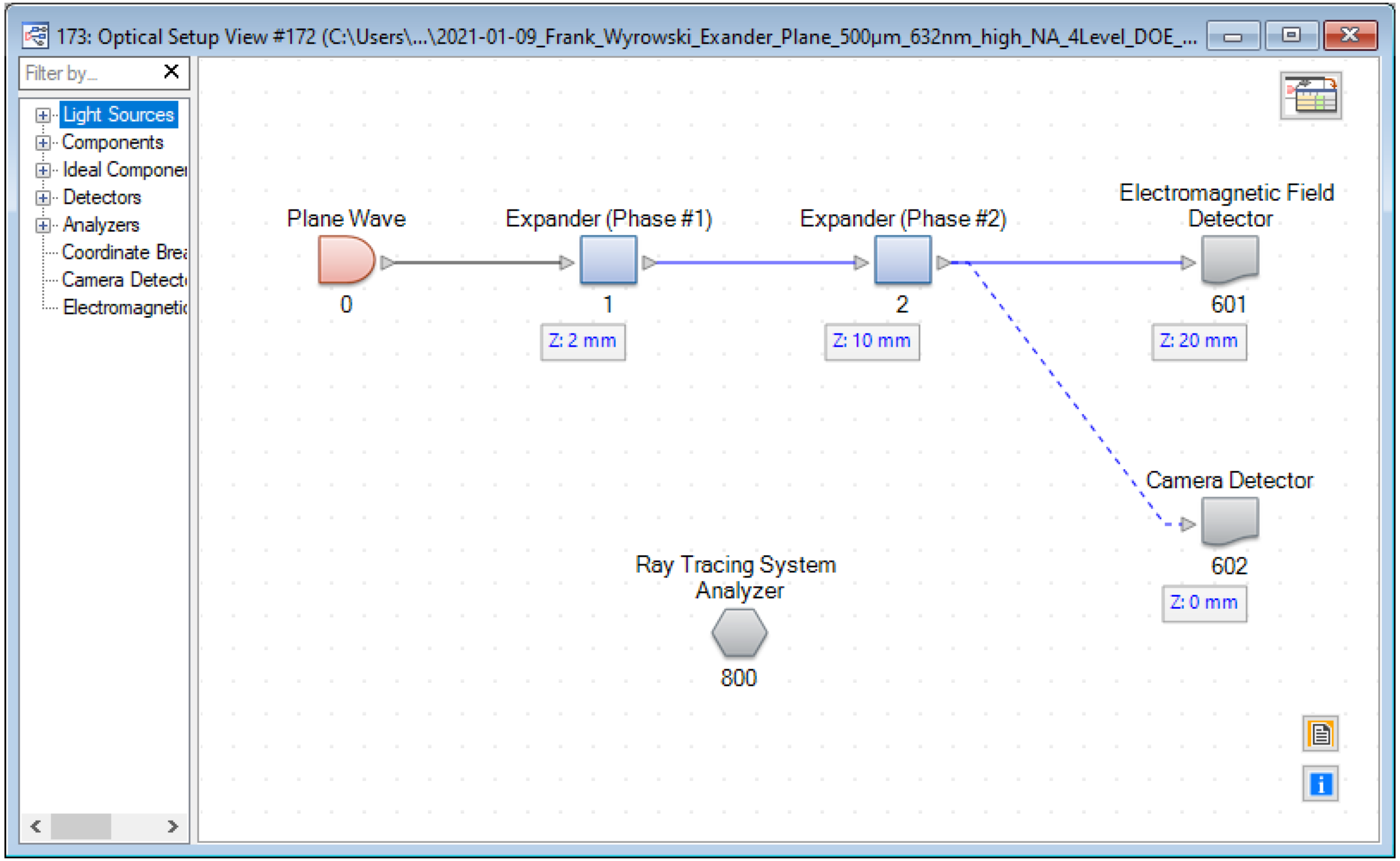
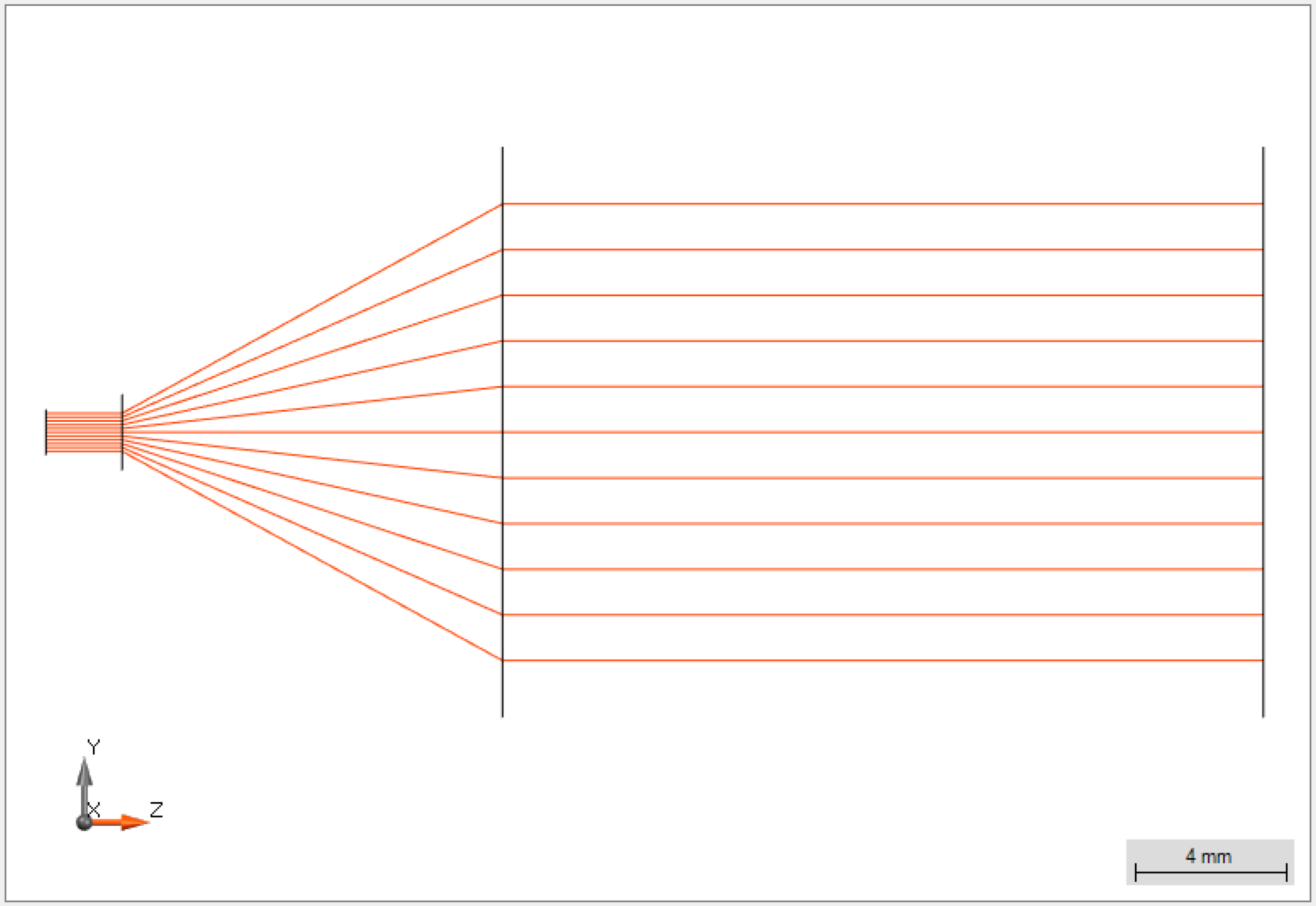
Beam Expander (1:10) – Functional Design



Beam Expander (1:10) – Functional Design: Ray Tracing



Design Workflow in VirtualLab Fusion

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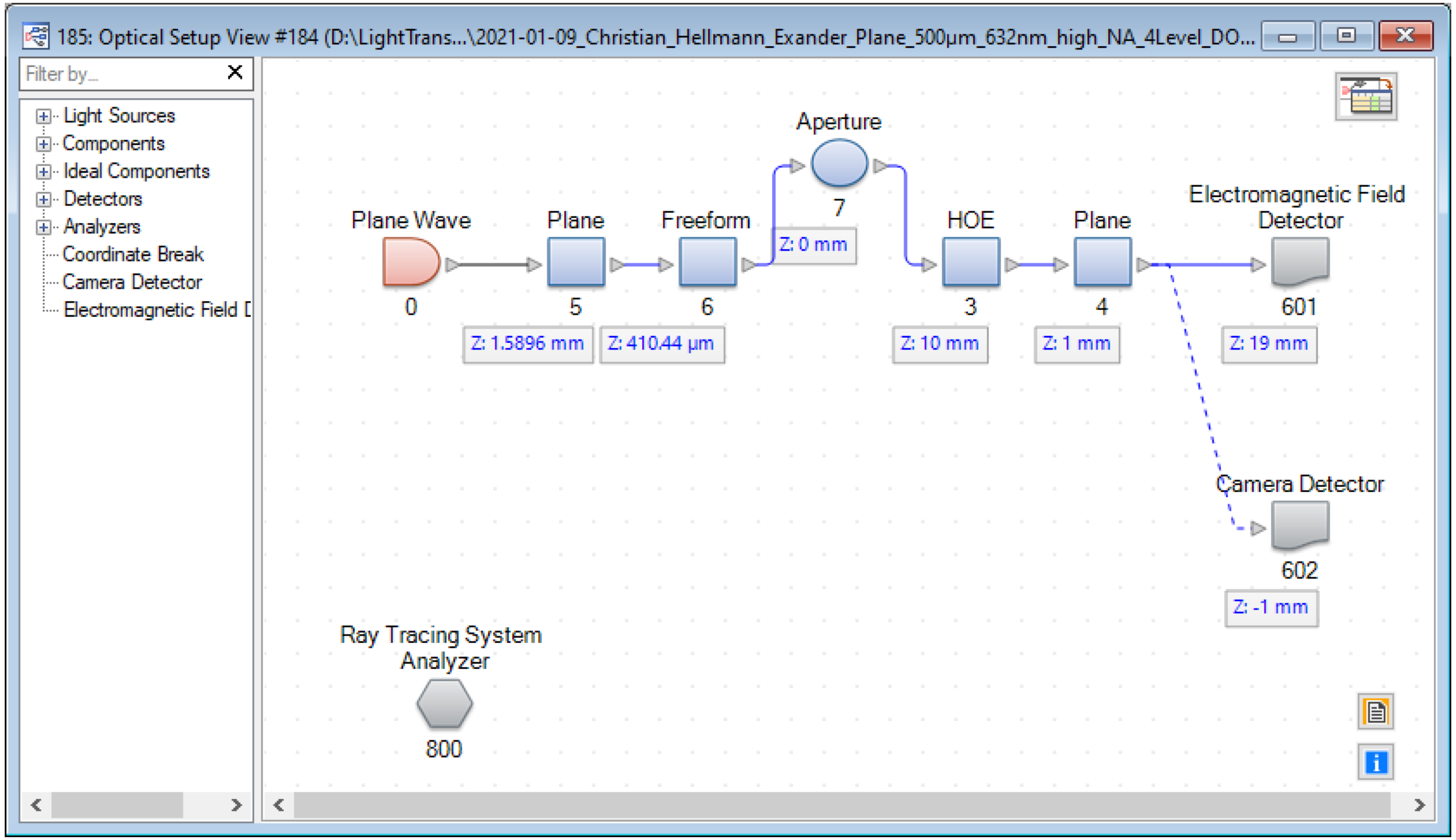
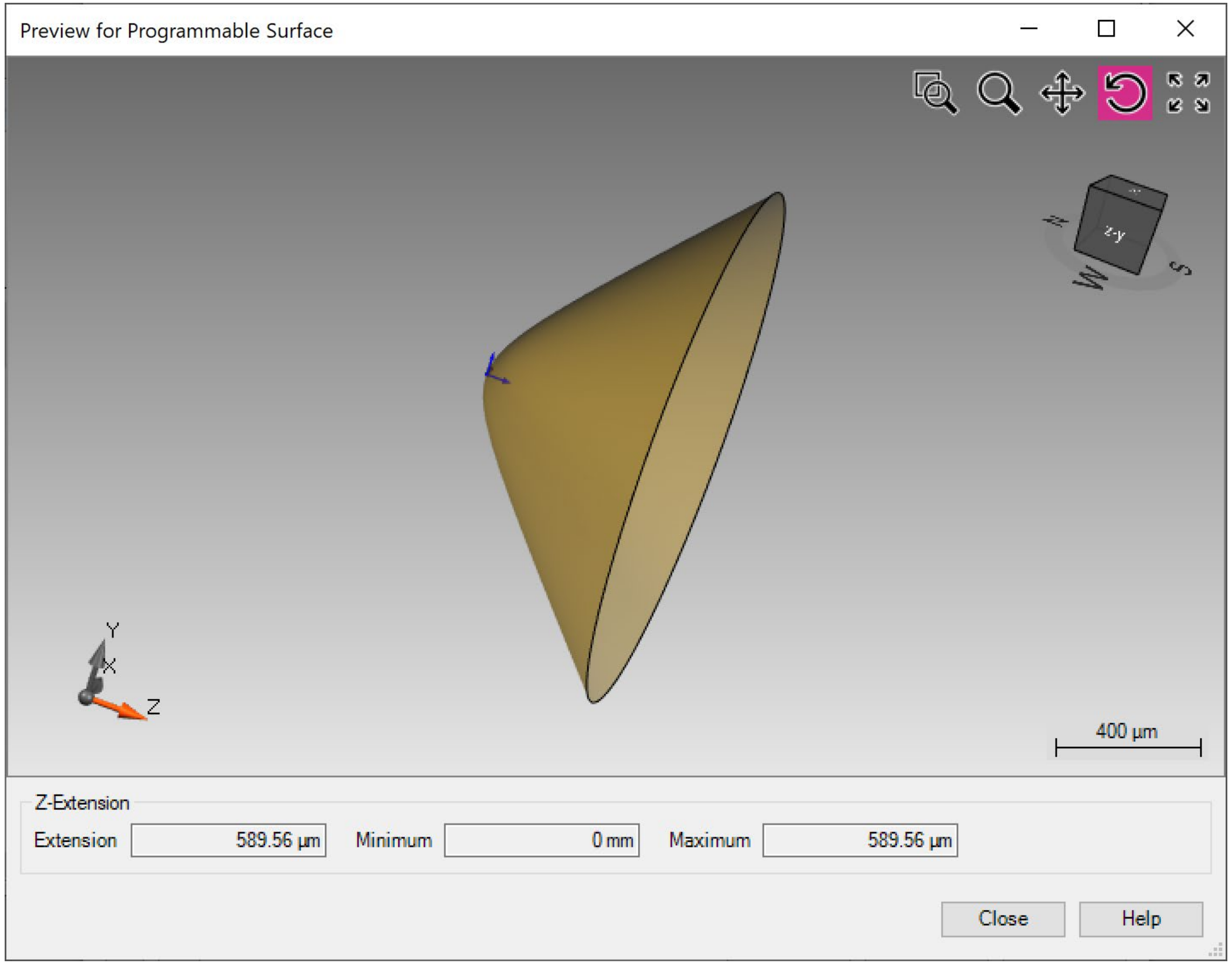
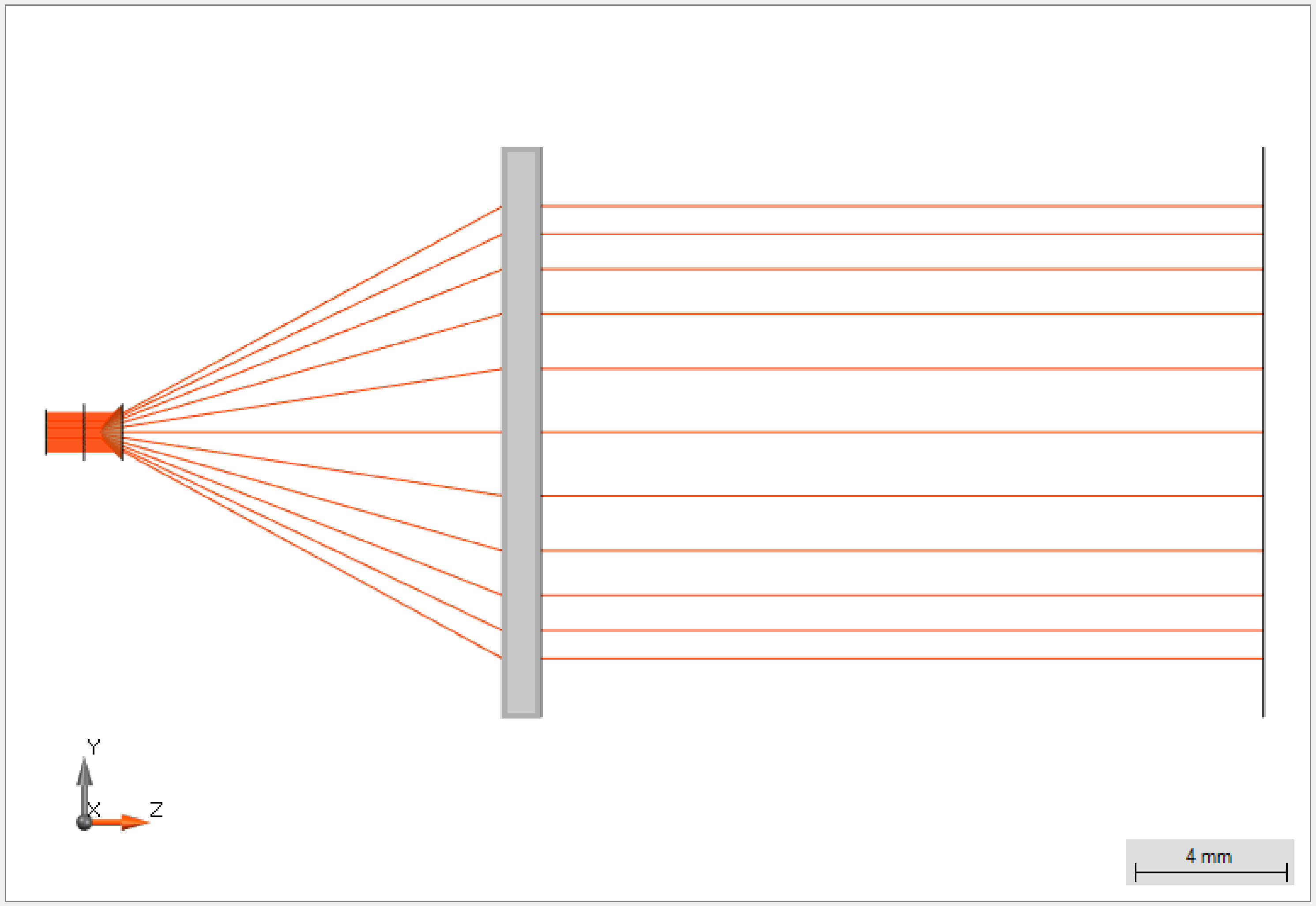
Beam Expander (1:10) – Structural Design: Lens + HOE



