LightTrans & PhotonicNet Webinar, 04.02.2021

Flat Optics – about Freeform, Fresnel, Diffractive and Meta Lenses

Frank Wyrowski and Christian Hellmann

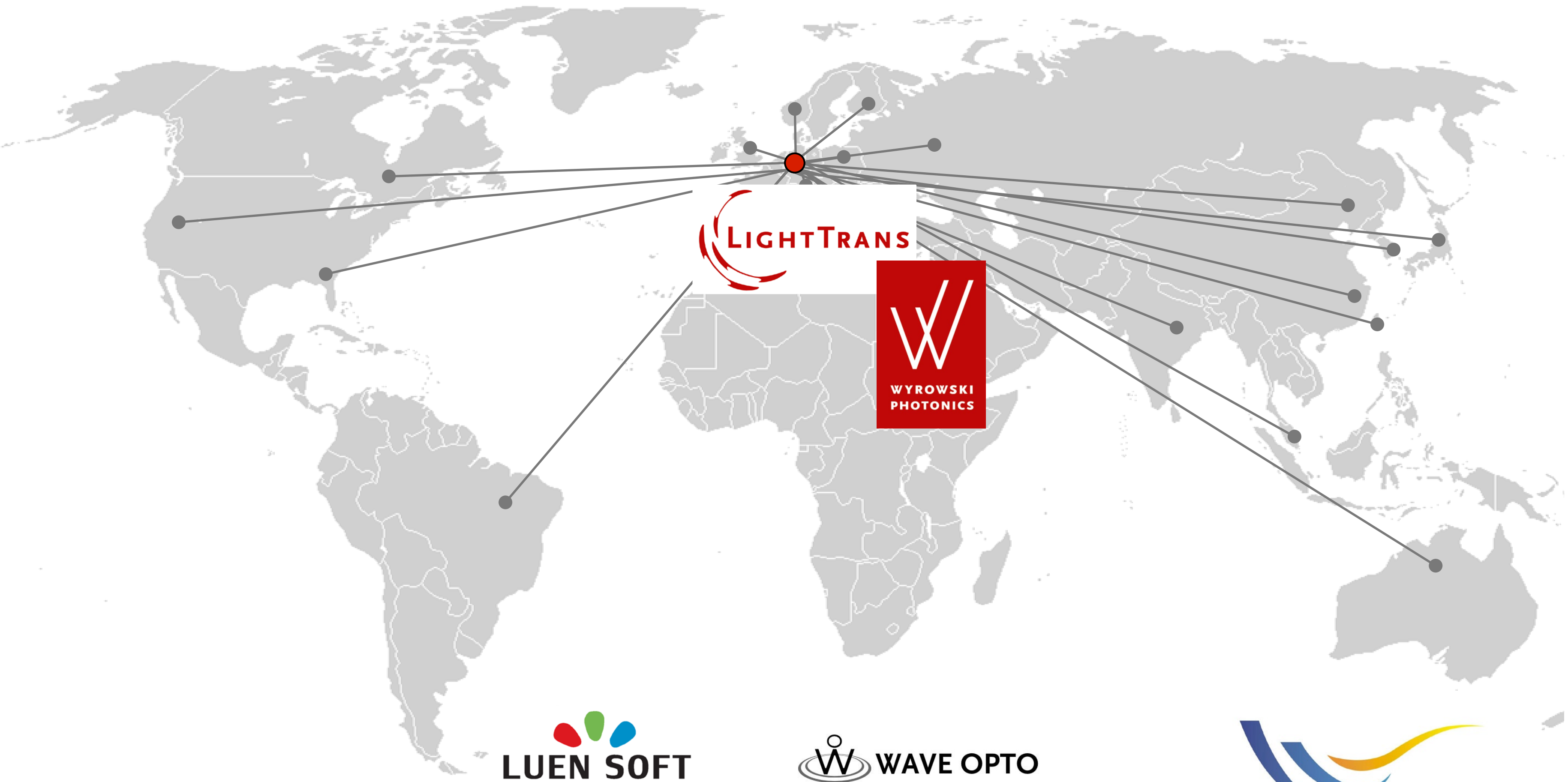
Frank Wyrowski, Jena, Germany

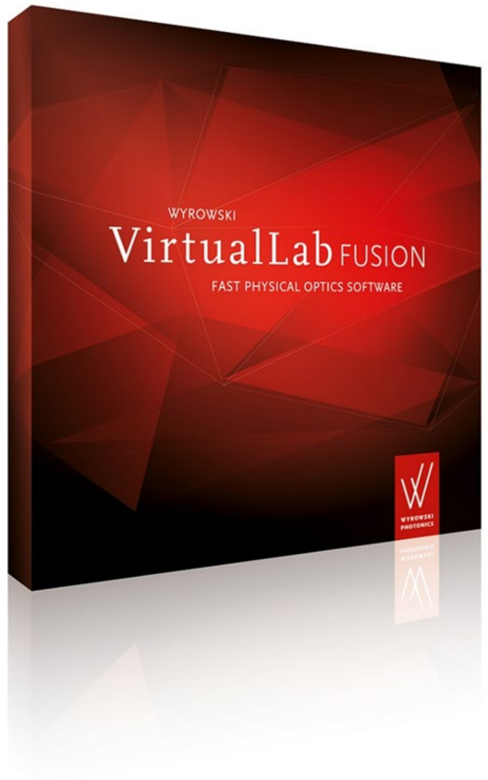
- Professor at University of Jena, Applied Computational Optics, IAP (1996)
- Co-Founder and President of LightTrans GmbH (1999)
- Co-Founder and President of Wyrowski Photonics (2014)

Co-Founder and CEO:
Christian Hellmann

Physical Optics Modeling and Design

Fast Physical Optics Modeling and Design Software





LUEN SOFT

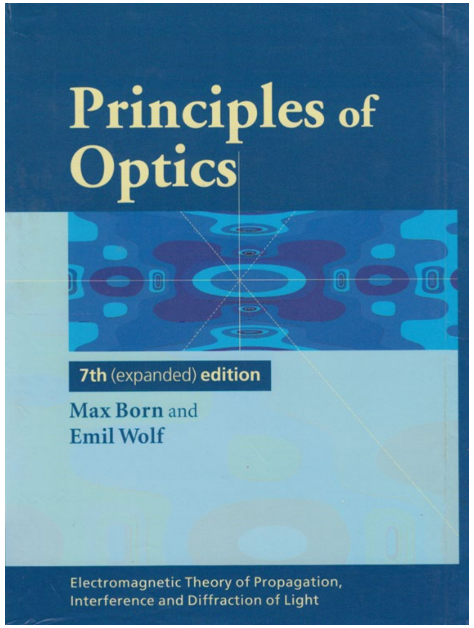
WAVE OPTO

T.E.M. Incorporated

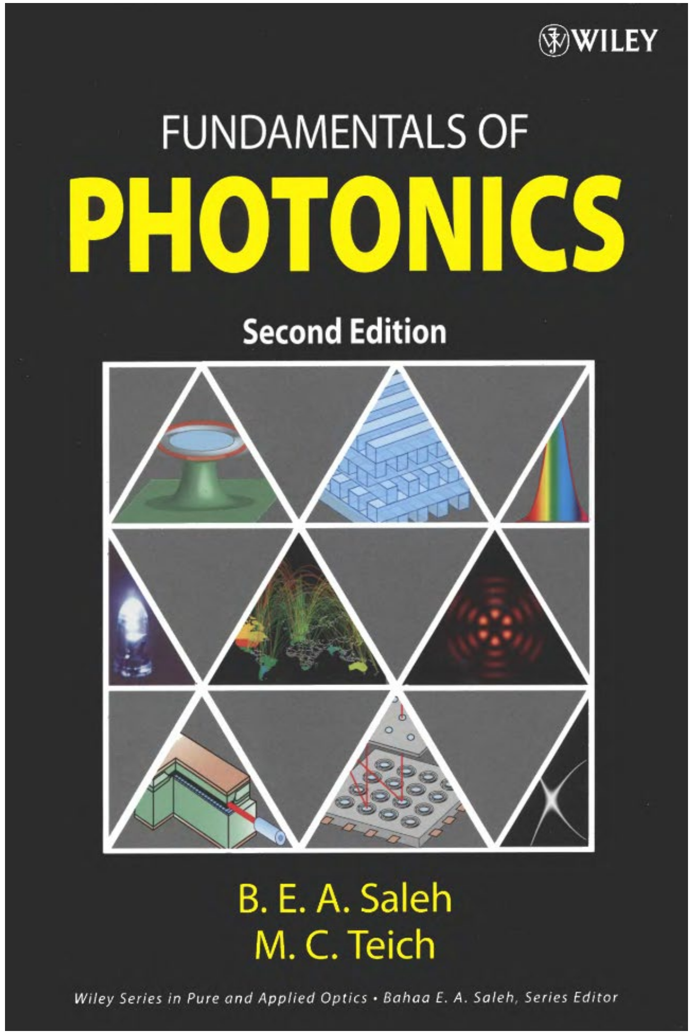
INFOTEK

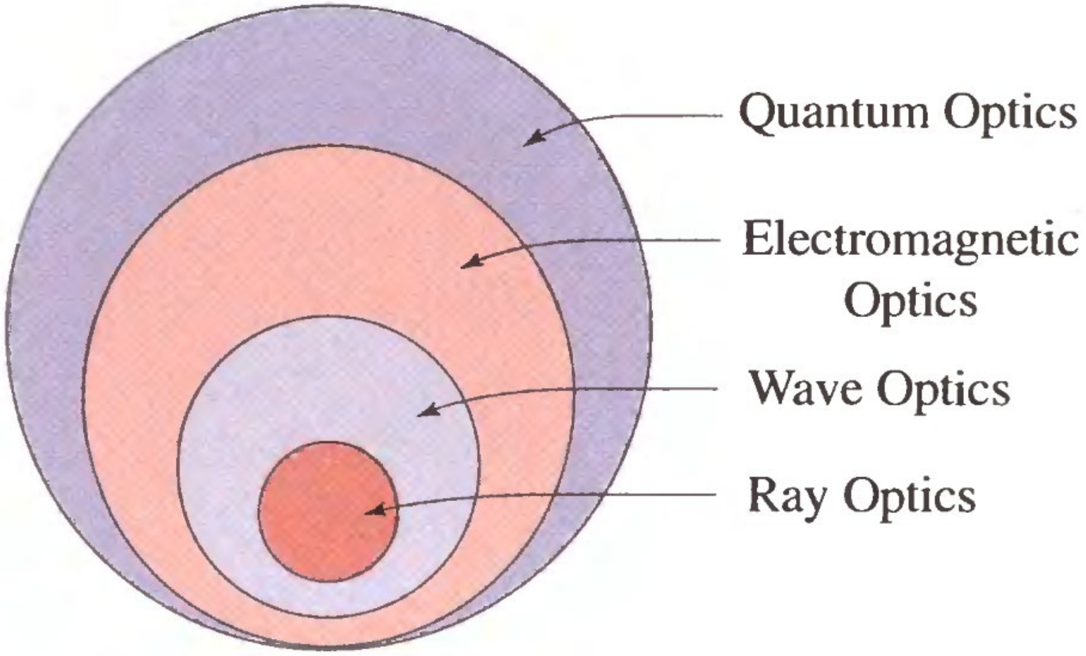
Physical Optics with VirtualLab Fusion

... learning from Max Born and Emil Wolf



Physical and Geometrical Optics: Traditional Understanding





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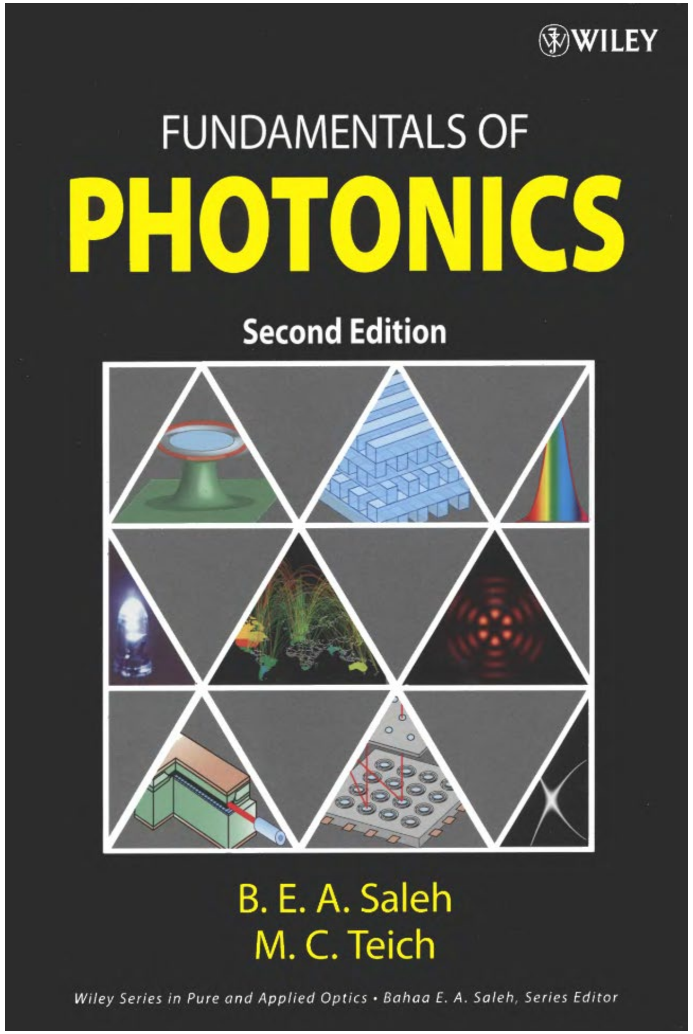

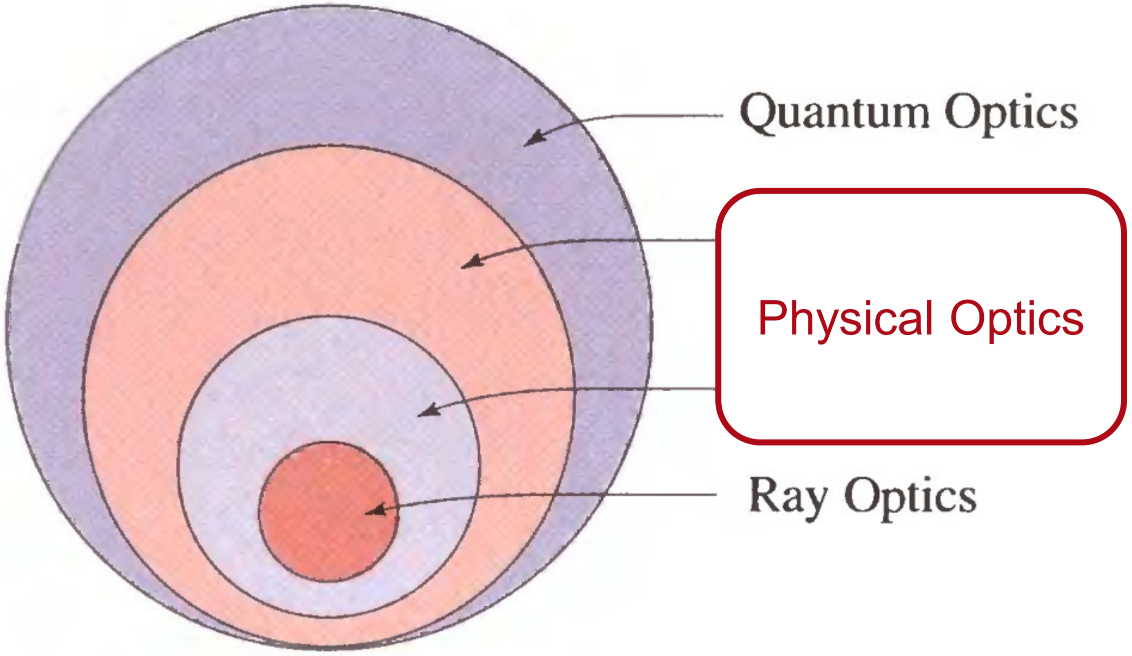

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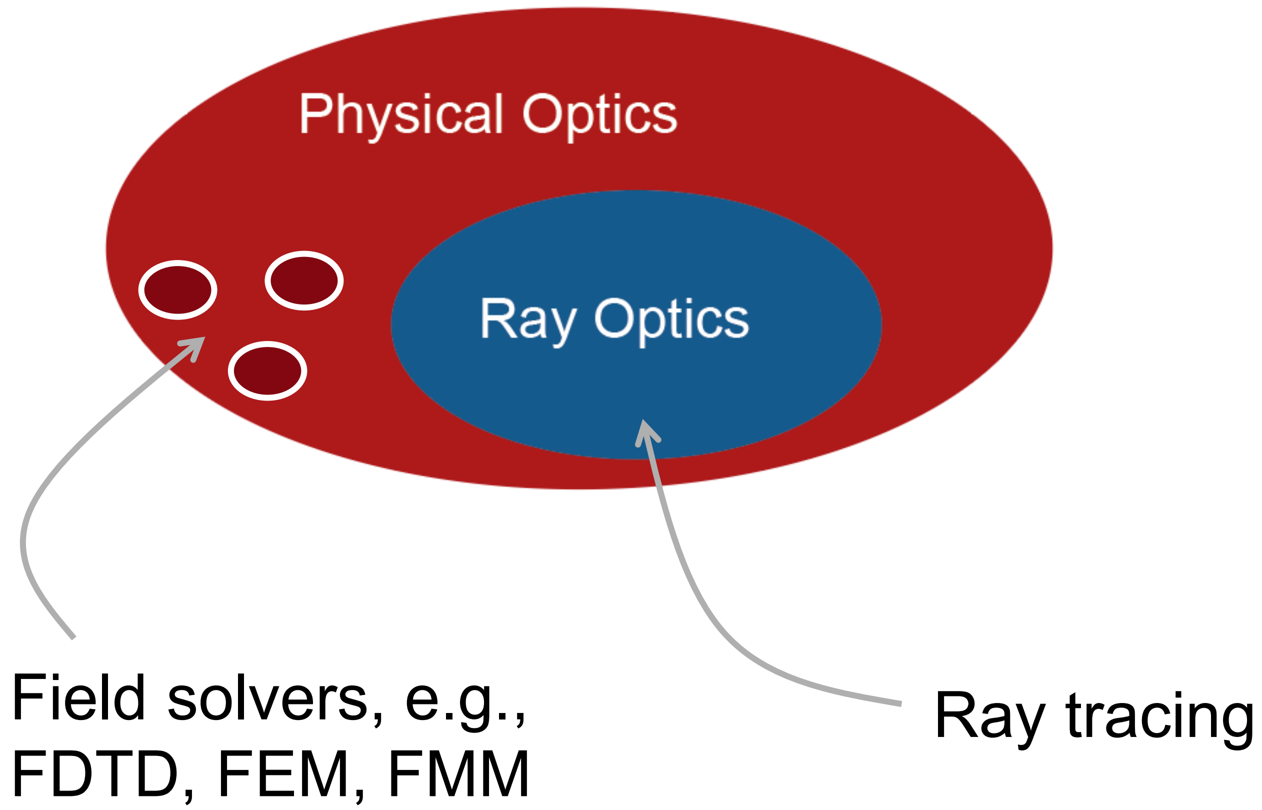
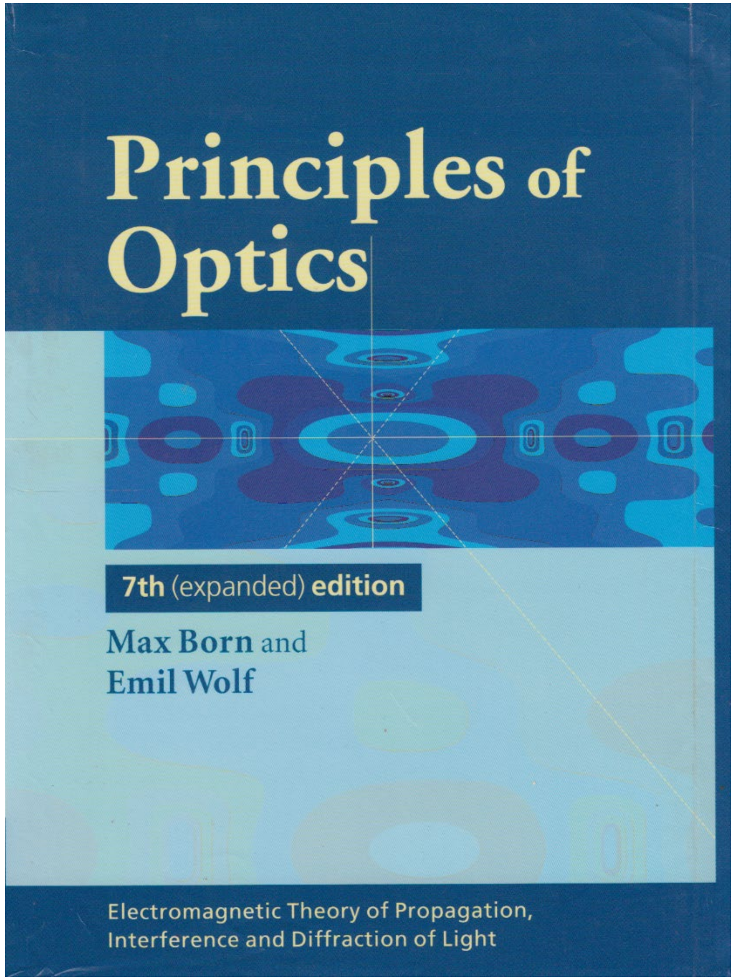
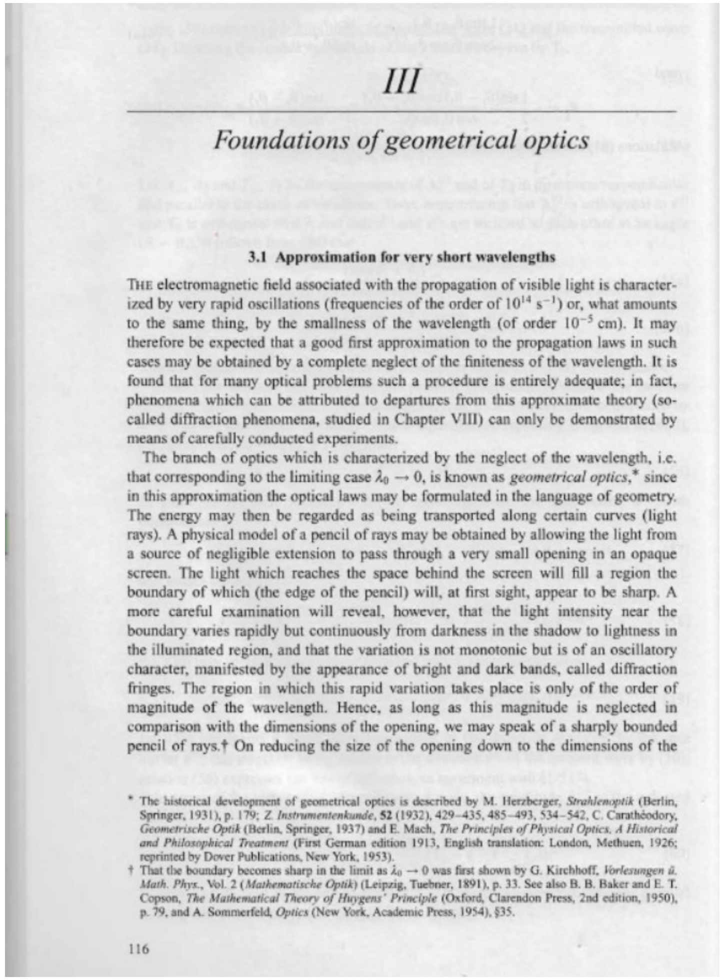


How to realize a seamless transition between ray and physical optics?

Geometric Branch of Physical Optics





III

Foundations of geometrical optics

3.1 Approximation for very short wavelengths

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

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

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

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

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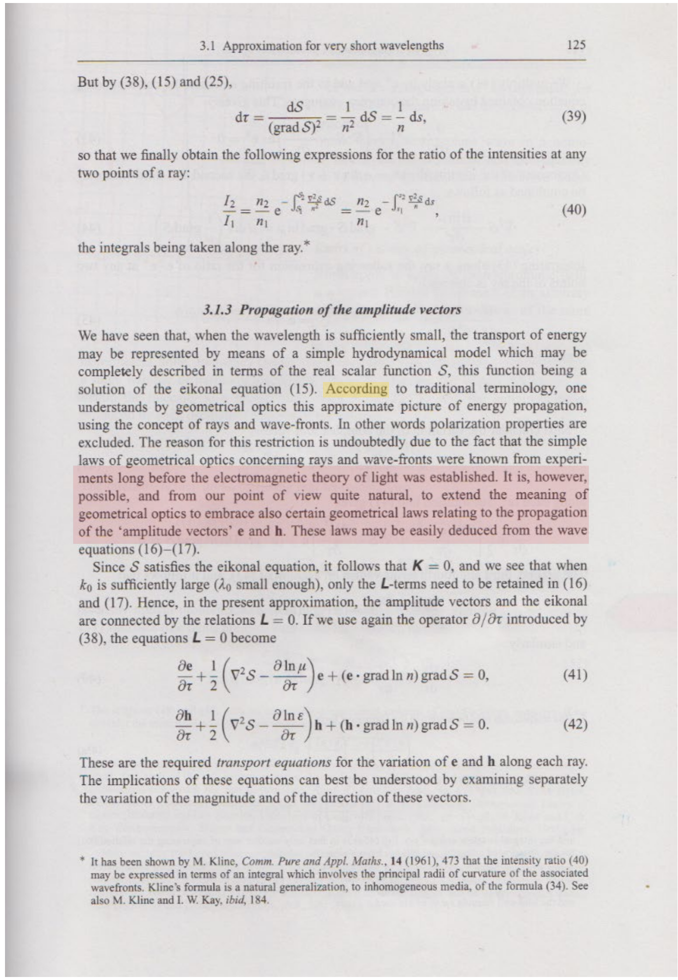
Geometric Branch of Physical Optics



3.1 Approximation for very short wavelengths 125

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

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

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

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

the integrals being taken along the ray.*

3.1.3 Propagation of the amplitude vectors

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

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

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

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

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

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

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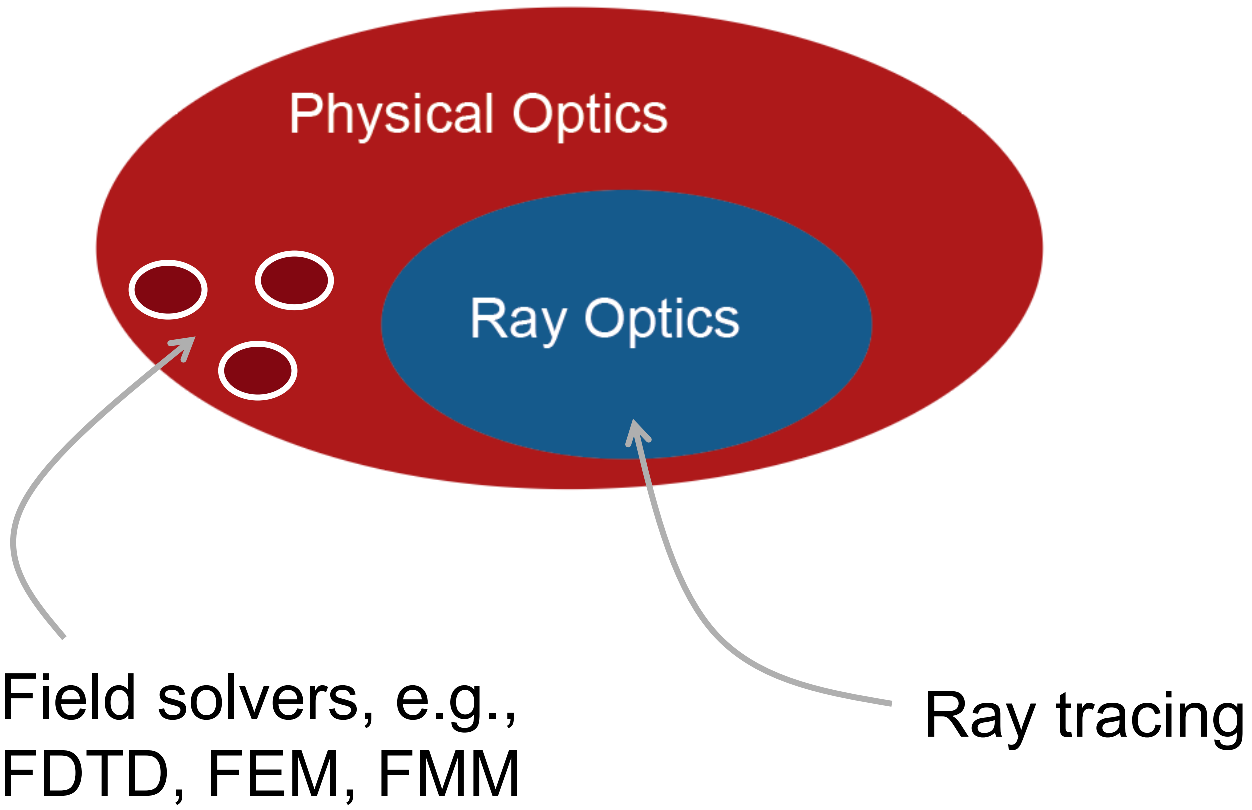
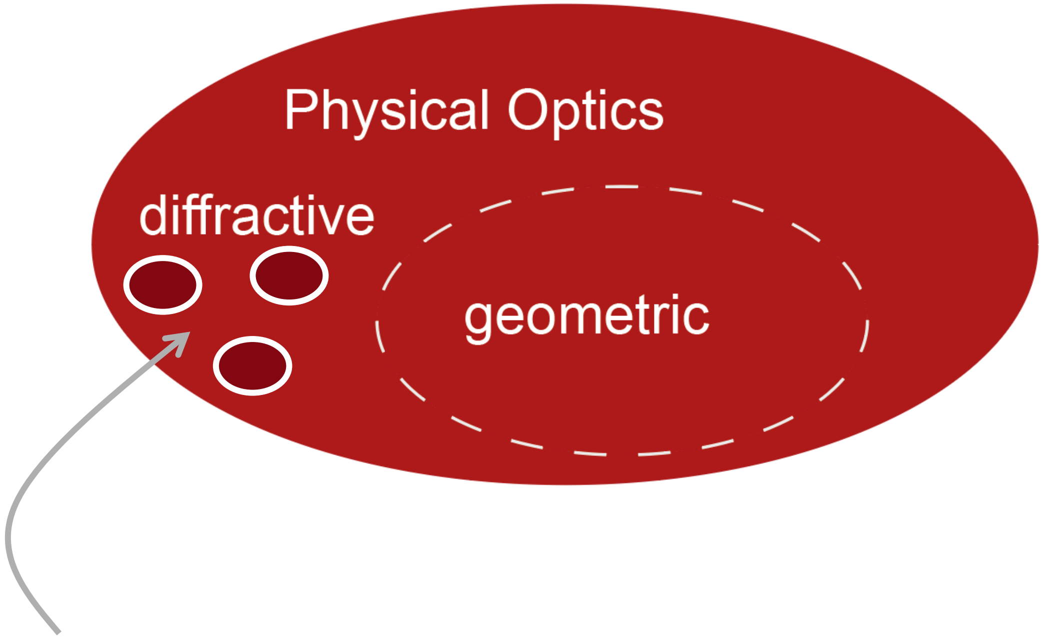


How to realize a seamless transition between ray and physical optics?

We follow Max Born's and Emil Wolf's point of view!

Diffractive and Geometric Branch of Physical Optics



Field solvers, e.g.,
FDTD, FEM, FMM

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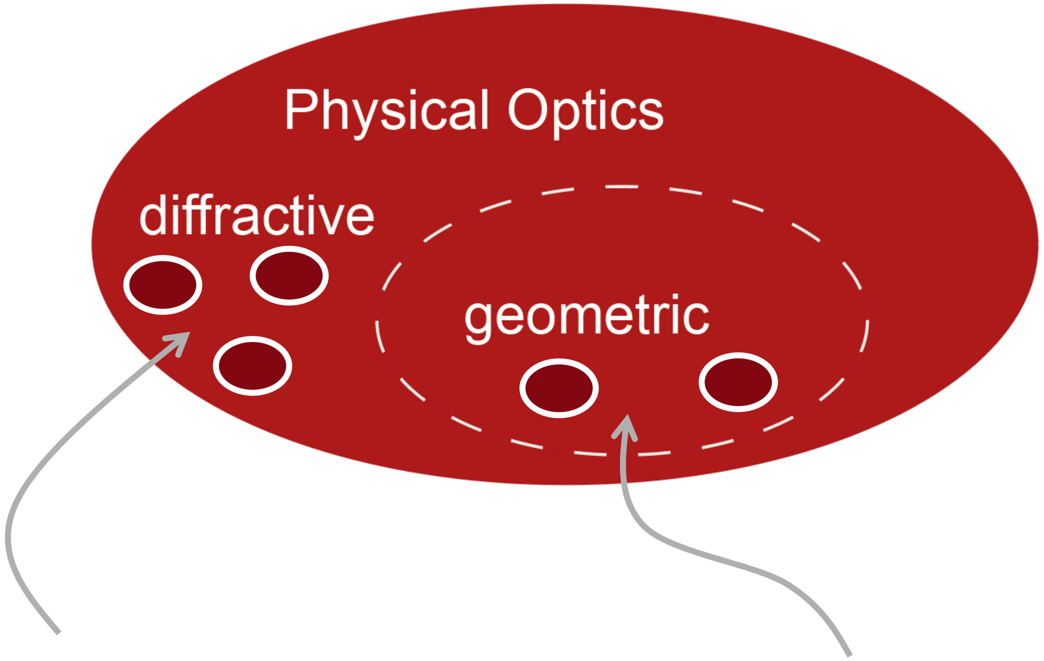
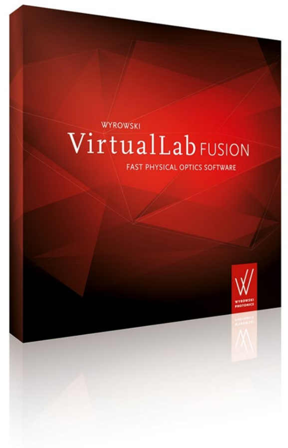


Field solvers, e.g.,
FDTD, FEM, FMM

Fast field solvers:
typically, at least as fast as ray tracing

Field Tracing:

- Connecting rigorous and approximated field solvers in different regions of the system.
- VirtualLab Fusion is a platform for in-built and customized solvers.