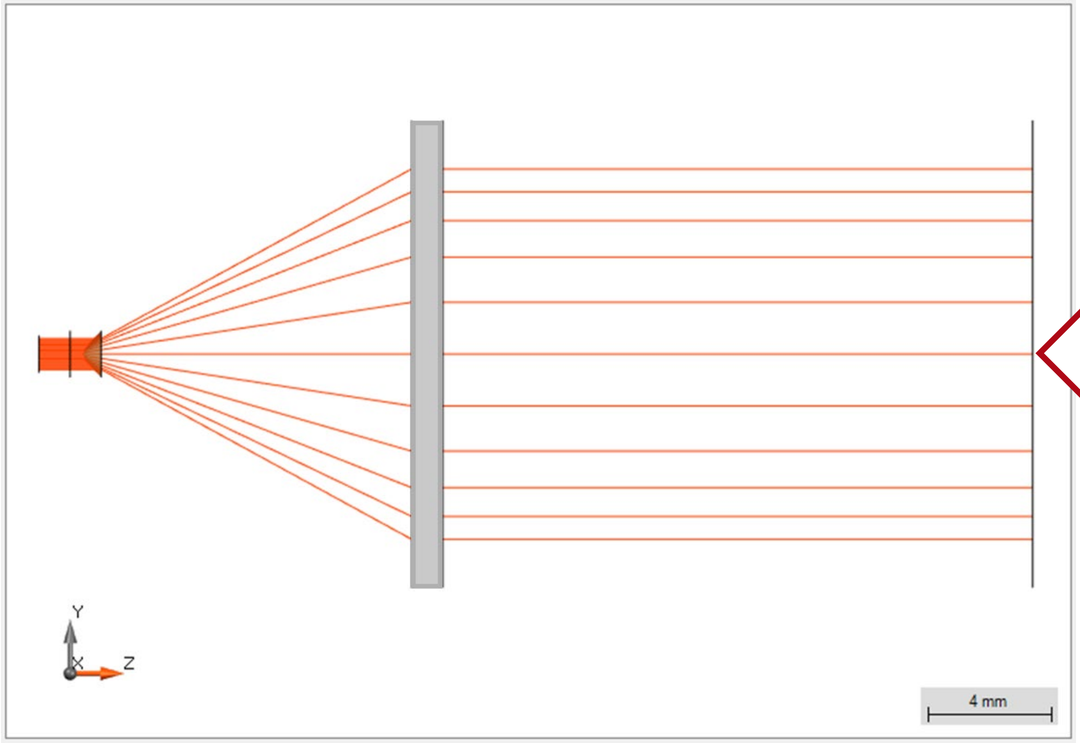
Beam Expander (1:10) – Structural Design: Lens



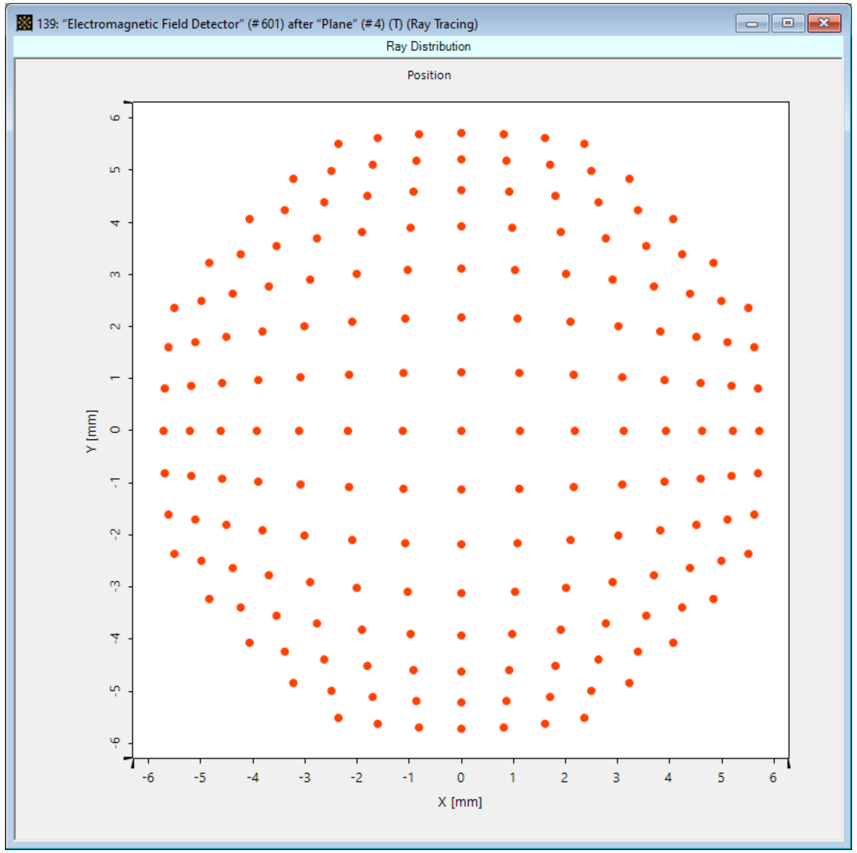
Beam Expander (1:10) – Structural Design: Lens + HOE



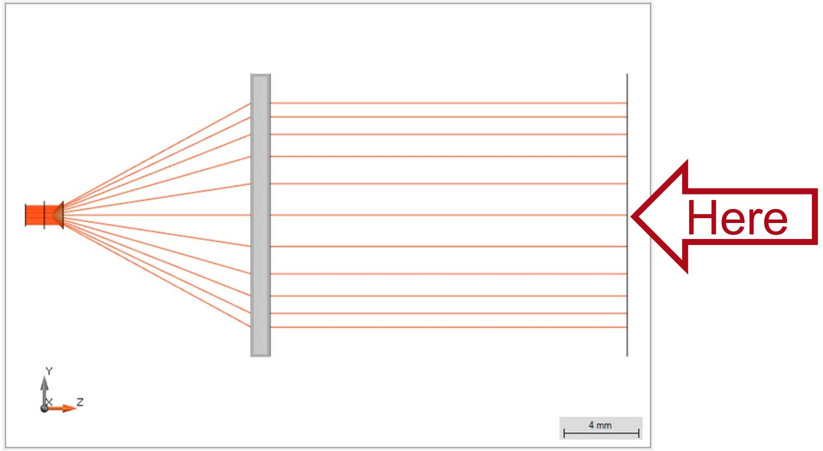
Beam Expander (1:10) – Structural Design: Lens + HOE

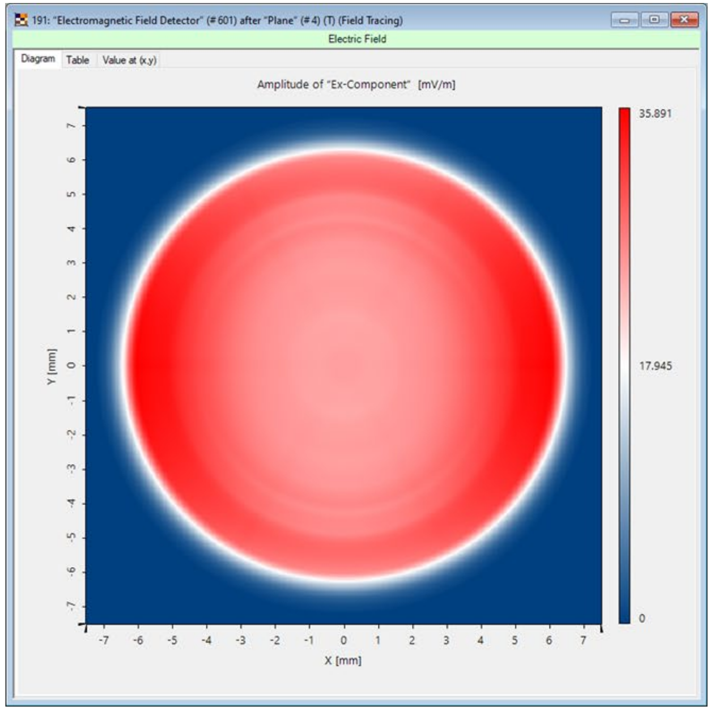


Here

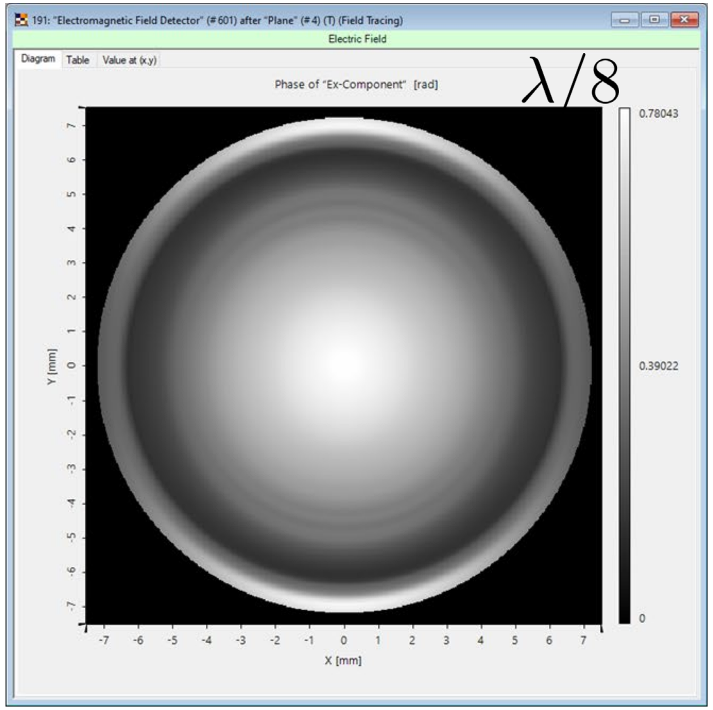


Beam Expander (1:10): Lens + HOE Output Beam





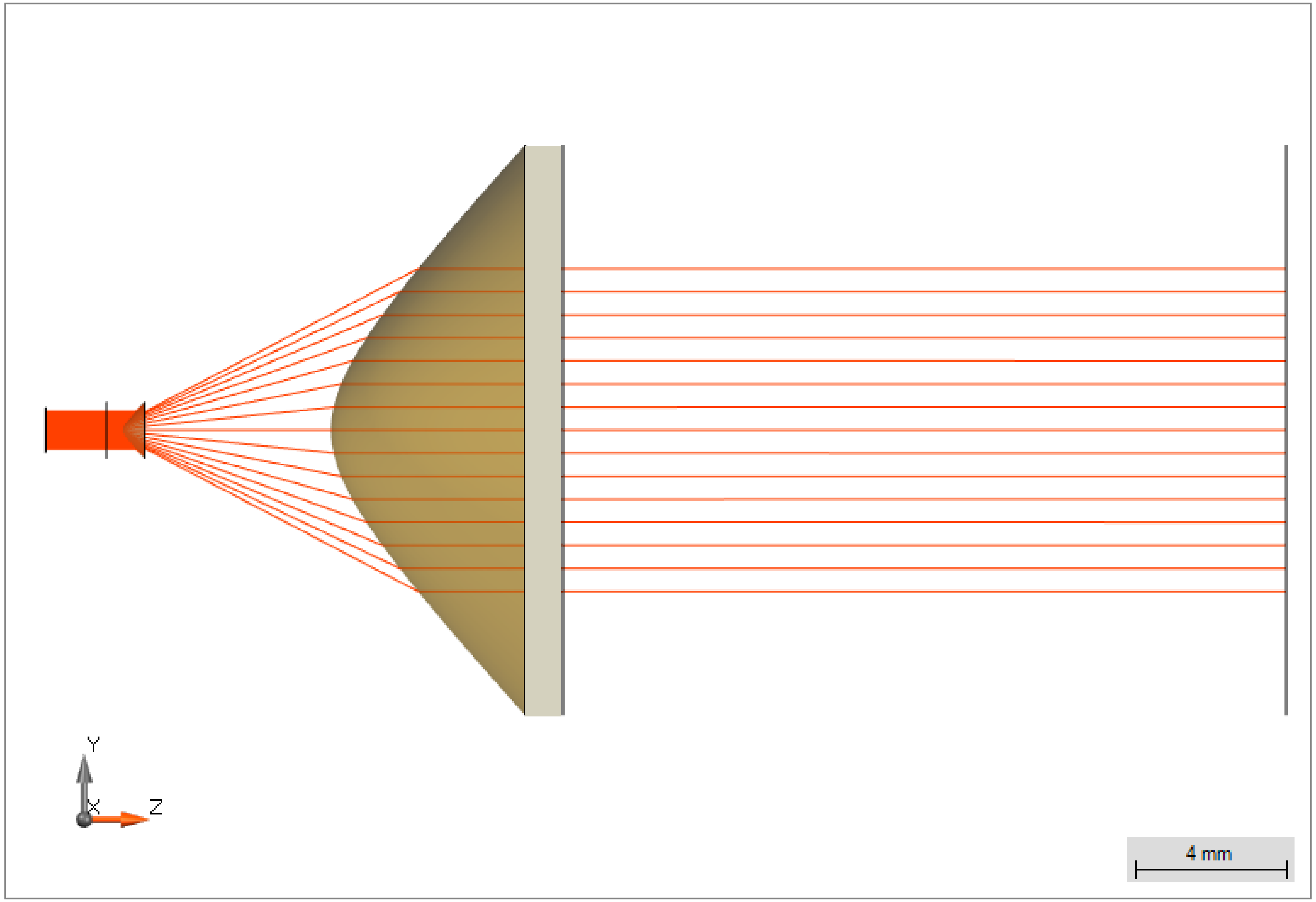
Amplitude after Beam Expander



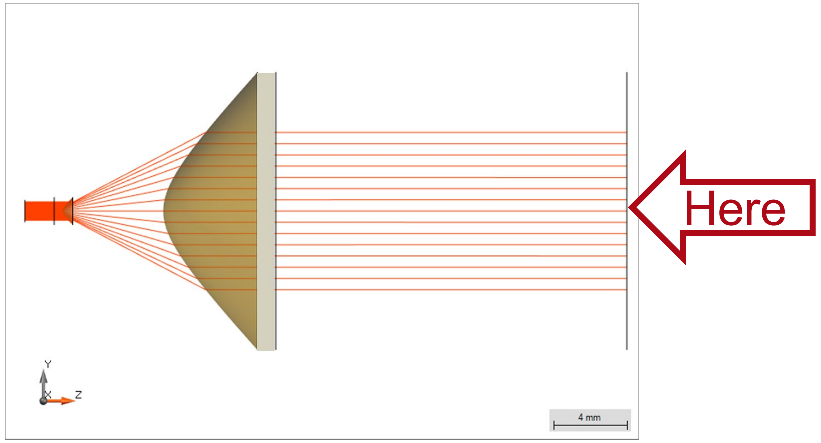
Phase after Beam Expander

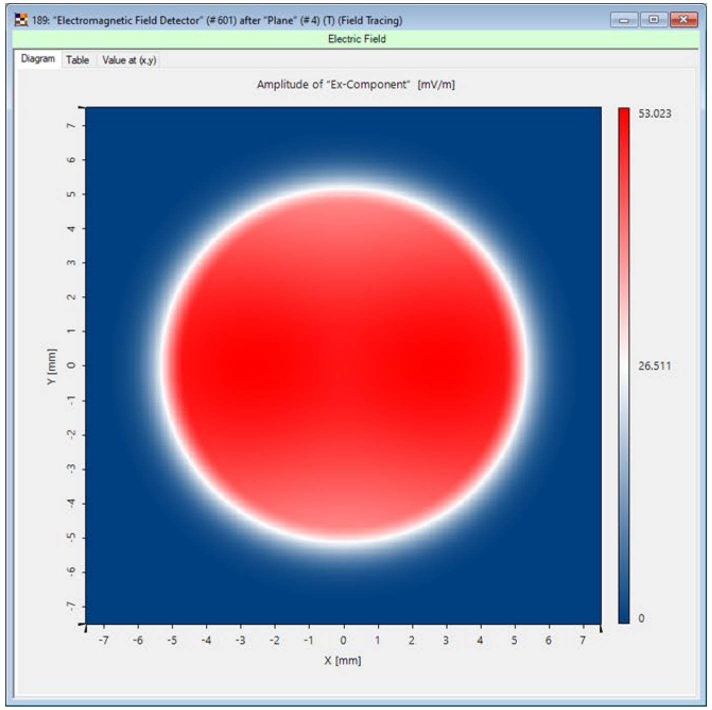
Efficiency of Freeform: 89.53%
Efficiency of HOE: 53,39%
System Efficiency: 47.8%

Beam Expander (1:10) – Structural Design: Lens + Lens

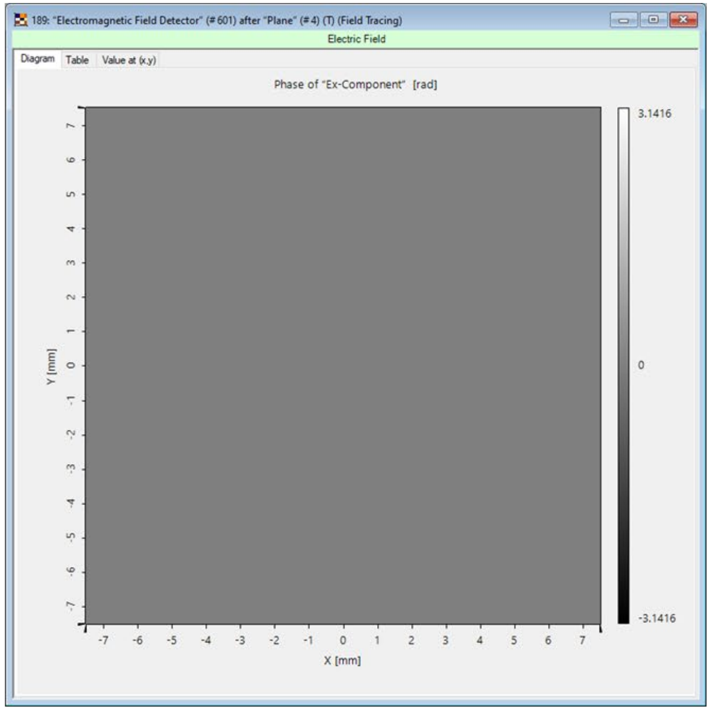


Beam Expander (1:10) : Lens + Lens Output Beam





Amplitude after Beam Expander

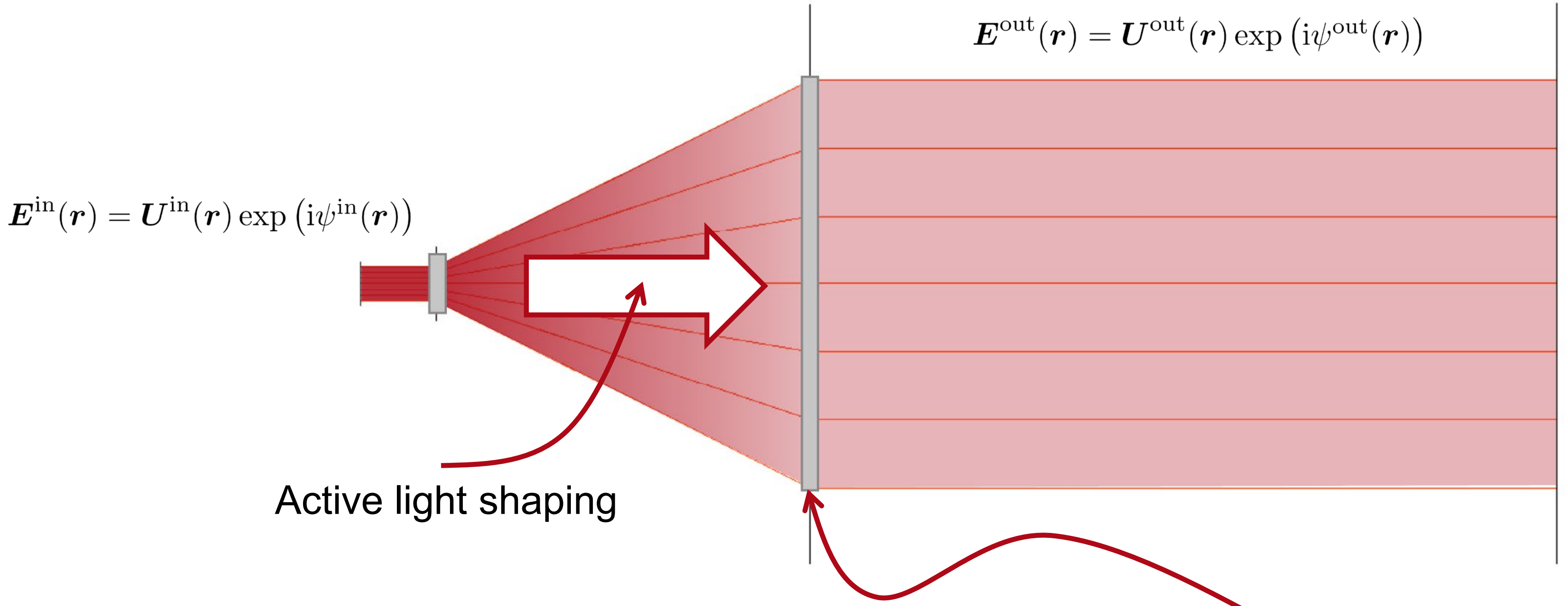


Phase after Beam Expander

Efficiency of Freeform #1: 89.53%
Efficiency of Freeform #2: 89.53%
System Efficiency: 80.16%

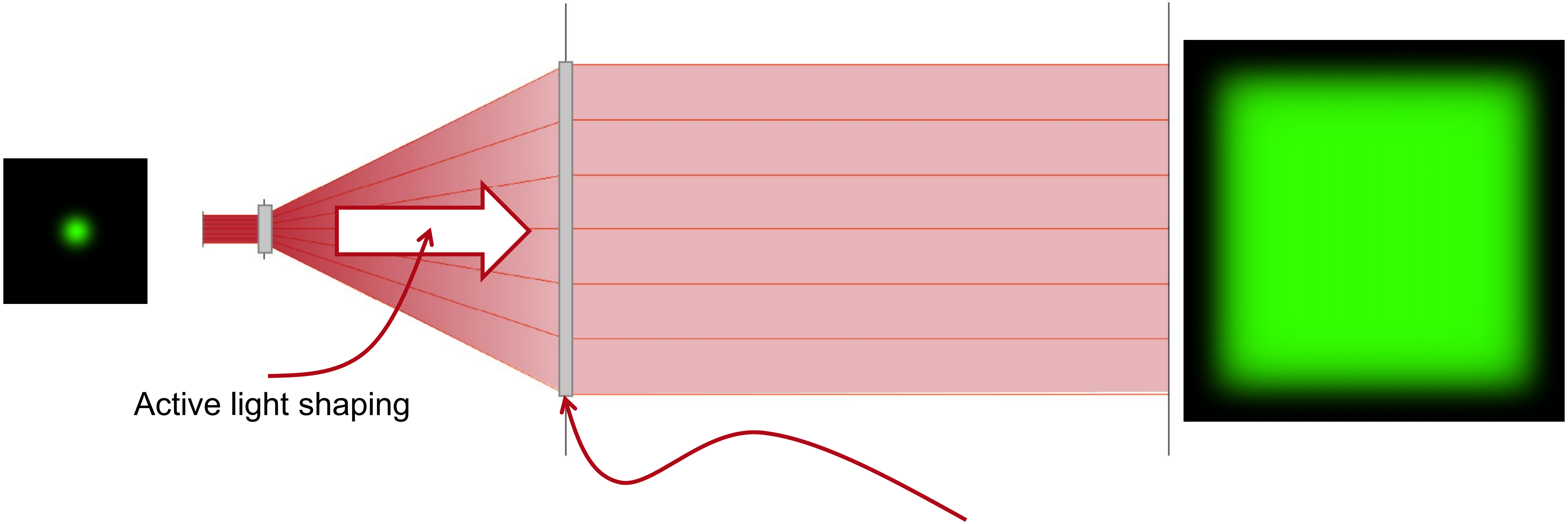
Beam expander with light shaping

Shaping Beam Expander: Scenario



Domain and irradiance matching:
Domains and irradiances of input and output fields must match to enable energy transport through the system.

Shaping Beam Expander: Scenario



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Design Workflow in VirtualLab Fusion

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FURTHER OPTIMIZATION

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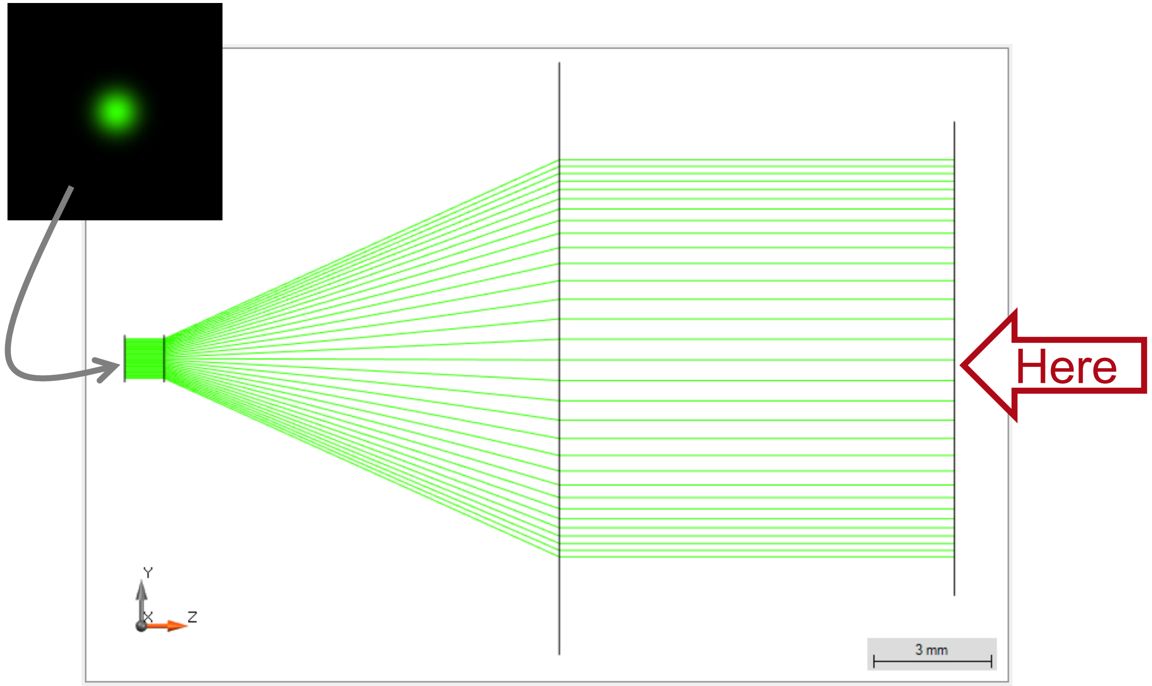
SYSTEM TOLERANCING