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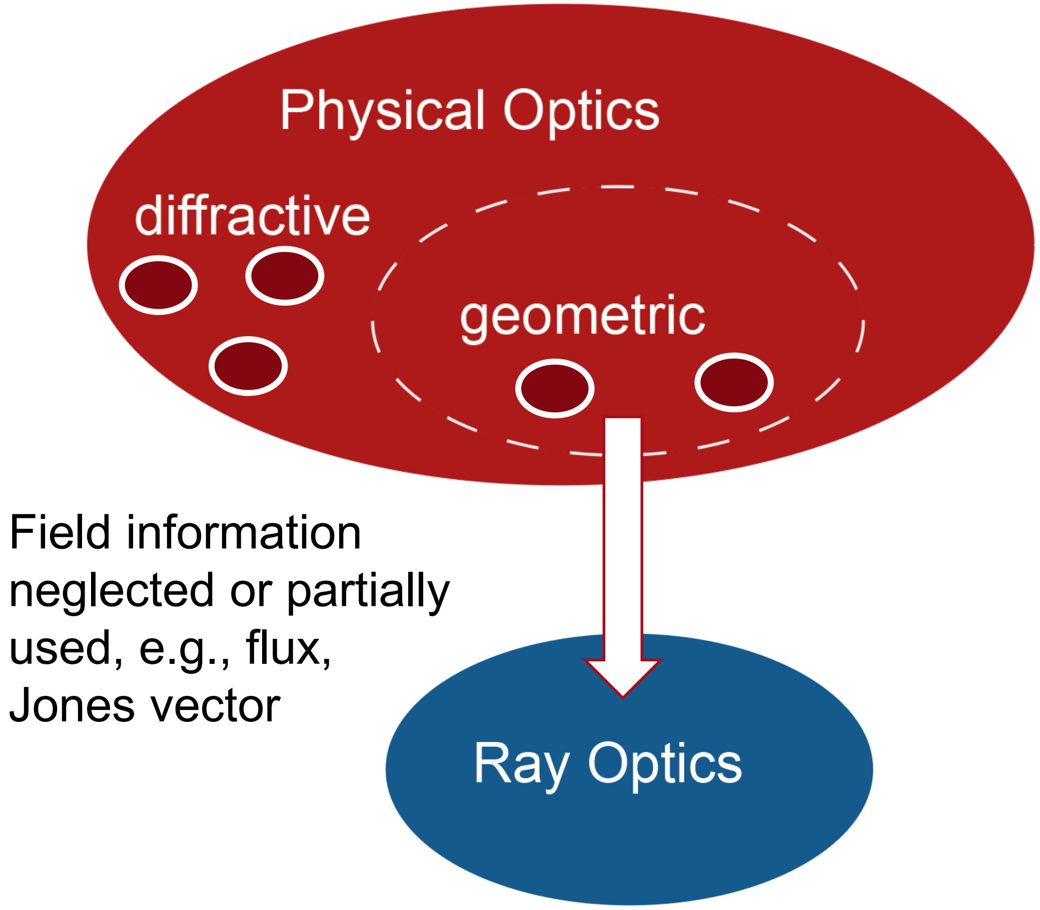

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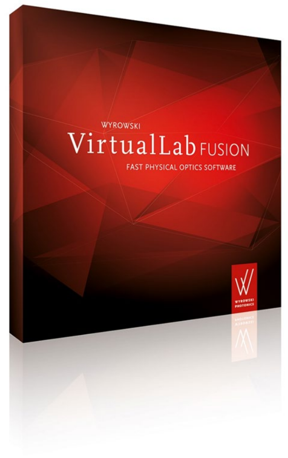
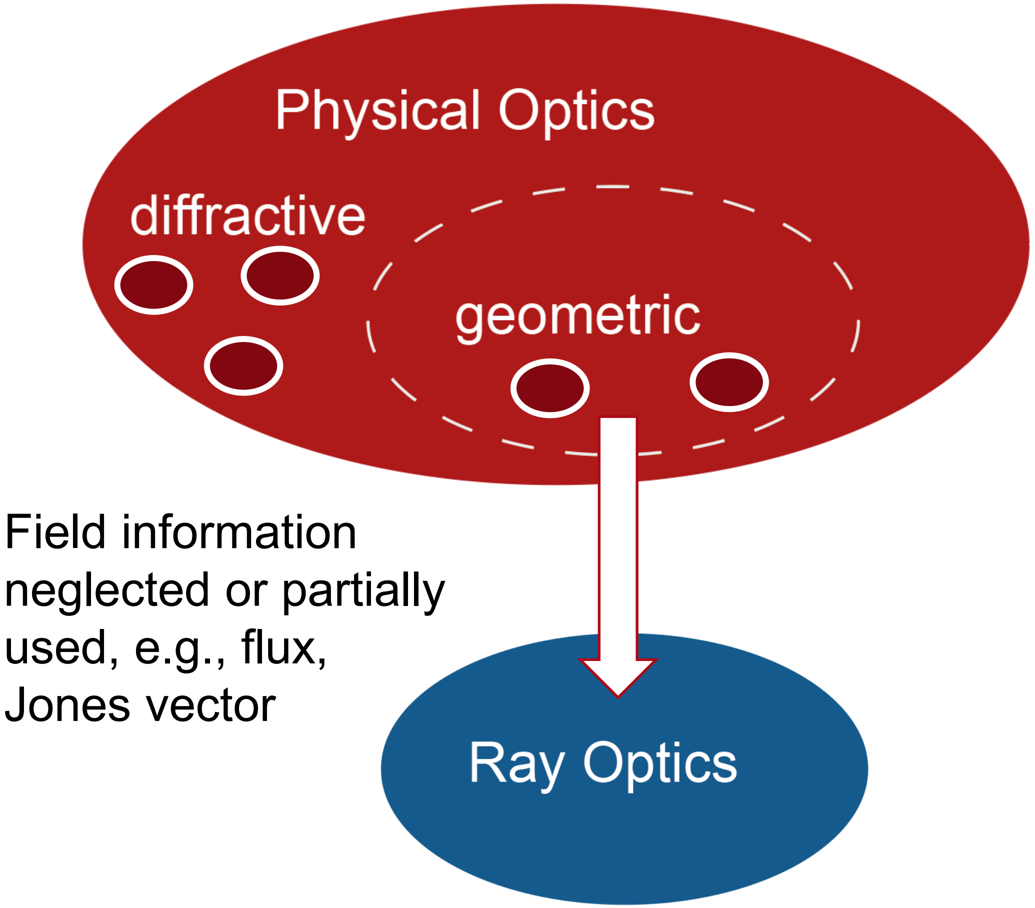
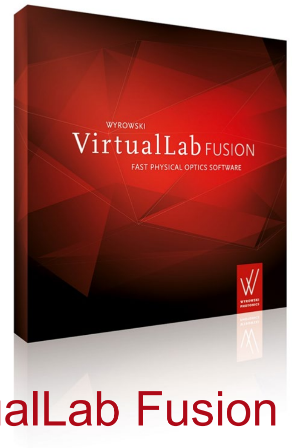


Diffractive and Geometric Branch of Physical Optics



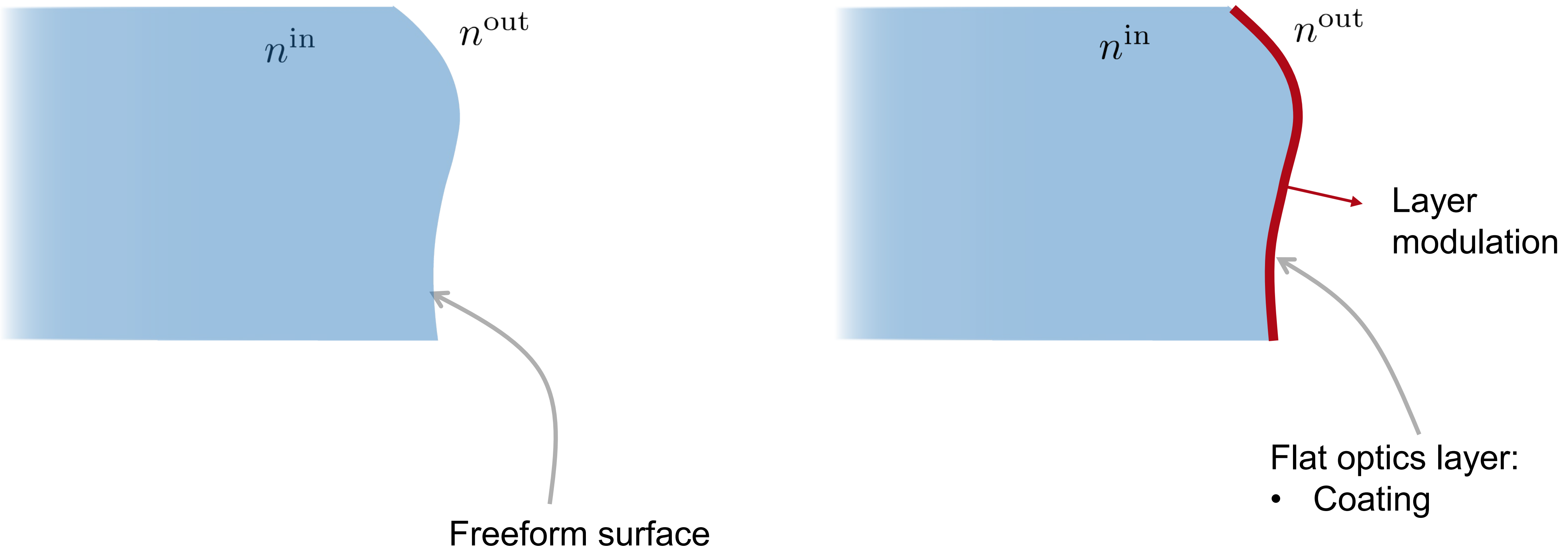
- All examples in webinar are done with the in-house version of VirtualLab Fusion!
- Typical speed of modeling and design tasks in talk: a few seconds to < 1 min
- Features already available or to be released in 2021.



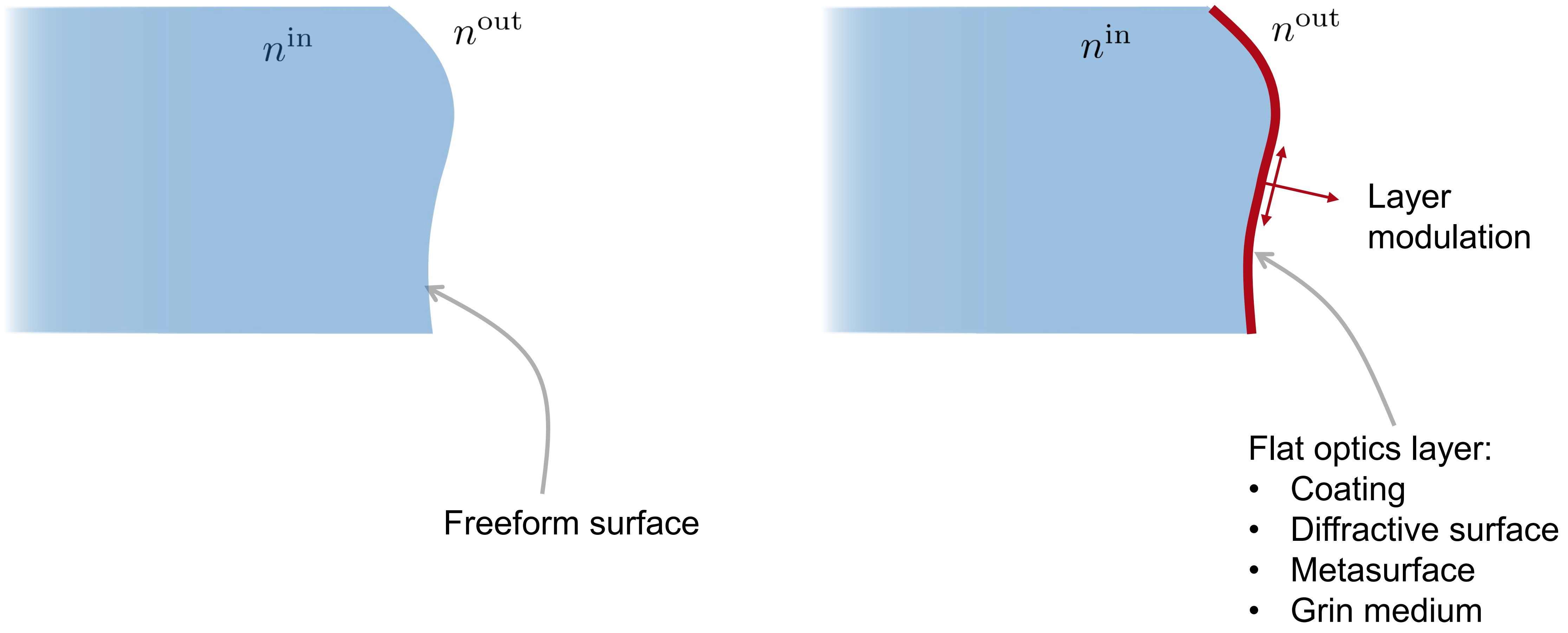
VirtualLab Fusion 2021

Freeform and Flat Optics: What? Why? How?

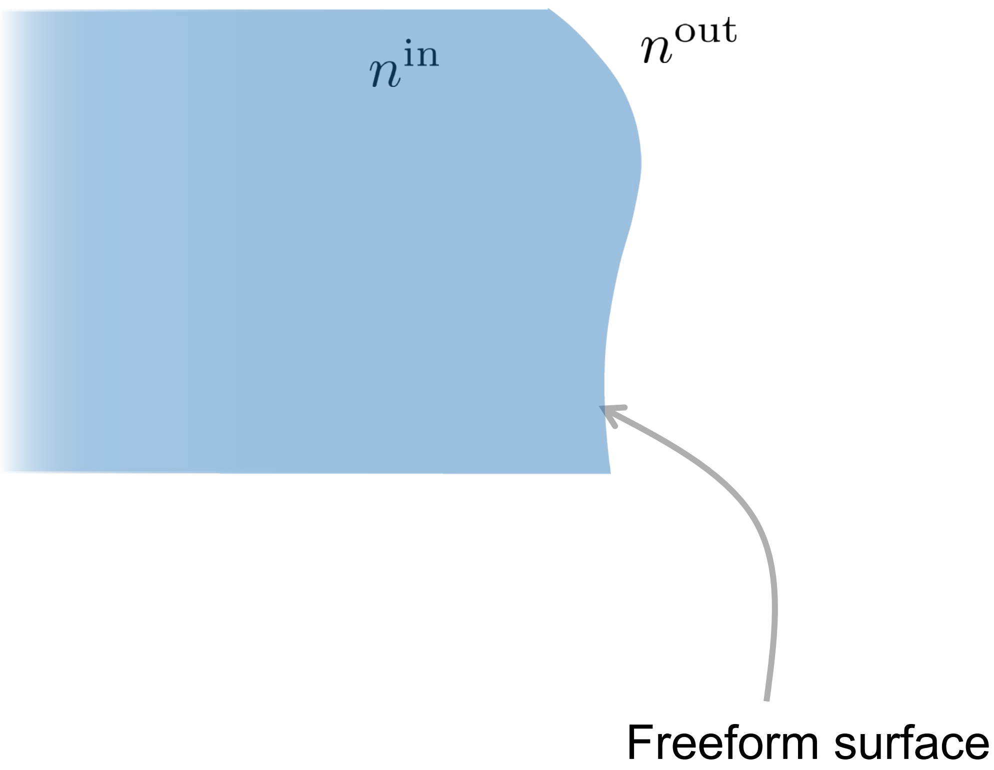
Freeform and Flat Optics

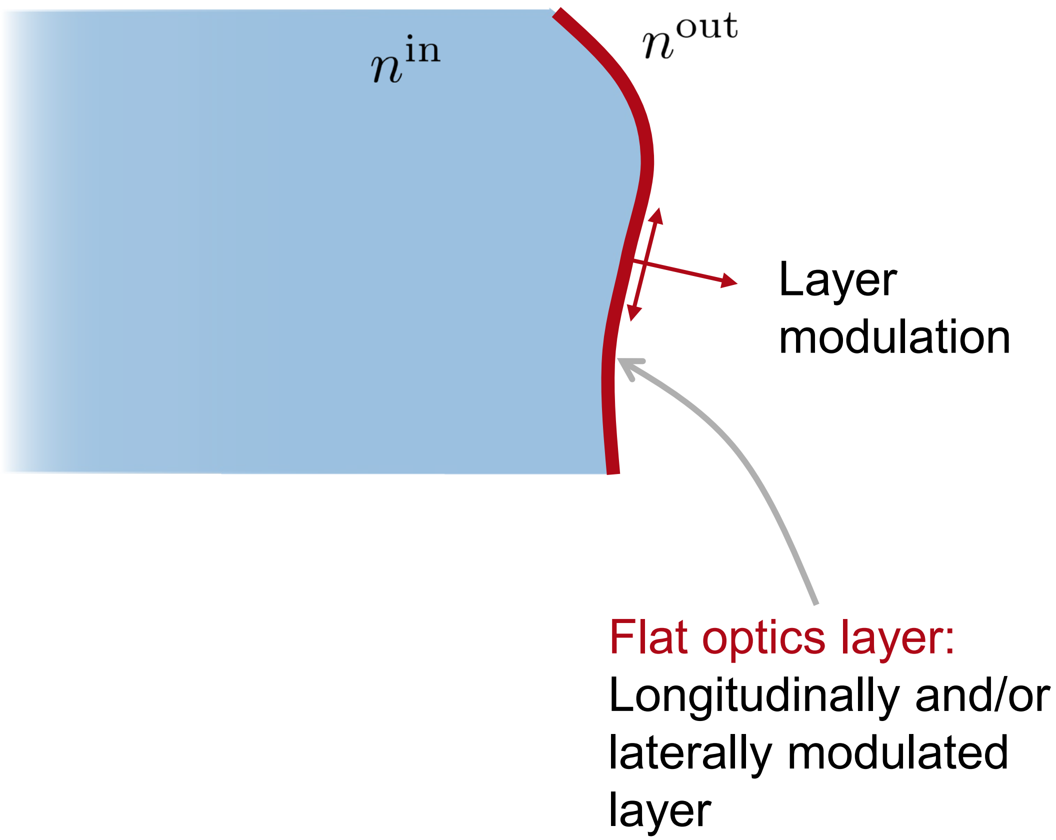


Freeform and Flat Optics

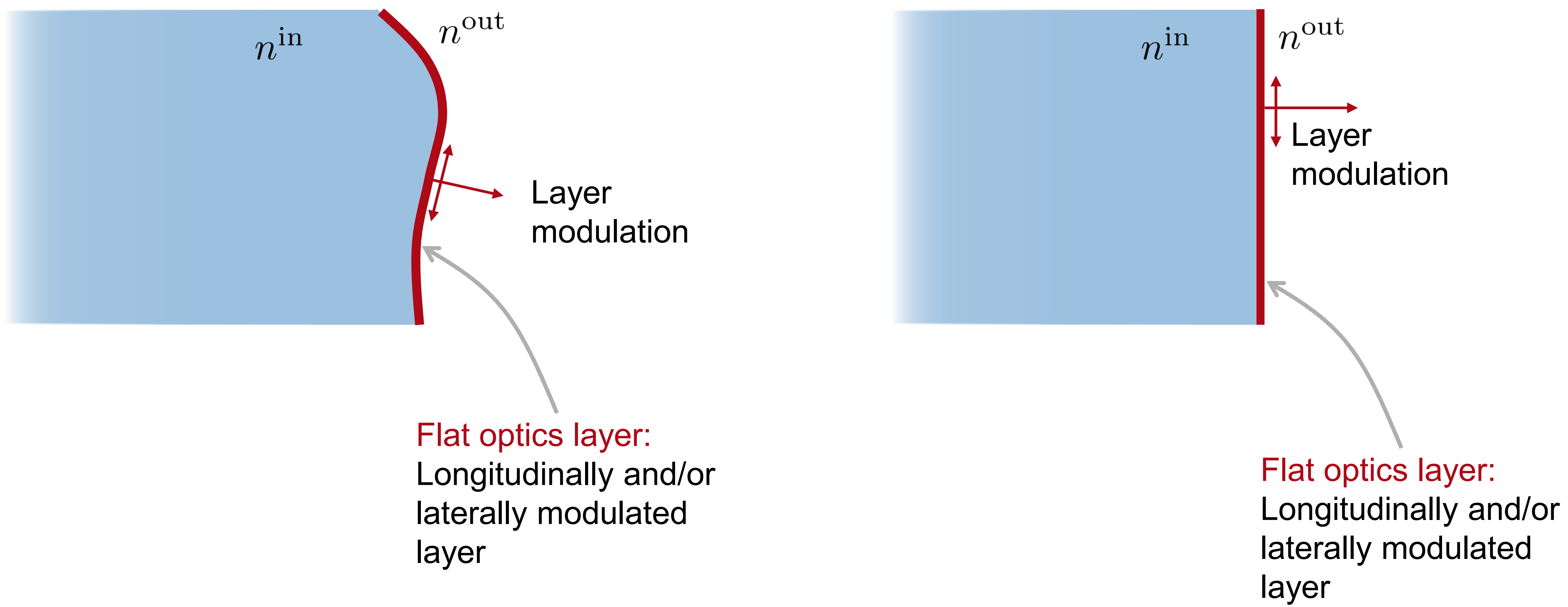


Freeform and Flat Optics

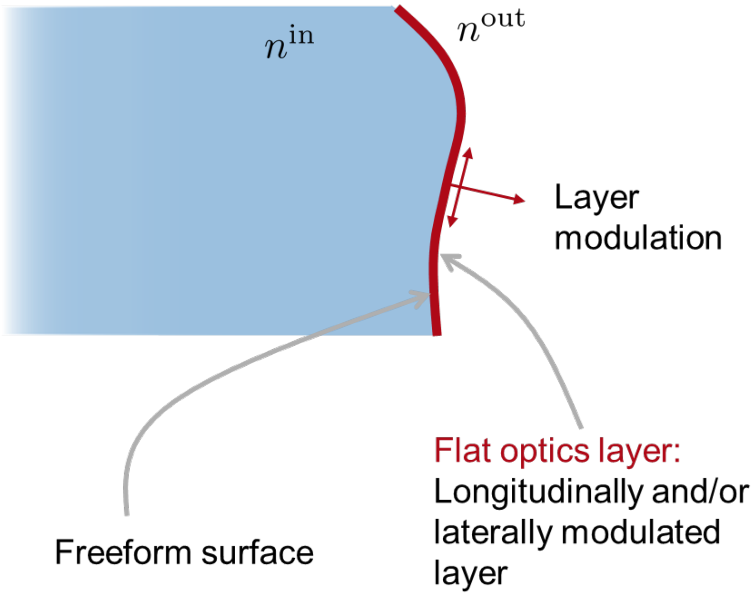


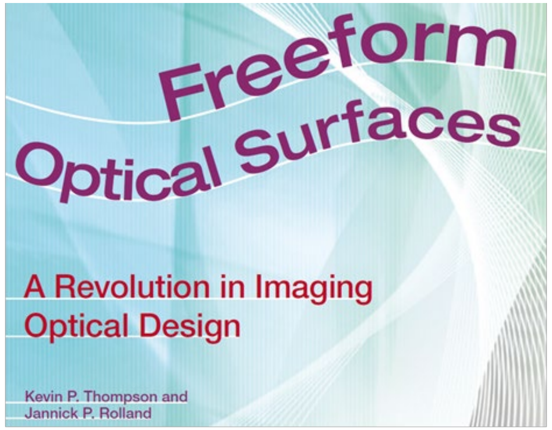


Flat Optics Fabrication: Planar Surfaces



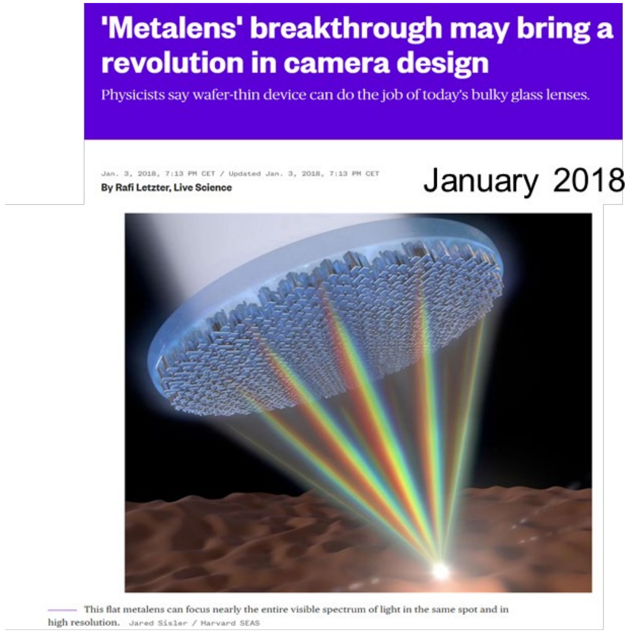
Freeform and Flat Optics: Why?





OPN Optics & Photonics News, June 2012

June 2012



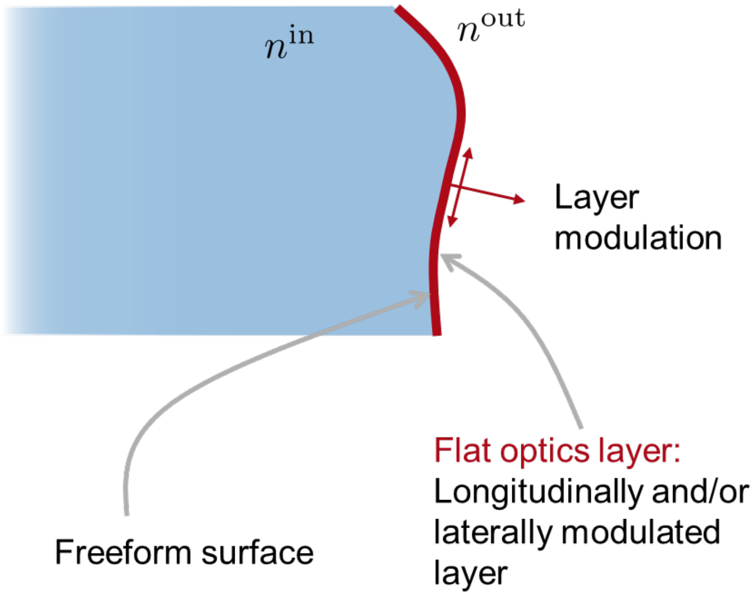
January 2018

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

Freeform and flat optics introduce new design freedoms!

Strongly dependent on available fabrication and further development.

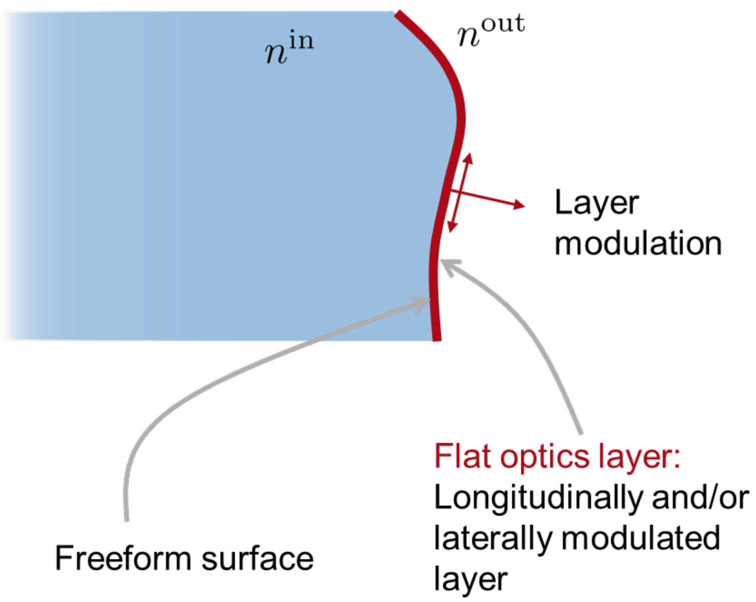
Freeform and Flat Optics: Why?



Freeform and flat optics introduce new design freedoms:

- Improve performance
- Reduce size and weight
- Less components
- Cost reduction
- Add new functionality, e.g., bifocal lenses, polarization dependency, …
- …

Freeform and Flat Optics: Why?



Freeform and flat optics introduce new design freedoms:

- Improve performance
- Reduce size and weight
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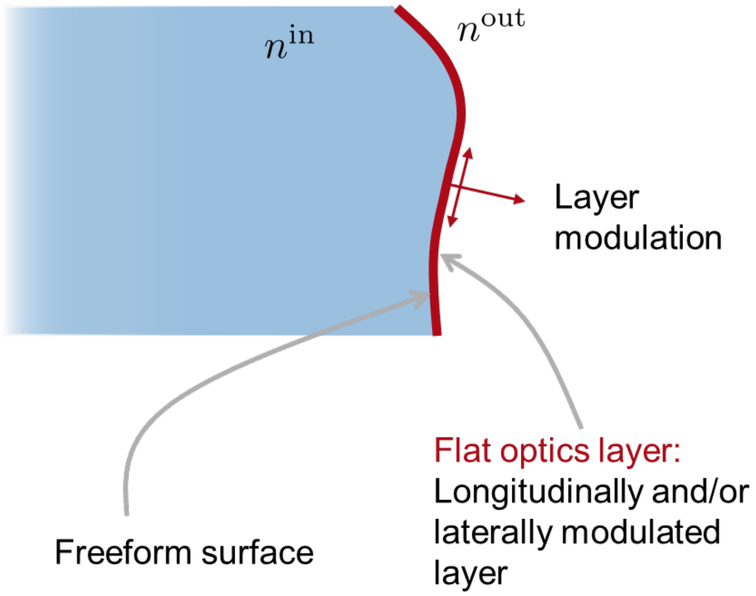
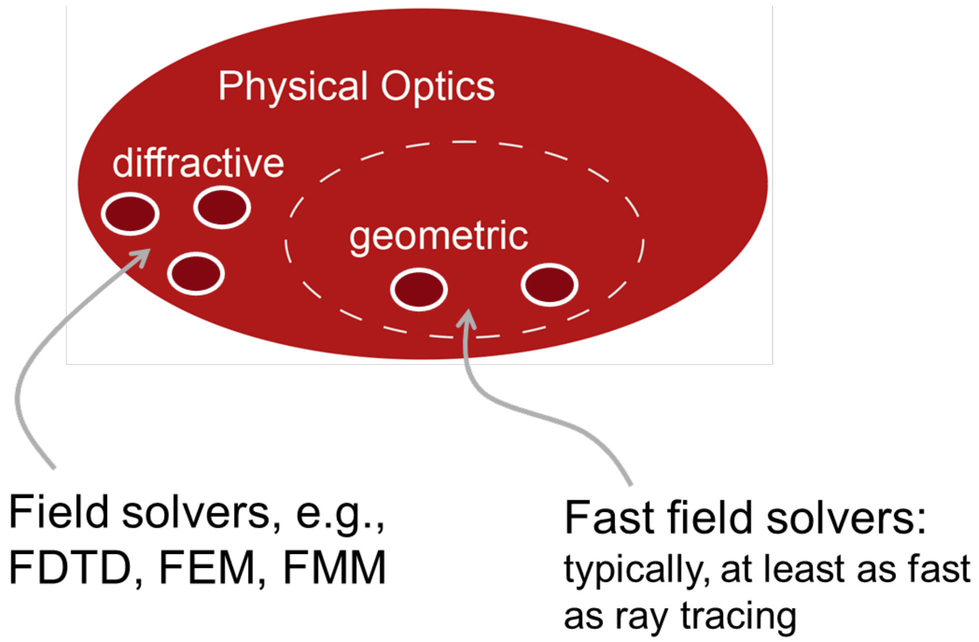
"Is it possible to replace a bulky glass system by one metalens" ?

… see end of webinar!

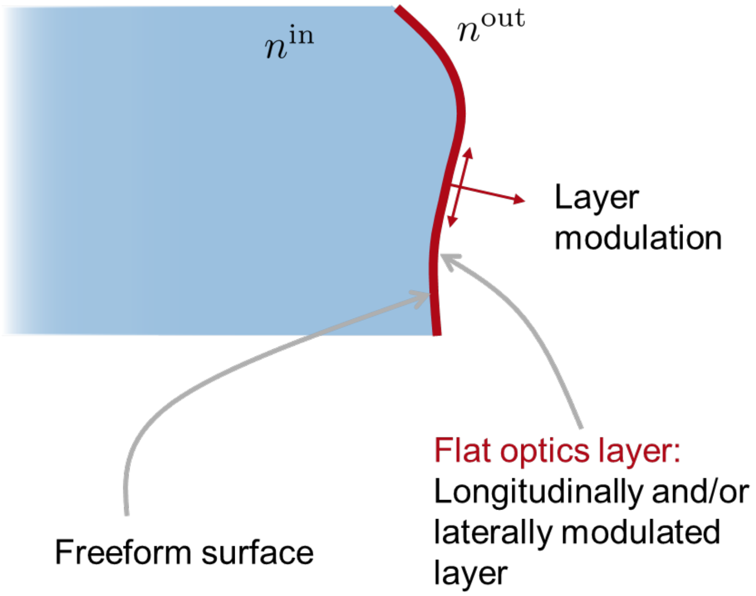
Freeform and Flat Optics: How?



- Flat optics requires physical optics modeling.



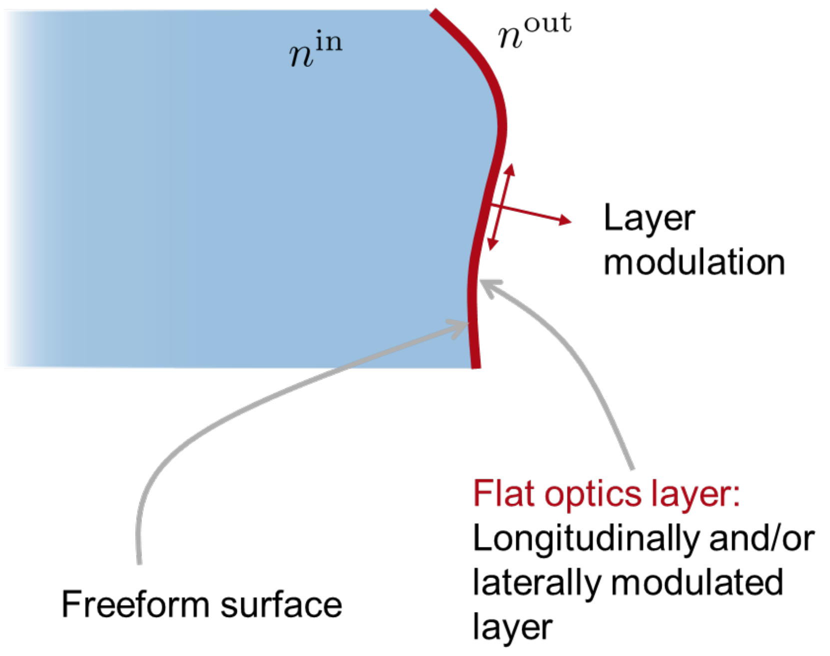
Freeform and Flat Optics: How?

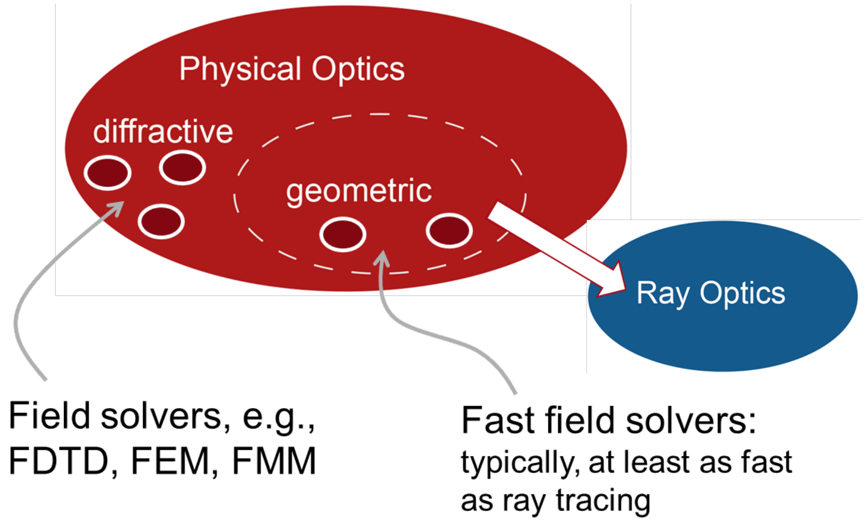


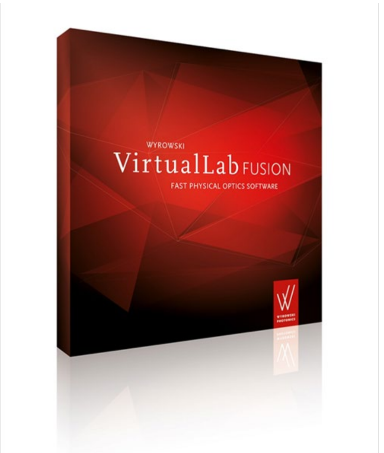
- Flat optics requires physical optics modeling.
- Typically, the large number of freeform and layer parameters is challenging for conventional parametric optimization.

Physical optics may give a fresh view and new ideas to optical design beyond conventional routines.

Freeform and Flat Optics: How?