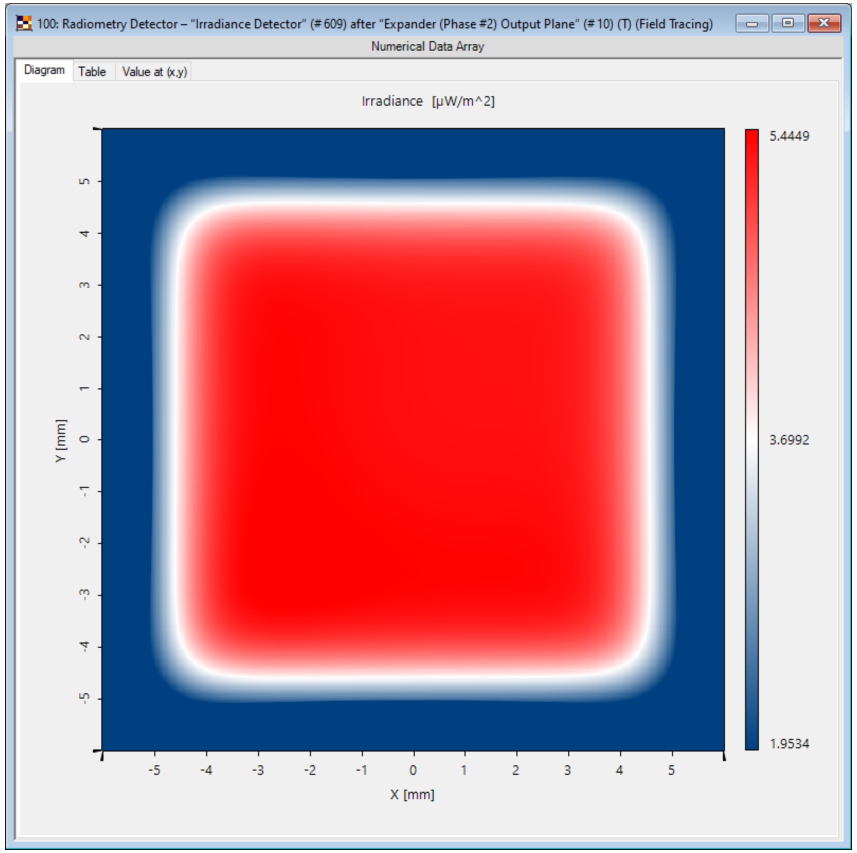
Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

FABRICATION DATA

Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

Shaping Beam Expander: Functional Design





Irradiance (by field tracing)

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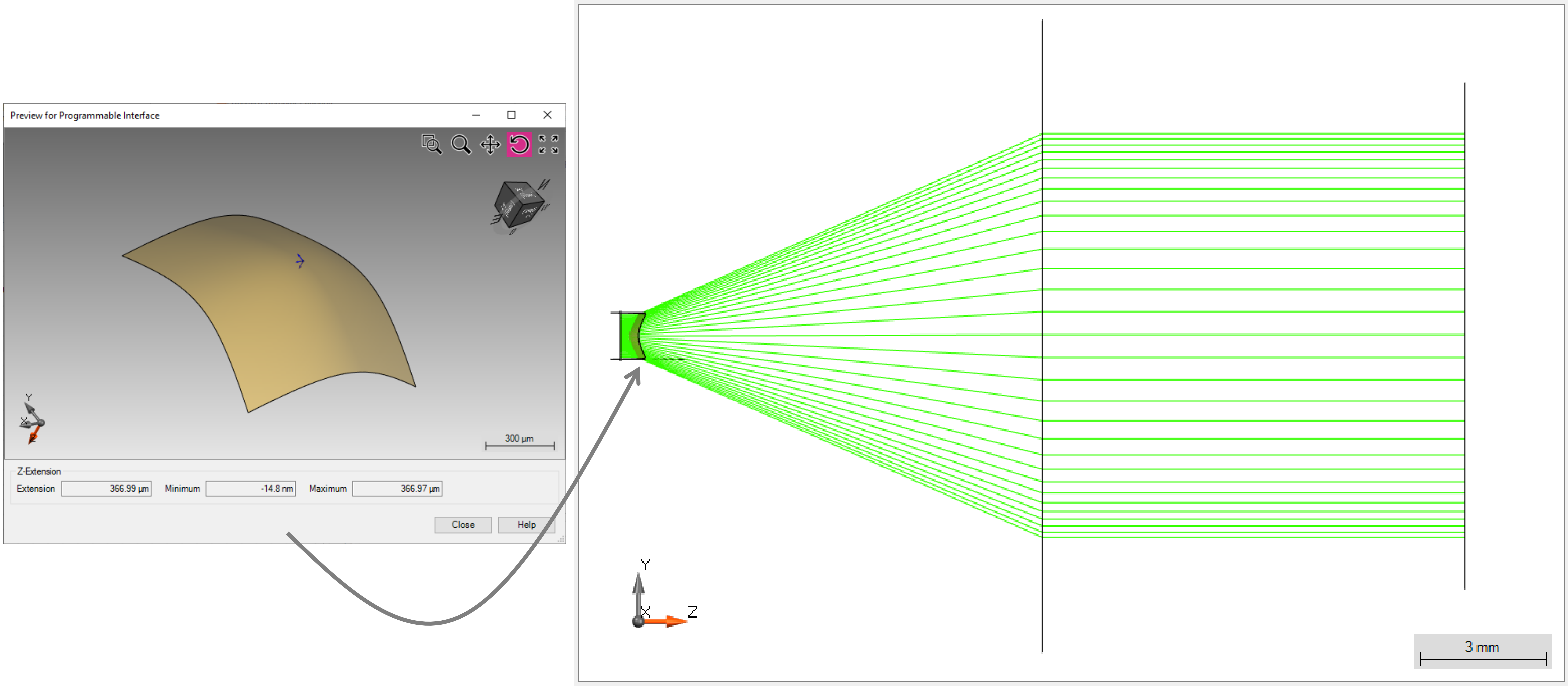
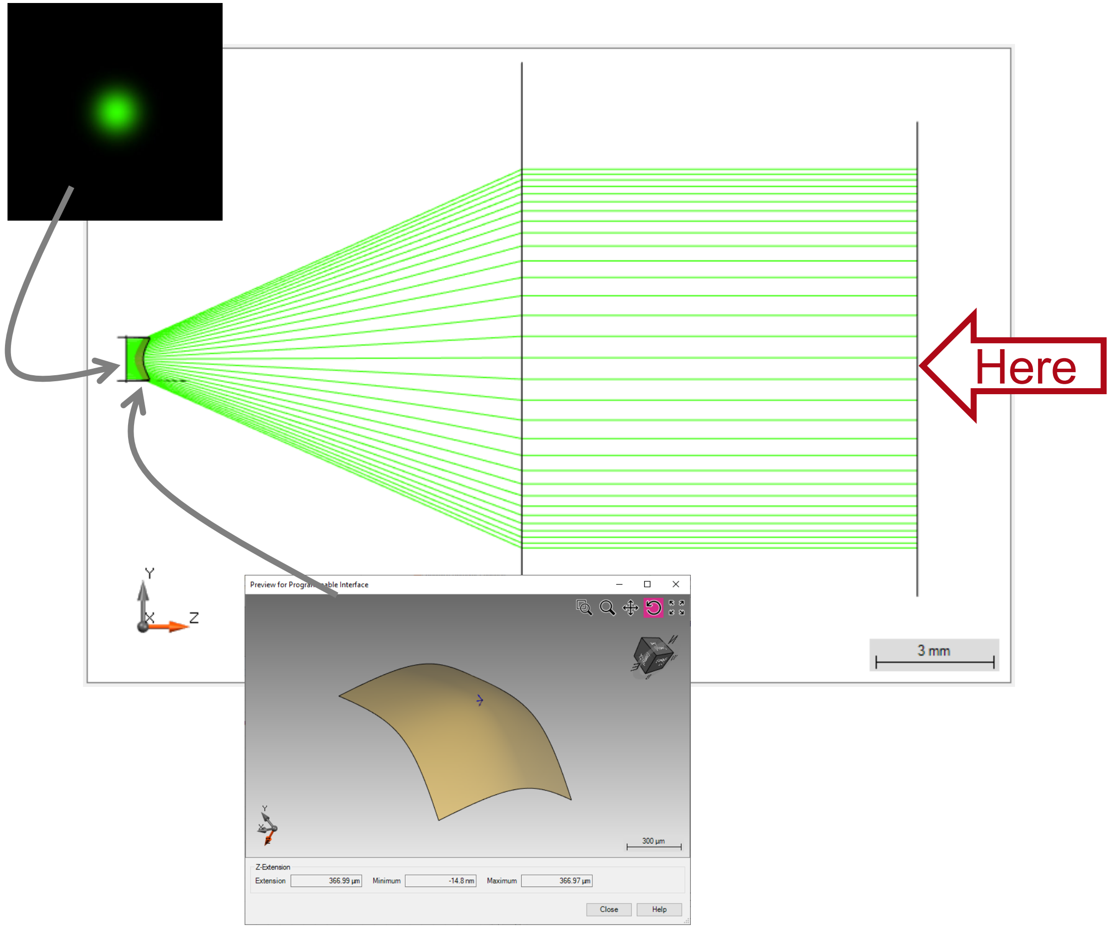
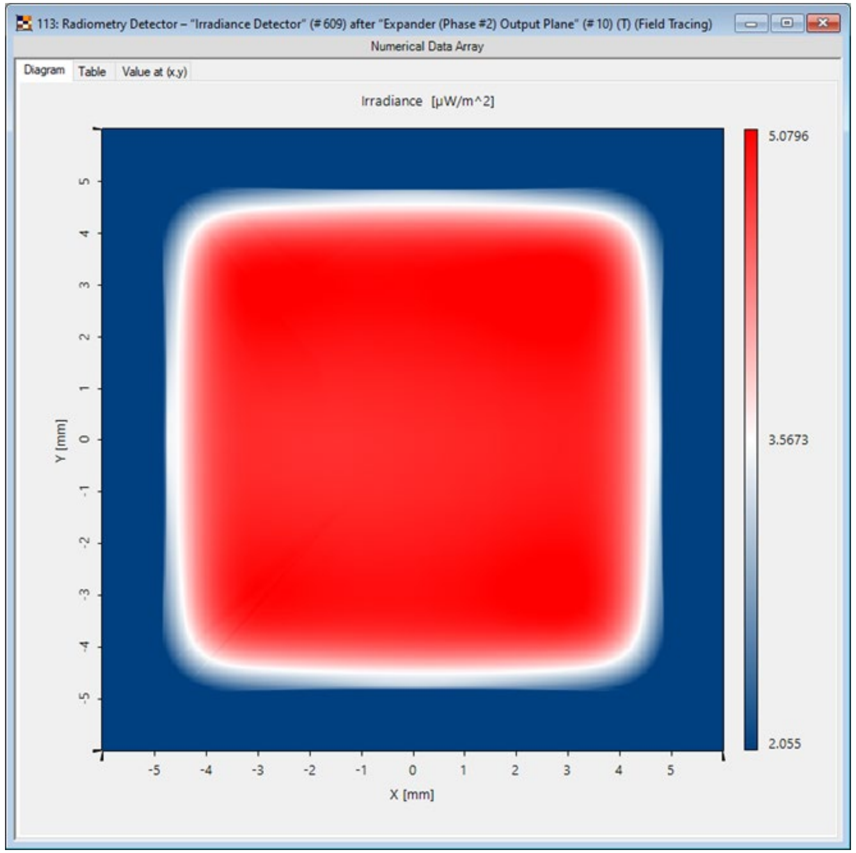
Shaping Beam Expander: Freeform + Functional



Shaping Beam Expander: Freeform + Functional





Irradiance (by field tracing)

Design and Analysis of a Hybrid Eyepiece for Correction of Chromatic Aberration

Functional design in Zemax® OpticStudio®

Design Workflow in VirtualLab Fusion

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Zemax® enables functional design of a wavefront phase response (binary surfaces) by parametric optimization

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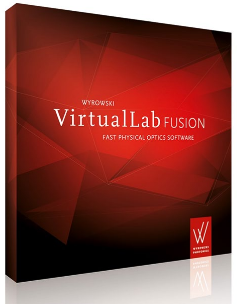
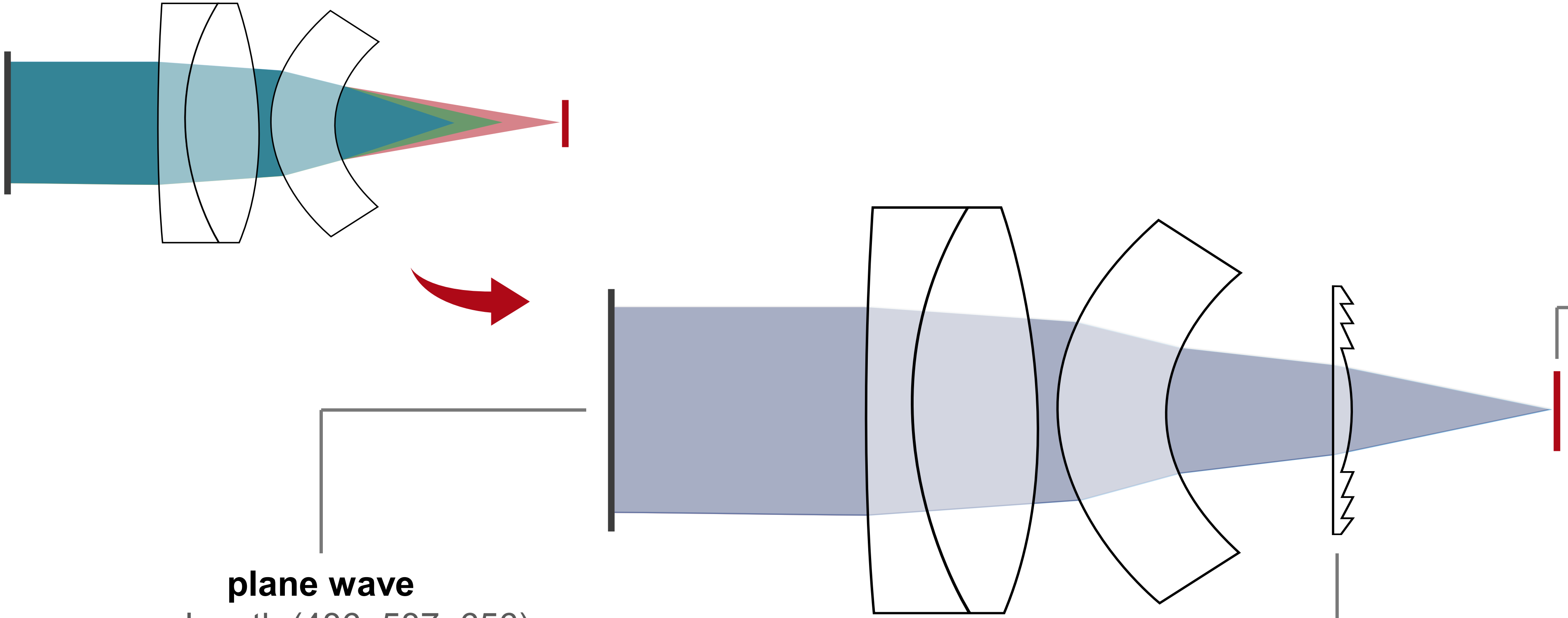
Import of Zemax file into VirtualLab Fusion and further processing of workflow.



Modeling and Design Scenario



detectors

- point spread function
- modulation transfer function (MTF)

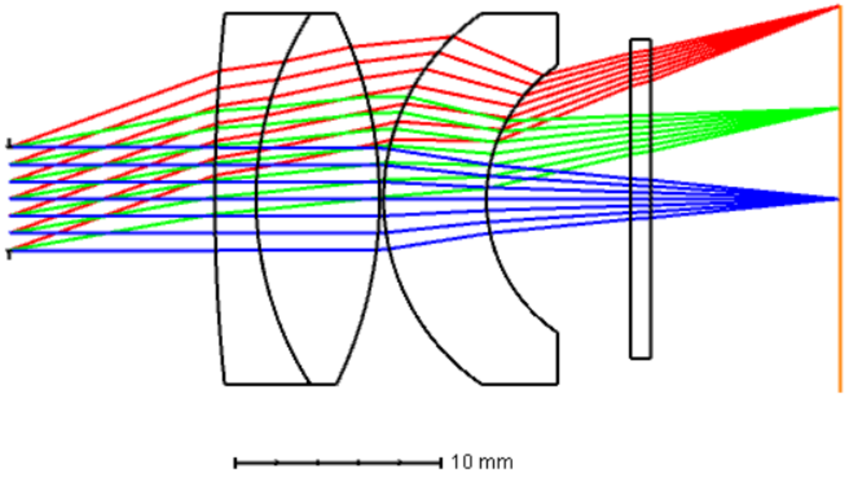
plane wave

- wavelength (486, 587, 656)nm
- field of view (40)°
- linearly polarized along x-axis
- aperture 5mm×5mm

lens solution

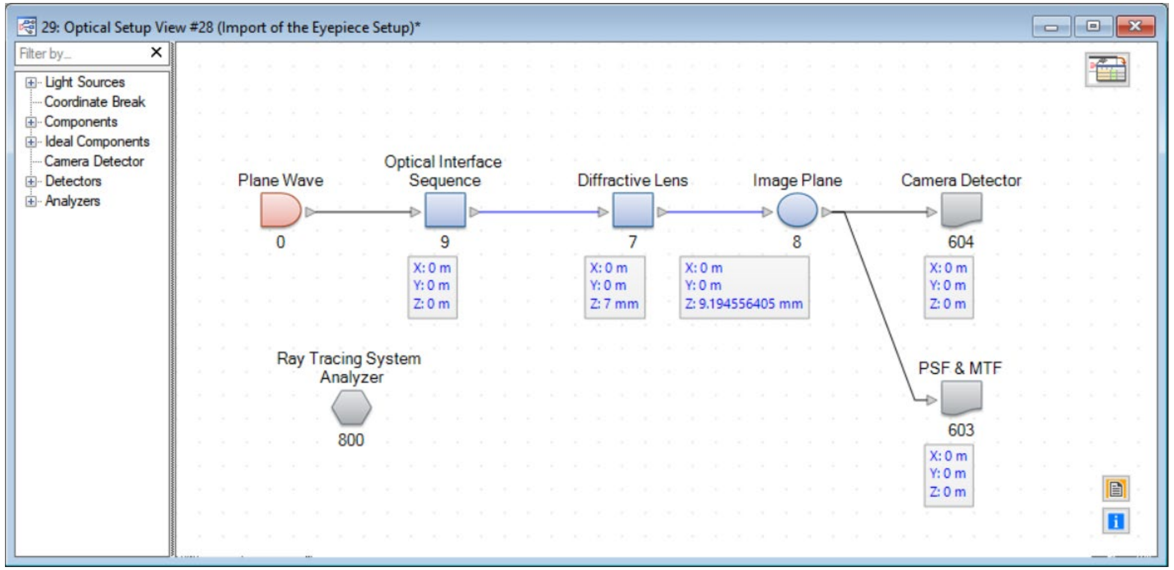
- wavefront response function
- diffractive lens
- meta lens

Design of Wavefront Surface Response in OpticStudio



Optical setup including the wavefront surface response was originally designed in OpticStudio

Import of the OpticStudio file to VirtualLab Fusion



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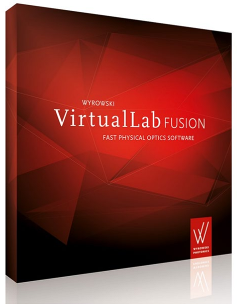
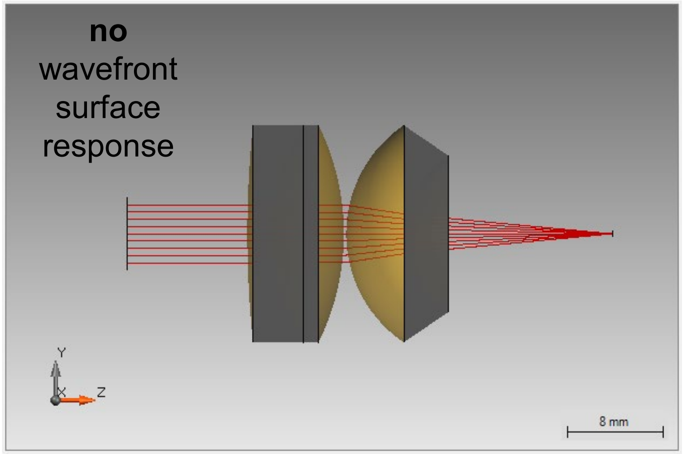
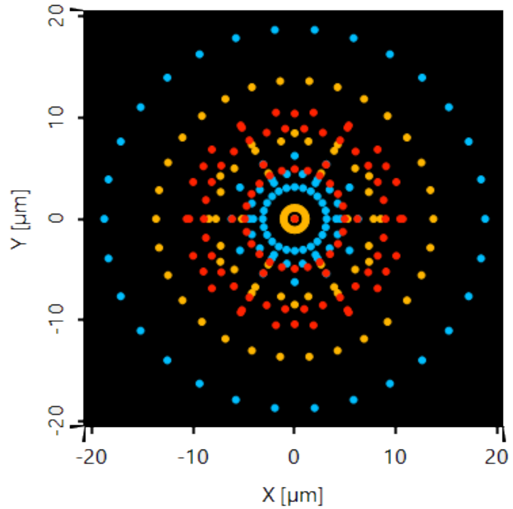
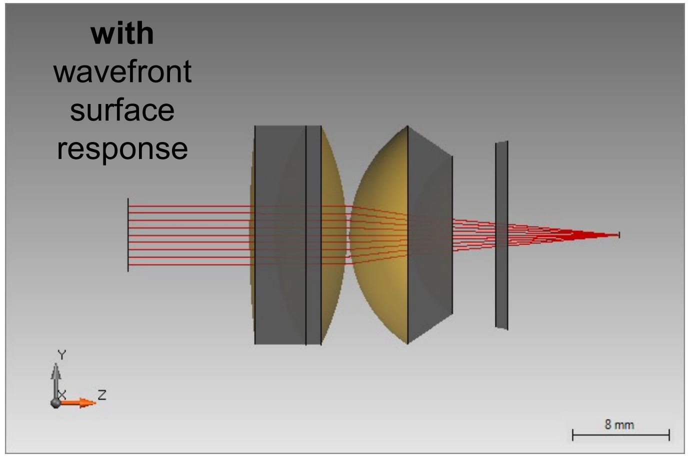
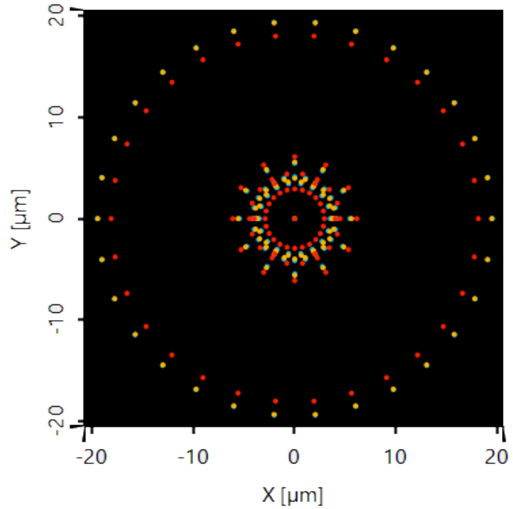