VirtualLab Fusion 2021

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

Optical Design Scenarios

… formulated by physical optics

Light Representation in Physical Optics

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

$$\boldsymbol{E}(\boldsymbol{r},\omega) = \begin{pmatrix} E_x(\boldsymbol{r},\omega) \\ E_y(\boldsymbol{r},\omega) \\ E_z(\boldsymbol{r},\omega) \end{pmatrix} . \qquad \lambda = \frac{2\pi}{\omega}\, n$$

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

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

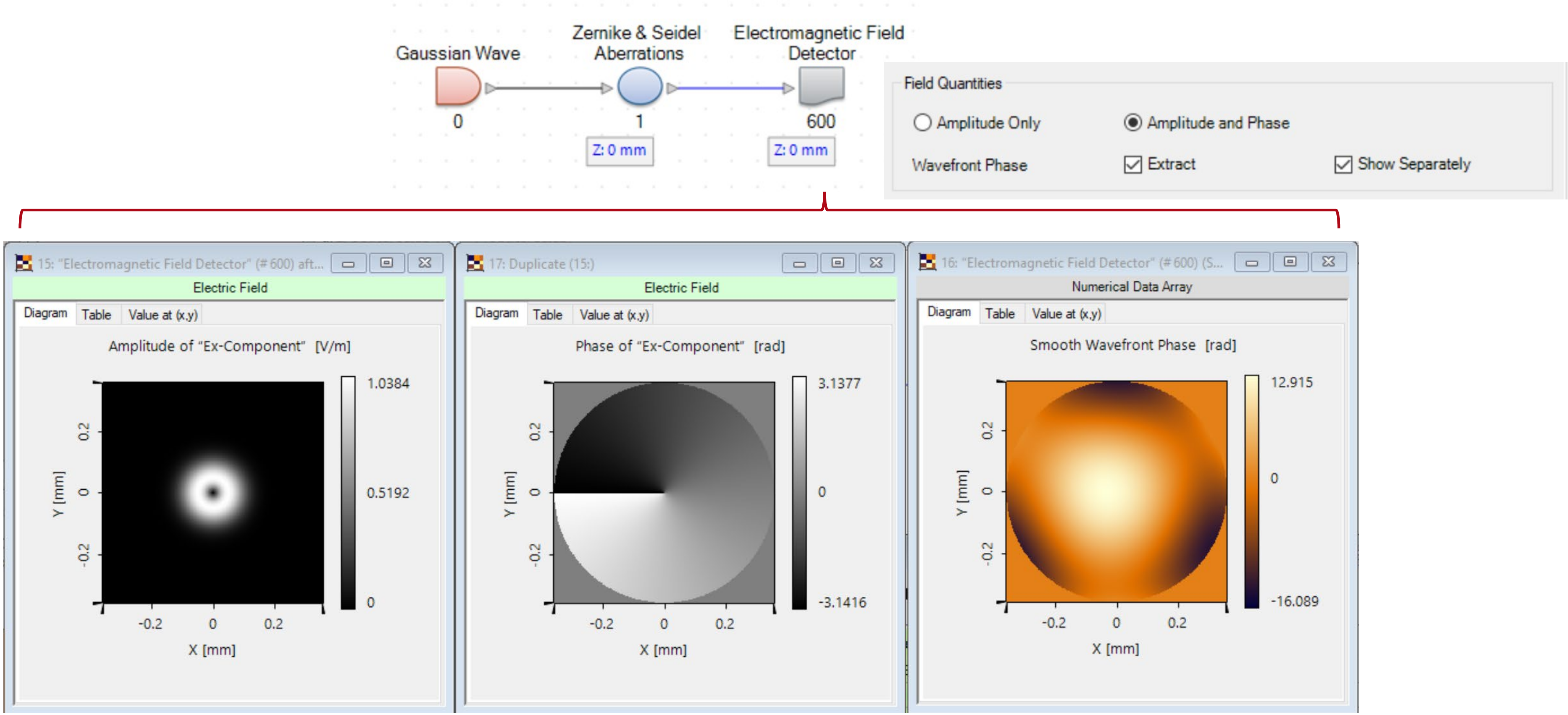
with ($\ell = x, y, z$)

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

1831 – 1879

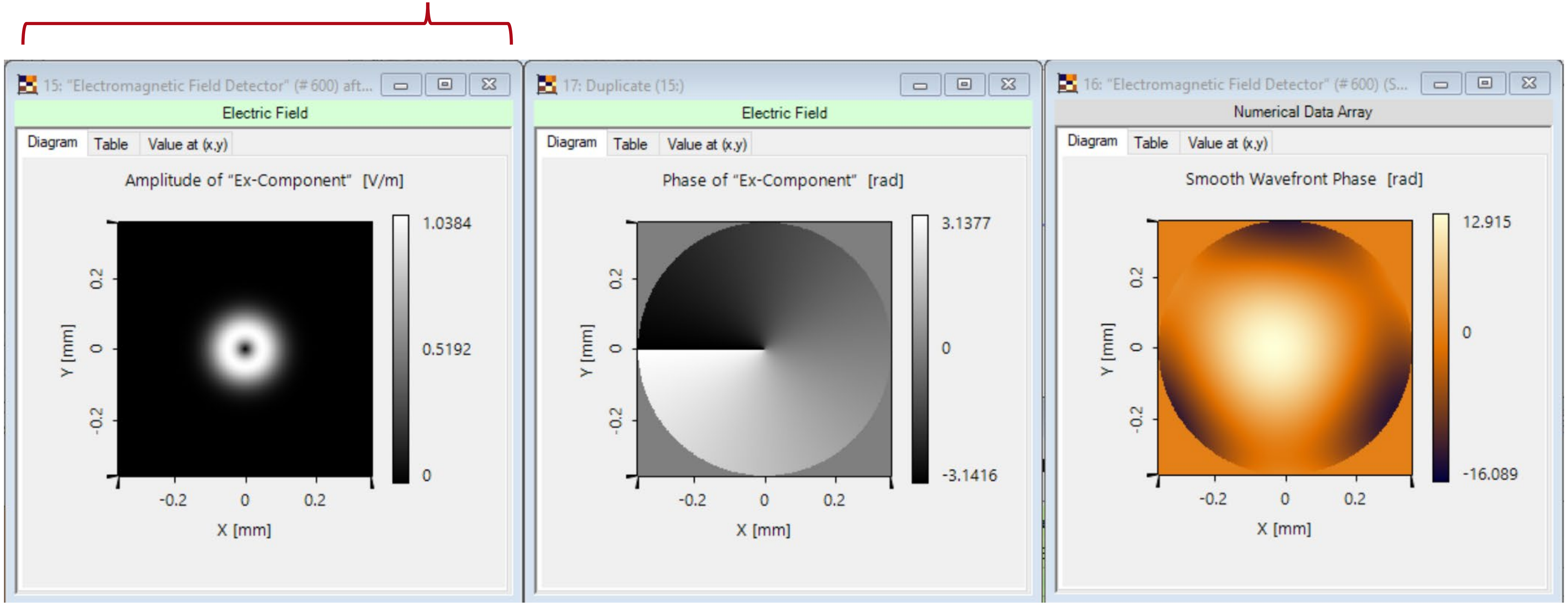
$$\nabla \times \boldsymbol{E}(\boldsymbol{r},\omega) = \mathrm{i}\omega\mu_0 \boldsymbol{H}(\boldsymbol{r},\omega)$$
$$\nabla \times \boldsymbol{H}(\boldsymbol{r},\omega) = -\mathrm{i}\omega\epsilon_0\check{\epsilon}_\mathrm{r}(\boldsymbol{r},\omega)\boldsymbol{E}(\boldsymbol{r},\omega)$$
$$\nabla \cdot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

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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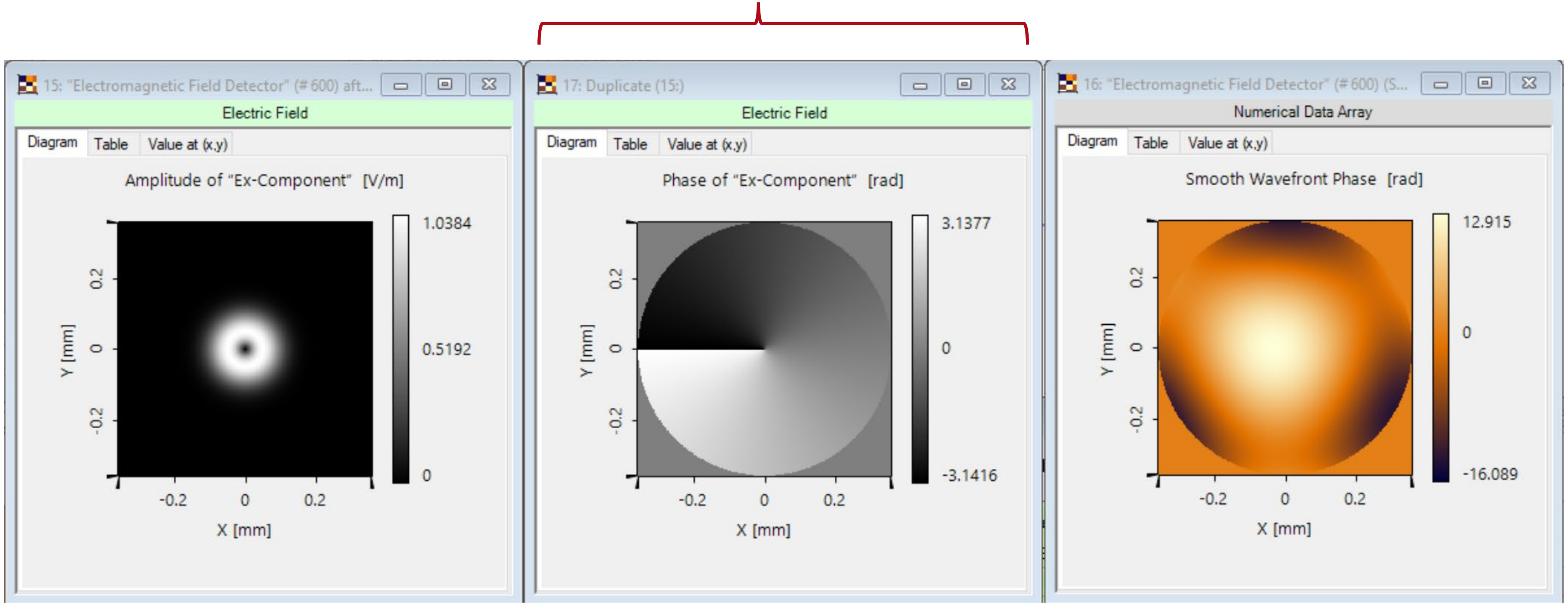

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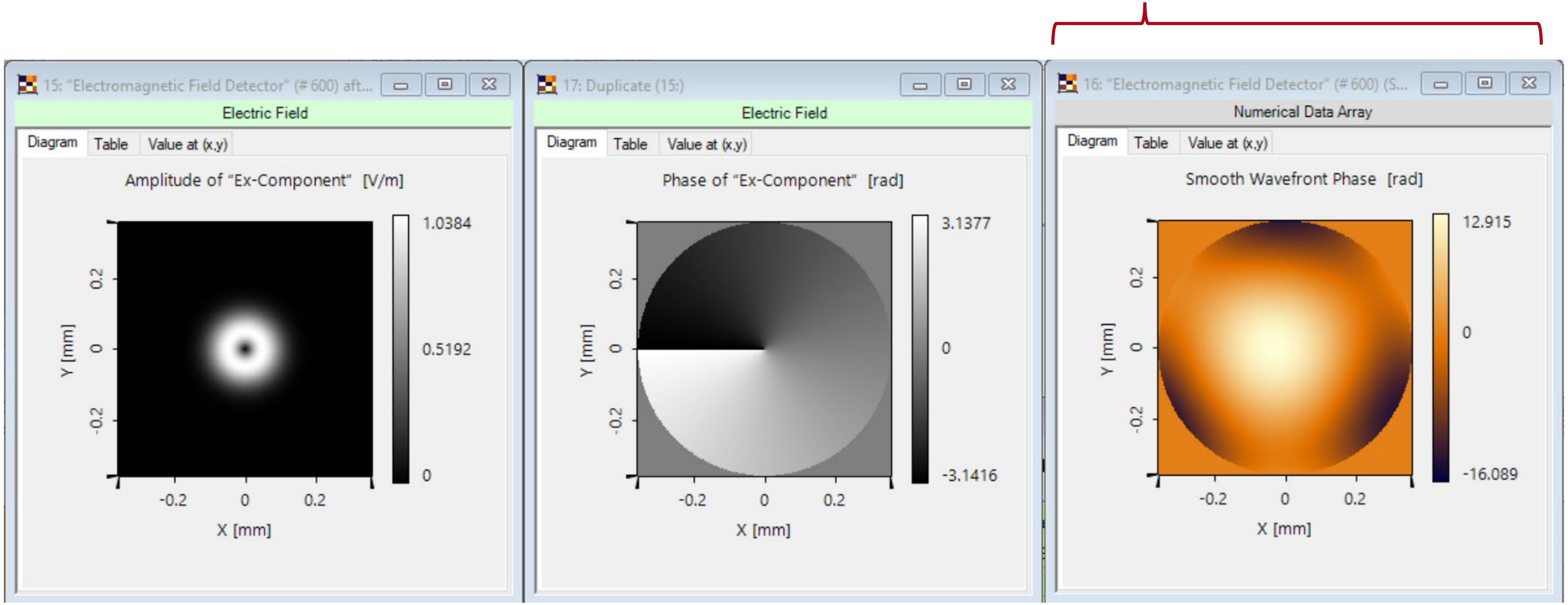
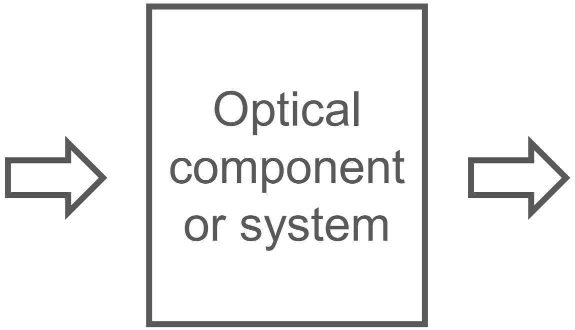


Design Scenarios: Field Transformation

Input fields (index α)

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

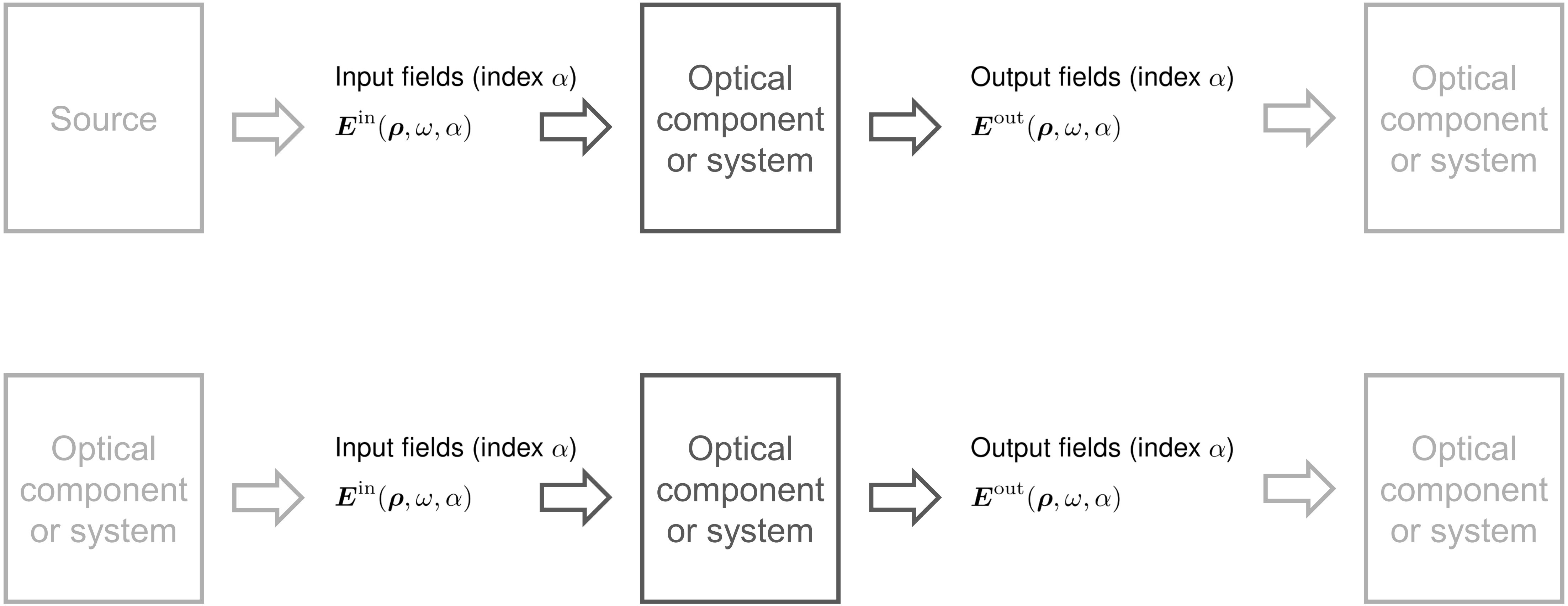
with $\boldsymbol{\rho} = (x,y)$



Output fields (index α)

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

Design Scenarios: Field Transformation



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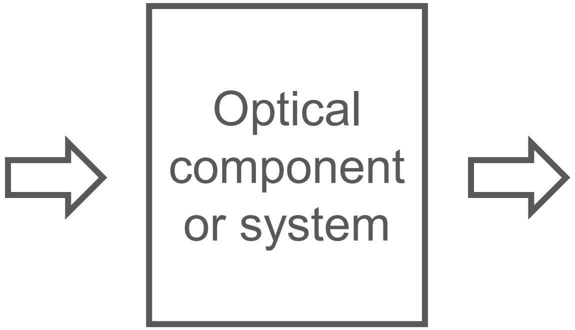


Output fields (index α)

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

Scenarios:

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

Multi-field design Set of N_α input and output fields ($\alpha = 0, \ldots, N_\alpha - 1$)

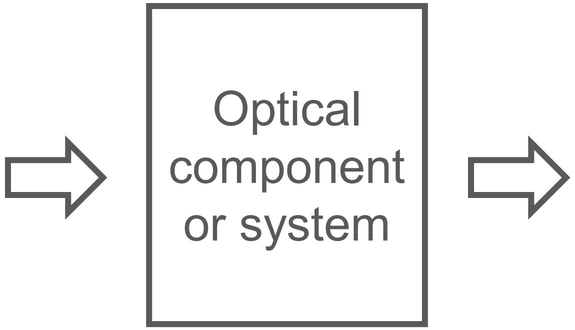
Monochromatic or polychromatic design

Design Scenarios: Imaging

Input fields (index α)

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

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



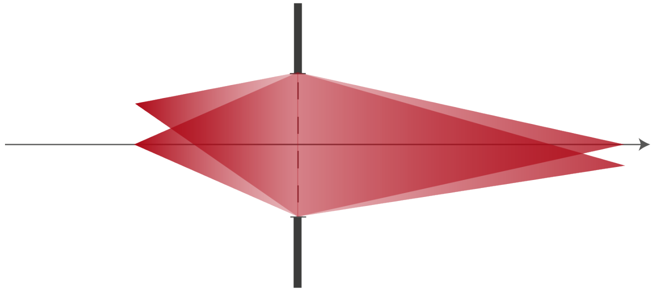
Output fields (index α)

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

Input fields with spherical wavefront phase

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

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



Fields with spherical wavefront phase

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

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

Scenarios:

Multi-field design: FOV Set of N_α input and output fields ($\alpha=0,\ldots,N_\alpha-1$)

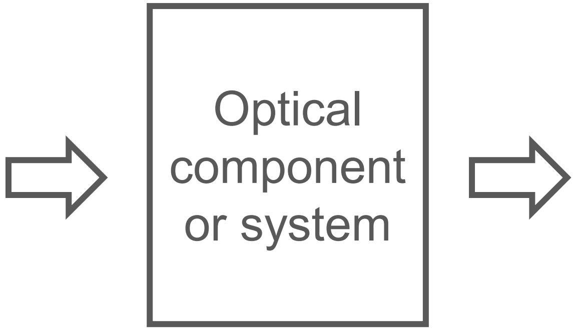
Monochromatic or polychromatic design

Design Scenarios: Light Shaping

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)

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

Specification of energy quantity like

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

Scenarios:

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

Multi-field design Set of N_α input and output fields ($\alpha = 0, \ldots, N_\alpha - 1$)

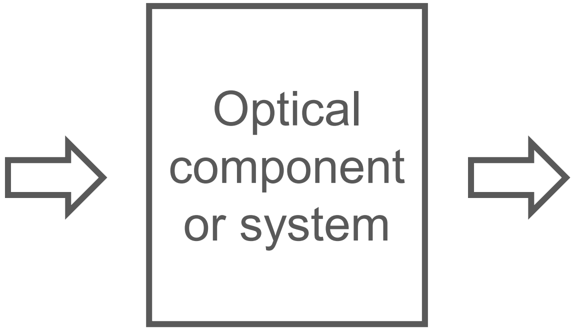
Monochromatic or polychromatic design

Manipulation and Control of Input Fields

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)

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

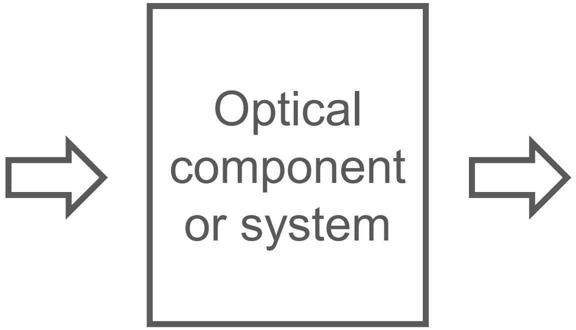
How to achieve the specified
transformations with sufficient accuracy?

Manipulation and Control of Input Fields

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)

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

Major manipulations of fields on their way through system:

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

Proposed Design Workflow

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.

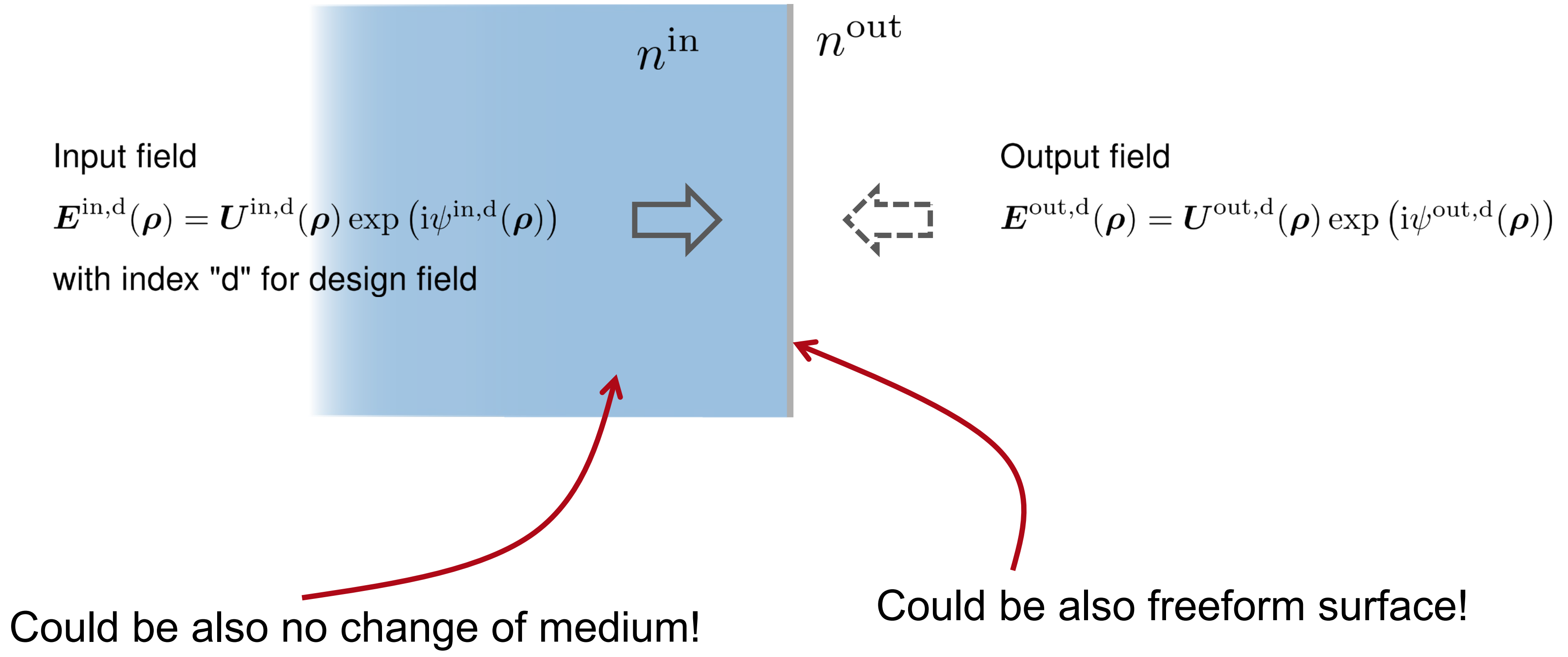
FABRICATION DATA

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

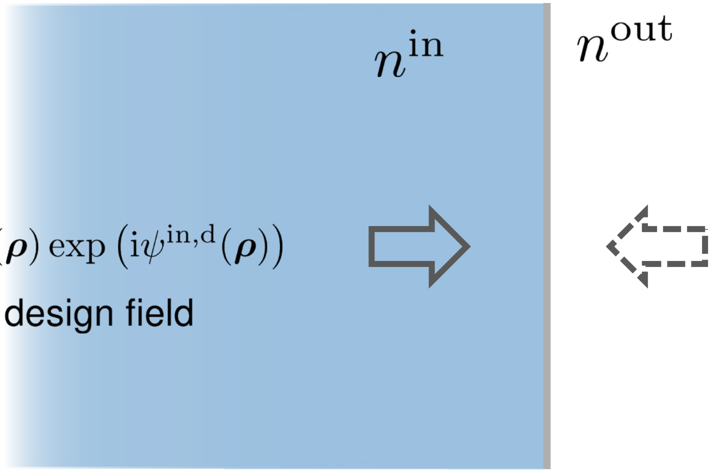
Functional Design

Single Field Scenario

Functional Design



Functional Design



Input field

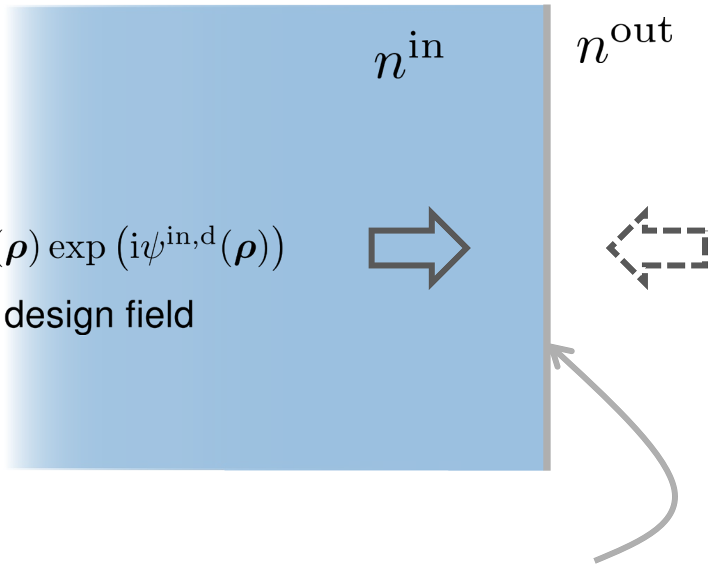
$\boldsymbol{E}^{\mathrm{in,d}}(\boldsymbol{\rho}) = \boldsymbol{U}^{\mathrm{in,d}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathrm{in,d}}(\boldsymbol{\rho})\right)$

with index "d" for design field

Output field

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

Functional Design



Input field

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

with index "d" for design field

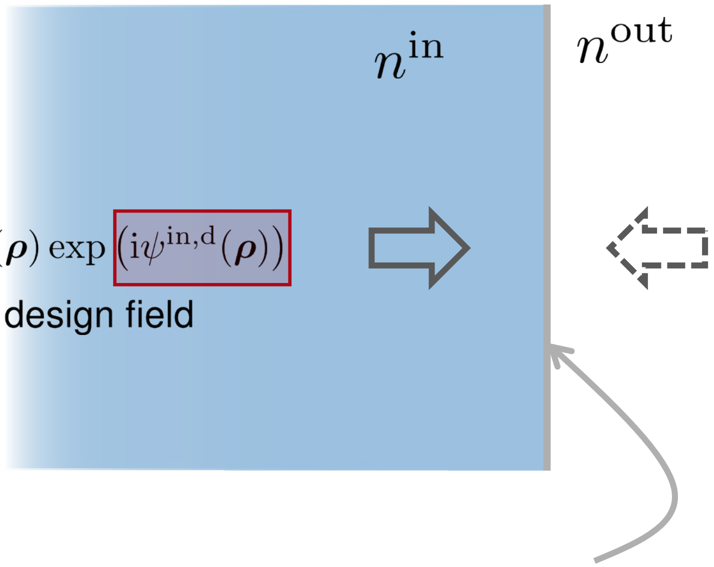
Output field

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

Wavefront phase response:

$$\Delta\psi^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{out,d}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$$

Wavefront Response Component (WRC)



Input field

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

with index "d" for design field

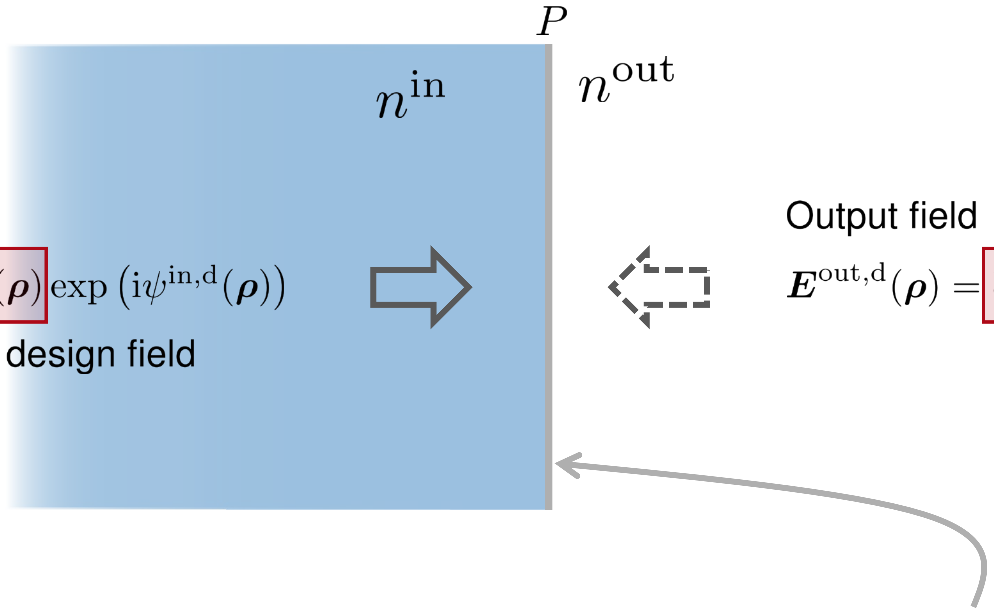
Output field

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

Wavefront phase response:

$$\Delta\psi^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{out,d}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$$

Domain and Irradiance Matching



Input field

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

with index "d" for design field

Output field

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

Domain and irradiance matching:

The domains $X(U^{\text{in}})$ and $X(U^{\text{out}})$ should match as good as possible on the plane P.

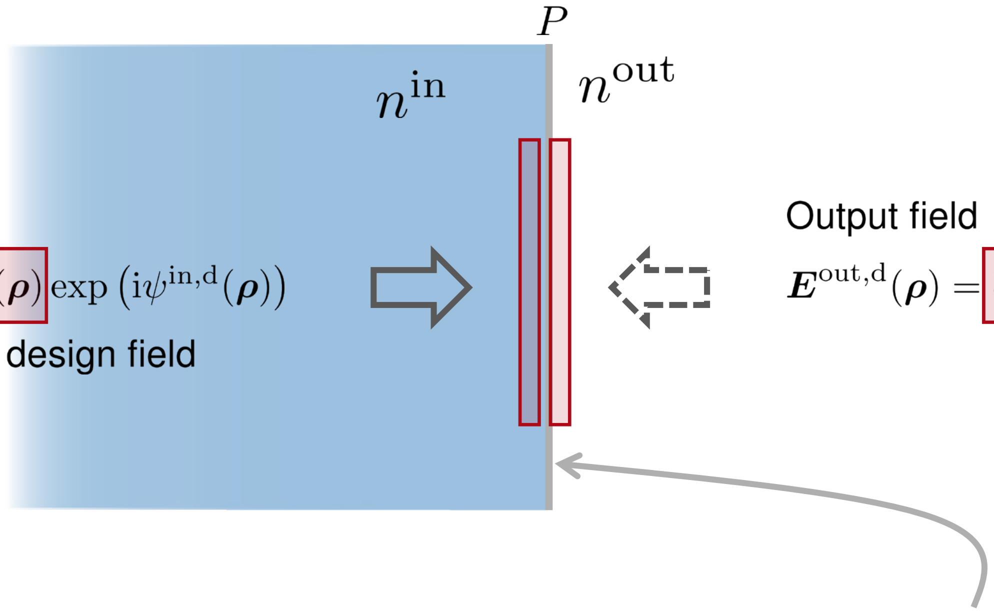
The irradiances E_{e}^{in} and $E_{\text{e}}^{\text{out}}$ should match as good as possible on the plane P.

Domain and Irradiance Matching

Input field

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

with index "d" for design field



Output field

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

Domain and irradiance matching:

The domains $X(U^{\mathrm{in}})$ and $X(U^{\mathrm{out}})$ should match as good as possible on the plane P.

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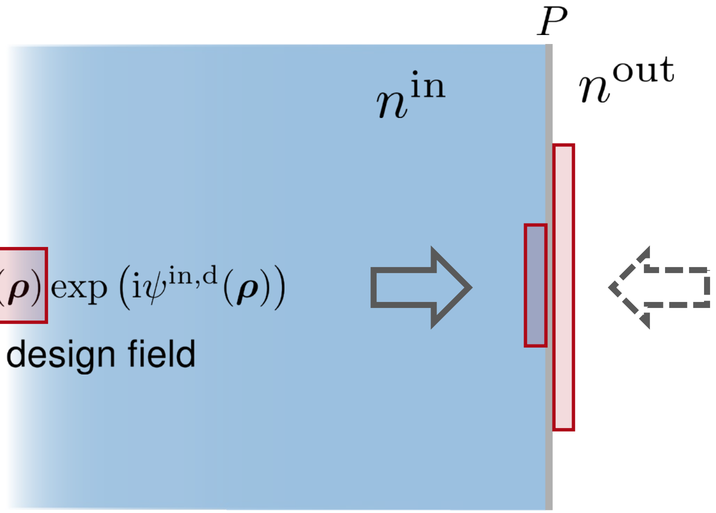
Domain and Irradiance Matching



Input field

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

with index "d" for design field

Output field

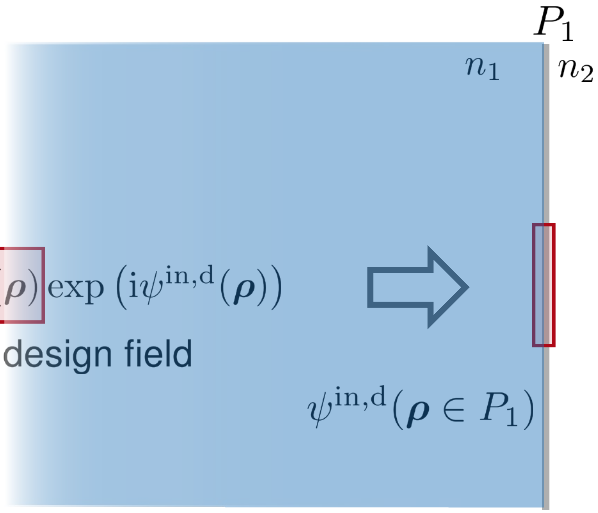
$$\boldsymbol{E}^{\mathrm{out,d}}(\boldsymbol{\rho}) = \boldsymbol{U}^{\mathrm{out,d}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathrm{out,d}}(\boldsymbol{\rho})\right)$$

Domain and Irradiance Matching: Two Components (WRC)

Input field

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

with index "d" for design field



Output field

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

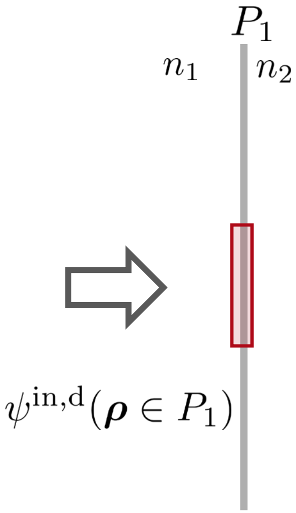
$\psi^{\mathrm{out,d}}(\boldsymbol{\rho} \in P)$

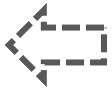
Domain and Irradiance Matching: Two Components (WRC)

Input field

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

with index "d" for design field





Output field

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

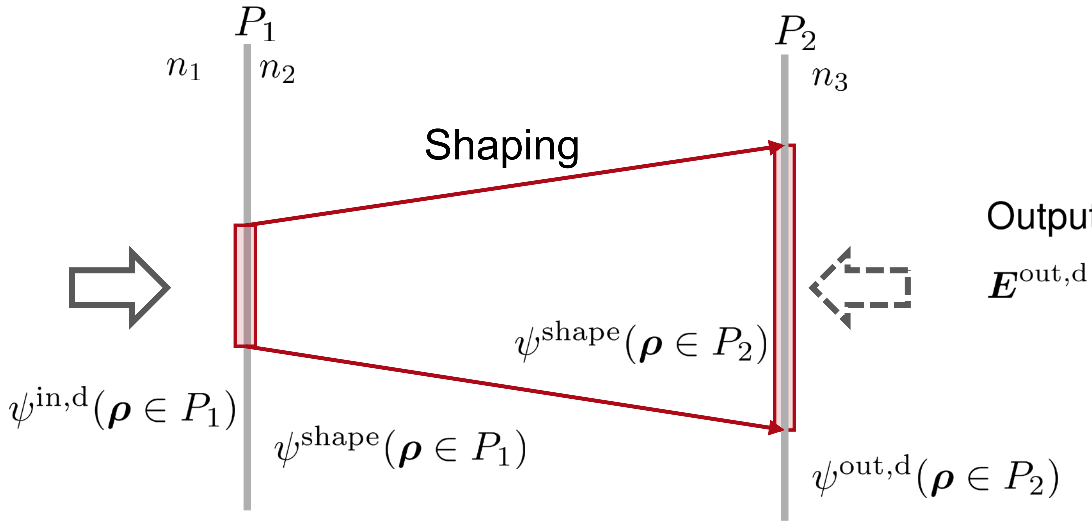
$\psi^{\mathrm{out,d}}(\boldsymbol{\rho} \in P)$

Domain and Irradiance Matching: Two Components (WRC)

Input field

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

with index "d" for design field



Output field

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Domain and Irradiance Matching: Two Components (WRC)

Input field

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

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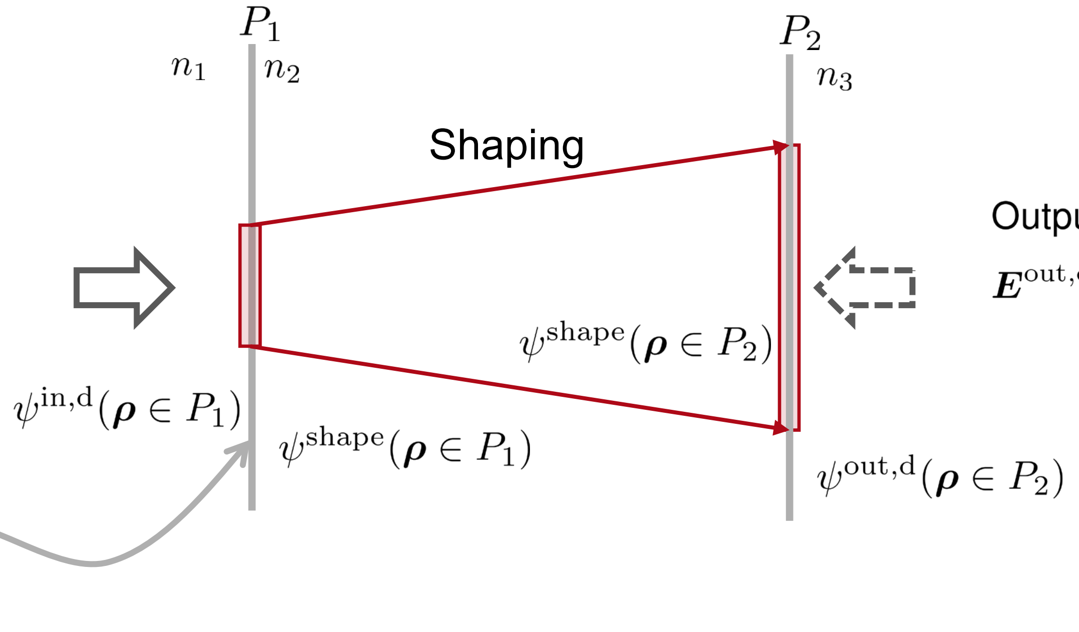


Output field

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

Wavefront phase response:

$$\Delta\psi_1^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{shape}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$$

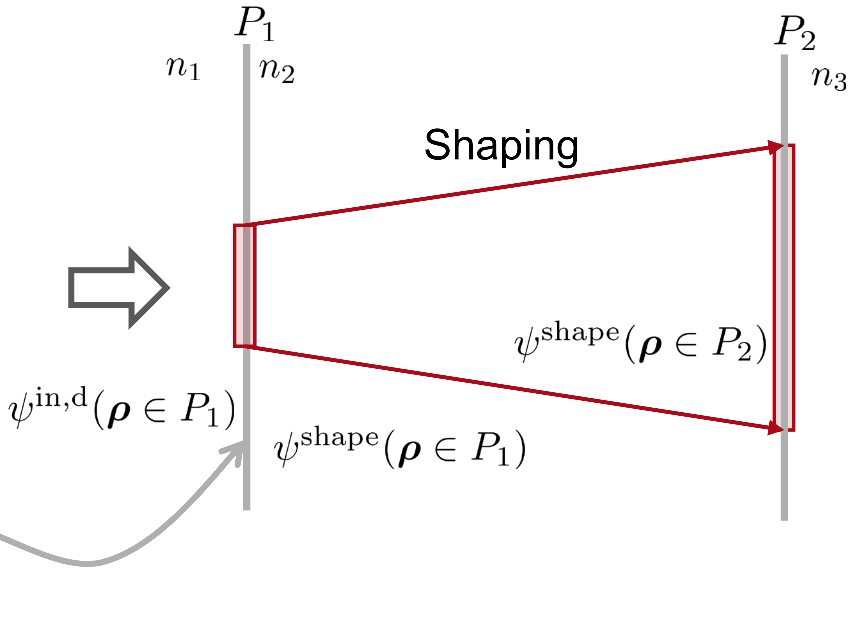
$\psi^{\mathrm{shape}}(\boldsymbol{\rho})$ determined by domain/irradiance shaping algorithm.