On-Axis Analysis: Comparison of Spot Diagram





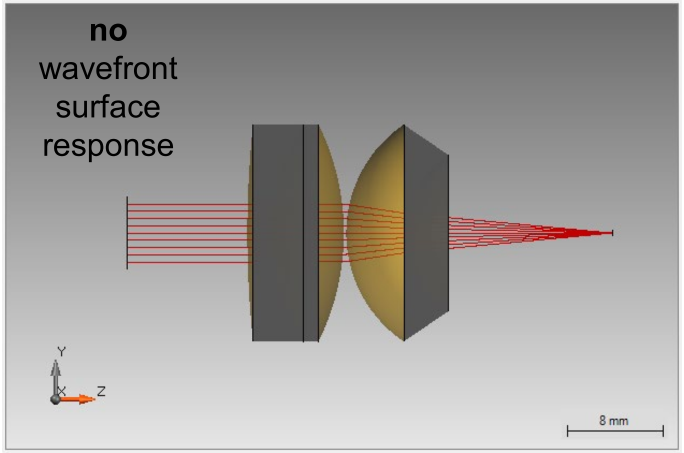


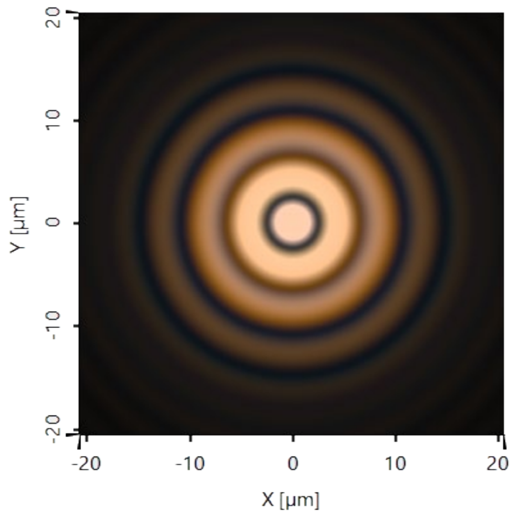


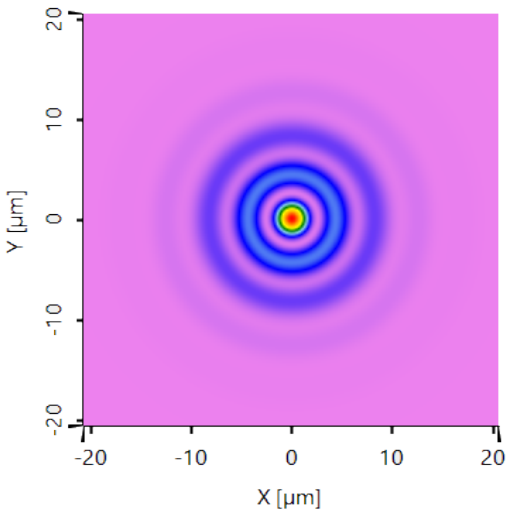
On-Axis Analysis: Comparison of PSF

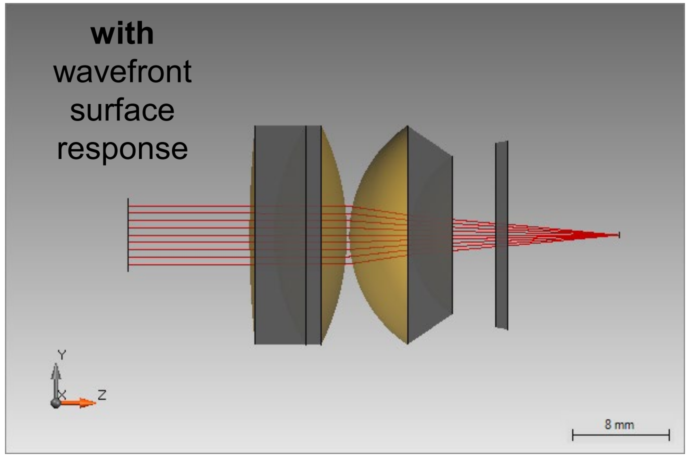
Real Color View

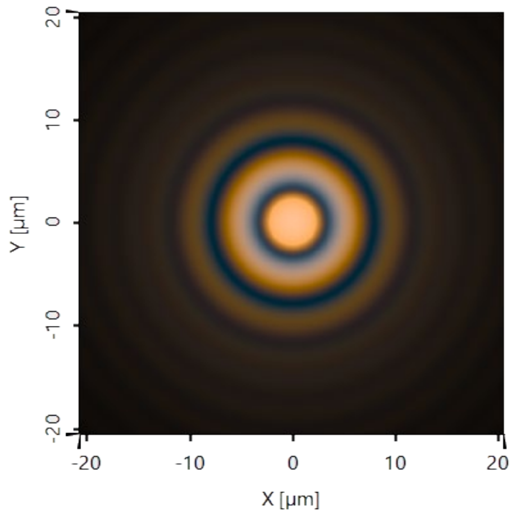
False Color View

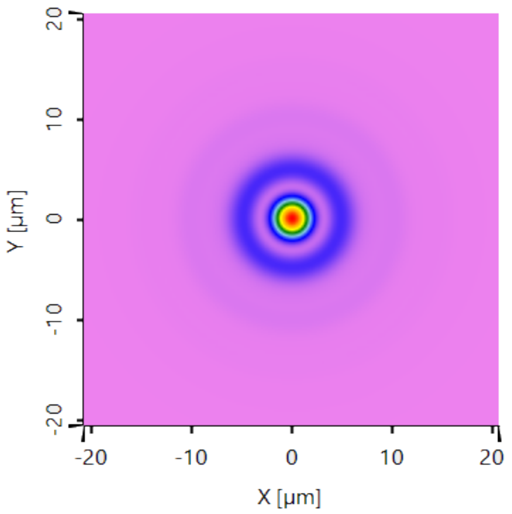




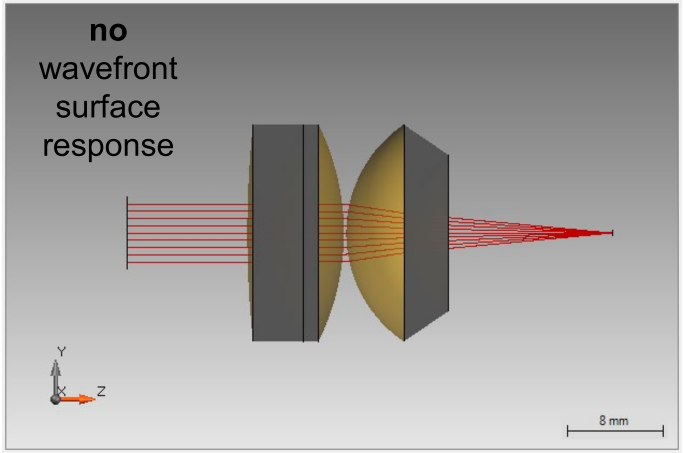


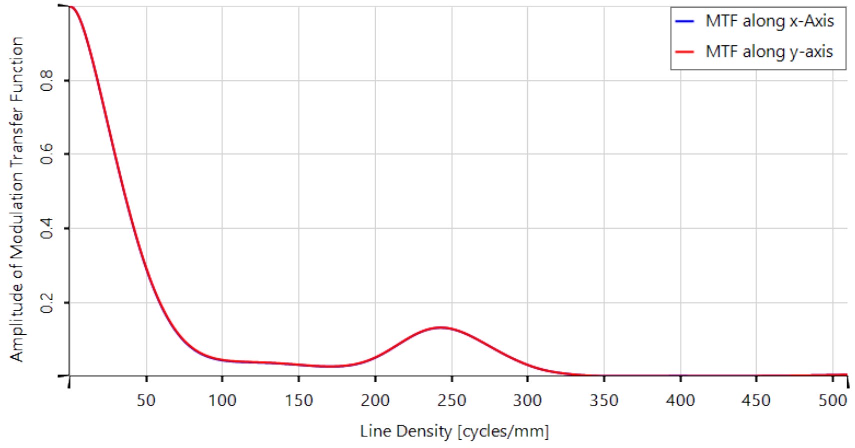


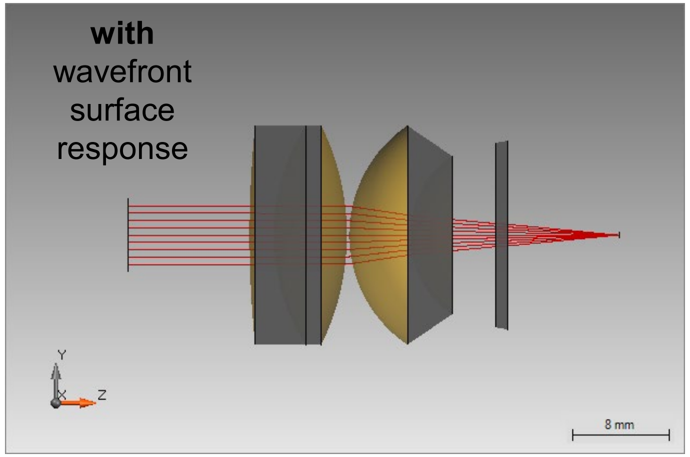


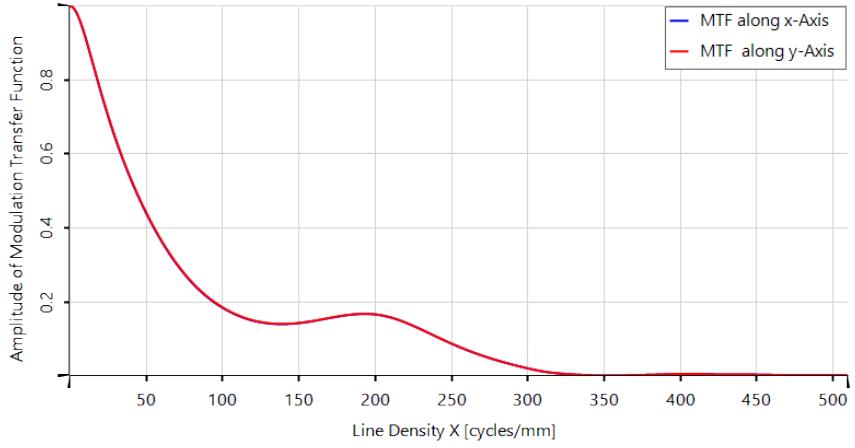


On-Axis Analysis: Comparison of MTF









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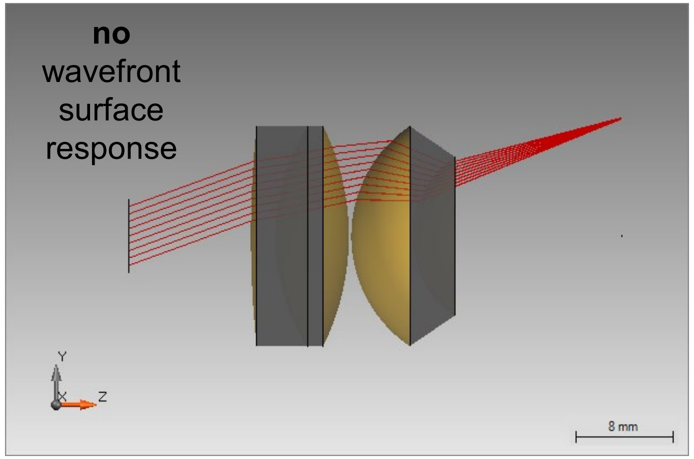
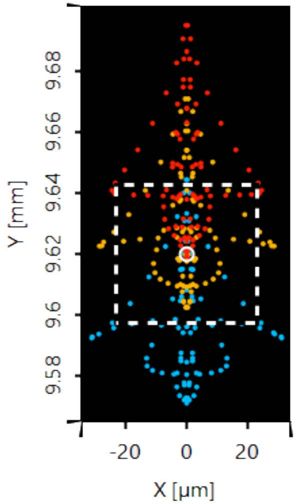
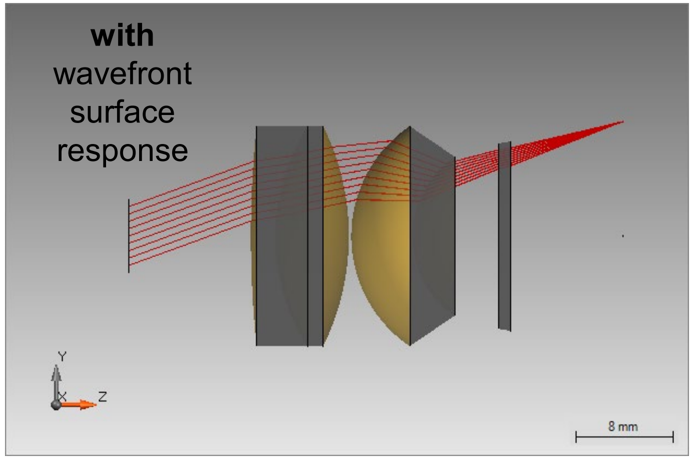
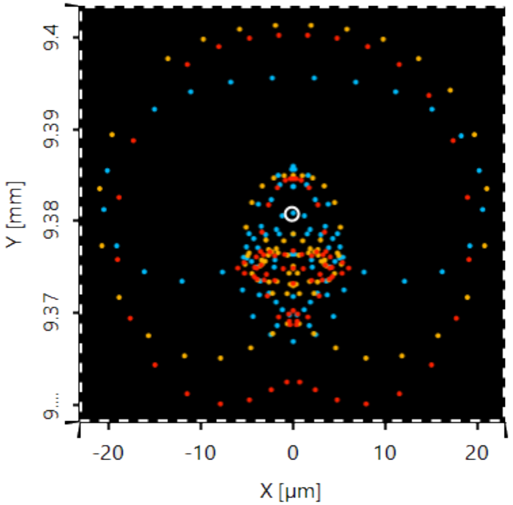
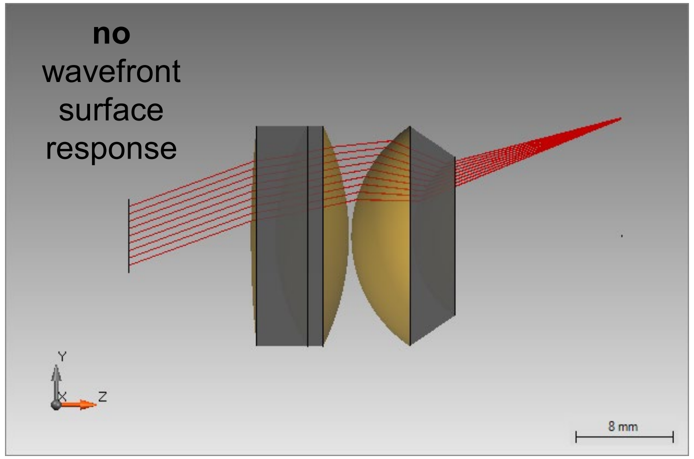


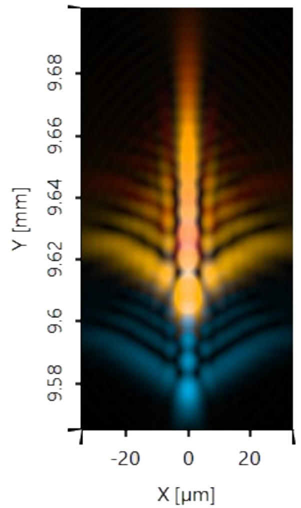


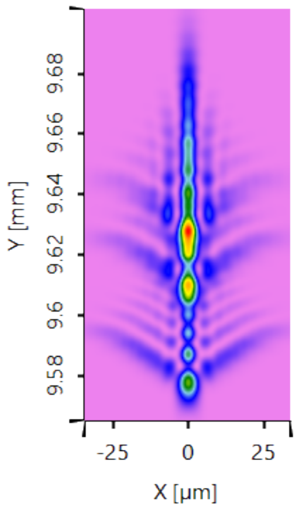


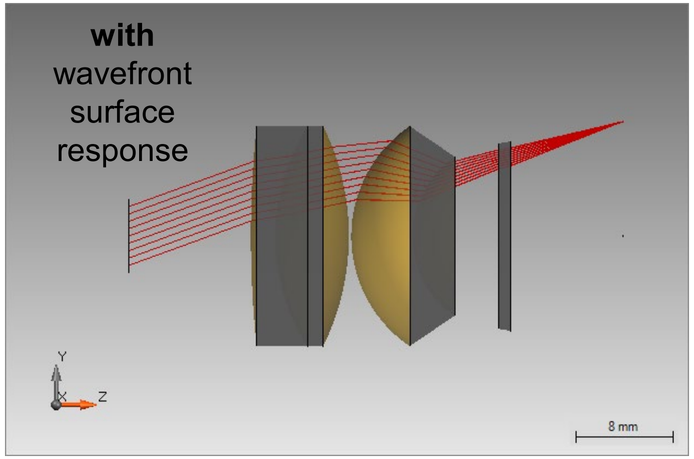


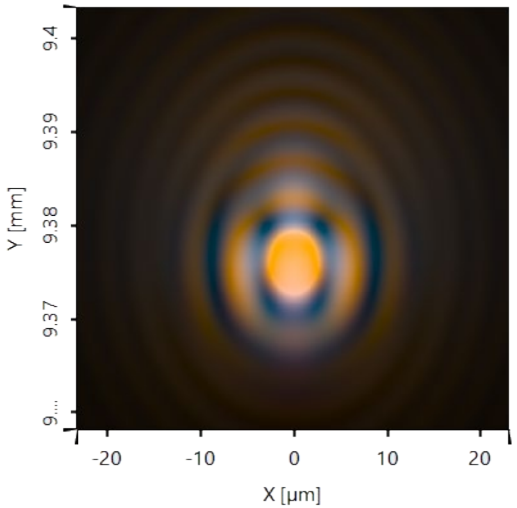
Off-Axis Analysis: Comparison of PSF

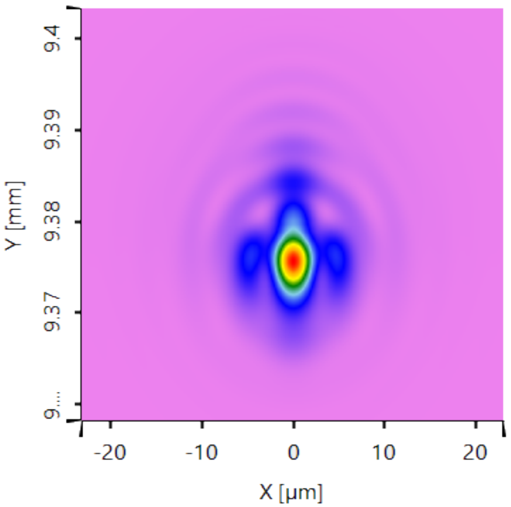




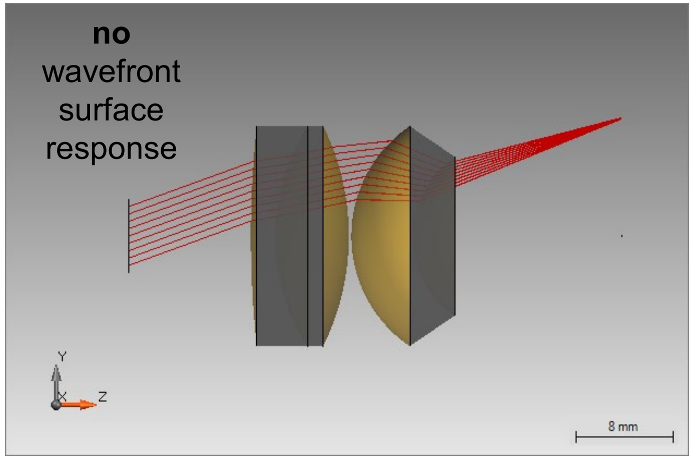


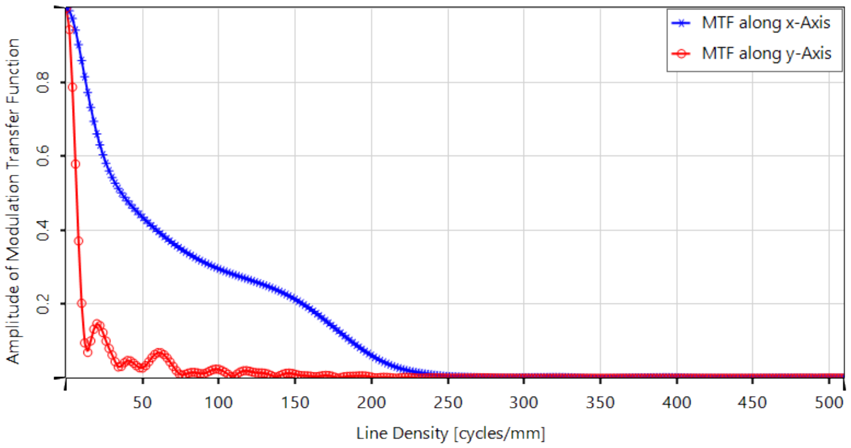


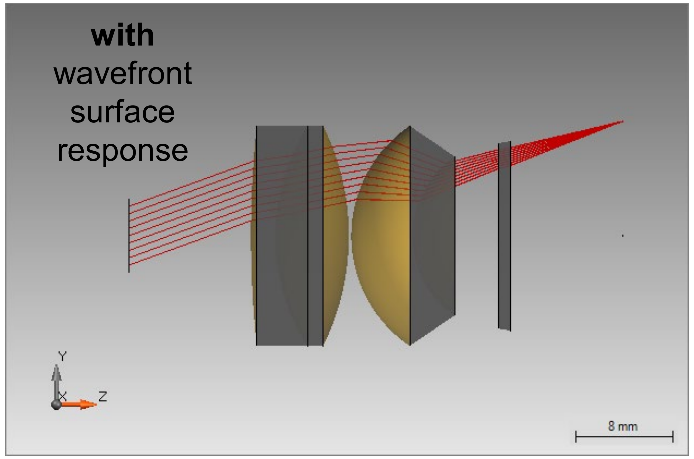


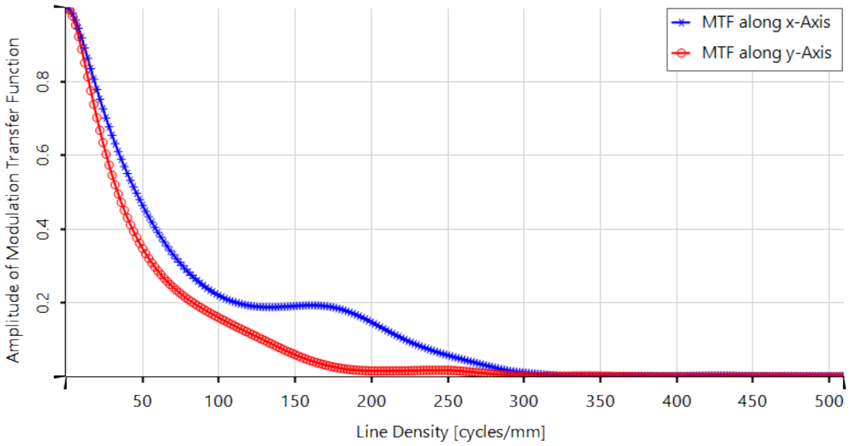


Off-Axis Analysis: Comparison of MTF









Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN

Design the system by introducing functional components to achieve the demanded system functionality.

STRUCTURAL DESIGN

Replace functional components by smooth surface or flat optics components.

MODELING & EVALUATION

Model the system with ray tracing and physical optics. Evaluate the performance by suitable detectors and merit functions.

FURTHER OPTIMIZATION

Use the modeling techniques to further optimize the system by, e.g., parametric optimization.