Domain and Irradiance Matching: Light Shaping

Input field

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

with index "d" for design field



Specification of energy quantity like

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

Wavefront phase response:

$\Delta\psi_1^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{shape}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$

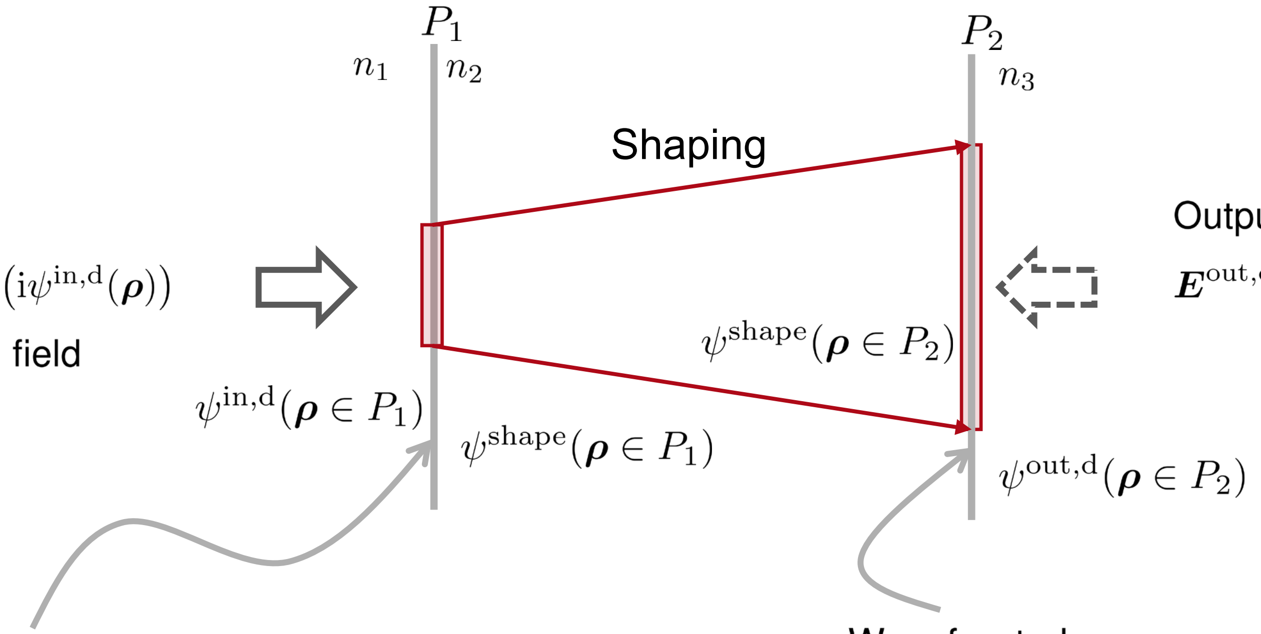
$\psi^{\mathrm{shape}}(\boldsymbol{\rho})$ determined by domain/irradinace shaping algorithm.

Domain and Irradiance Matching: Two Components (WRC)

Input field

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

with index "d" for design field



Output field

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

Wavefront phase response:

$\Delta\psi_1^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{shape}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$

$\psi^{\mathrm{shape}}(\boldsymbol{\rho})$ determined by domain/irradinace shaping algorithm.

Wavefront phase response:

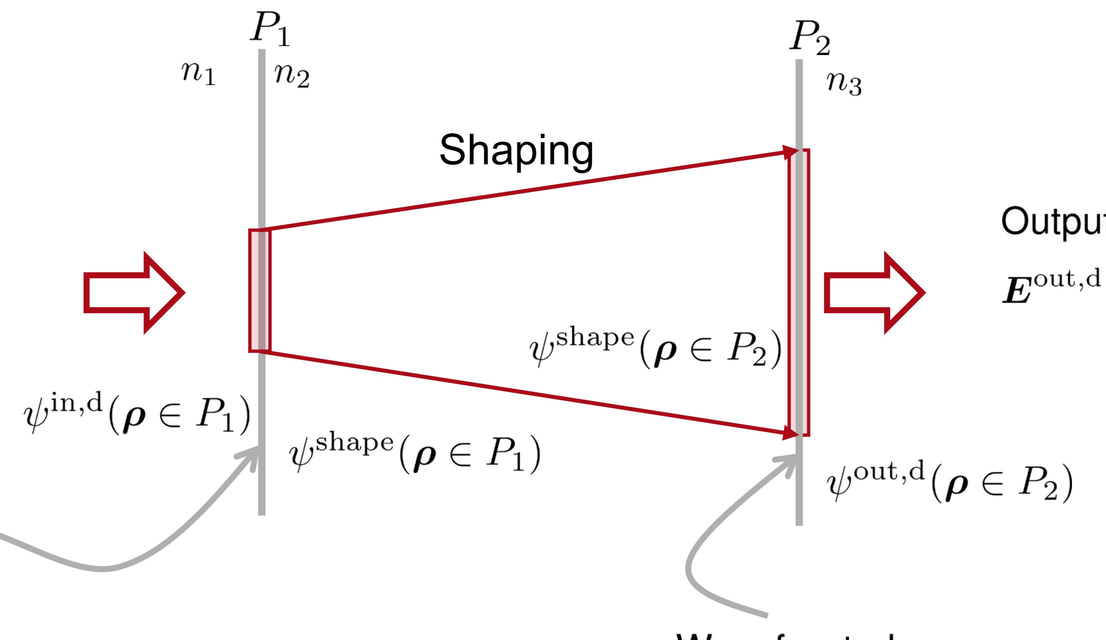
$\Delta\psi_2^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{out,d}}(\boldsymbol{\rho}) - \psi^{\mathrm{shape}}(\boldsymbol{\rho})$

Domain and Irradiance Matching: Two Components (WRC)

Input field

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

with index "d" for design field



Output field

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

Wavefront phase response:

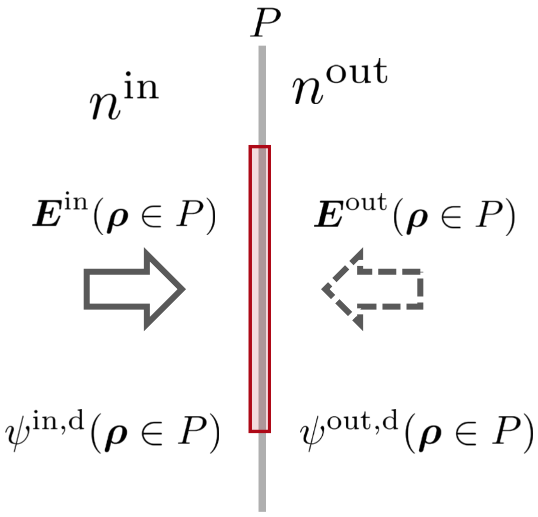
$$\Delta\psi_1^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{shape}}(\boldsymbol{\rho}) - \psi^{\mathrm{in,d}}(\boldsymbol{\rho})$$

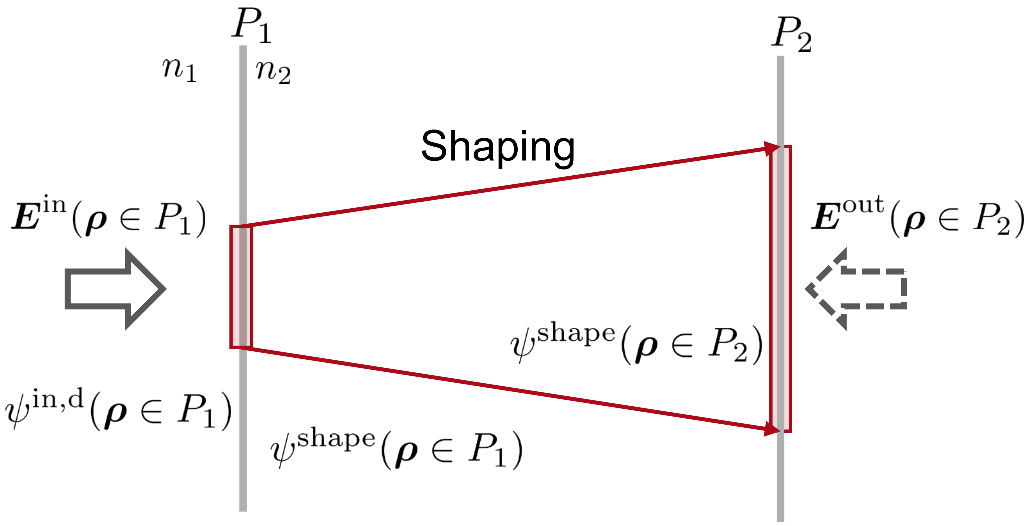
$\psi^{\mathrm{shape}}(\boldsymbol{\rho})$ determined by domain/irradinace shaping algorithm.

Wavefront phase response:

$$\Delta\psi_2^{\mathrm{d}}(\boldsymbol{\rho}) = \psi^{\mathrm{out,d}}(\boldsymbol{\rho}) - \psi^{\mathrm{shape}}(\boldsymbol{\rho})$$

Functional Design: Single Field

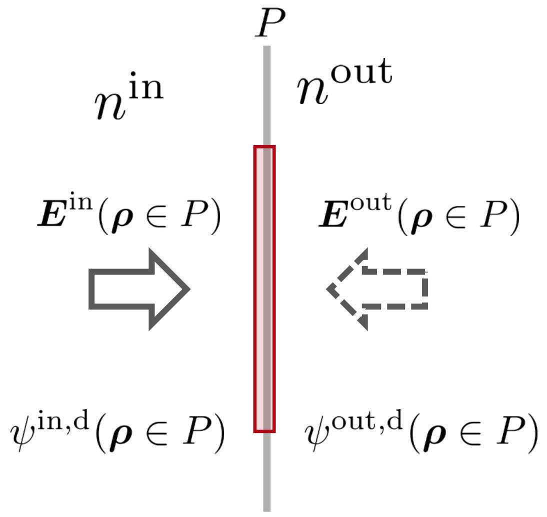


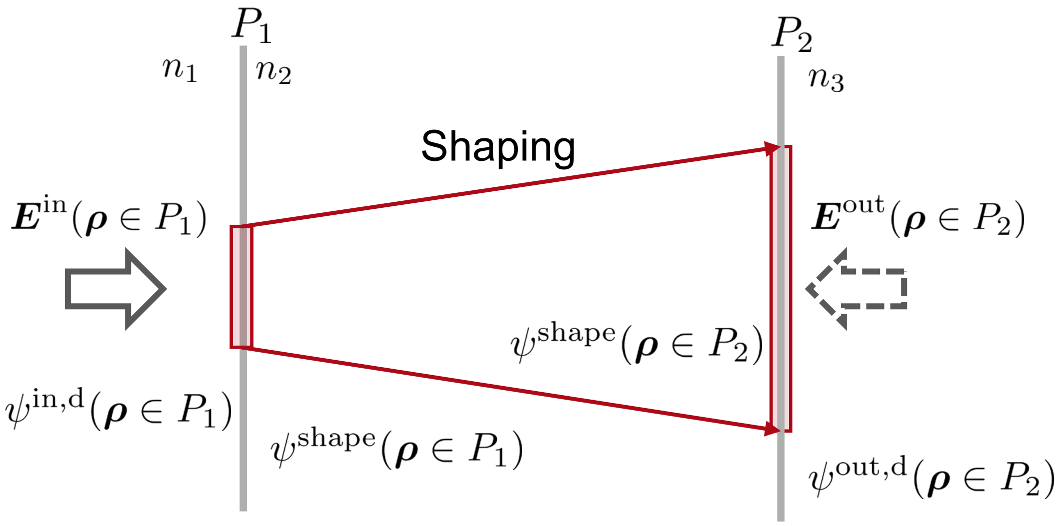


Wavefront Response Component
- Wavefront design

Wavefront Response Component (combination)
- Irradiance shaping

Functional Design: Single Field





Wavefront Response Component
- Wavefront design

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Wavefront Response Component (combination)
- Irradiance shaping
- Wavefront design

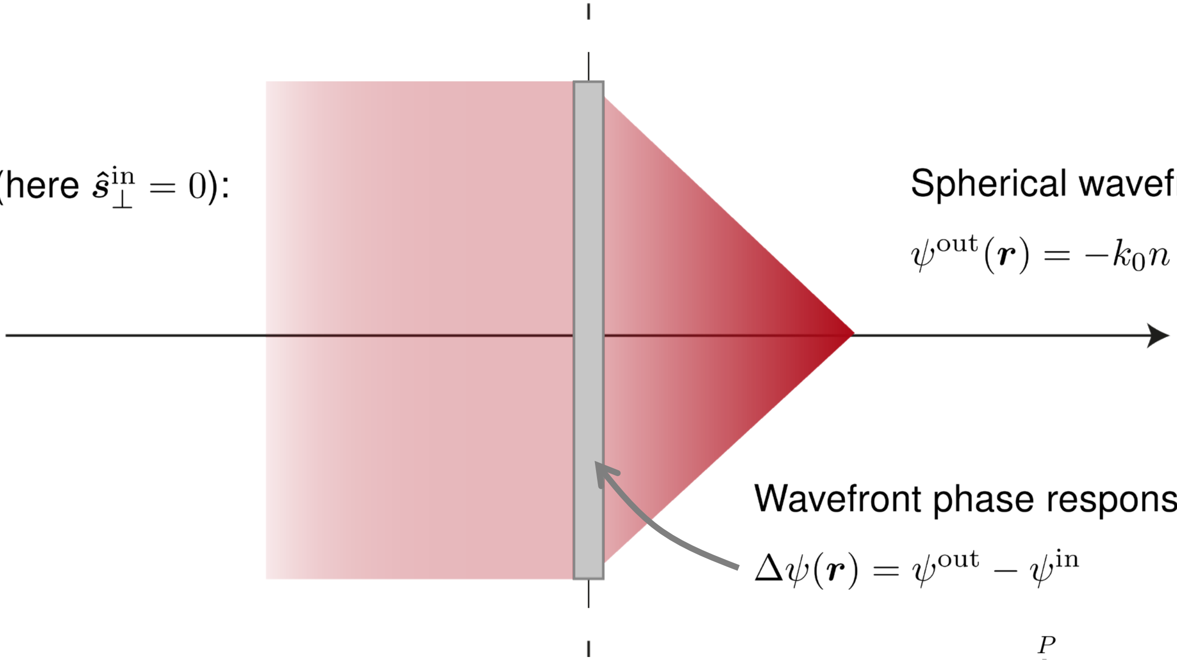
Example Focusing

Functional Design

Focusing Lens: Functional Design

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

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

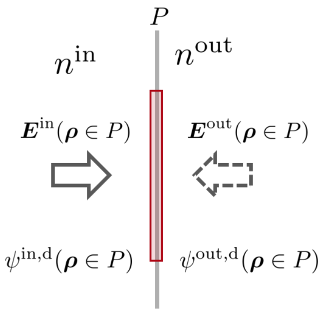


Spherical wavefront phase (here $\boldsymbol{\rho}^{\text{out}} = 0$):

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

Wavefront phase response function:

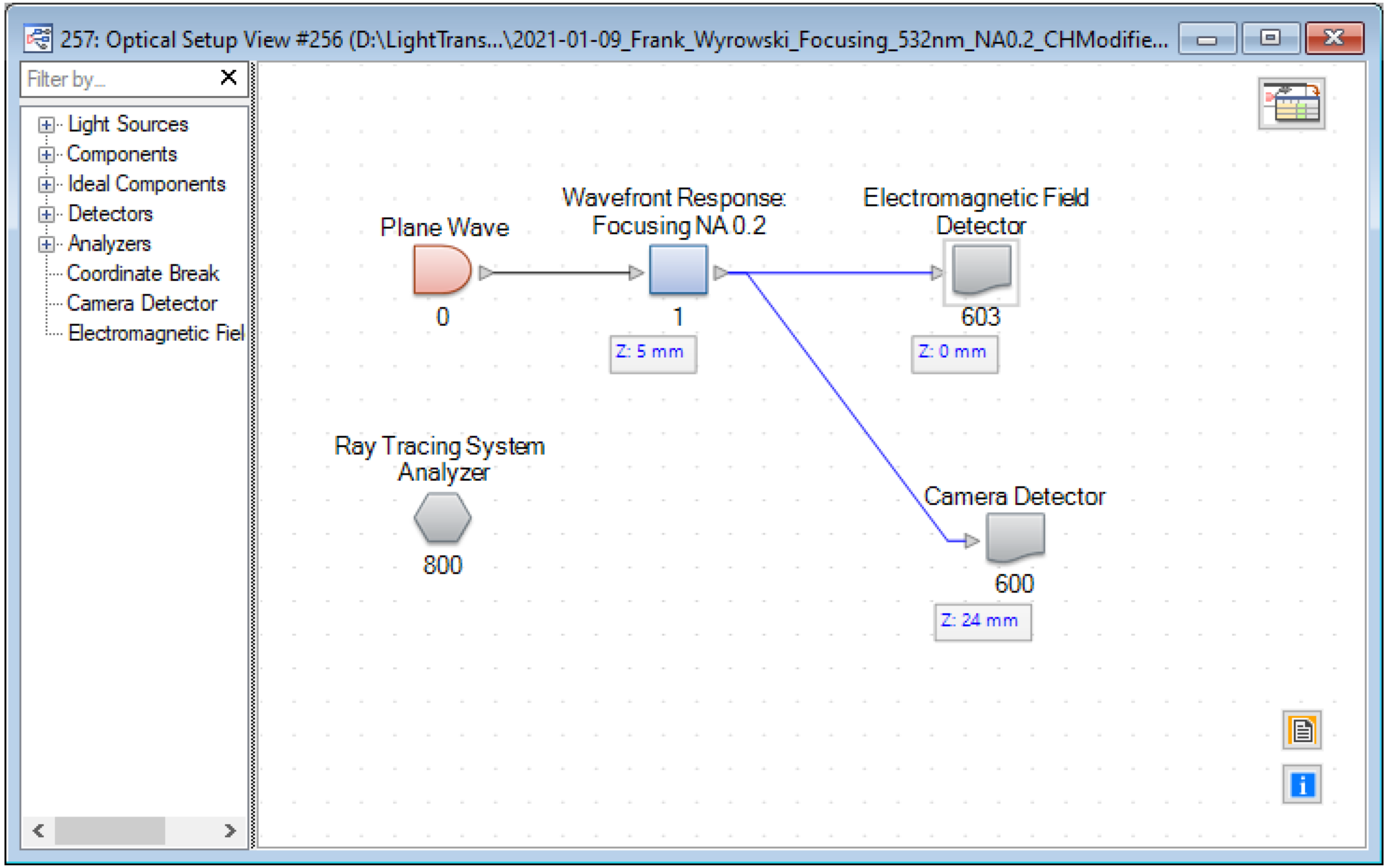
$$\Delta\psi(\boldsymbol{r}) = \psi^{\text{out}} - \psi^{\text{in}}$$



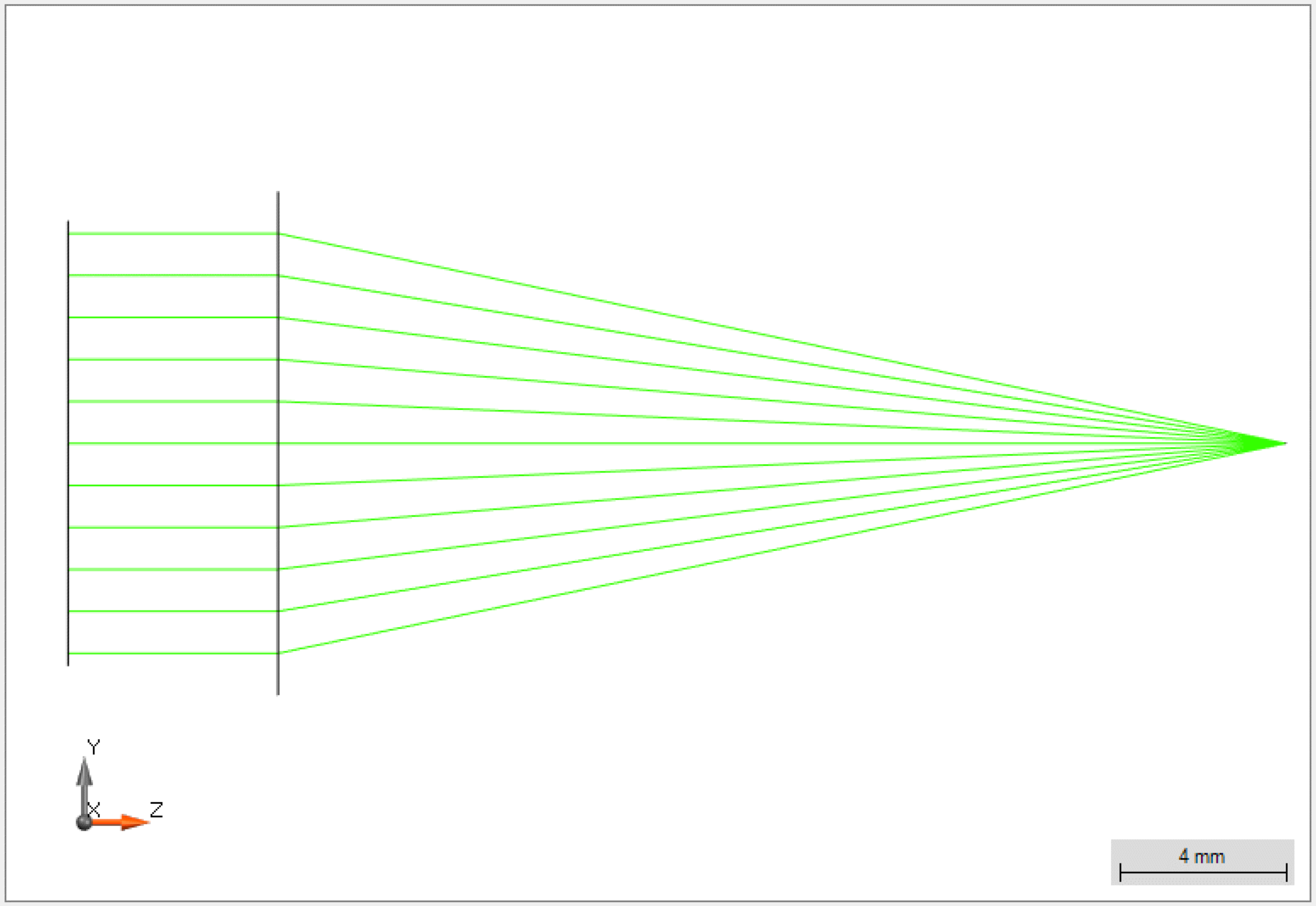
Wavefront Response Component

- Wavefront design

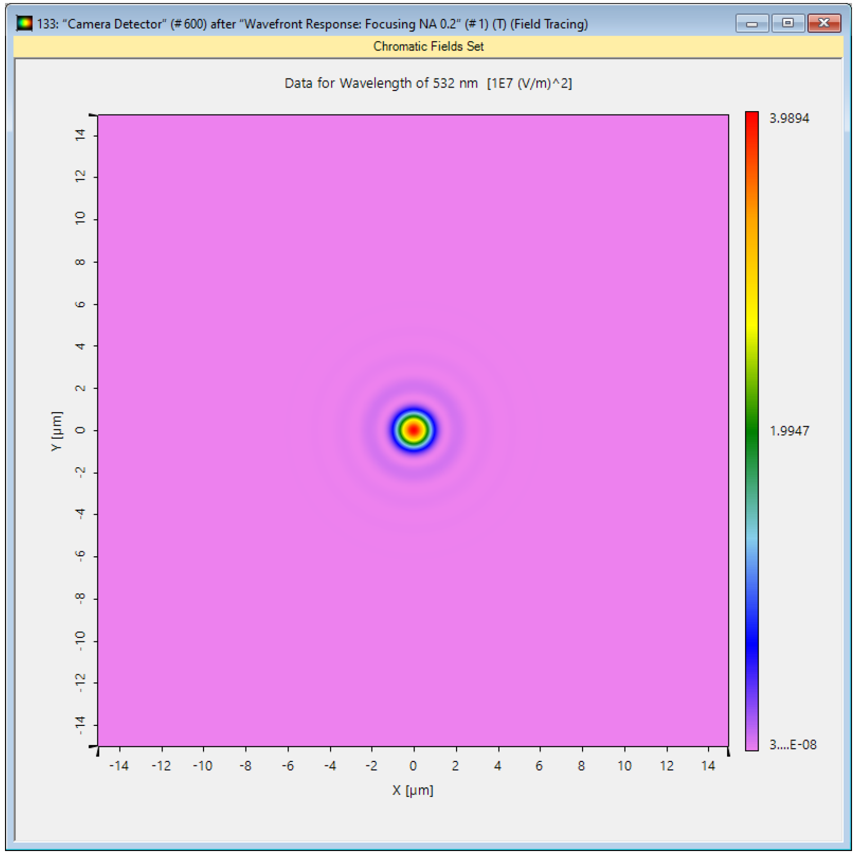
Functional Design: Focusing (NA = 0.2)



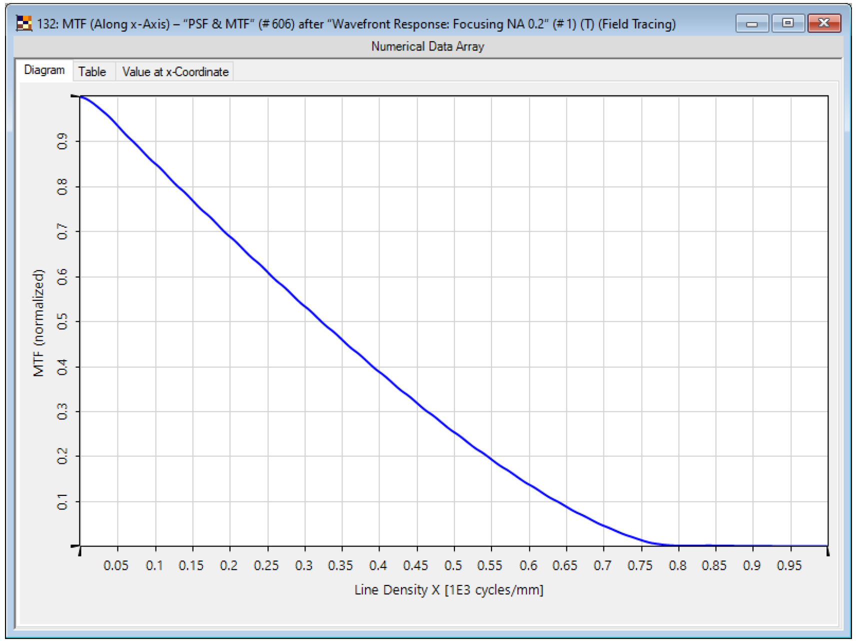
Functional Design: Focusing (NA = 0.2) – Ray Tracing



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



Field in Focus (False Color)

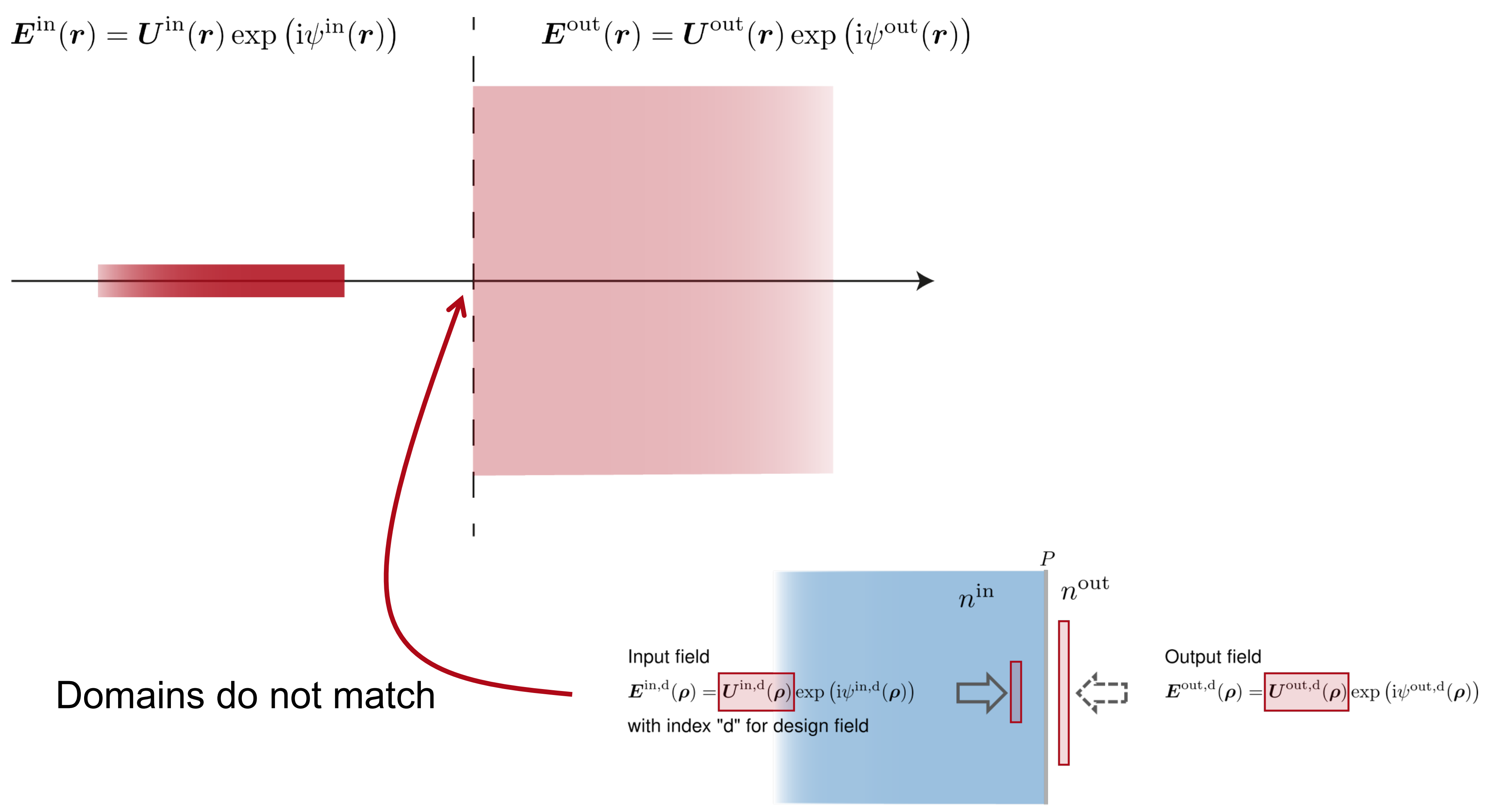


MTF

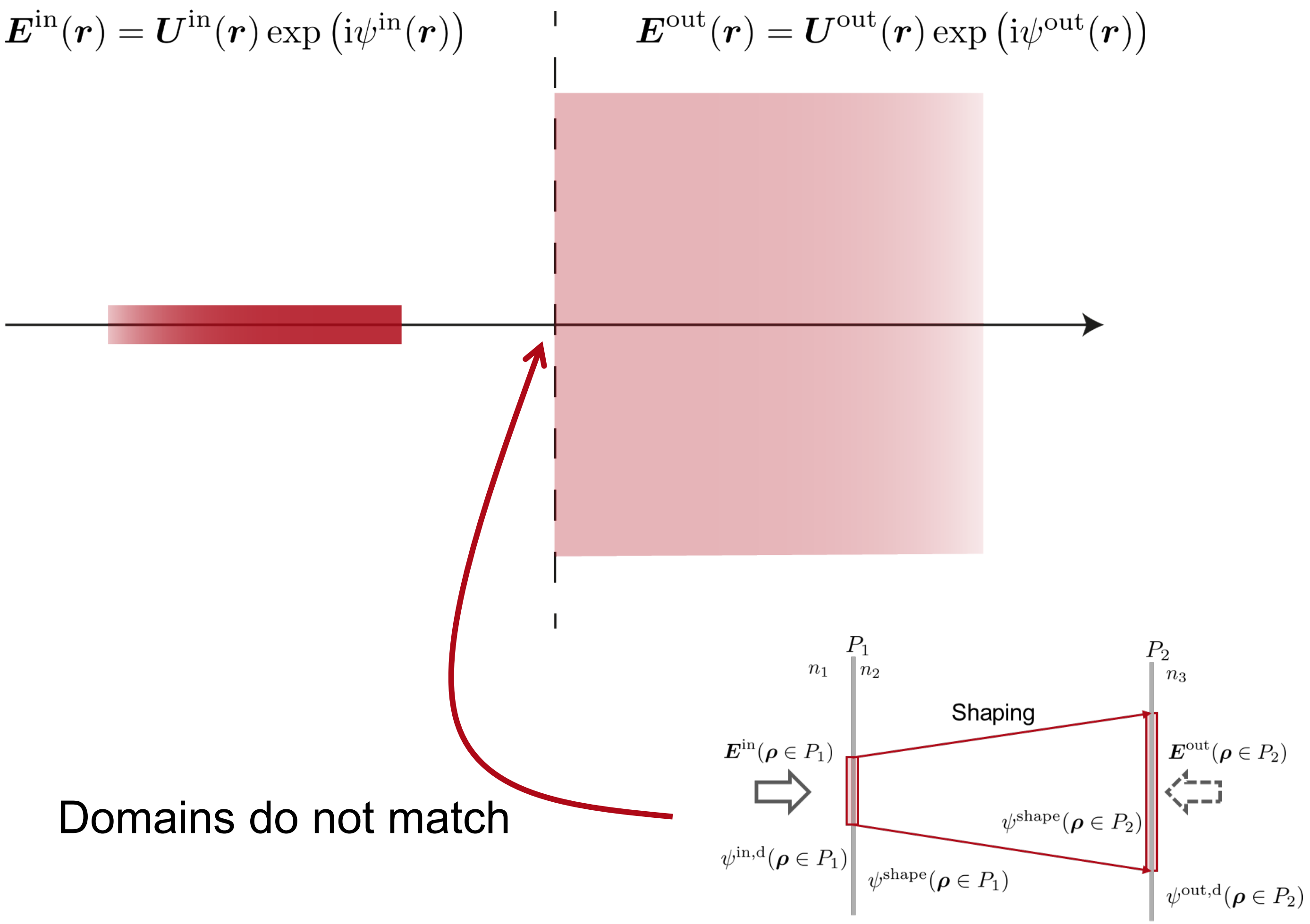
Beam Expander

Functional Design

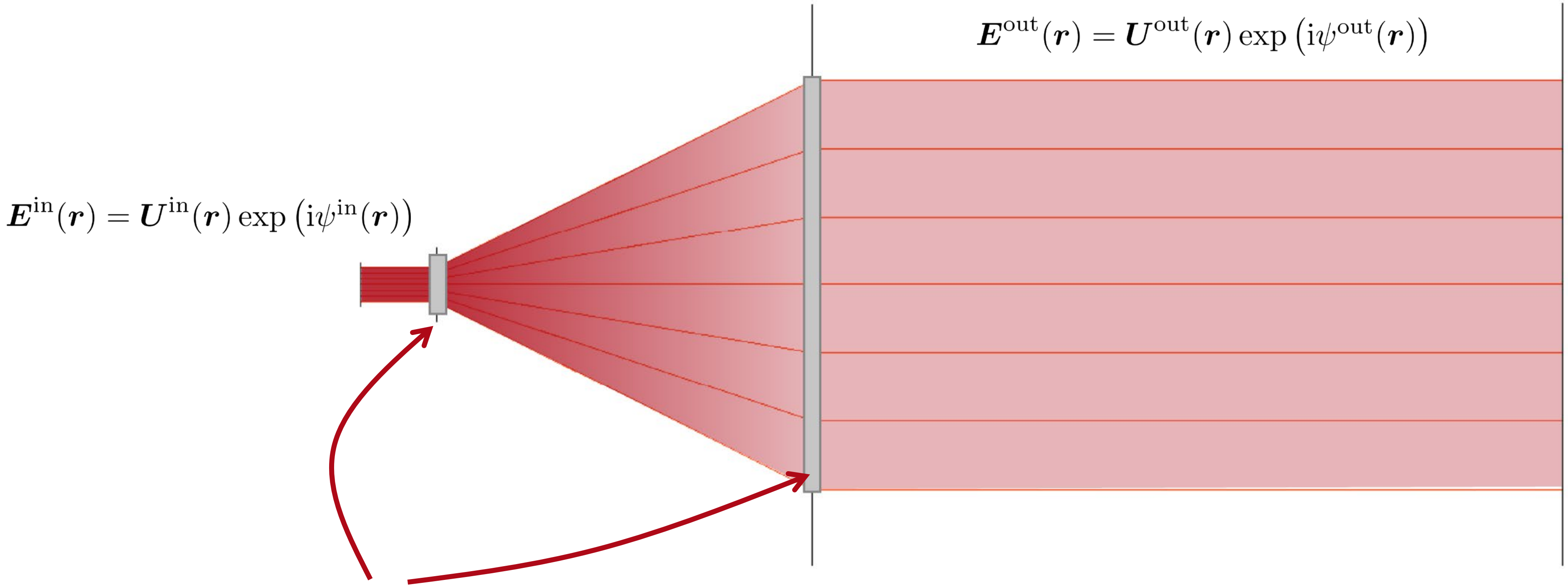
Beam Expander: Scenario



Beam Expander: Scenario

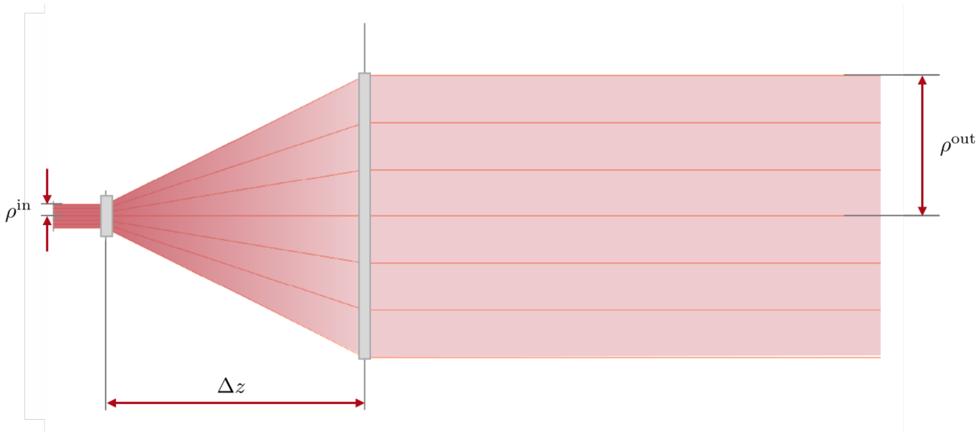


Beam Expander: Functional Design



Two functional components:
Divergent and convergent 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

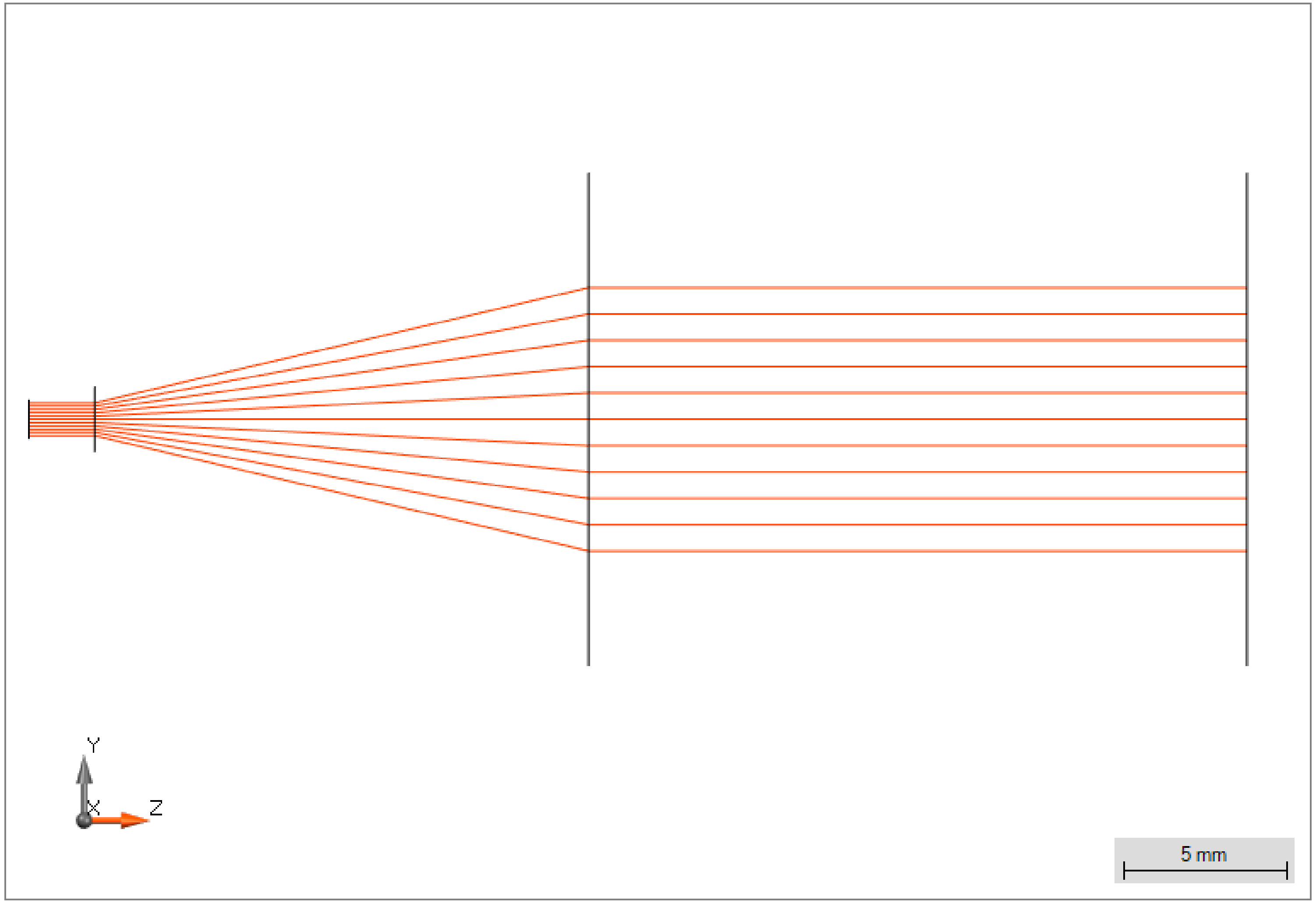
$$R_1 = \frac{\Delta z}{(\zeta - 1)}$$
$$R_2 = -(\Delta z + R_1)$$
$$\text{NA} = \frac{n}{\sqrt{1 + \left(\Delta z/\rho^{\text{out}}\right)^2}}$$

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

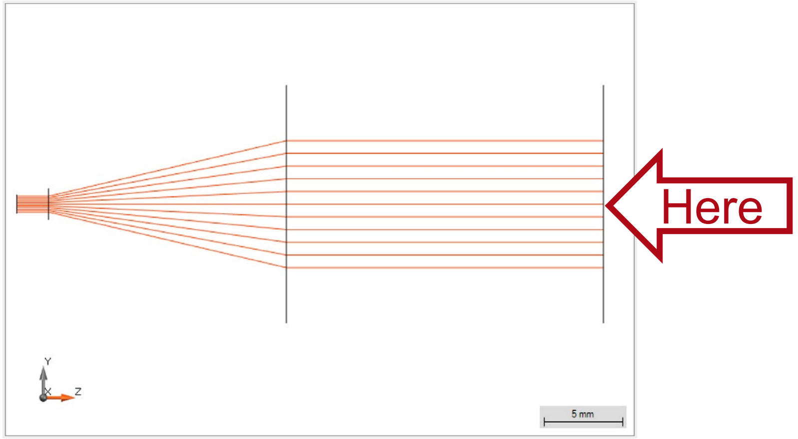
- Thus, the functional design results by analytical considerations to the wavefront phases:

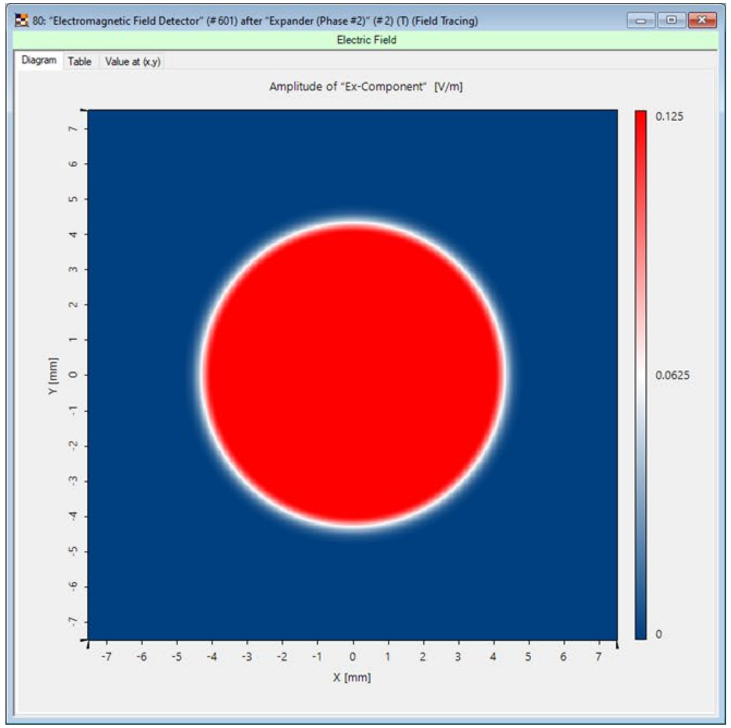
$$\Delta\psi_1(\boldsymbol{\rho}, k_0) = k_0 n \sqrt{\|\boldsymbol{\rho}\|^2 + R_1^2}$$
$$\Delta\psi_2(\boldsymbol{\rho}, k_0) = -k_0 n \sqrt{\|\boldsymbol{\rho}\|^2 + R_2^2}$$

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

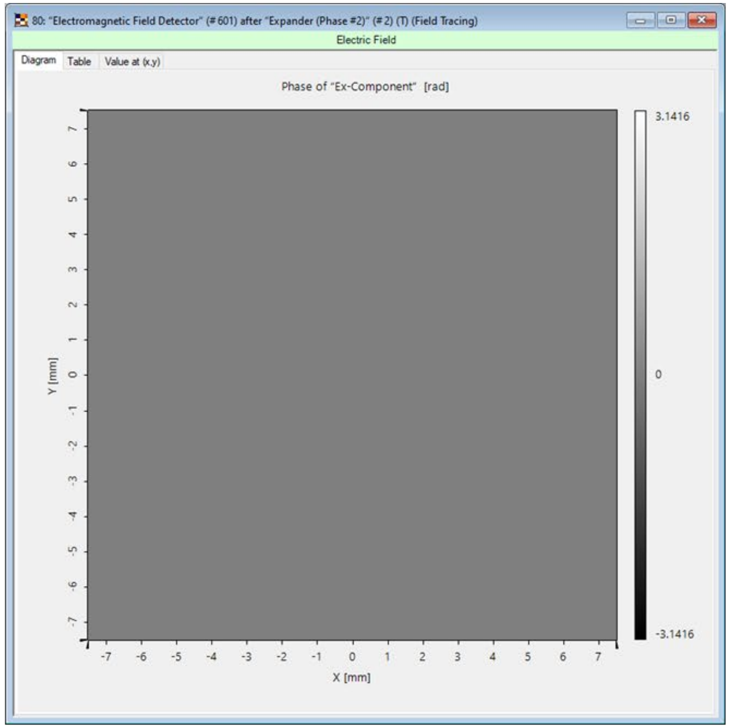


Beam Expander (1:5) – Functional Design: Output Beam





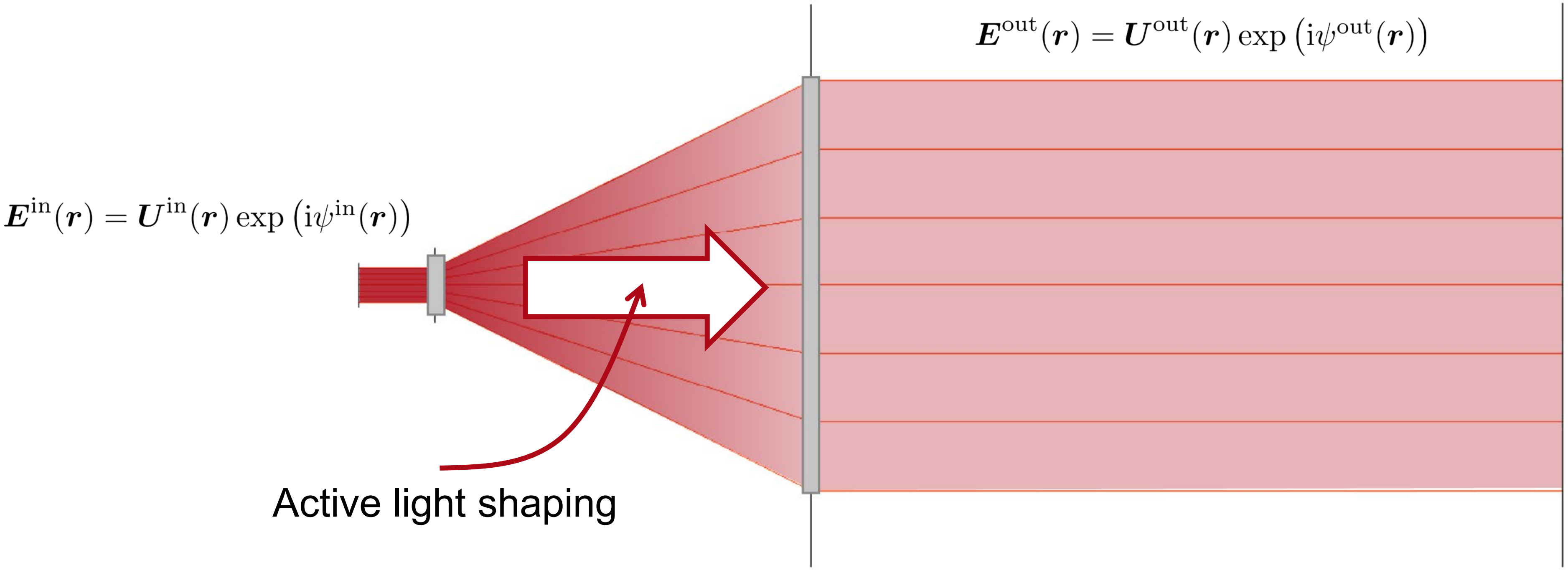
Amplitude after Beam Expander



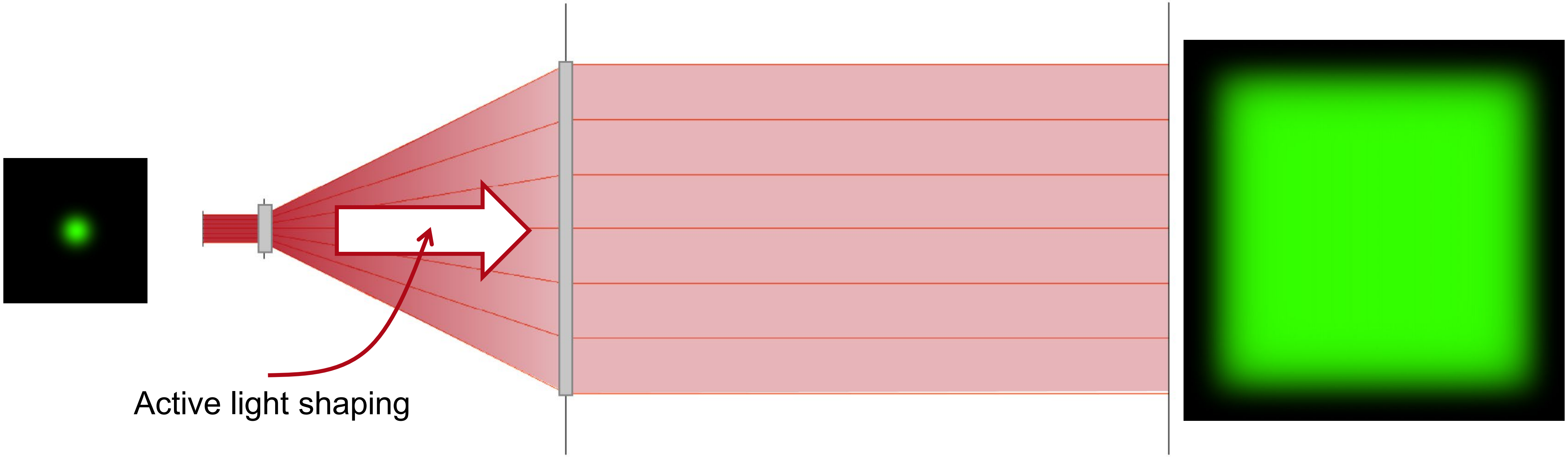
Phase after Beam Expander

Beam Expander Combined with Light Shaping

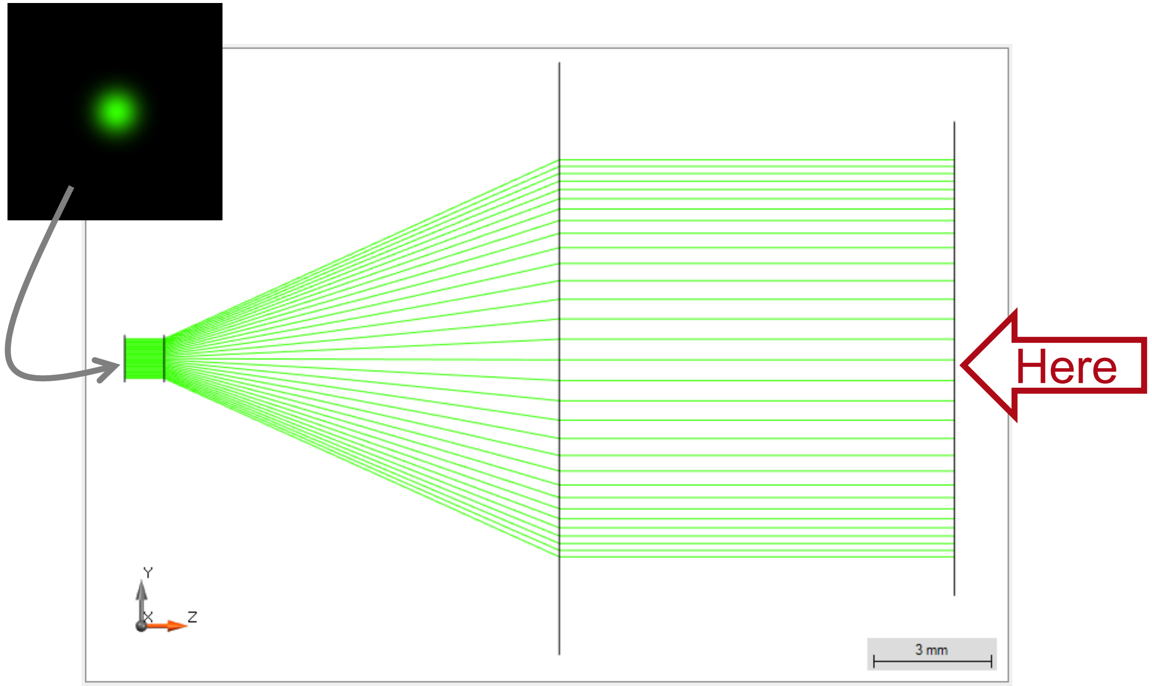
Shaping Beam Expander: Scenario

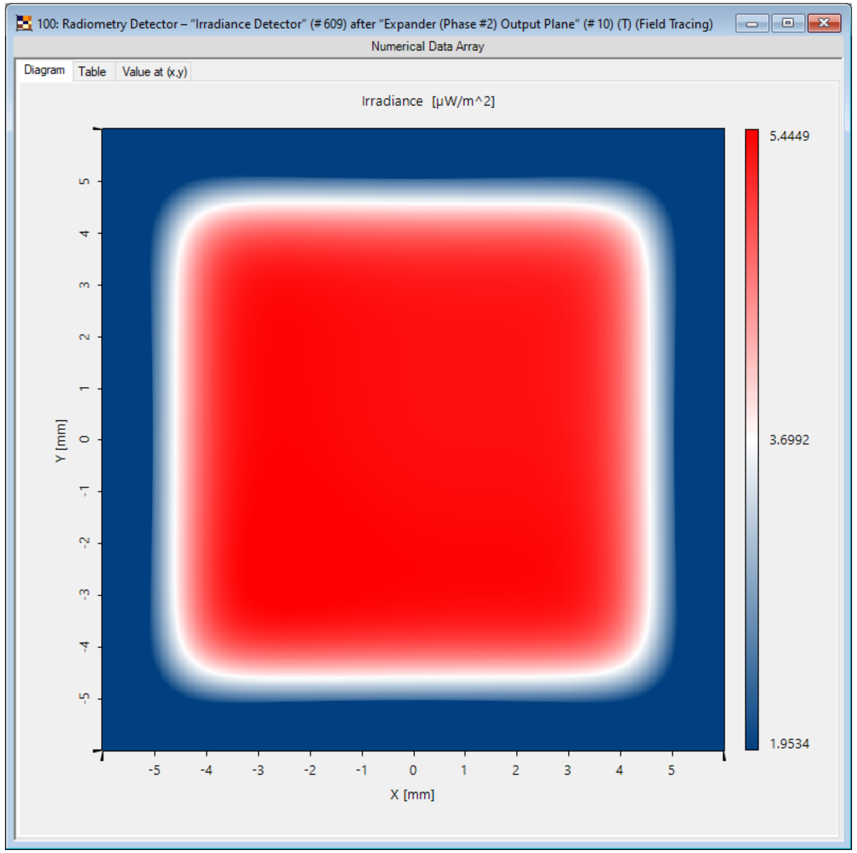


Shaping Beam Expander: Scenario



Shaping Beam Expander: Functional Design





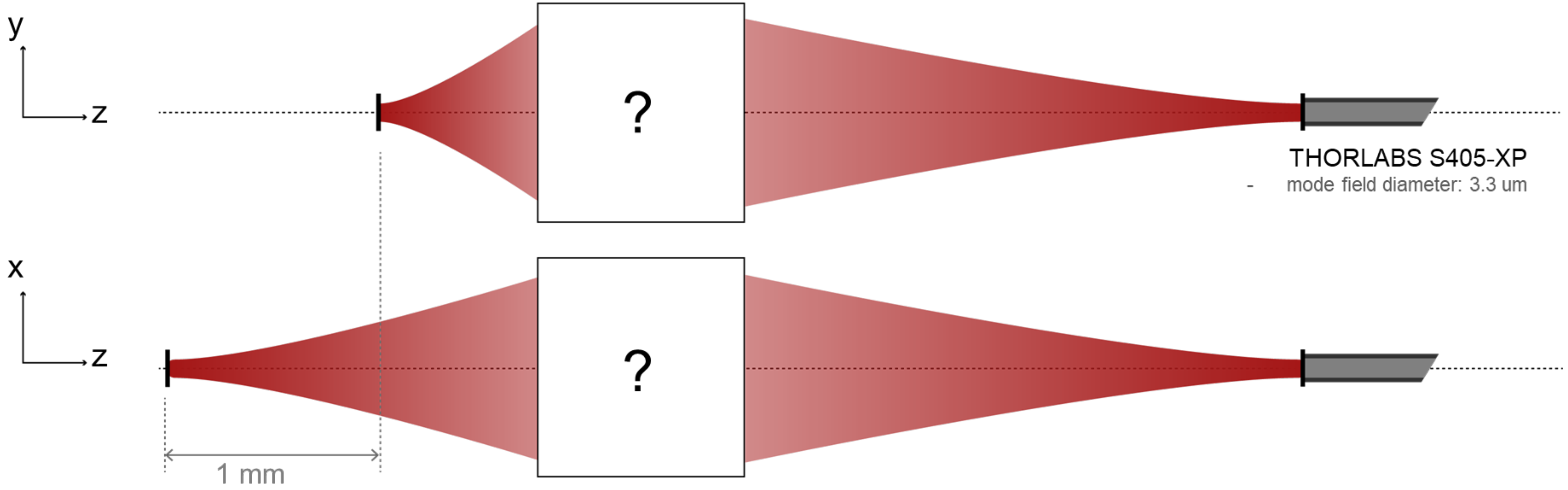
Irradiance (by field tracing)

Example Fiber Coupling

Scenario: Laser Diode Coupling Into Fiber

laser diode with astigmatism

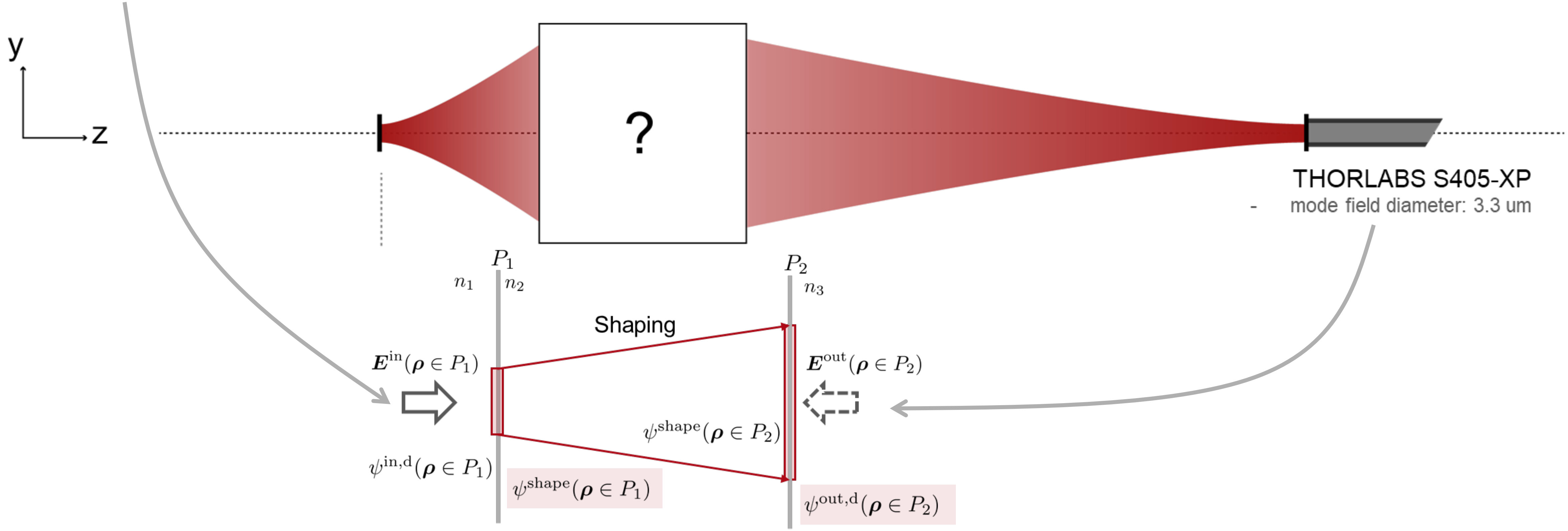
- wavelength 405 nm
- half divergent angle (1/e^2): 8.74° x 15.63°
- astigmatism between y and x: -1 mm



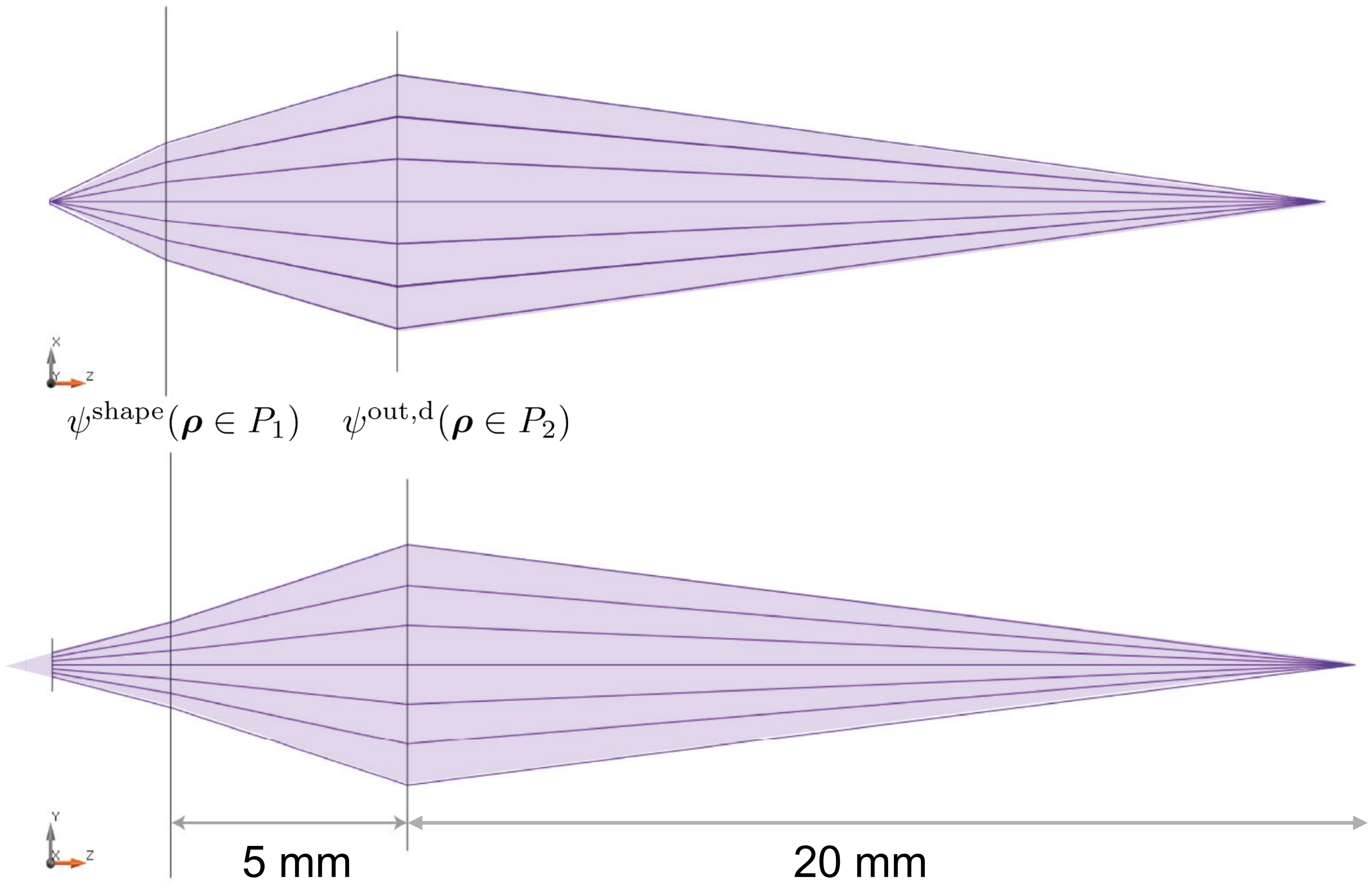
Functional Design: Laser Diode Coupling Into Fiber

laser diode with astigmatism

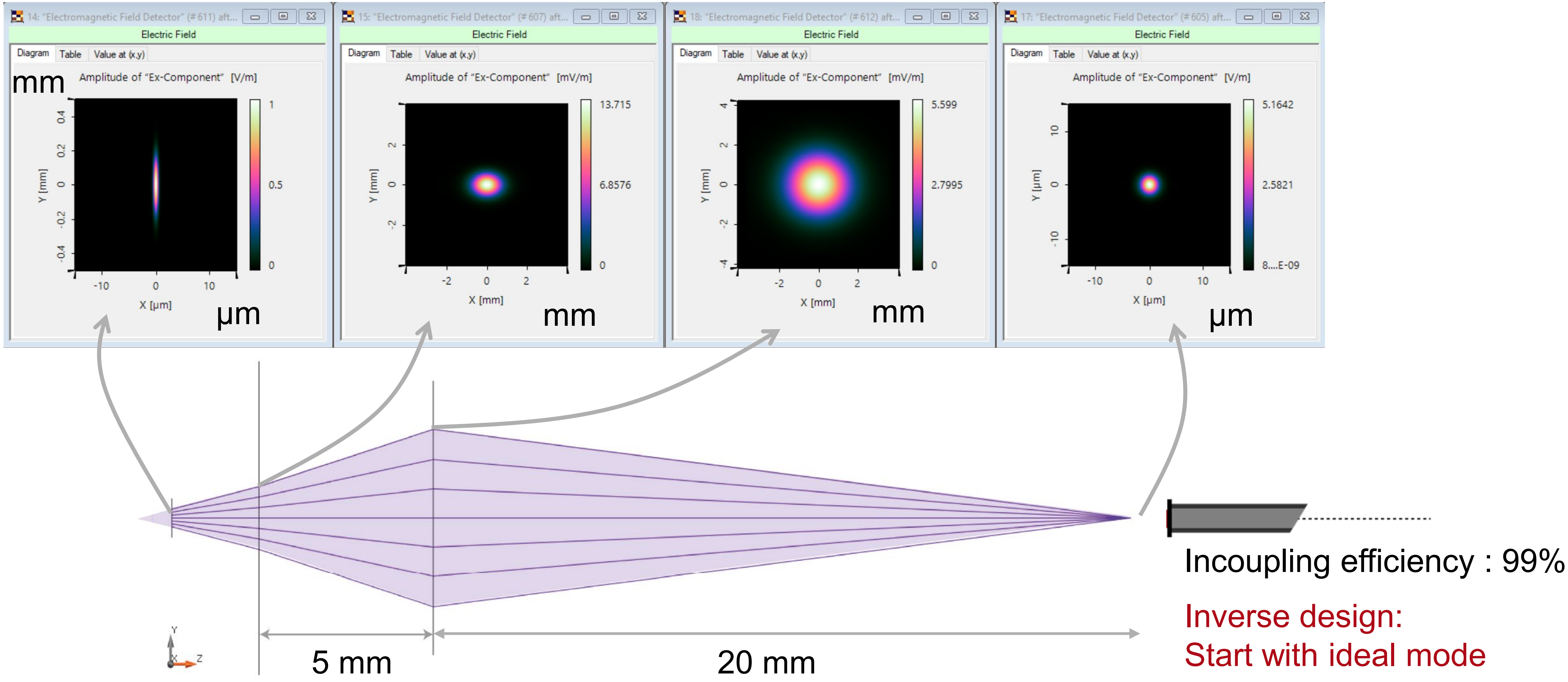
- wavelength 405 nm
- half divergent angle (1/e^2): 8.74° x 15.63°
- astigmatism between y and x: -1 mm



Laser Diode Coupling Into Fiber: Ray Tracing



Laser Diode Coupling Into Fiber: Field Tracing



$\psi^{\text{shape}}(\boldsymbol{\rho} \in P_1)$ $\psi^{\text{out,d}}(\boldsymbol{\rho} \in P_2)$

Incoupling efficiency : 99%

Inverse design:
Start with ideal mode

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Repl comp freef flat c comp

MODELING & EVALUATION

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

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

Functional design provides Wavefront Response Components with specified $\Delta\psi^{\mathrm{d}}(\boldsymbol{\rho})$

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and 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

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

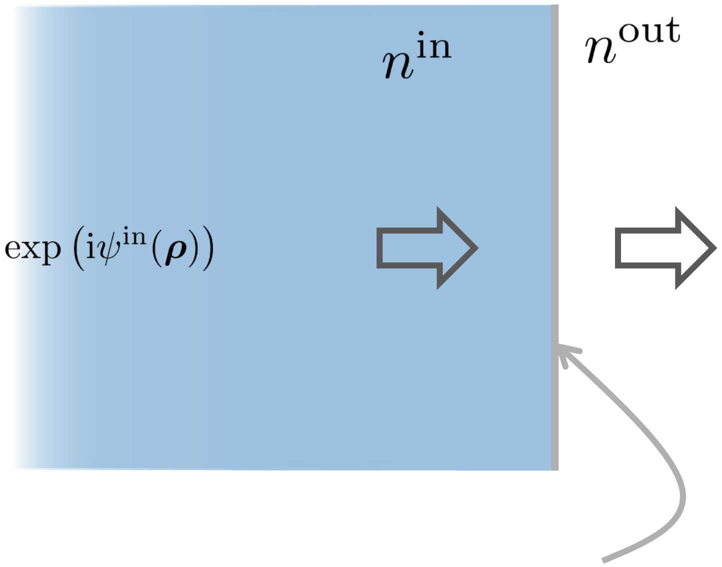
Structural Design

Single Field Scenario

Wavefront Response by Flat Optics

Input field

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



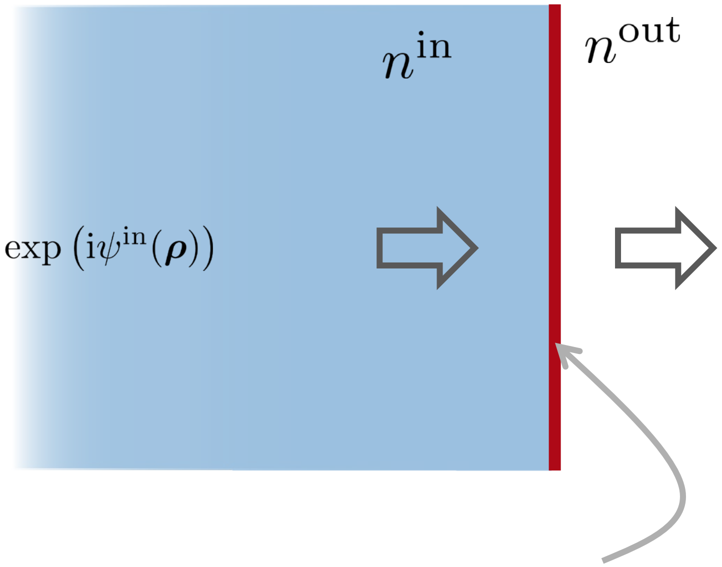
Output field

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

Wavefront phase response:

$$\psi^{\mathrm{out}}(\boldsymbol{\rho}) = \psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi^{\mathrm{d}}(\boldsymbol{\rho})$$

Wavefront Response by Flat Optics



Input field

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

Output field

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

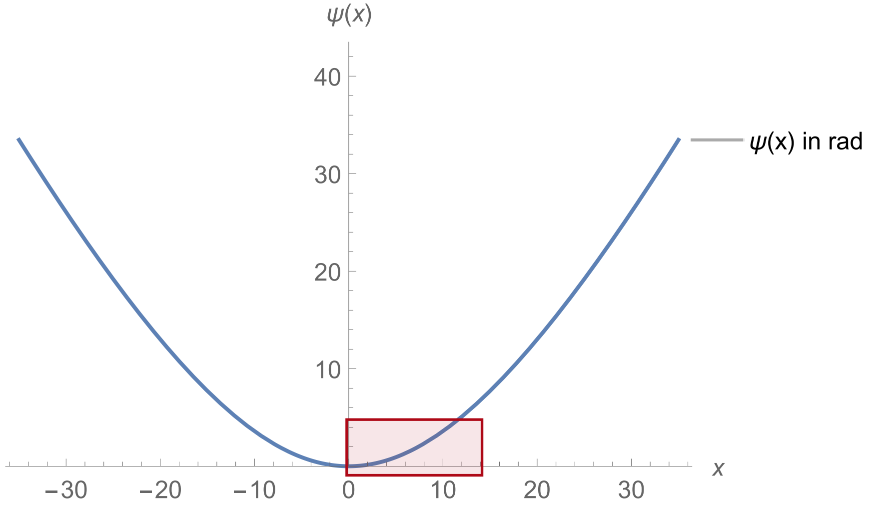
Wavefront phase response:

$$\psi^{\mathrm{out}}(\boldsymbol{\rho}) = \psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi^{\mathrm{d}}(\boldsymbol{\rho})$$

How is it possible to realize a wavefront phase response by a **THIN** layer?