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Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

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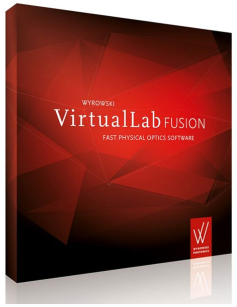
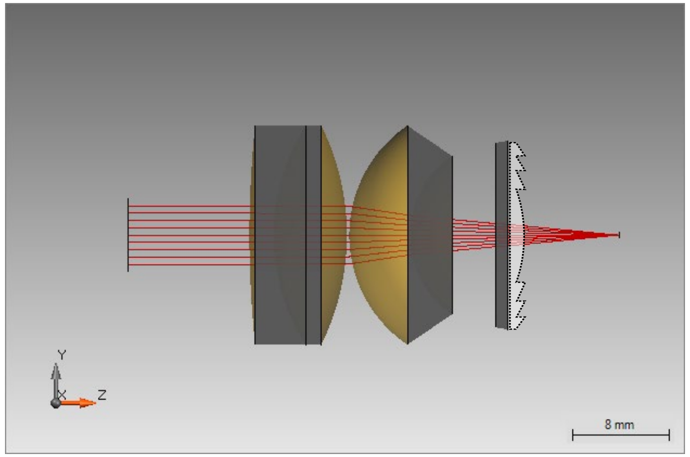
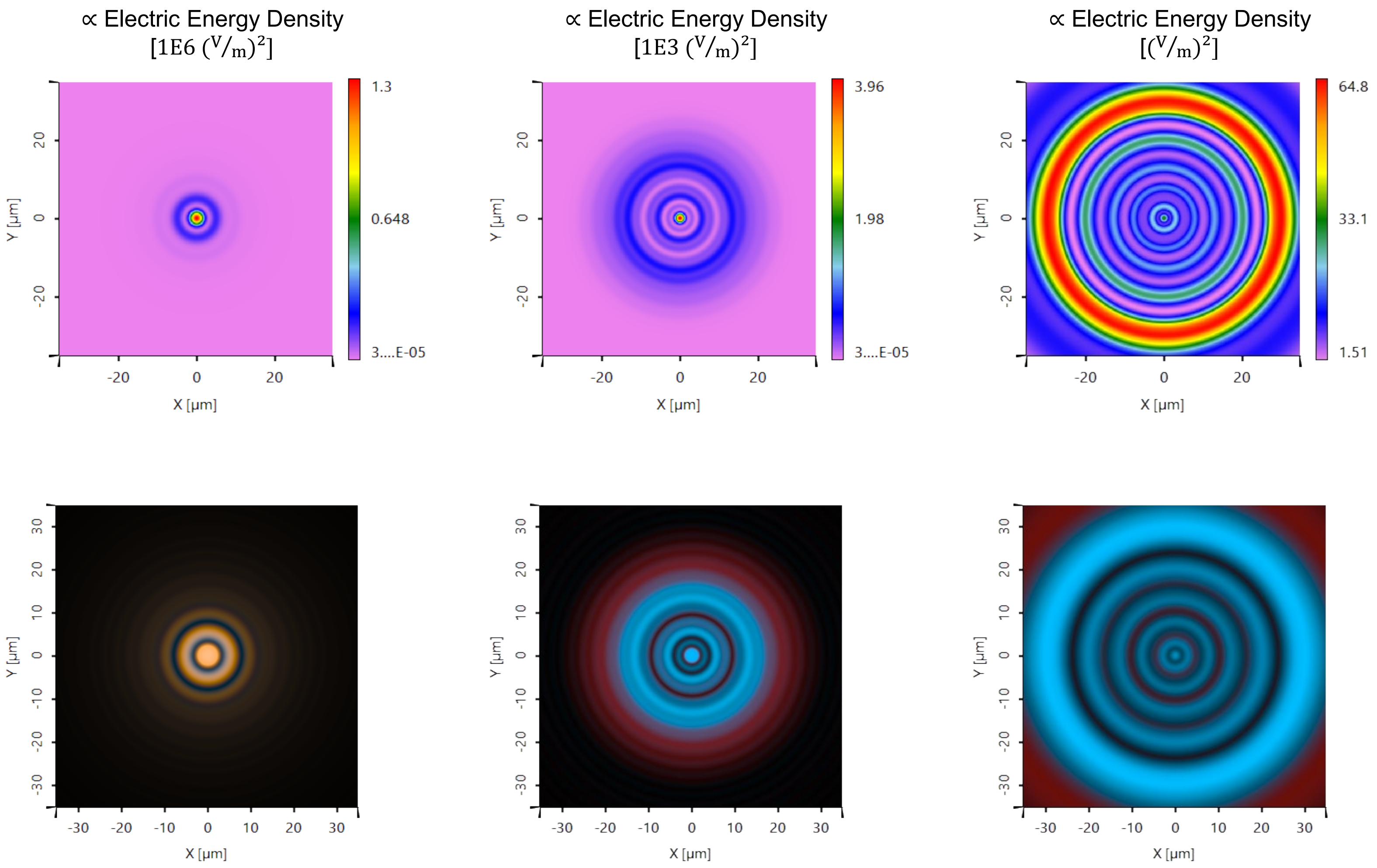


On-Axis Analysis: Inclusion of Higher Orders





+1st diffraction order

0th diffraction order

-1st diffraction order

simulation time per order ~seconds

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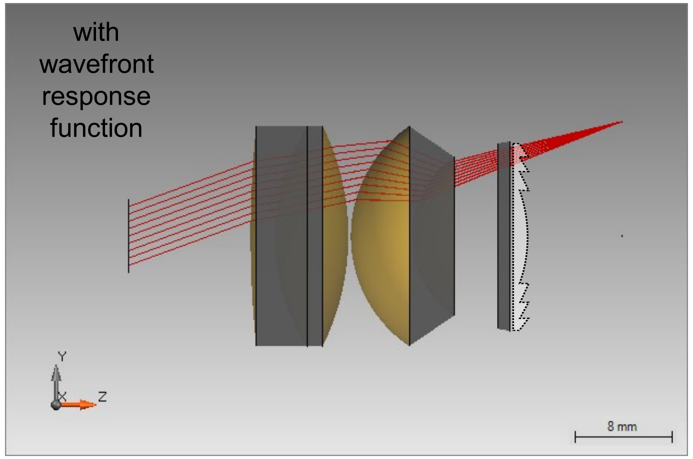
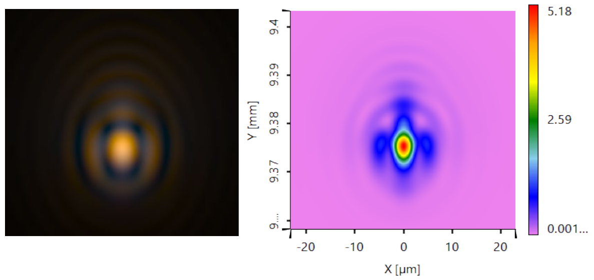
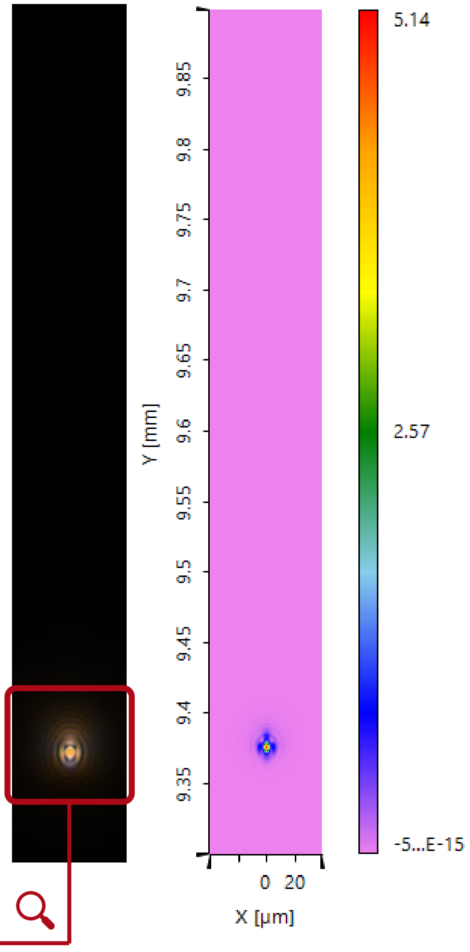


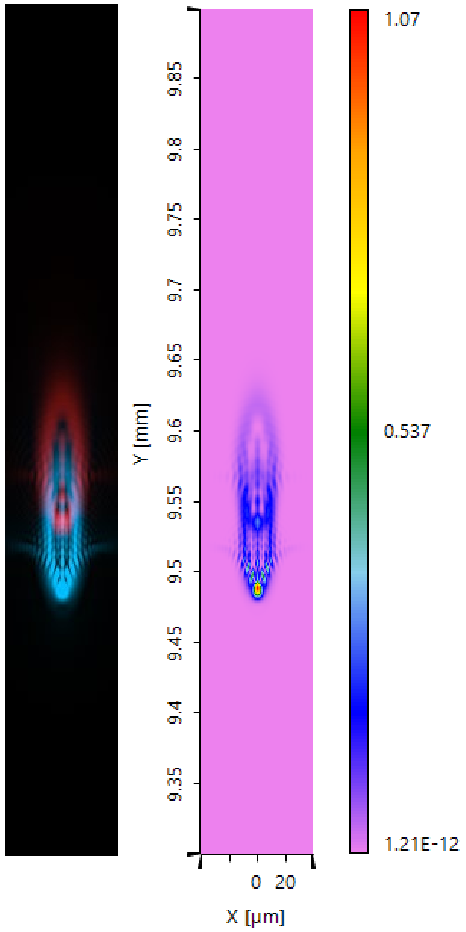


∝ Electric Energy Density [1E5 $(^{V}/_{m})^2$]



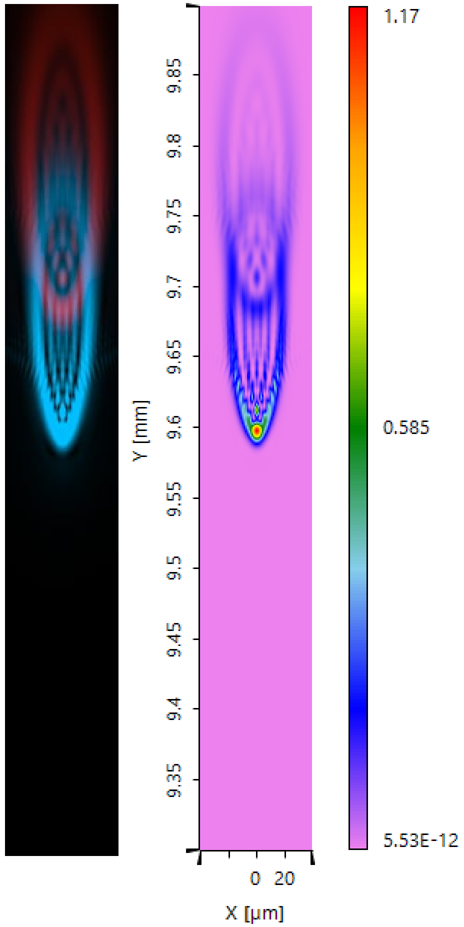
$+1^{st}$ diffraction order

∝ Electric Energy Density [1E3 $(^{V}/_{m})^2$]



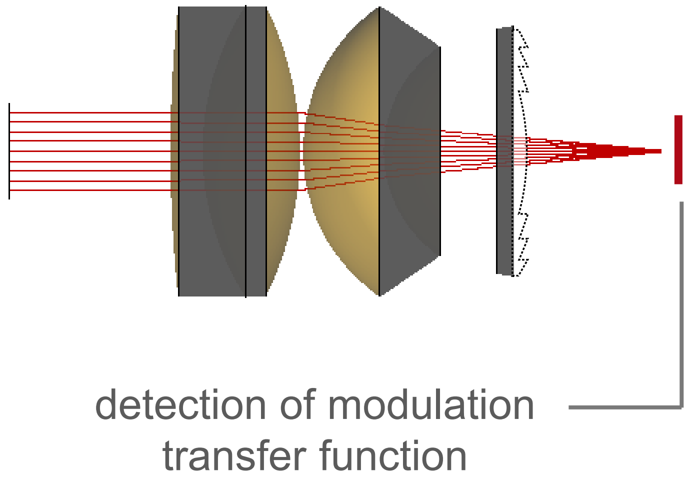
0^{th} diffraction order

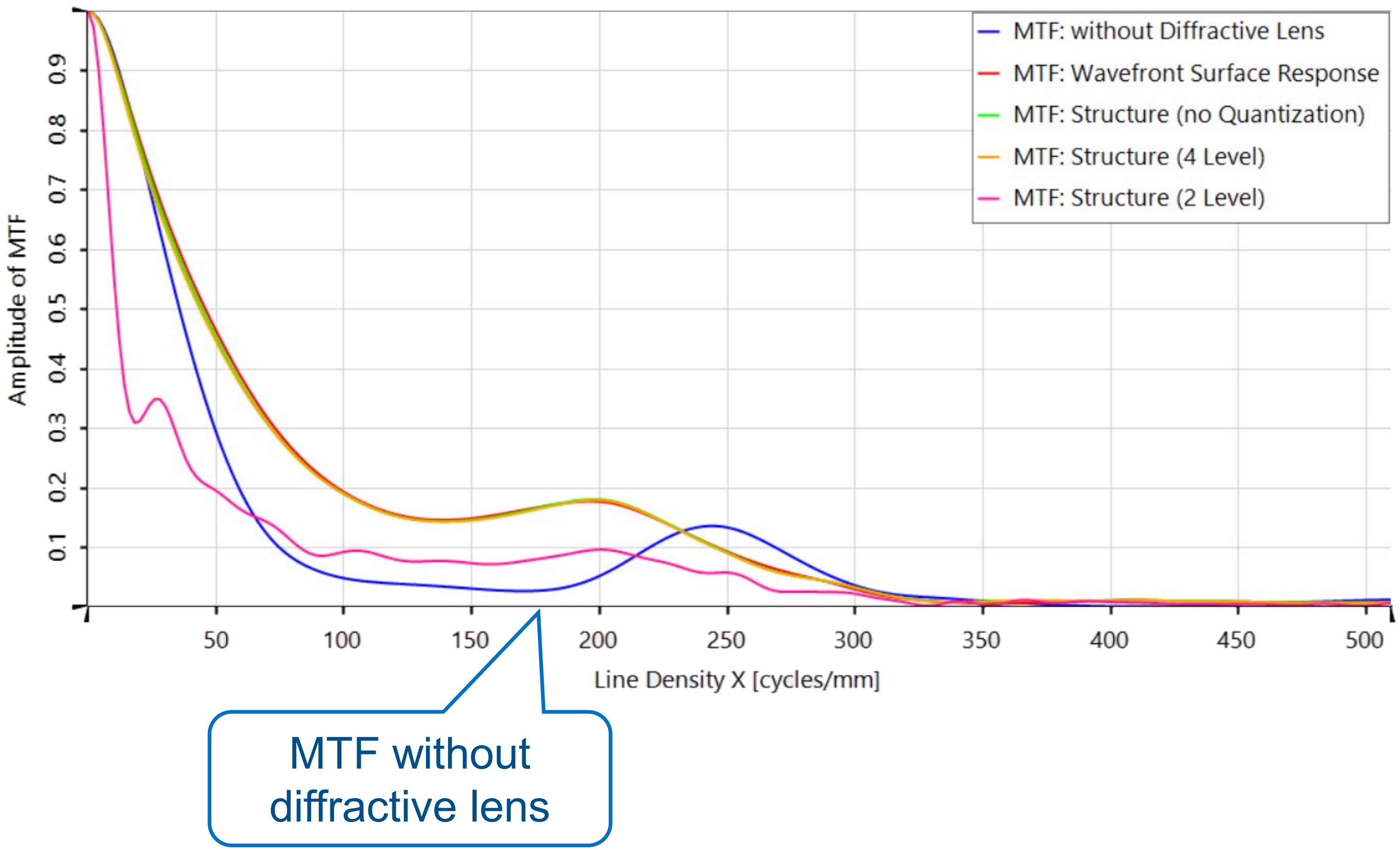
∝ Electric Energy Density [1E2 $(^{V}/_{m})^2$]



-1^{st} diffraction order

MTF for Various Diffractive Lens Structures





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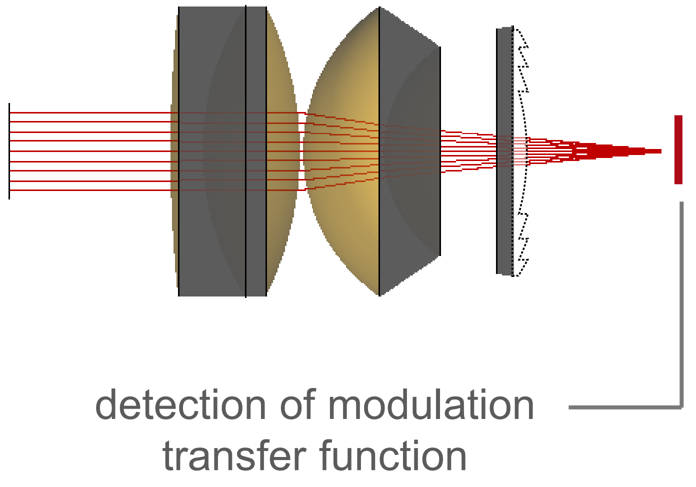