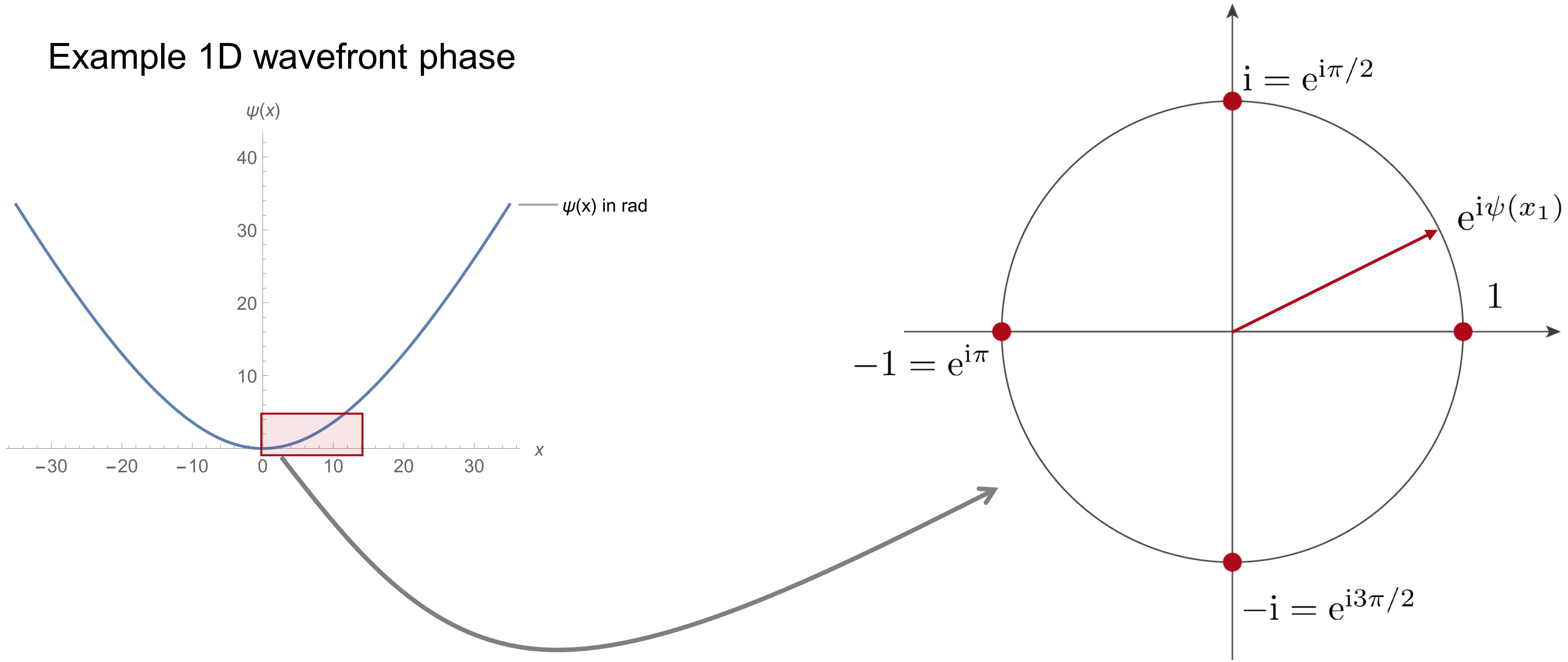
What Allows Flat Optics to Work?

Example 1D wavefront phase



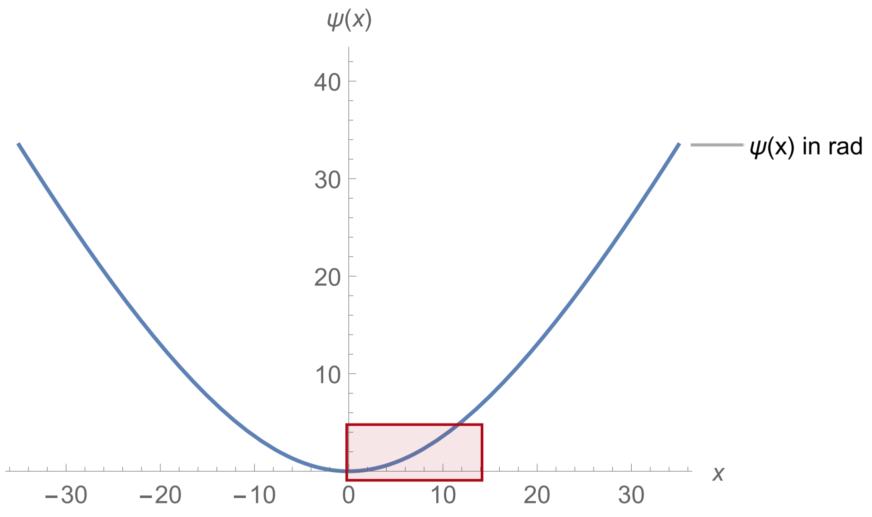
What Allows Flat Optics to Work?

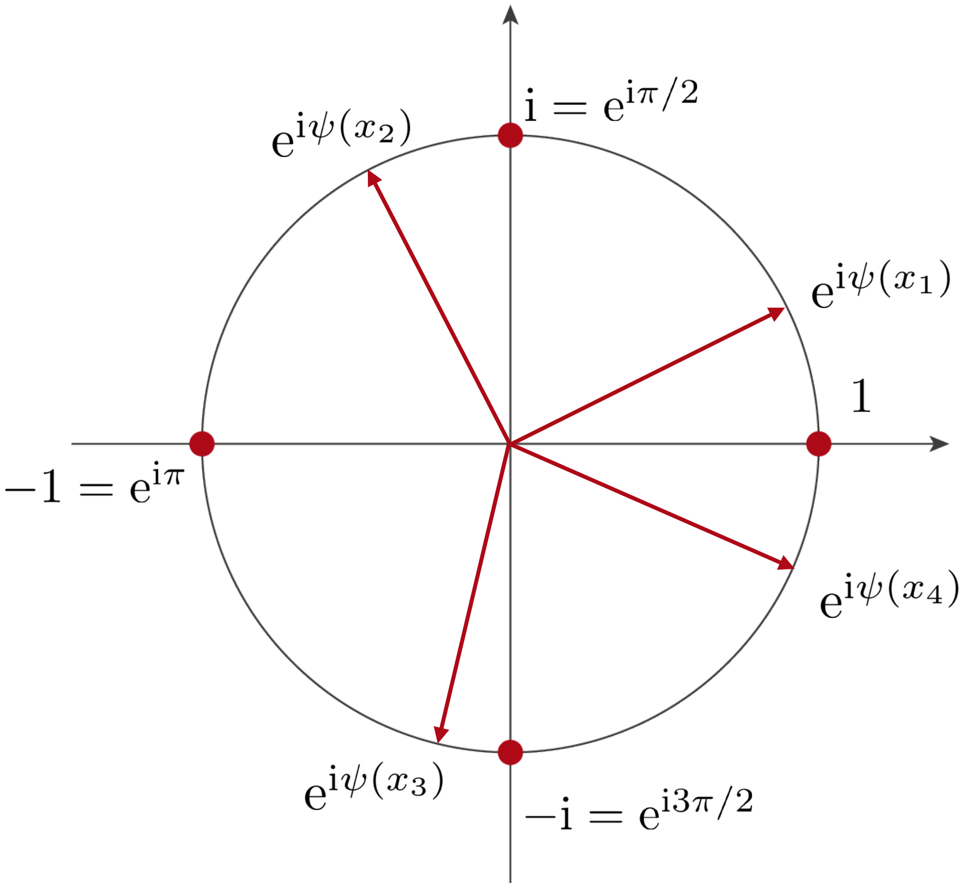
Example 1D wavefront phase



What Allows Flat Optics to Work?

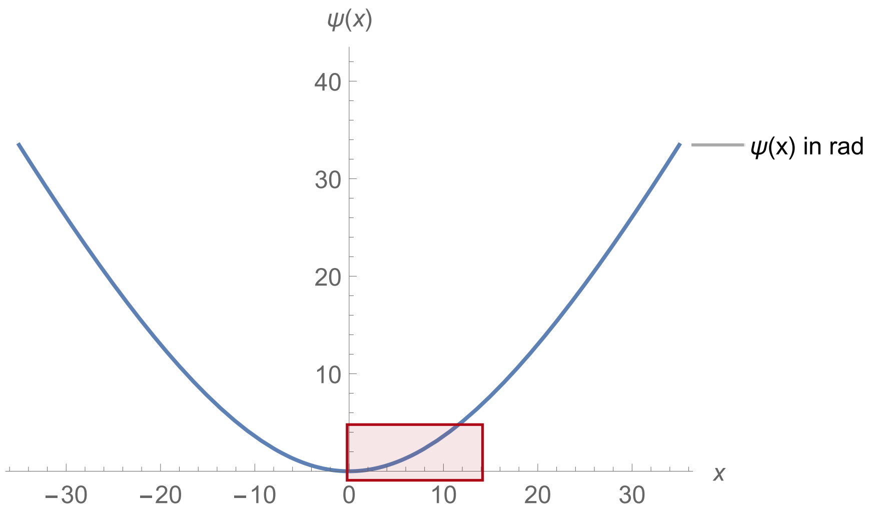
Example 1D wavefront phase

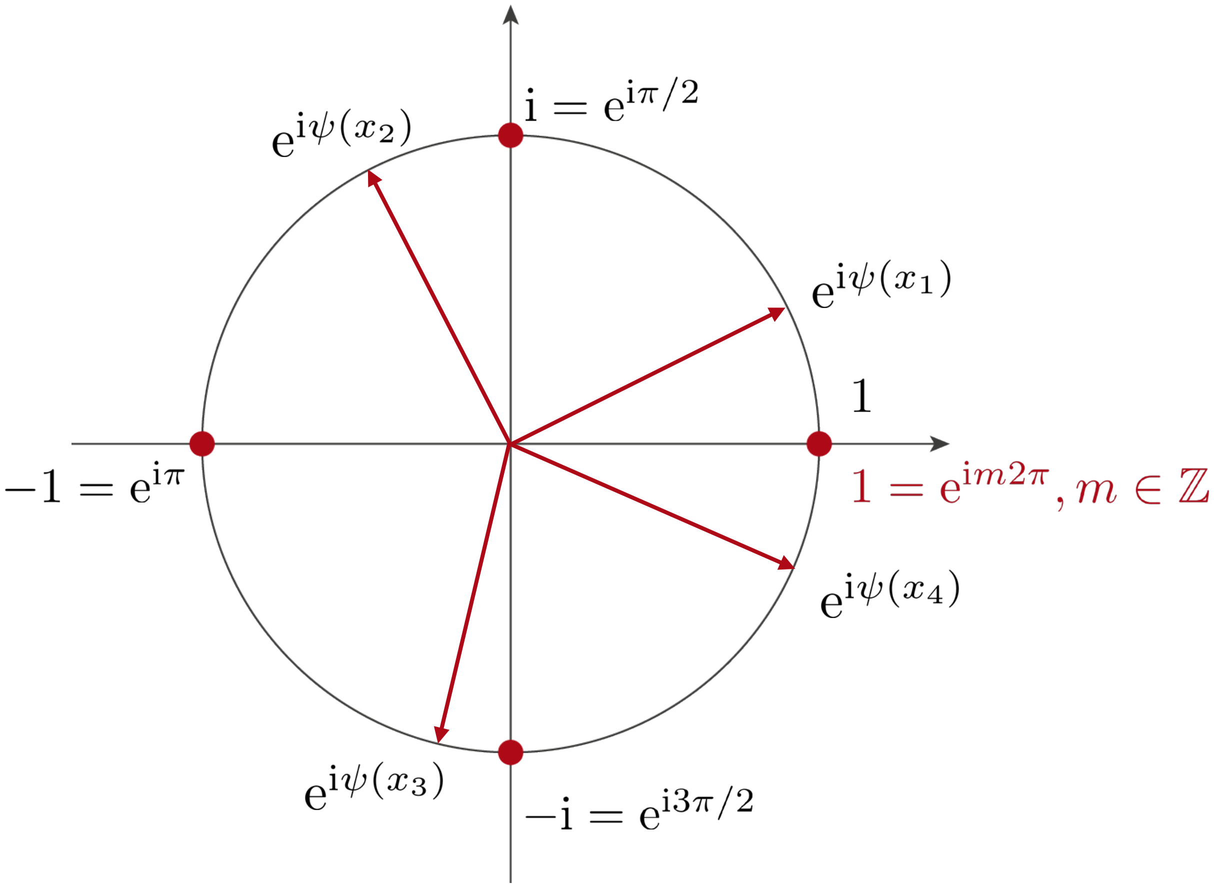




What Allows Flat Optics to Work?

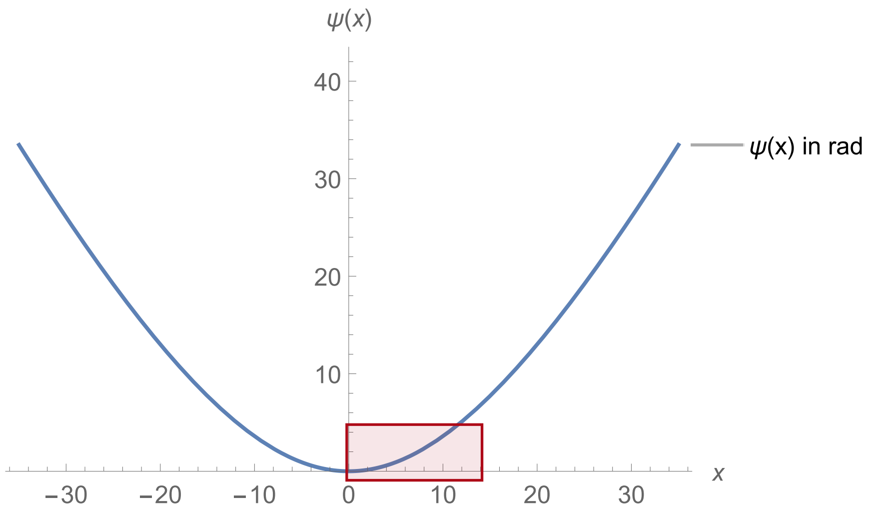
Example 1D wavefront phase

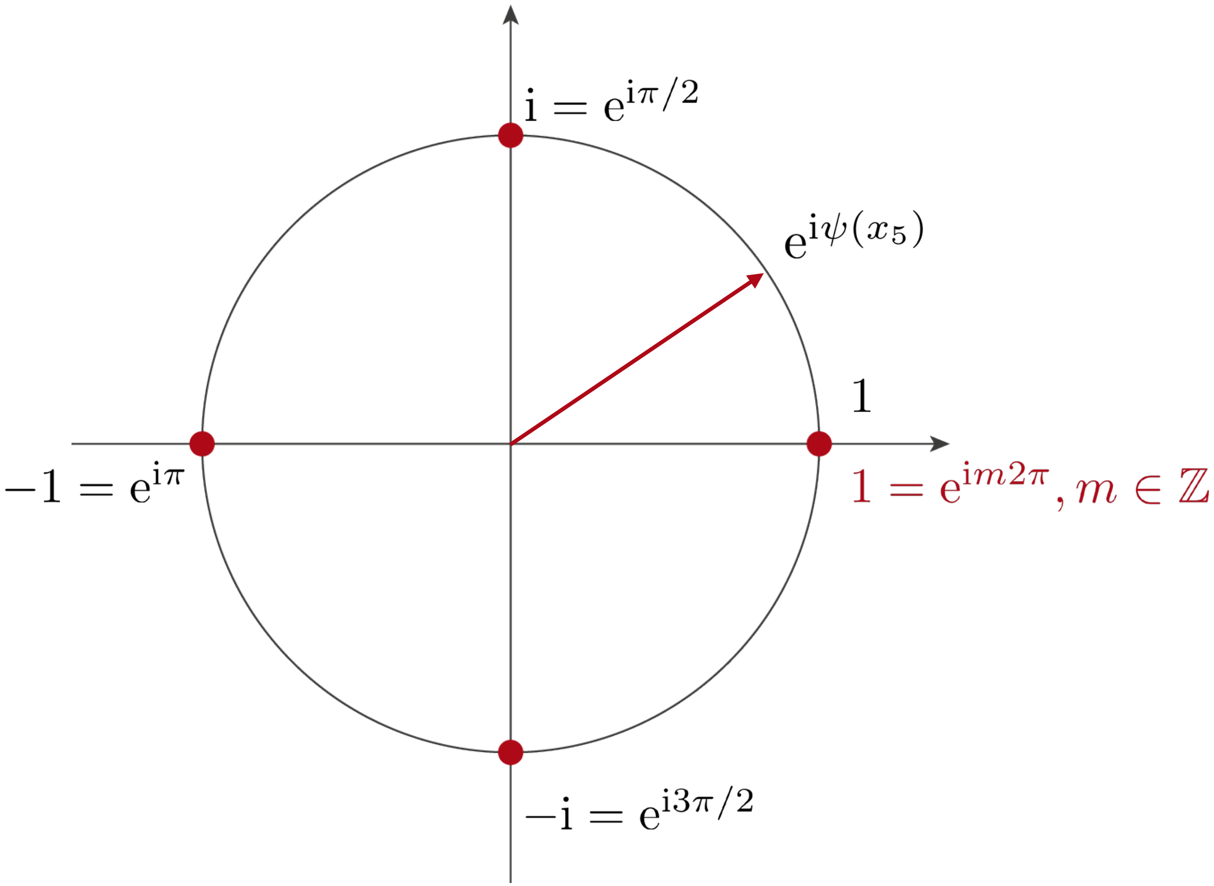




What Allows Flat Optics to Work?

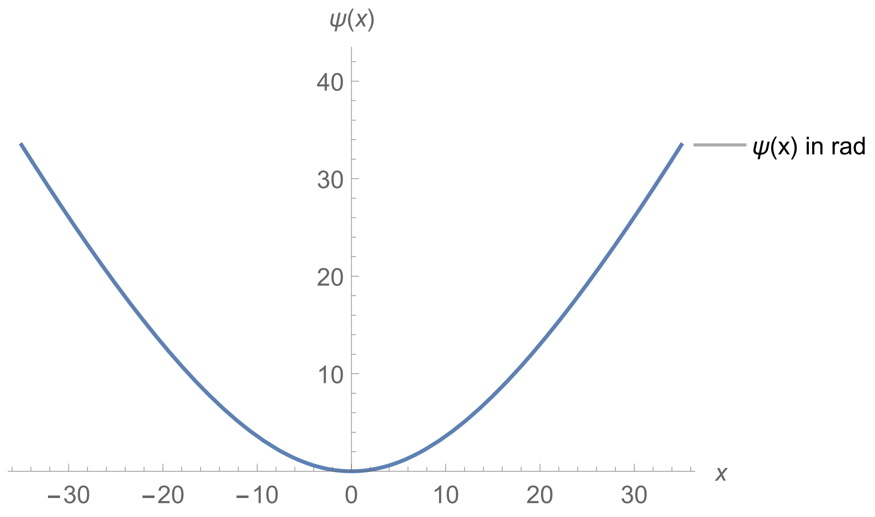
Example 1D wavefront phase

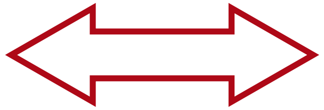


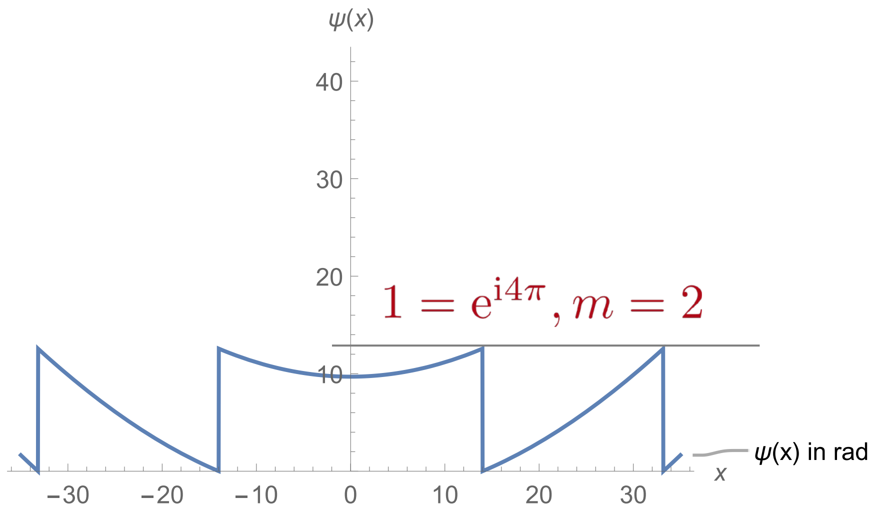


What Allows Flat Optics to Work?

Example 1D wavefront phase

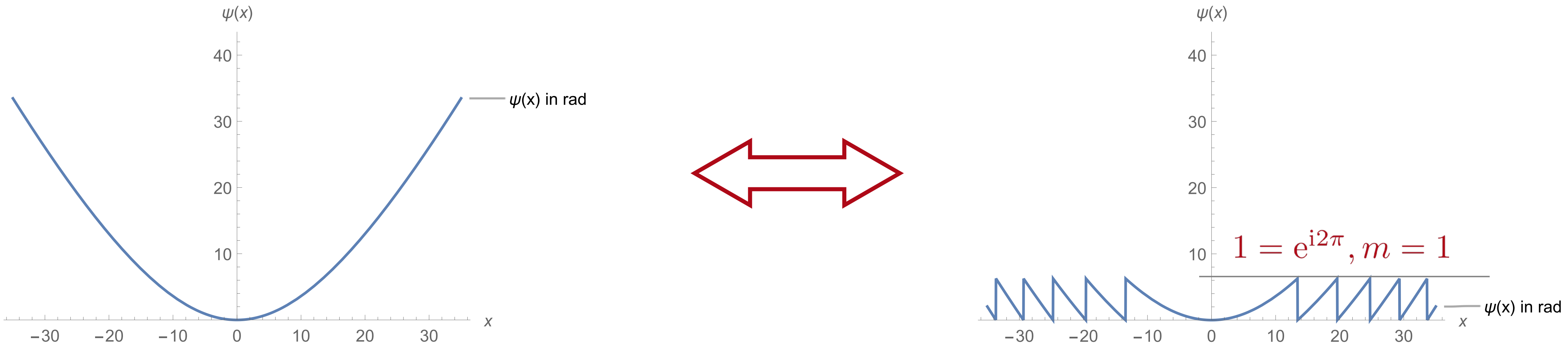






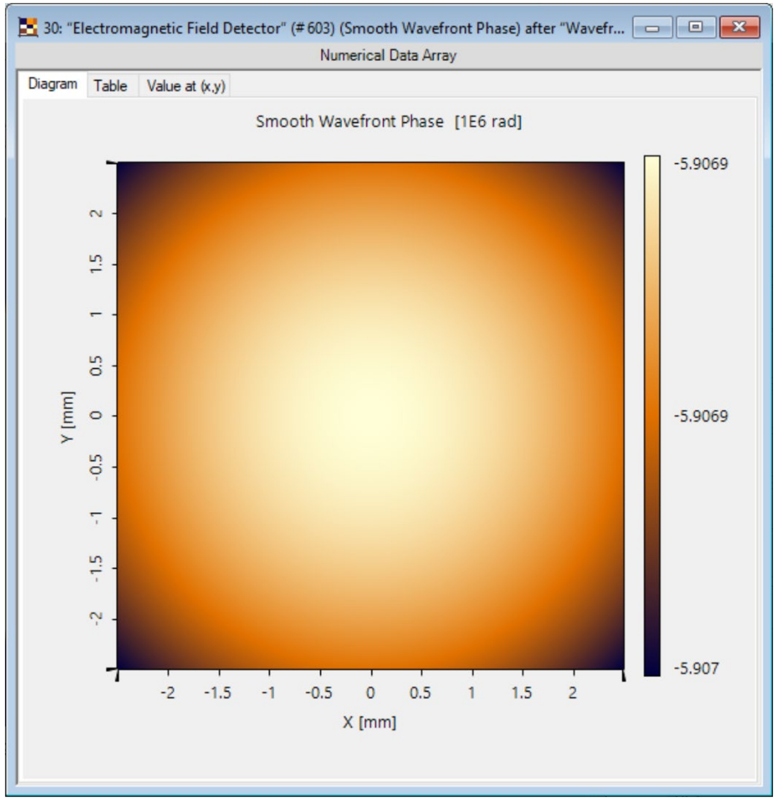
What Allows Flat Optics to Work?

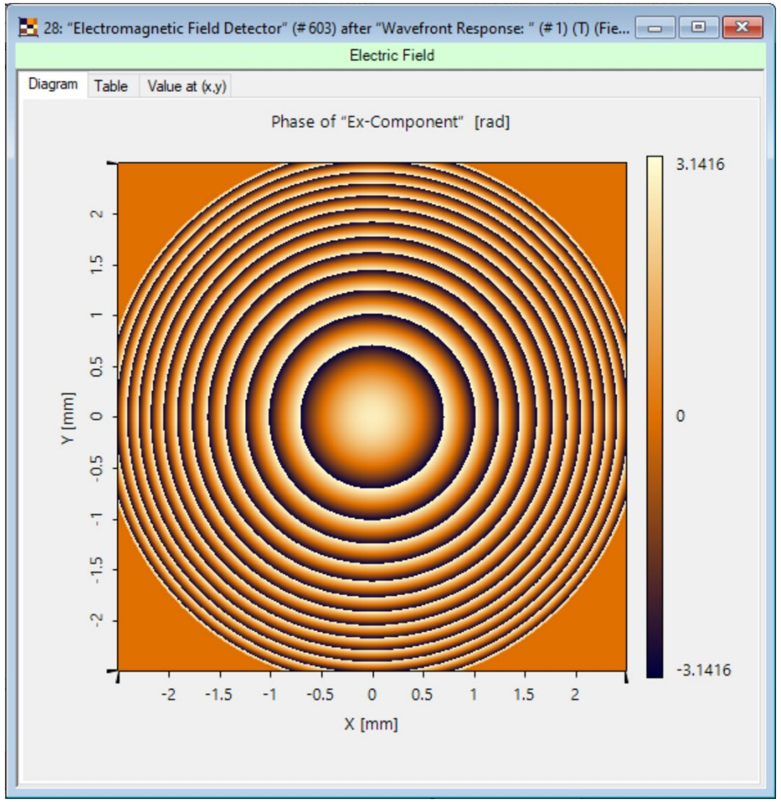
Example 1D wavefront phase



What Allows Flat Optics to Work?

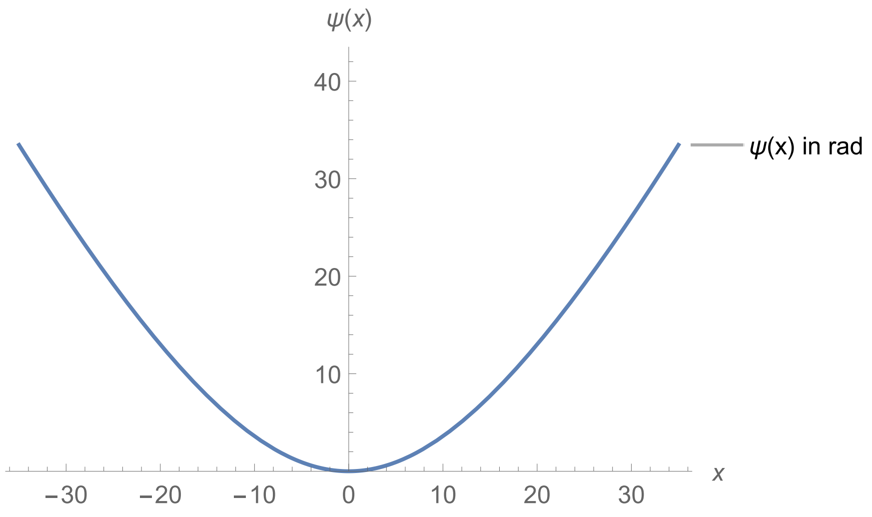
$$1 = e^{i2\pi}, m = 1$$

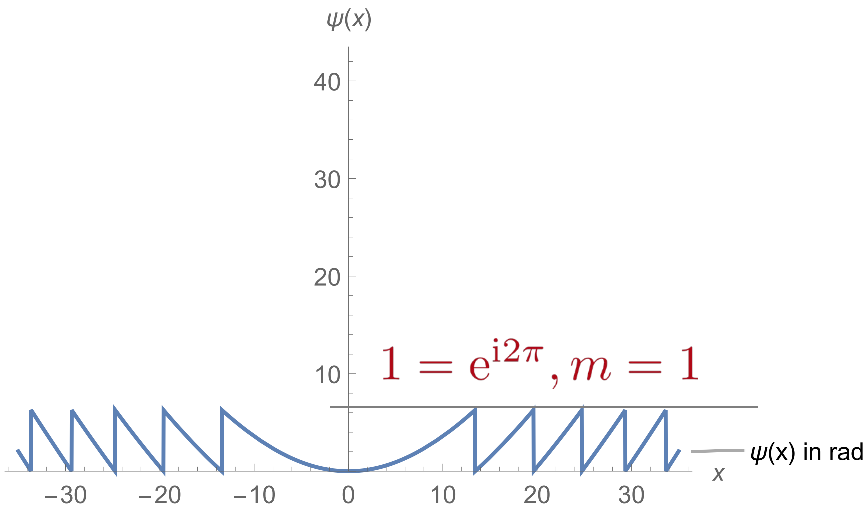




What Allows Flat Optics to Work?

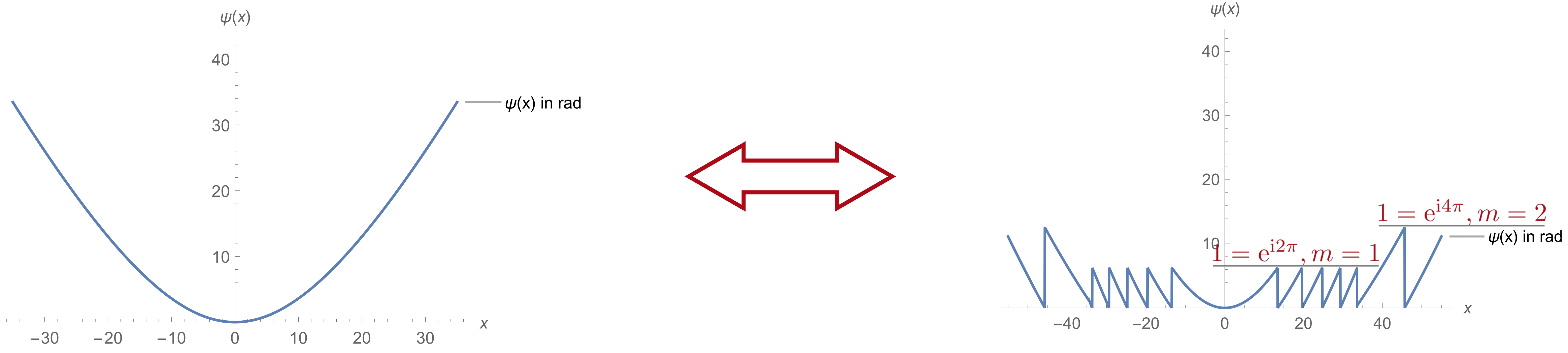
Example 1D wavefront phase





Segmented Phase Manipulation

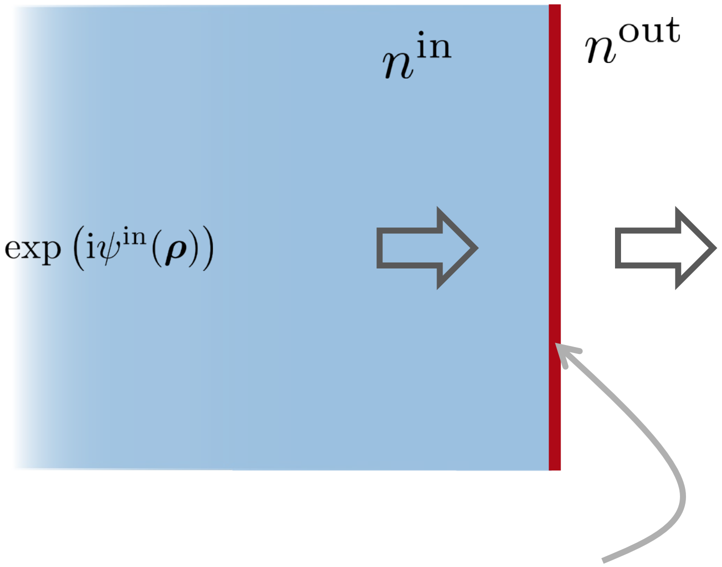
Example 1D wavefront phase



Wavefront Response by Flat Optics

Input field

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



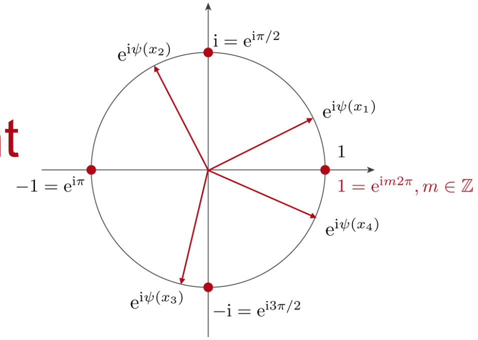
Output field

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

Wavefront phase response:

$$\psi^{\mathrm{out}}(\boldsymbol{\rho}) = \psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi^{\mathrm{d}}(\boldsymbol{\rho})$$

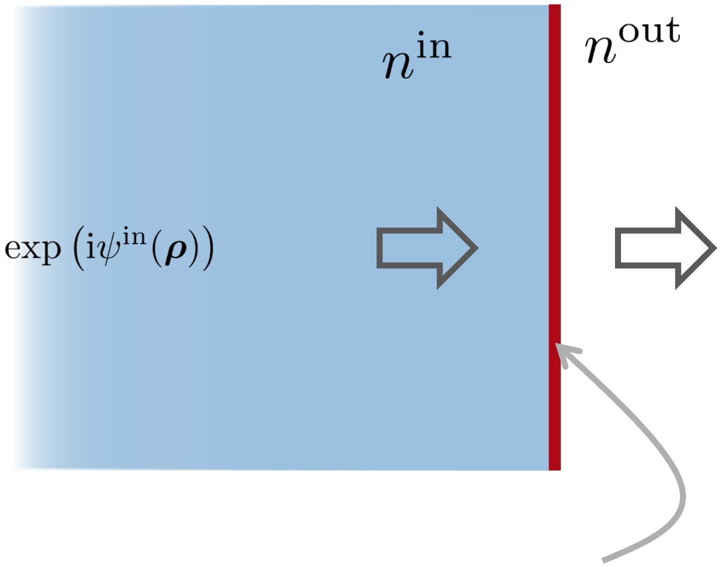
How is it possible to realize a wavefront phase response by a **THIN** layer?



Wavefront Response of Surface + Structured Layer

Input field

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



Output field

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

Wavefront phase response:

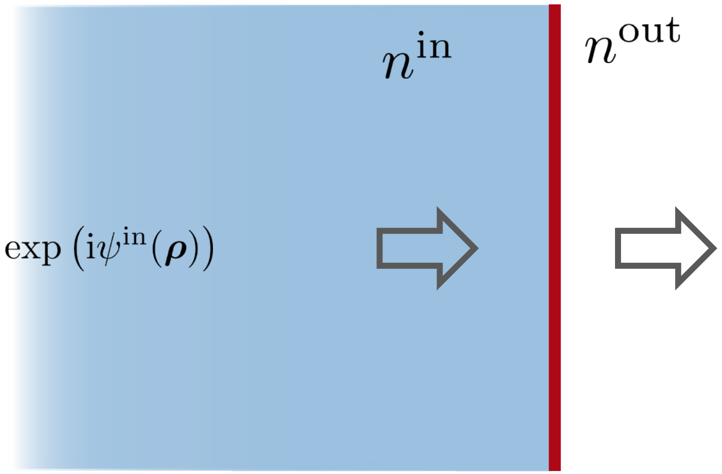
$$\psi^{\mathrm{out}}(\boldsymbol{\rho}) = \psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi^{\mathrm{d}}(\boldsymbol{\rho})$$

What effects can be used to realize a wavefront phase response by a surface + structured layer?

Vectorial Field Response Operator: Integral

Input field

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



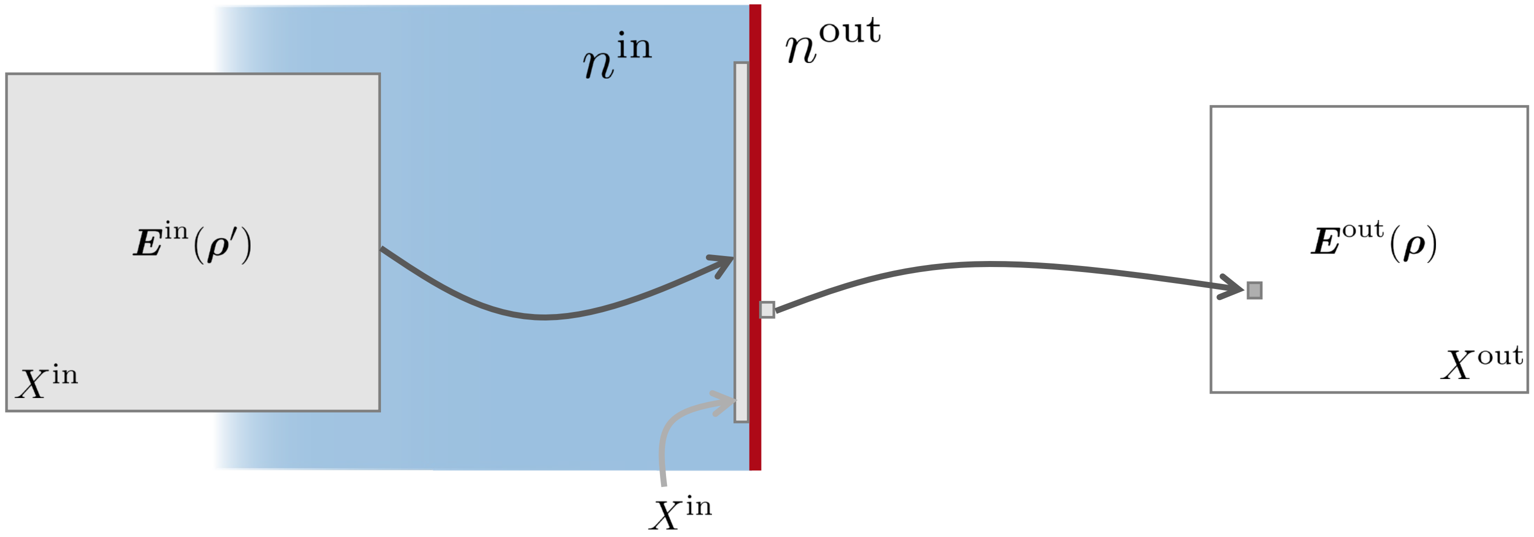
Output field

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

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

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

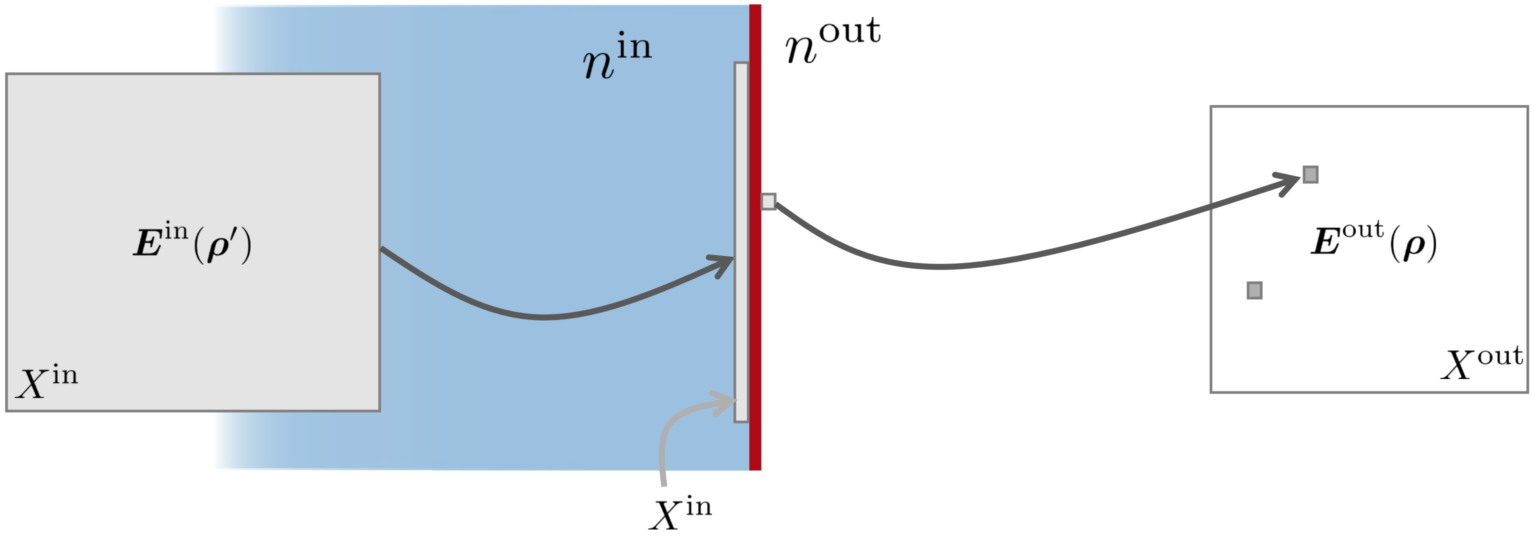
Vectorial Field Response Operator: Integral



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

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

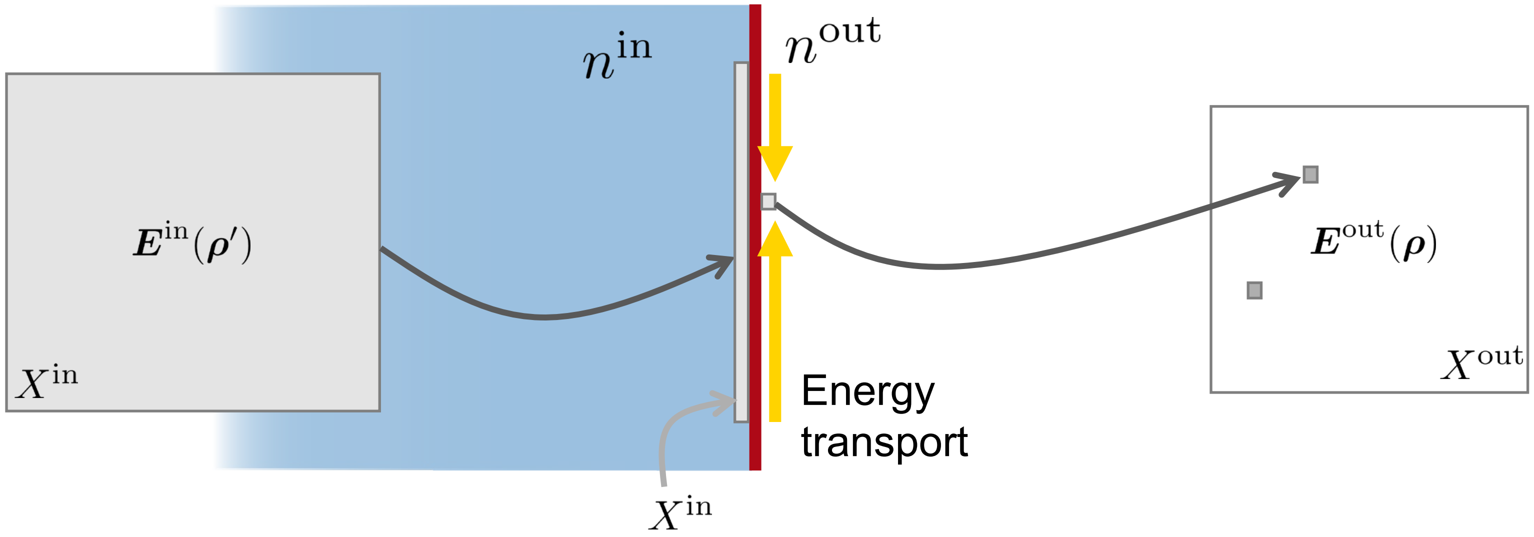
Vectorial Field Response Operator: Integral



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

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

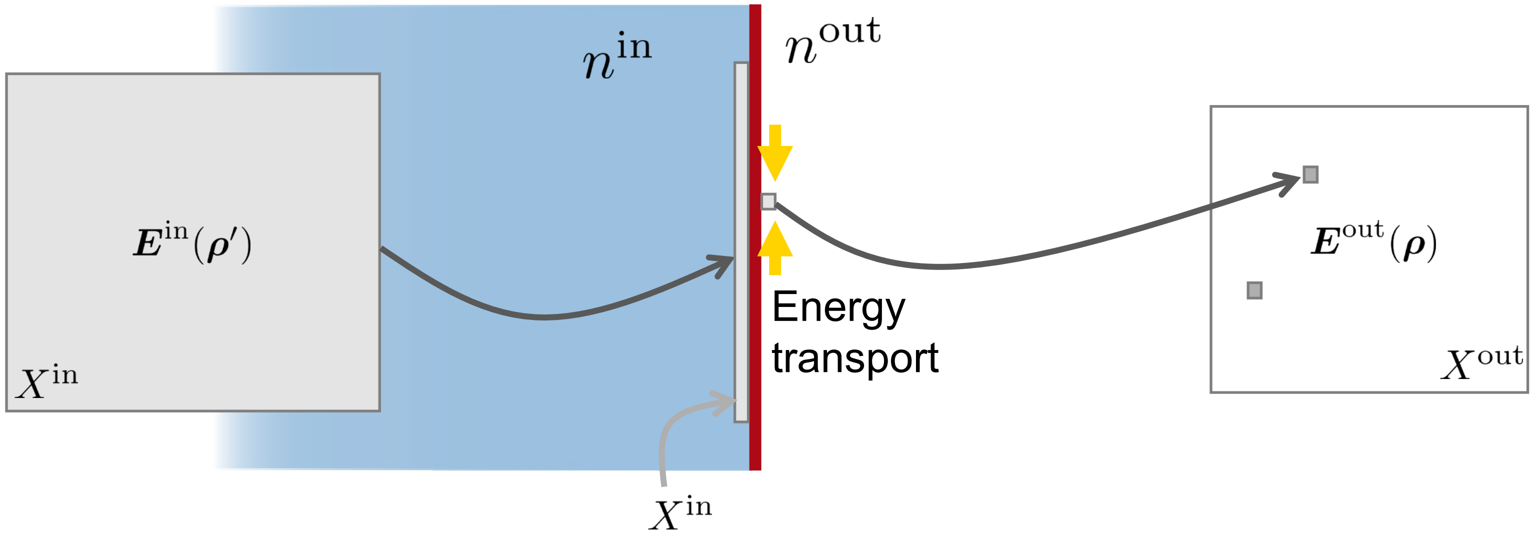
Vectorial Field Response Operator: Integral



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

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

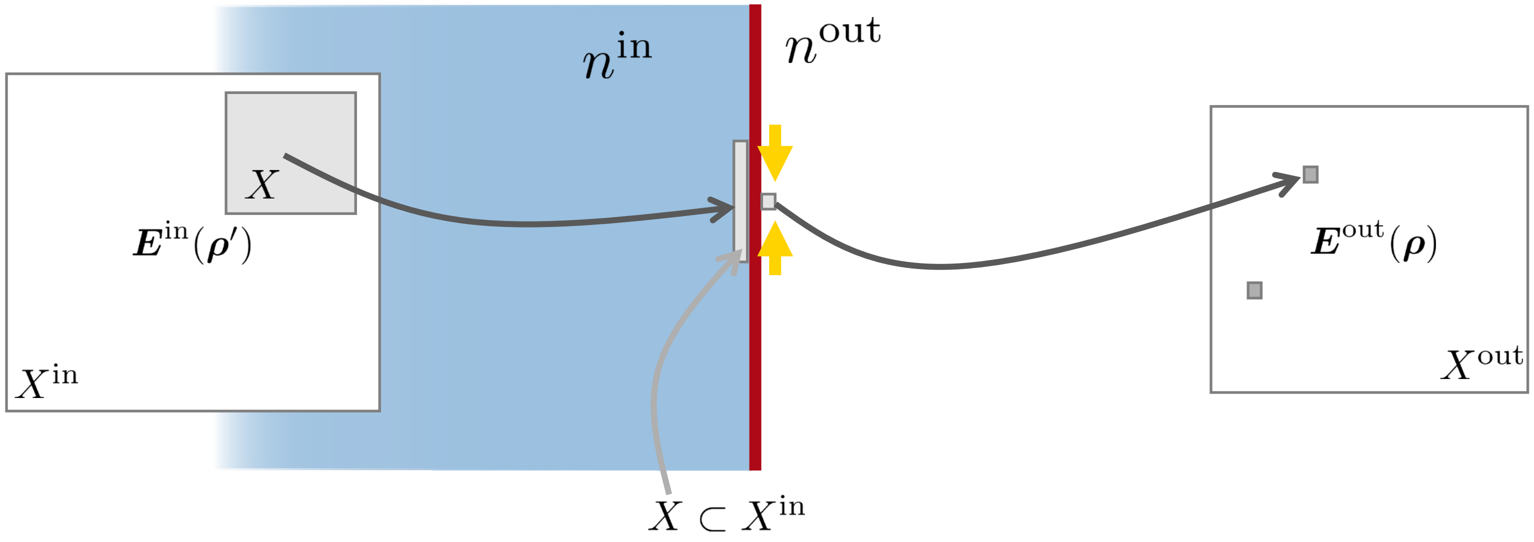
Vectorial Field Response Operator: Integral



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

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

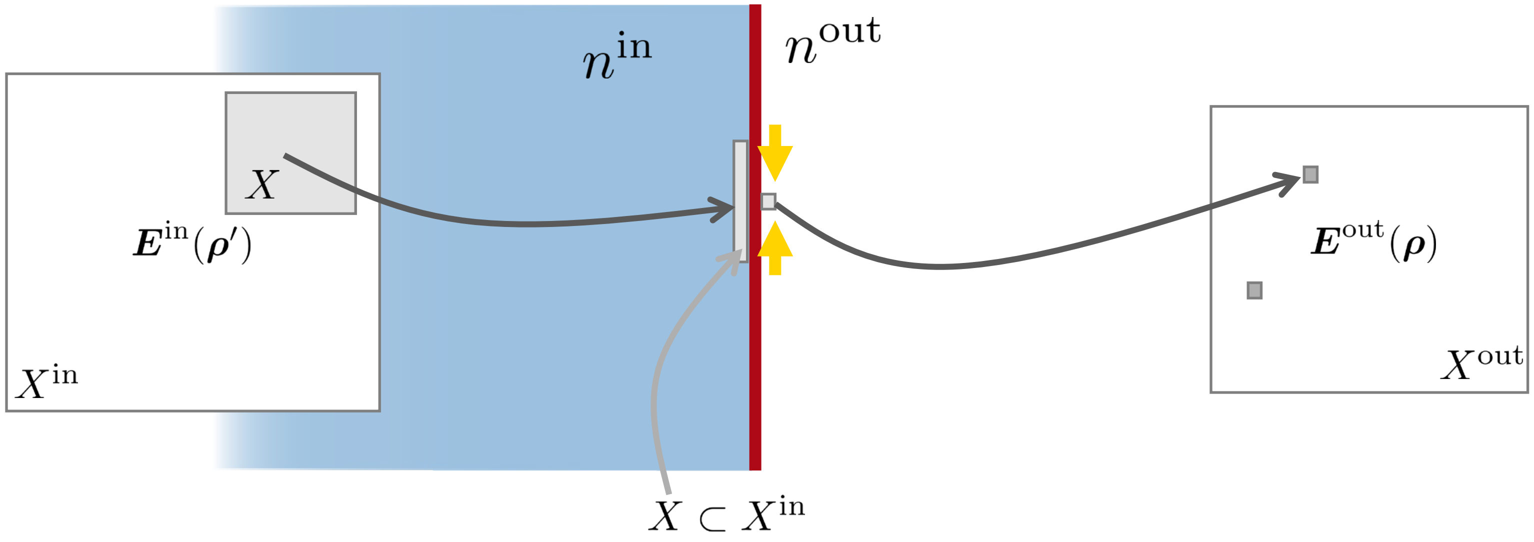
Vectorial Field Response Operator: Local Integration



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

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

Vectorial Field Response Operator: Local Integration



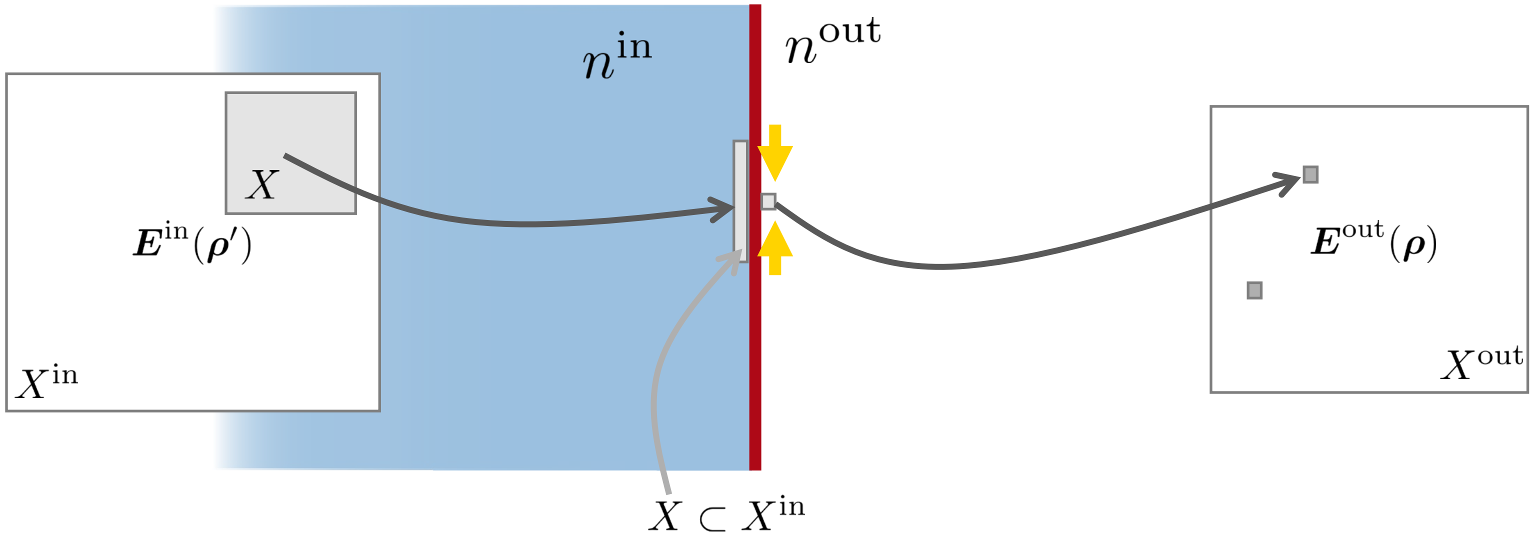
$$\boldsymbol{E}^{\text{out}}(\boldsymbol{\rho}) = \mathcal{B}(\boldsymbol{\rho}' \mapsto \boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}'))(\boldsymbol{\rho})$$
$$= \int\int_{X \subset X^{\text{in}}} \mathbf{B}(\boldsymbol{\rho}, \boldsymbol{\rho}') \boldsymbol{E}^{\text{in}}(\boldsymbol{\rho}')\, \mathrm{d}x'\,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

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

VirtualLab Fusion 2021

Local use of FMM/RCWA tested and in preparation

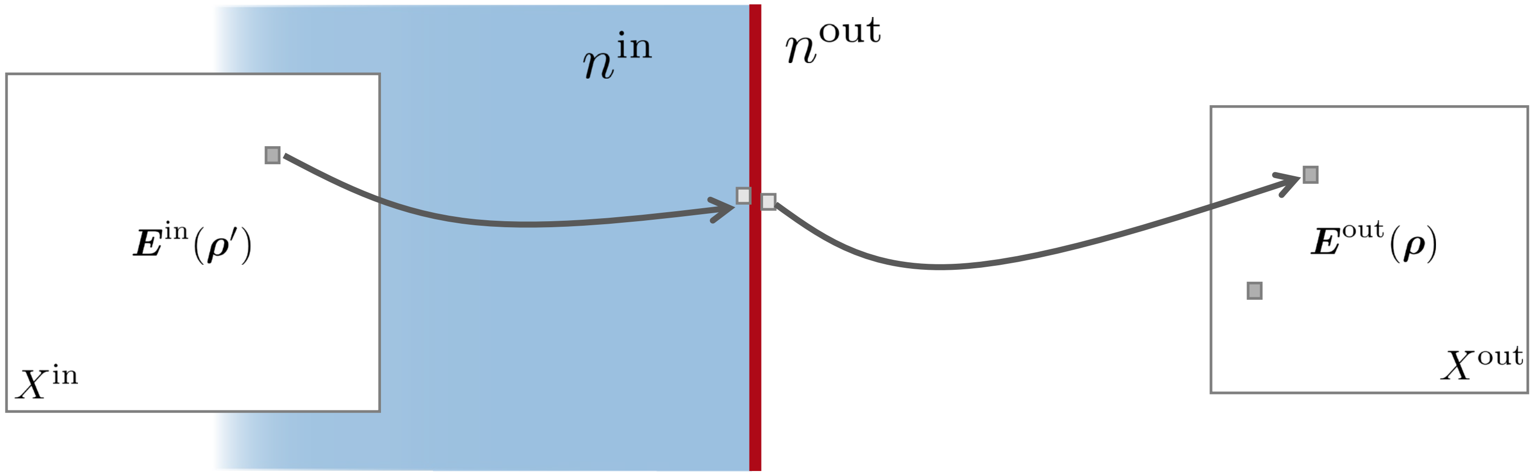
Vectorial Field Response Operator: Local Integration



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

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

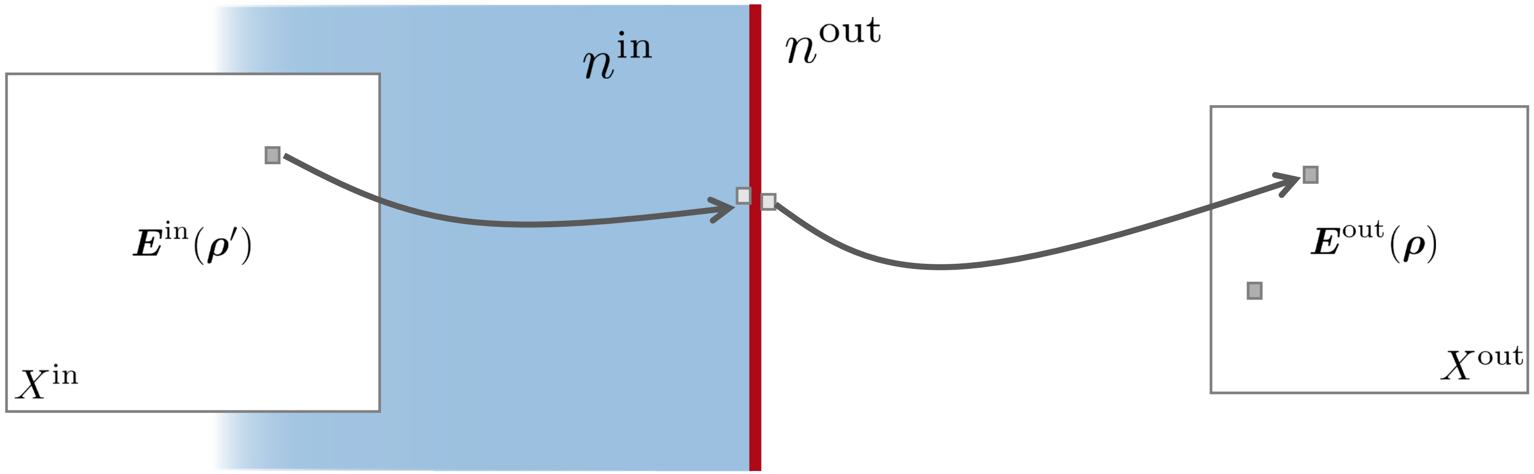
Vectorial Field Response Operator: Pointwise



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

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

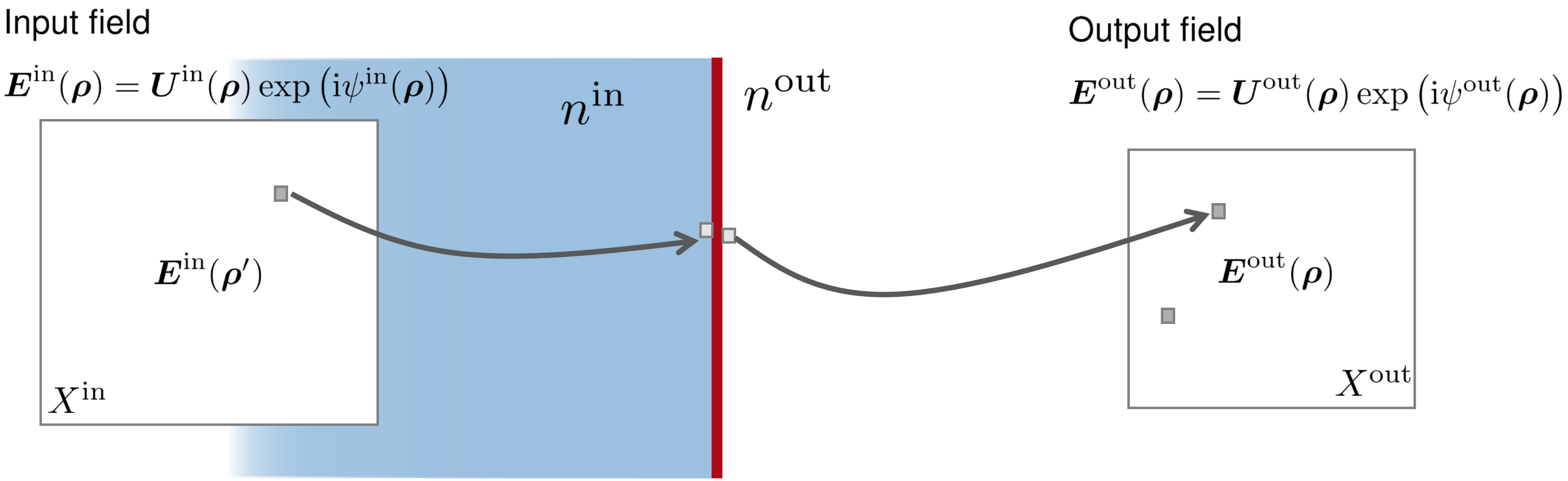
Vectorial Field Response: Pointwise



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

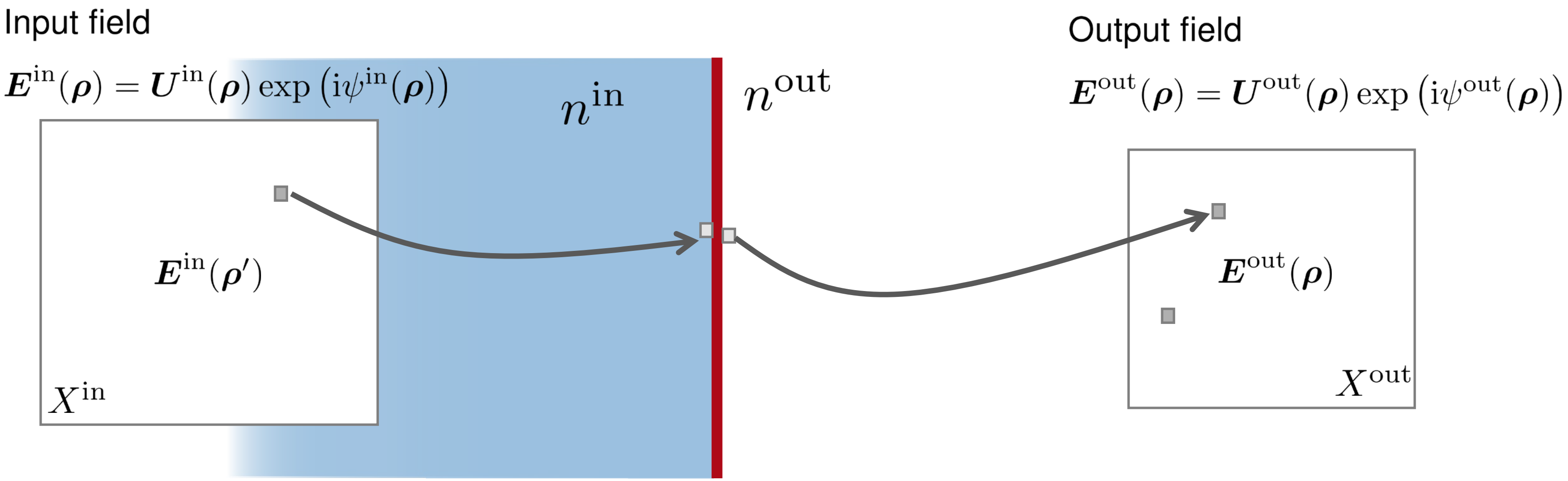
Vectorial Field Response: Pointwise



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

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

Vectorial Field Response: Pointwise



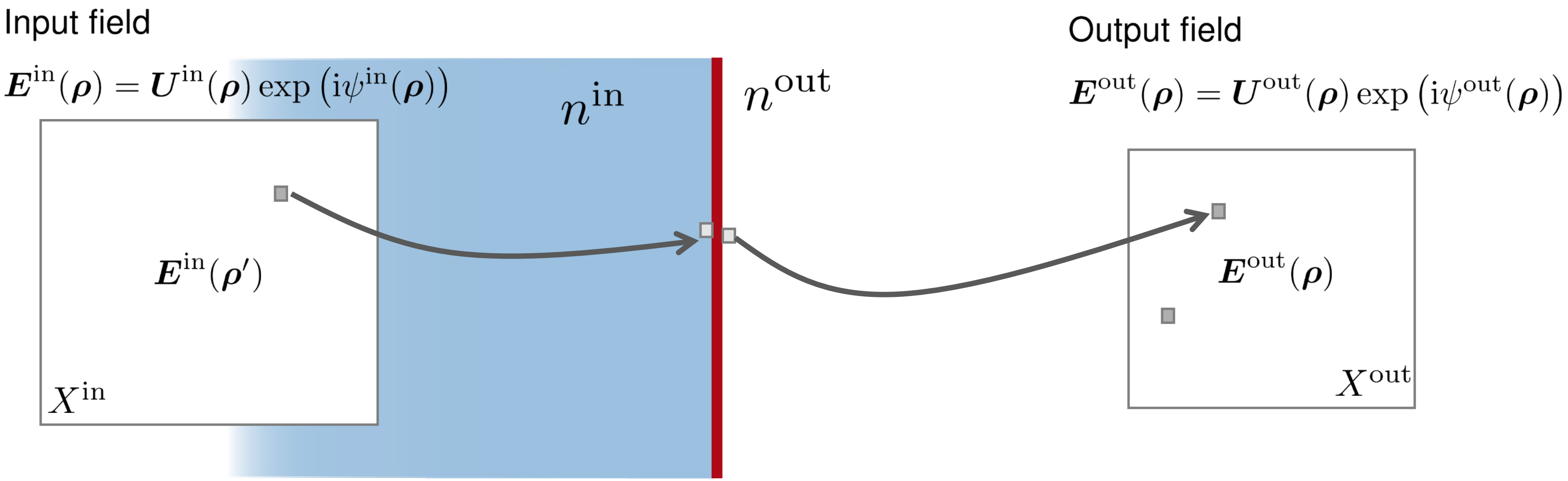
U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

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

Basic arguments and methods remain valid for

- Curved surfaces
- Transmission and reflection

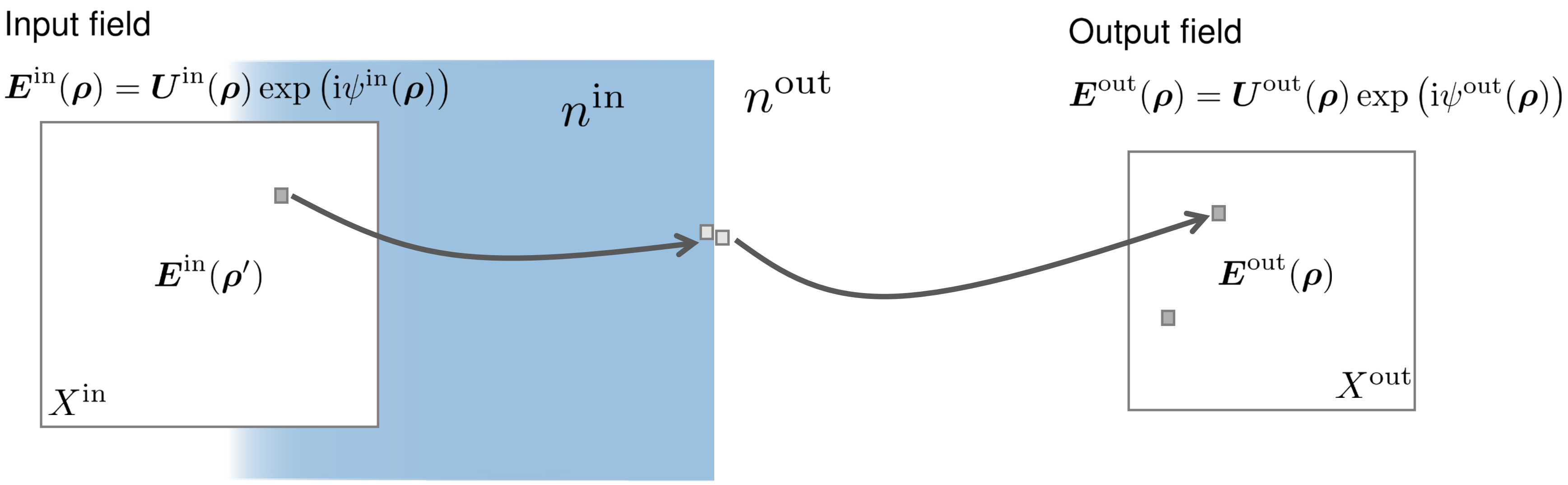
Vectorial Field Response: Surface w/o Layer



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

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

Vectorial Field Response: Surface w/o Layer

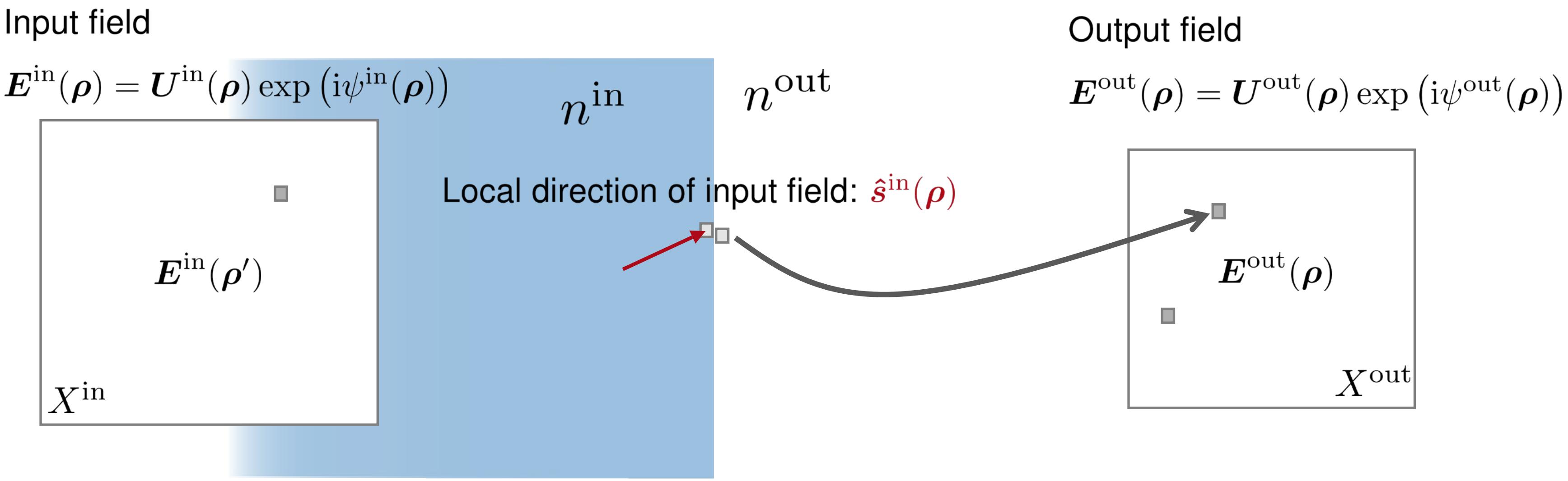


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}')\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

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

- Response given by Fresnel’s equations
- Field response: S matrix

Vectorial Field Response: Surface w/o Layer



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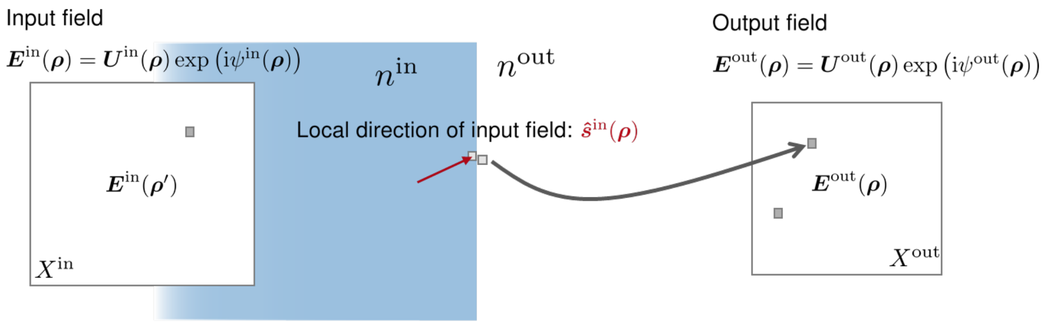
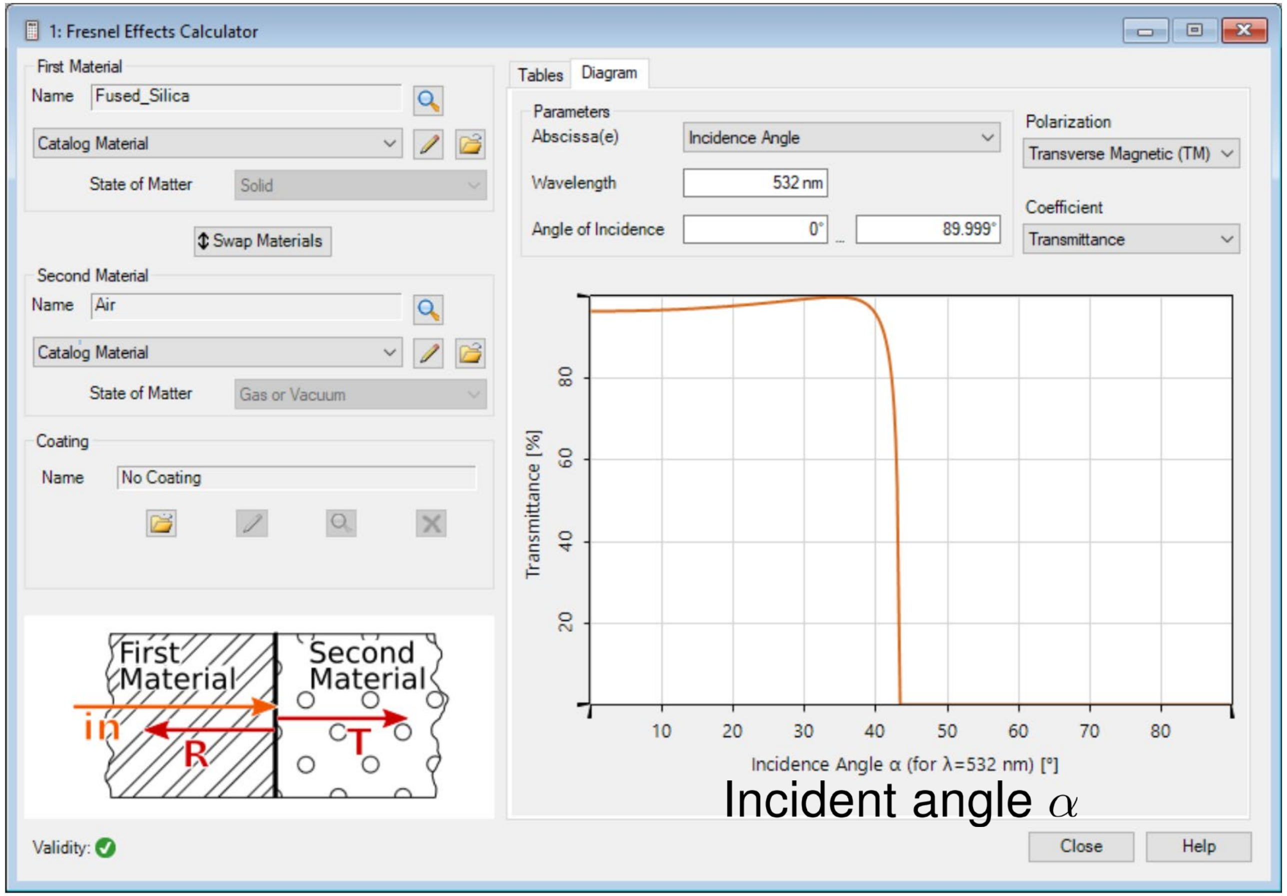
Wavefront phase response: $\psi^{\mathrm{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho}')) \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho})$

- Response given by Fresnel's equations
- Field response: S matrix

Vectorial Field Response: Surface w/o Layer

$\underline{\mathbf{b}}(\alpha)U^{\text{in}} \mapsto |U^{\text{out}}|$ (TM mode) $\Rightarrow$ Transmittance $T(\alpha)$