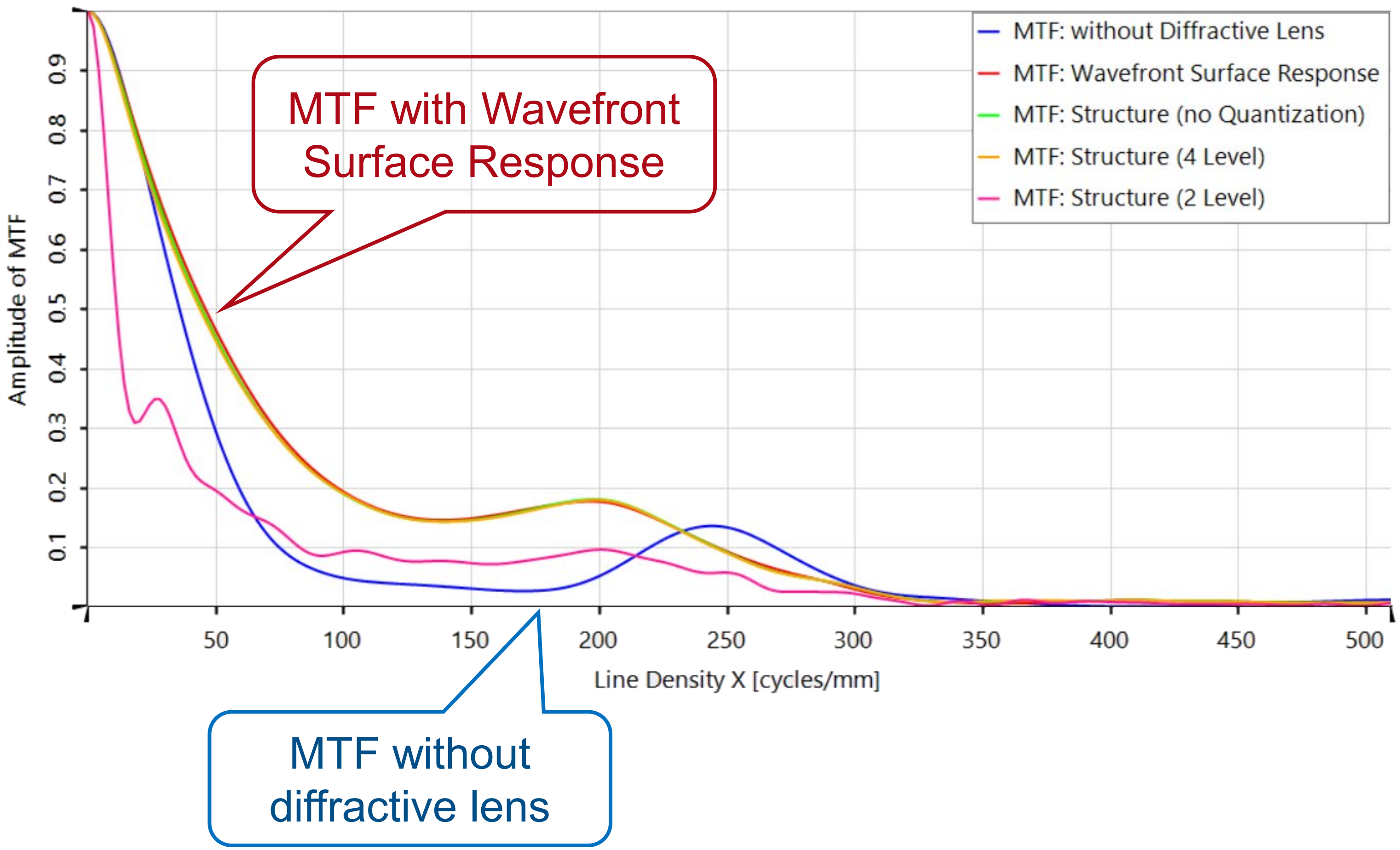

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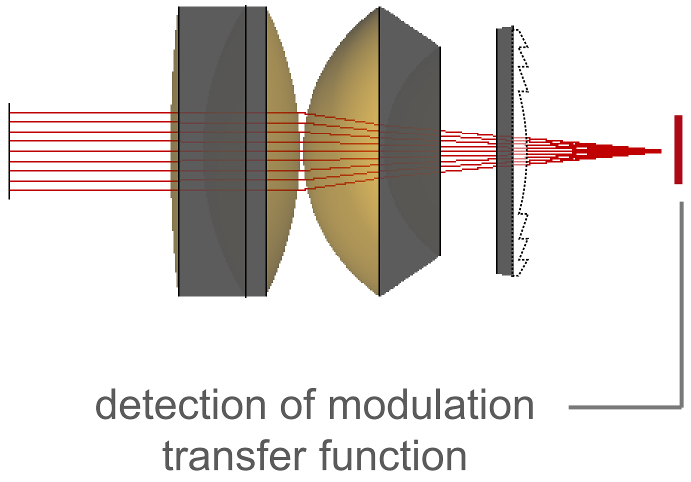

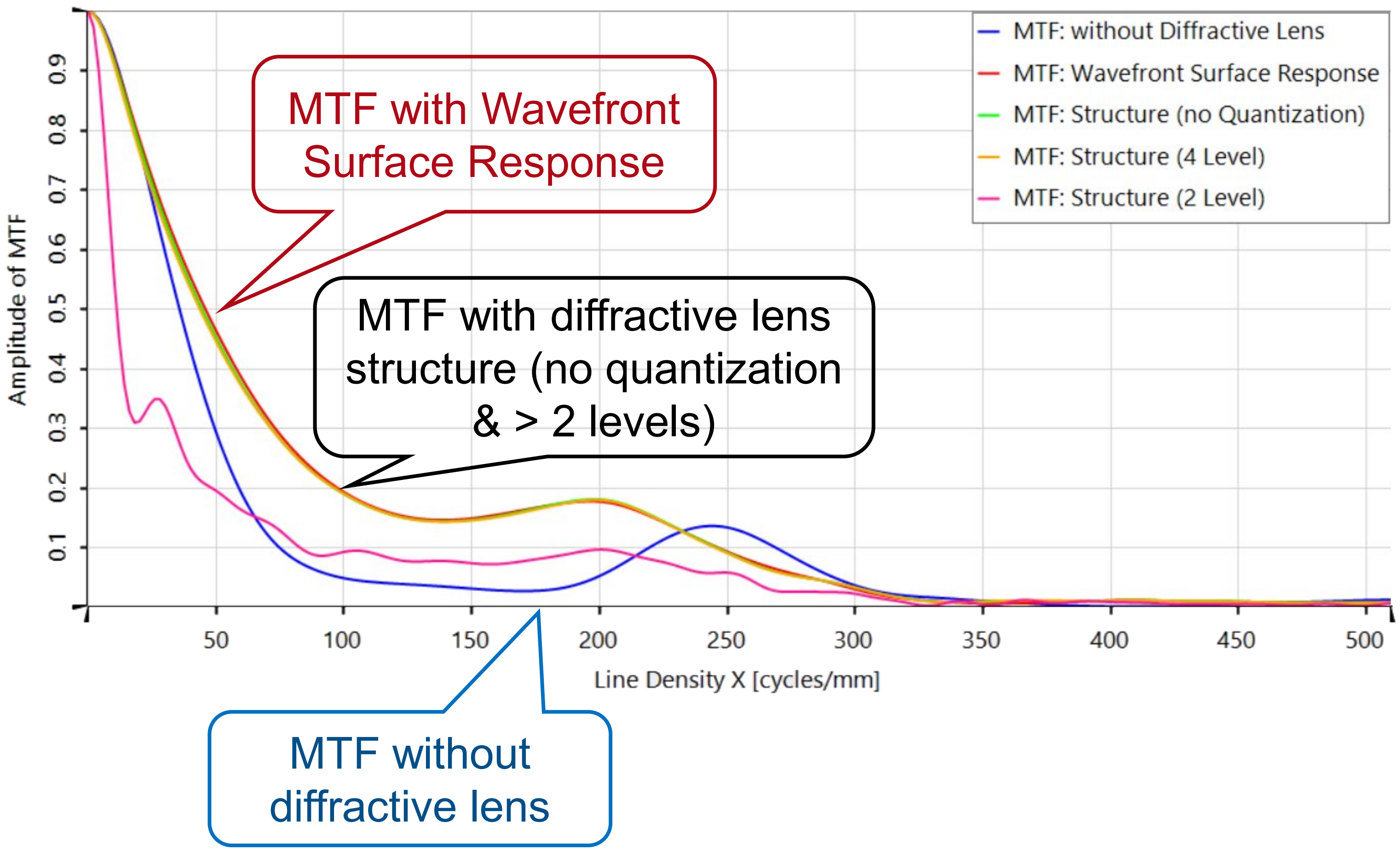

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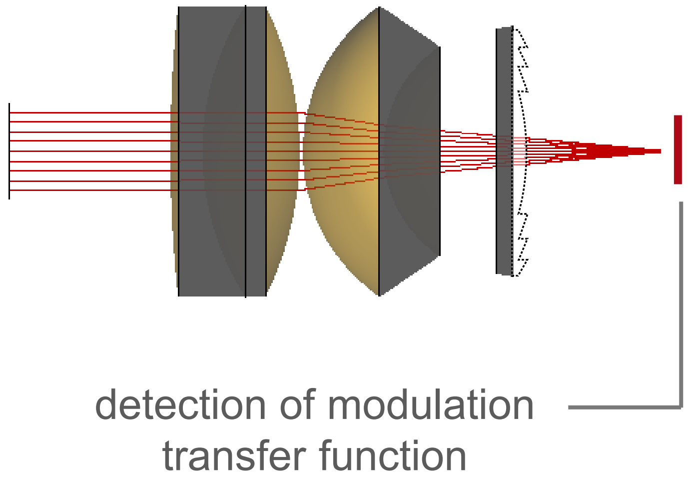

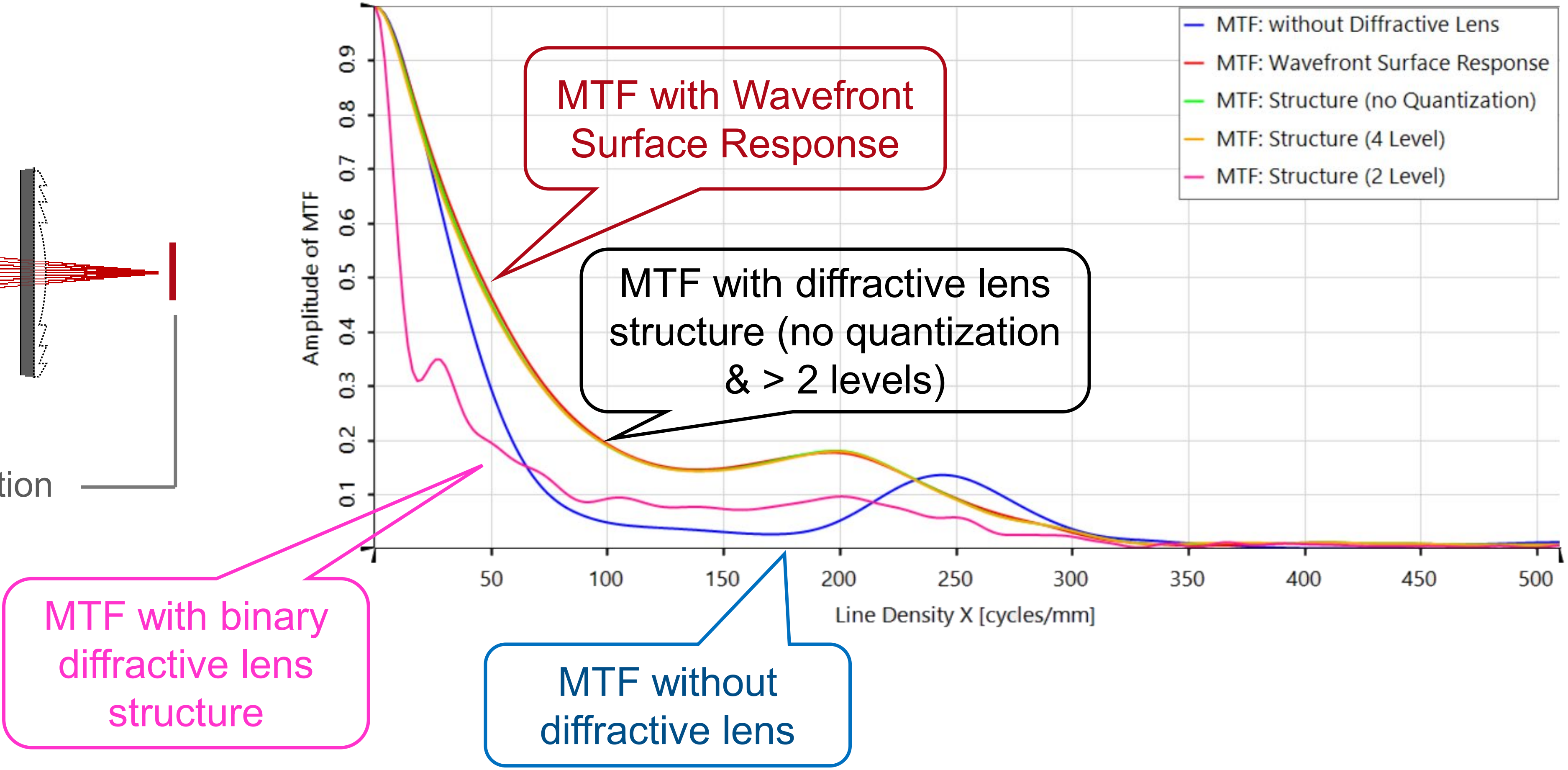

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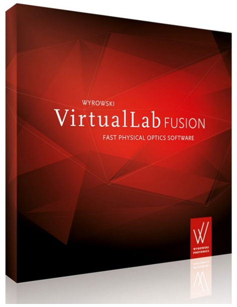
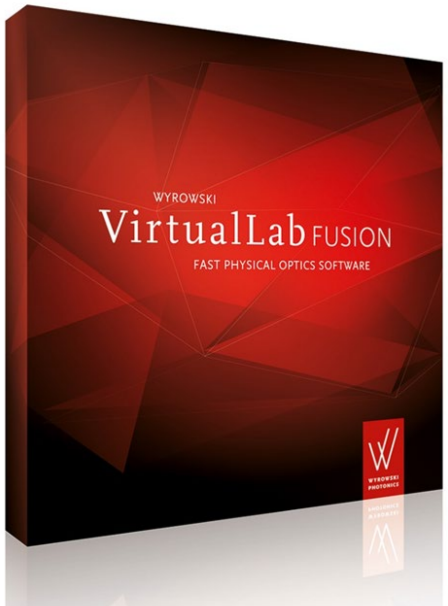


Conclusion

- VirtualLab Fusion provides a steadily growing number of tools for flat and freeform optics.
- Functional design concepts essential in workflow.
- New surface design techniques avoid parametric optimization.
- VirtualLab Fusion modeling and design tools allow the investigation of pros and cons of flat and freeform optics.
- Techniques demonstrated in this webinar are:
  - All available in-house for modeling and design services
  - Partly included in current version of VirtualLab Fusion
  - All will be released in 2021



VirtualLab Fusion 2021