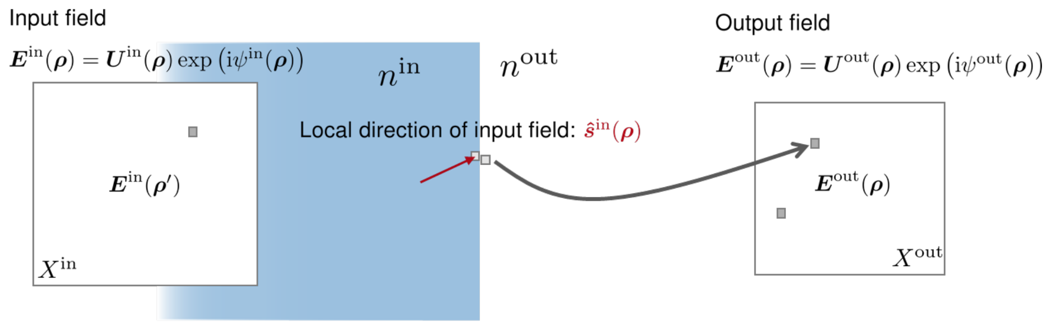


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\text{in}}(\boldsymbol{\rho}'))\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

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

- Response given by Fresnel's equations
- Field response: S matrix

Vectorial Field Response: Surface w/o Layer

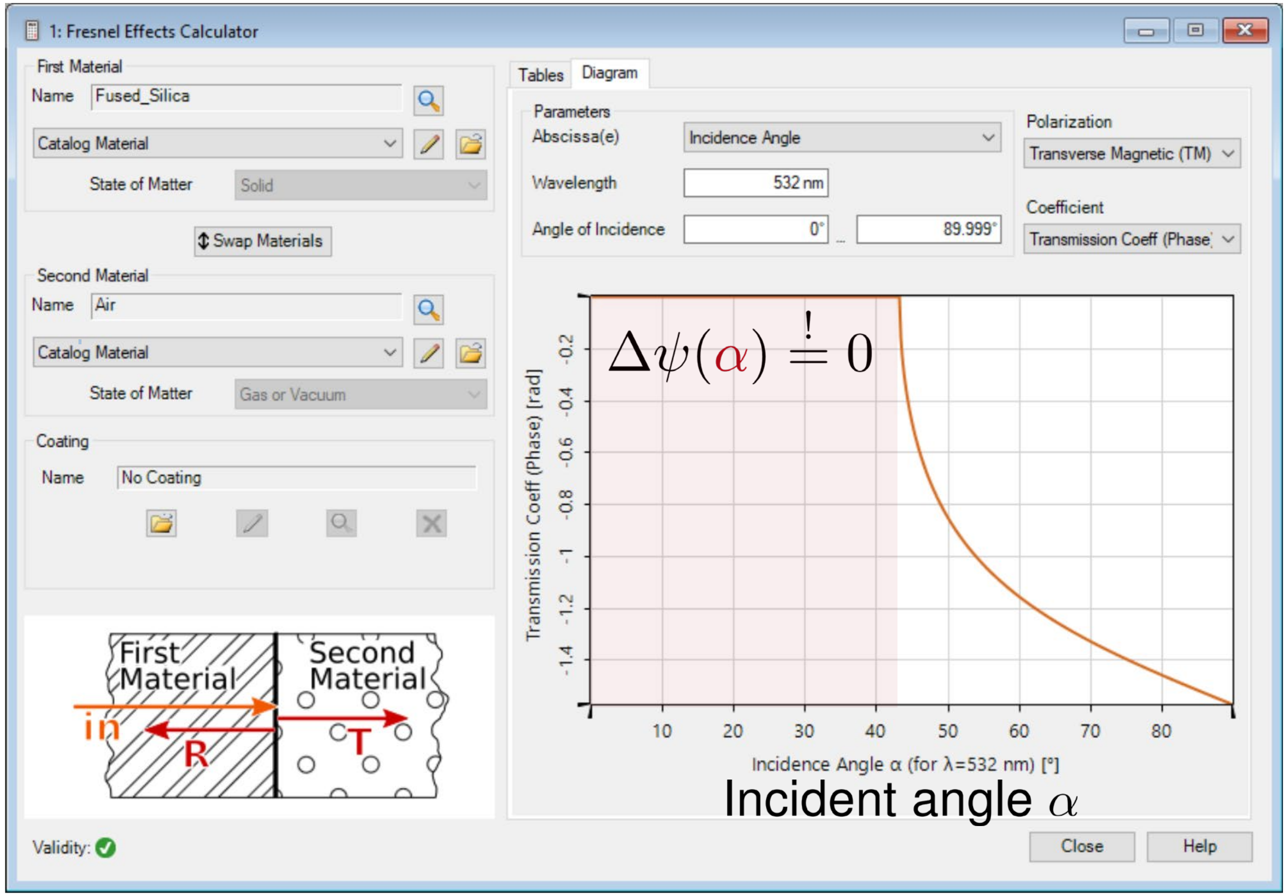


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\text{in}}(\boldsymbol{\rho}'))\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

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

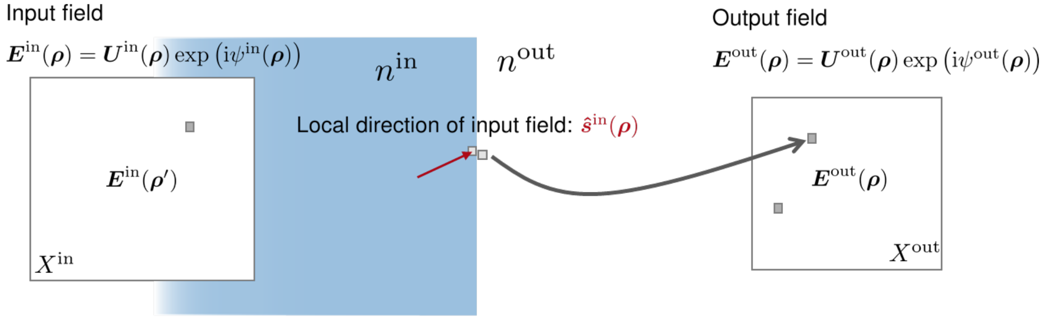
- Response given by Fresnel's equations
- Field response: S matrix

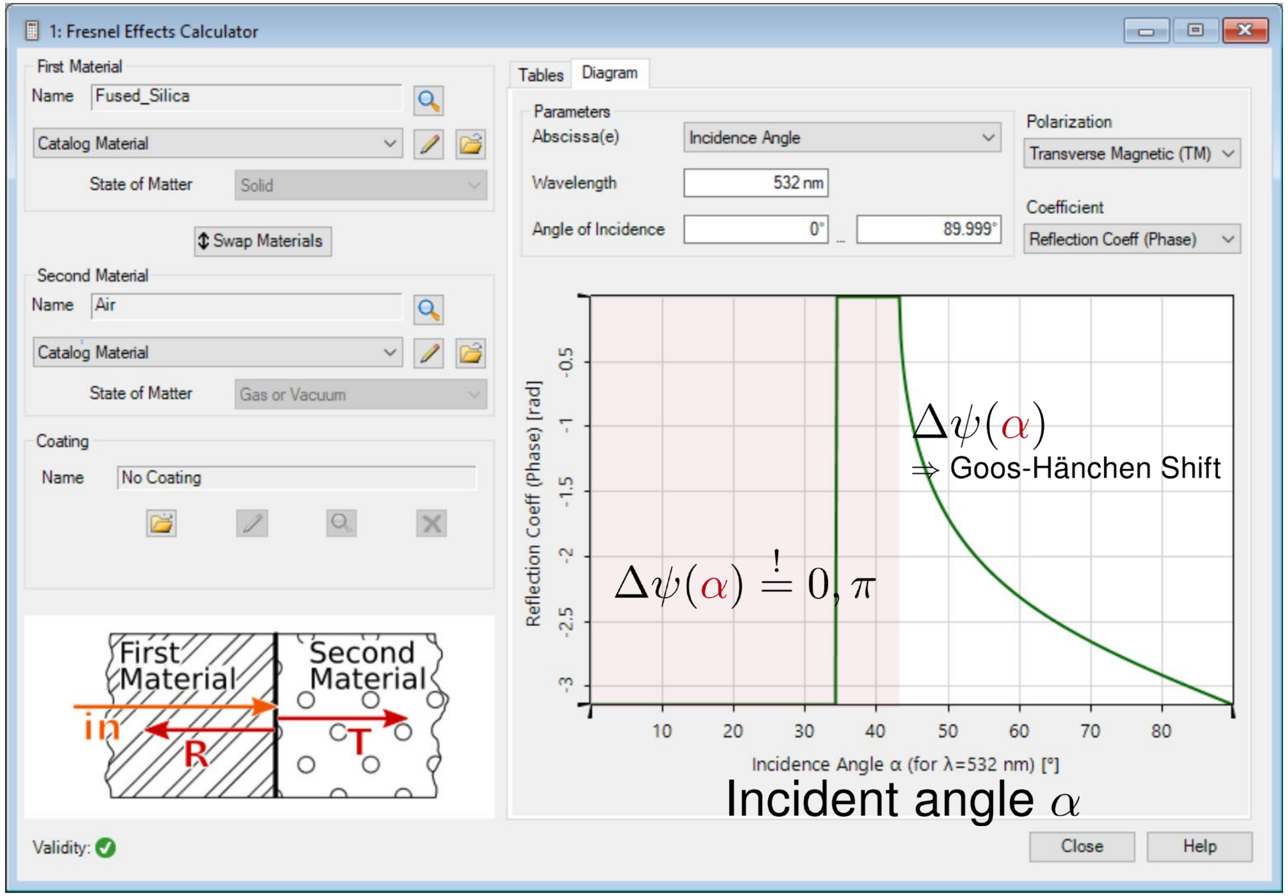
Transmission: $\Delta\psi(\alpha)$ (TM mode)



Vectorial Field Response: Surface w/o Layer

Reflection: $\Delta\psi(\alpha)$ (TM mode)





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

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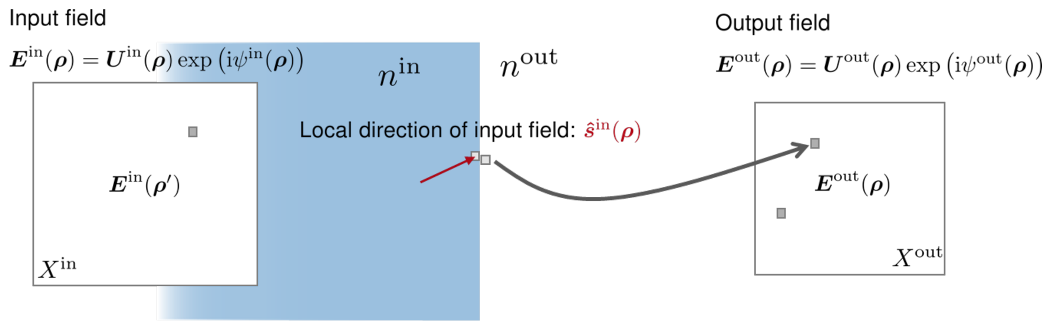
- Response given by Fresnel's equations
- Field response: S matrix

Vectorial Field Response: Surface w/o Layer



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

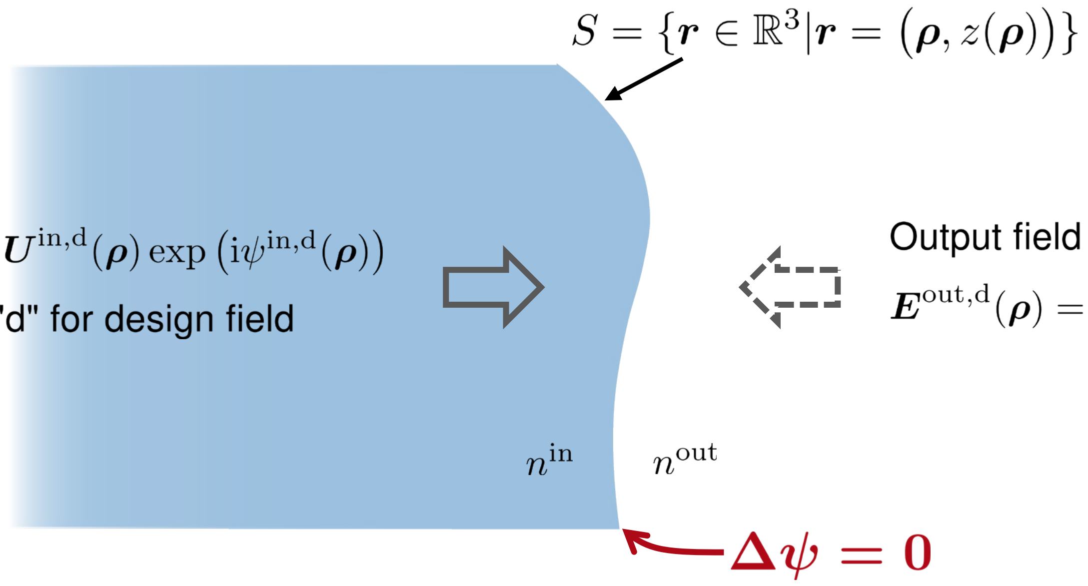
Wavefront phase response: $\psi^{\rm in}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\rm in}(\boldsymbol{\rho}')) \mapsto \psi^{\rm out}(\boldsymbol{\rho})$

Surfaces between Dielectrics (Transmisson):

$$\Delta\psi \stackrel{!}{=} 0$$

- Wavefront response control not possible by surface effect!
- Wavefront control w/o structured layer requires CURVED surfaces.

Freeform Surface Design by Inverse Propagation



Input field

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

with index "d" for design field

Output field

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

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

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

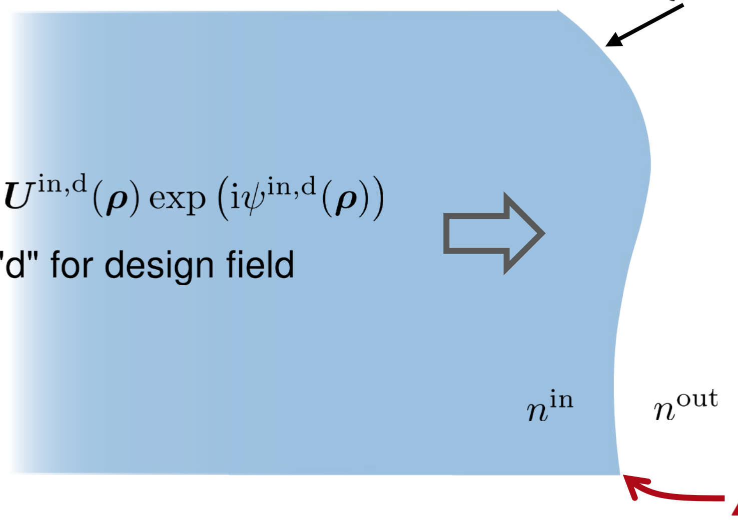
Freeform Surface Design by Inverse Propagation

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

Input field

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

with index "d" for design field



Output field

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

n^{in} n^{out}

$\boldsymbol{\Delta\psi = 0}$

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

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

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Freeform surface design algorithm w/o parametric optimization for single field scenario.

Available surface representations include:

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

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and flat optics components.

MODELING & EVALUATION

detectors and merit functions.

FURTHER OPTIMIZATION

- Freeform design

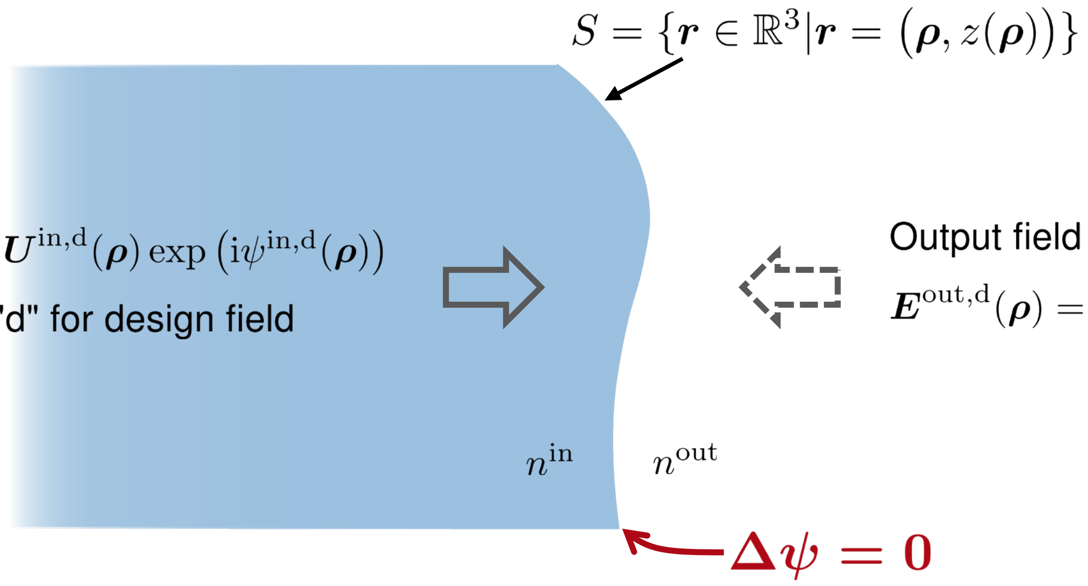
SYSTEM TOLERANCING

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.

Freeform Surface Design by Inverse Propagation



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

with index "d" for design field

Output field

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

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

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

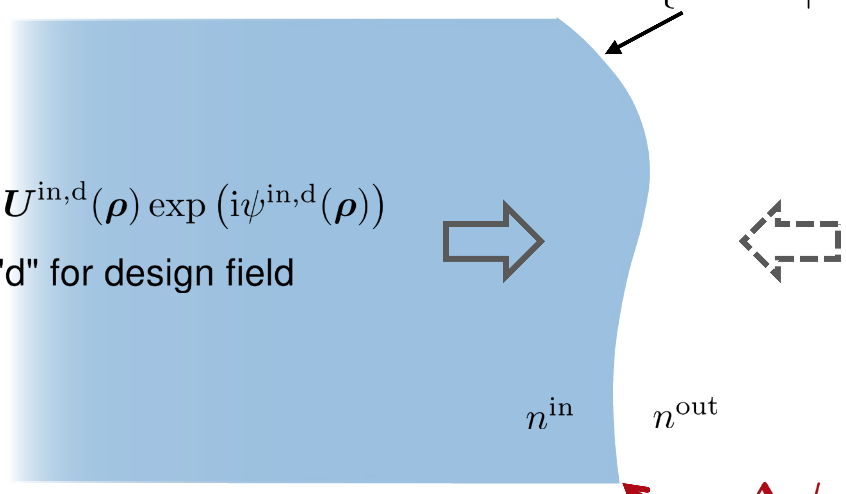
Segmented Component Design by Inverse Propagation

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

Input field

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

with index "d" for design field



Output field

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

$\boldsymbol{\Delta\psi = m\, 2\pi}$

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

$$\psi^{\text{out,d}}(\boldsymbol{r} \in S) - \psi^{\text{in,d}}(\boldsymbol{r} \in S) = \boxed{\Delta\psi(\boldsymbol{r} \in S) \overset{!}{=} m\, 2\pi}$$

Segmented Component Design by Inverse Propagation

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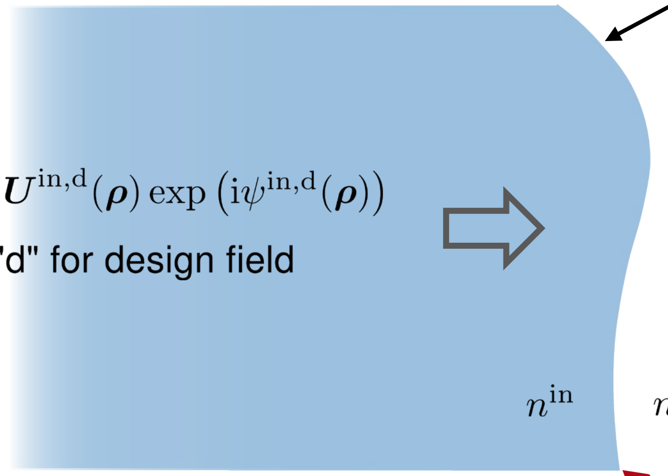
with index "d" for design field



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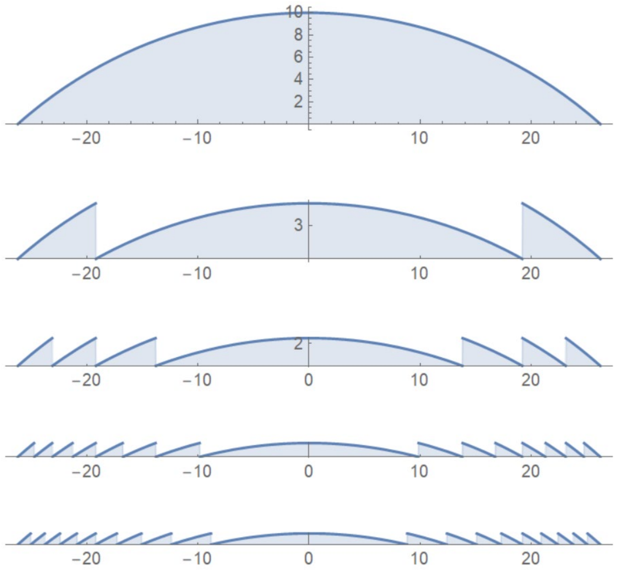

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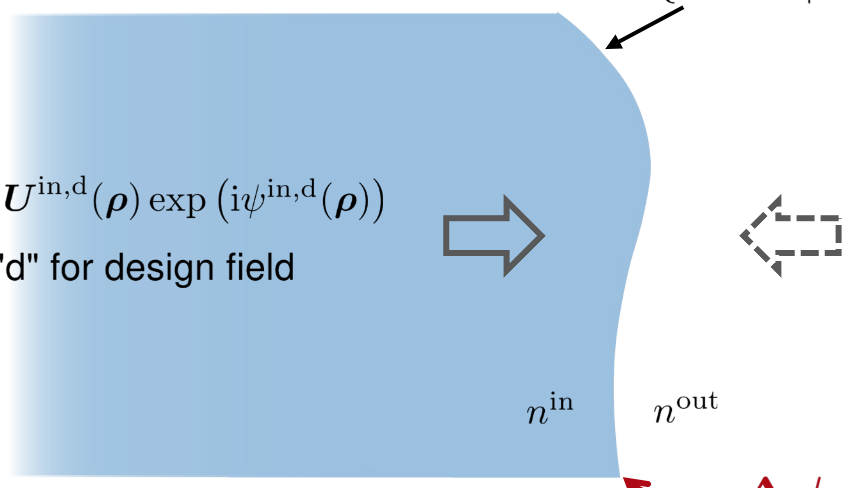

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$$\boldsymbol{\Delta\psi = m\, 2\pi}$$

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

$$\psi^{\mathrm{out,d}}(\boldsymbol{r} \in S) - \psi^{\mathrm{in,d}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} m\, 2\pi$$

Segmented Elements:

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

Holographic Optical Elements (HOE):

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

Segmented Component Design by Inverse Propagation

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

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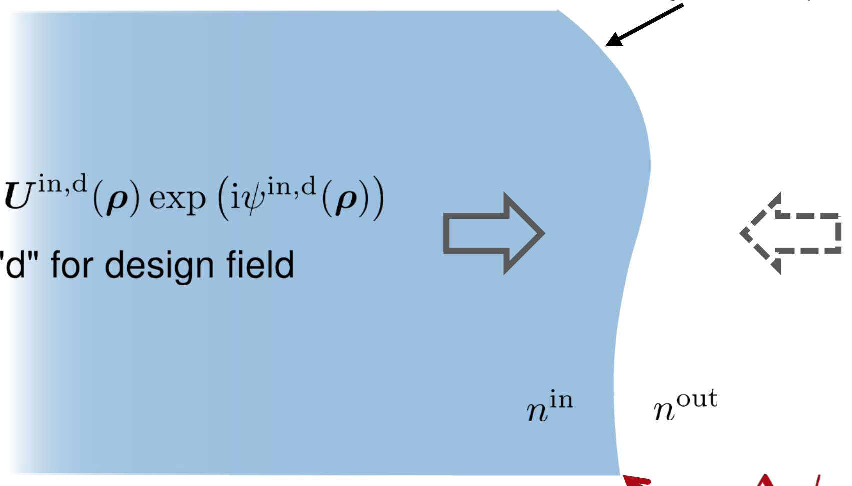
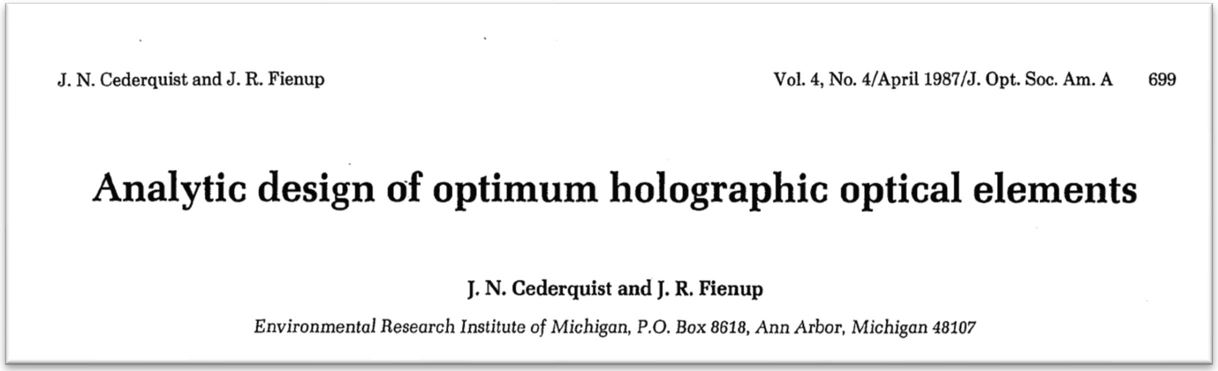
$\boldsymbol{E}^{\mathrm{in,d}}(\boldsymbol{\rho}) = \boldsymbol{U}^{\mathrm{in,d}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathrm{in,d}}(\boldsymbol{\rho})\right)$

with index "d" for design field





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

$$\boldsymbol{\Delta\psi = m\, 2\pi}$$

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

$$\psi^{\mathrm{out,d}}(\boldsymbol{r} \in S) - \psi^{\mathrm{in,d}}(\boldsymbol{r} \in S) = \boxed{\Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} m\, 2\pi}$$

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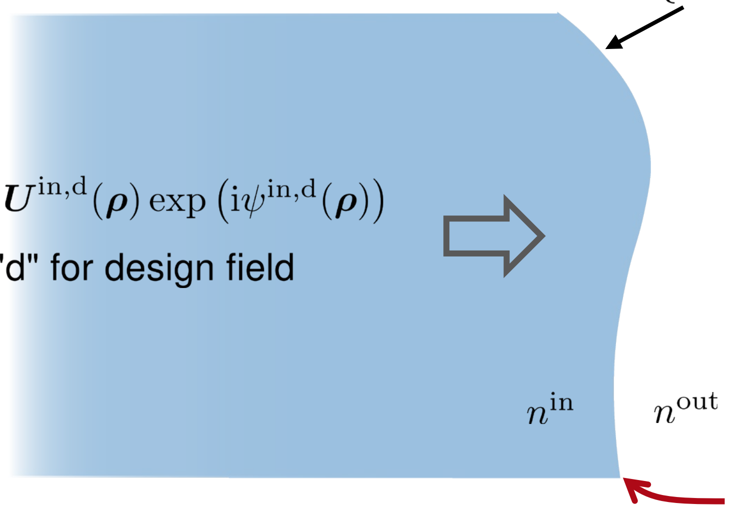
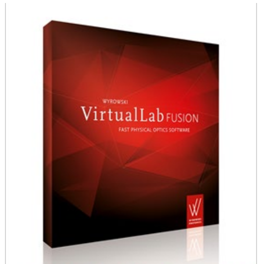
with index "d" for design field



Output field

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



VirtualLab Fusion 2021

$$\boldsymbol{\Delta\psi = m\,2\pi}$$

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

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Segmented Elements:

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

Holographic Optical Elements (HOE):

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

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and flat optics components.

MODELING & EVALUATION

merit functions.

FURTHER OPTIMIZATION

- Freeform design
- Segmented components
- Fresnel lenses
- HOE

SYSTEM TOLERANCING

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

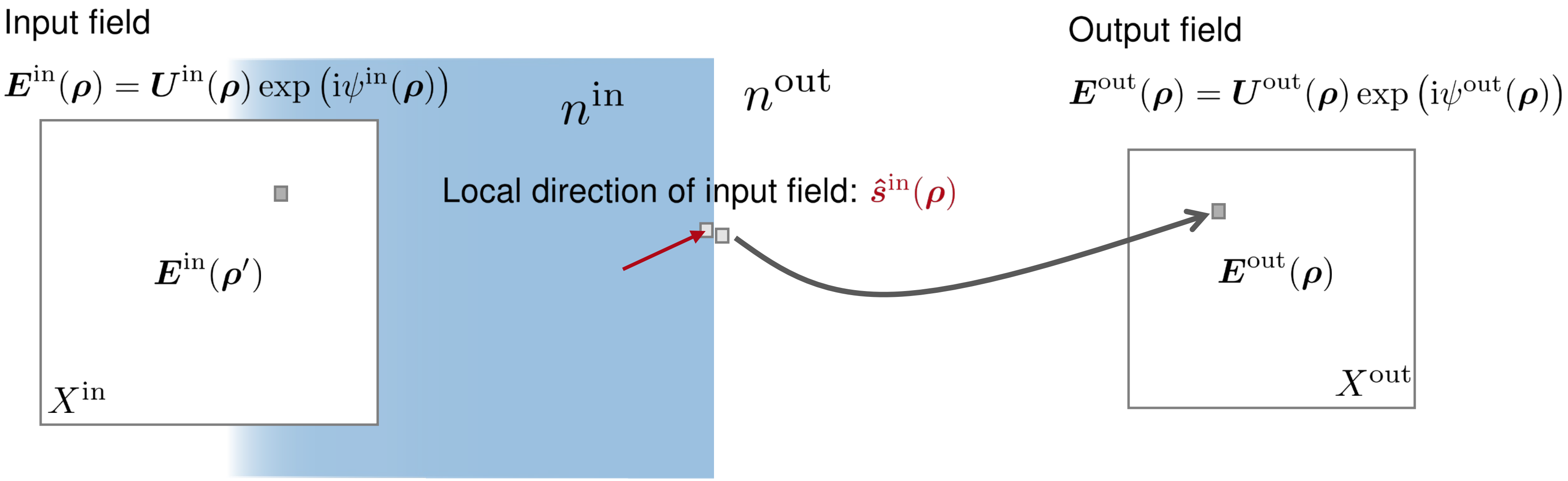
FABRICATION DATA

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

All surfaces are designed with the same technique and follow the same physical principles: Wavefront phase response is realized by local optical path length differences!

⇨ Phase response by surface effects?

Vectorial Field Response: Surface w/o Layer



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

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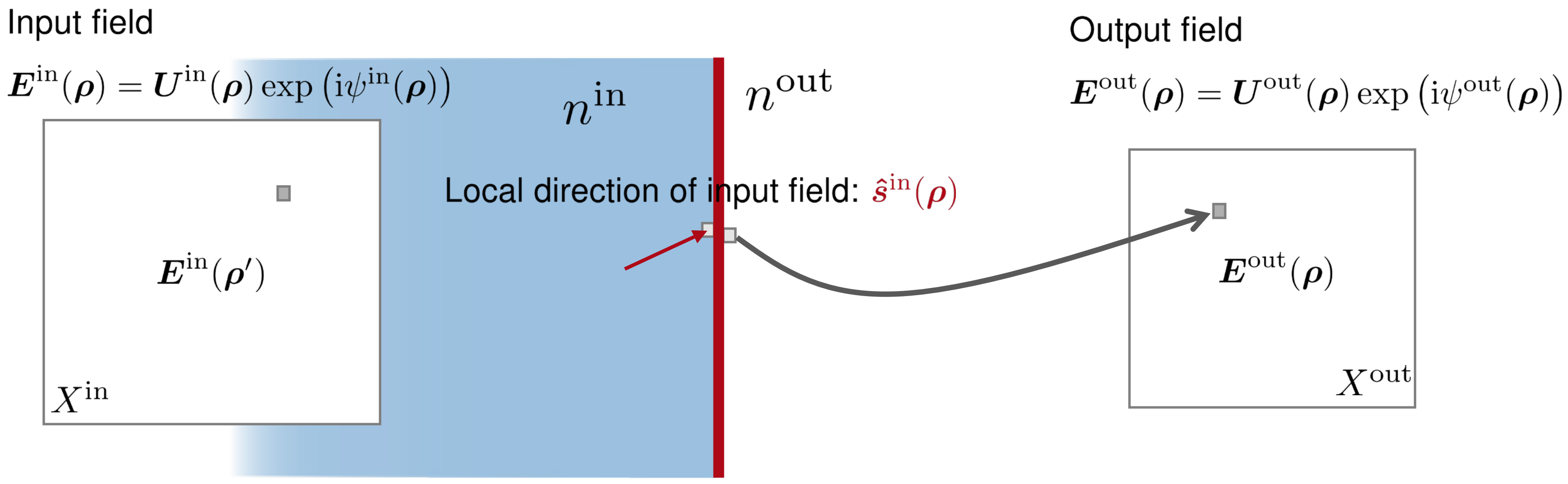
- Response given by Fresnel's equations
- Field response: S matrix

Vectorial Field Response: Surface with Layer



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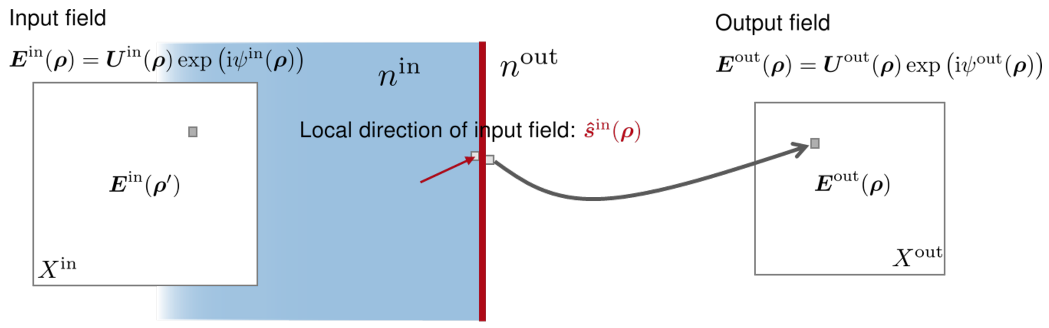
Wavefront phase response: $\psi^{\mathrm{in}}(\boldsymbol{\rho}') + \Delta\psi(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho}'))) \mapsto \psi^{\mathrm{out}}(\boldsymbol{\rho})$

- Field response: S matrix

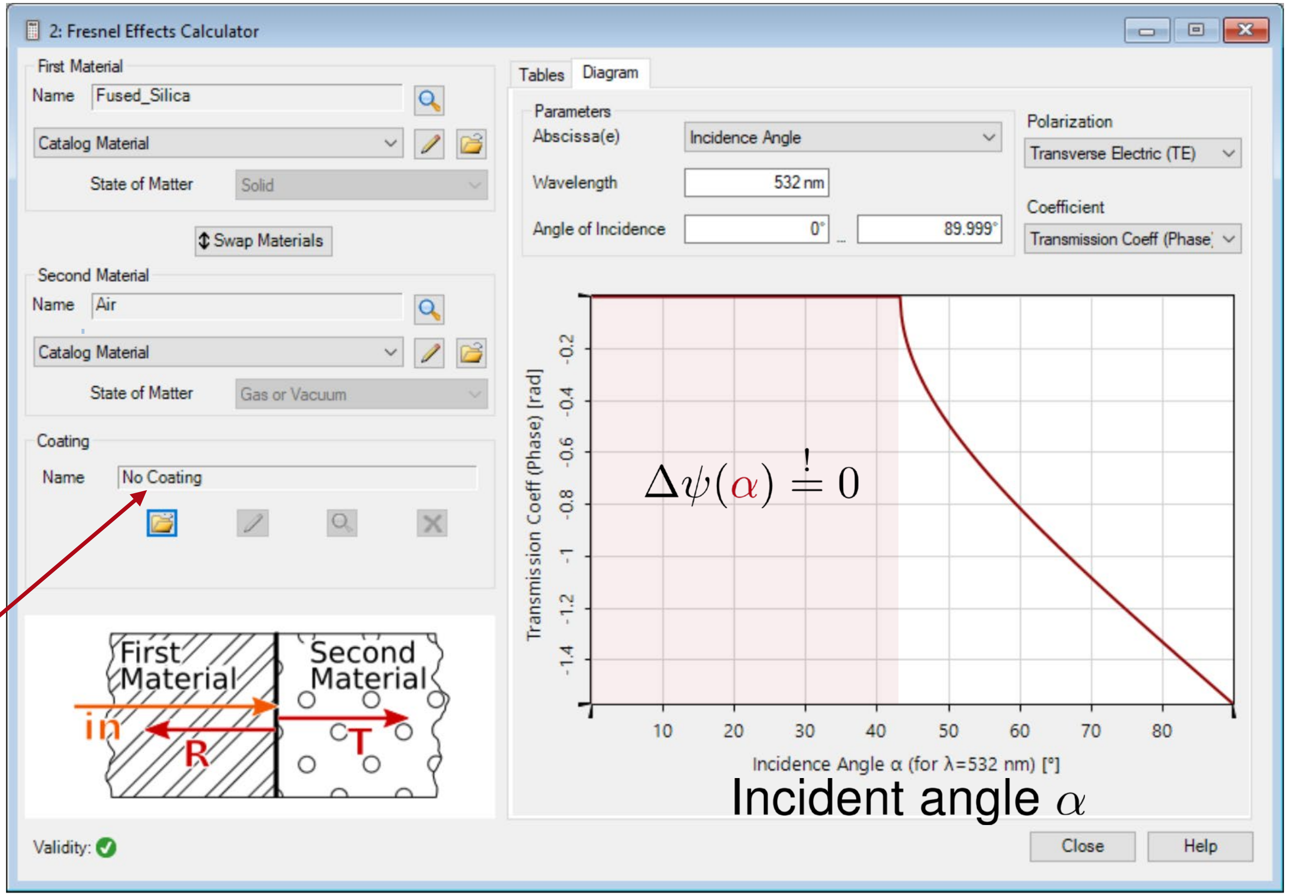
Wavefront Response: Surface w/o Coating



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

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

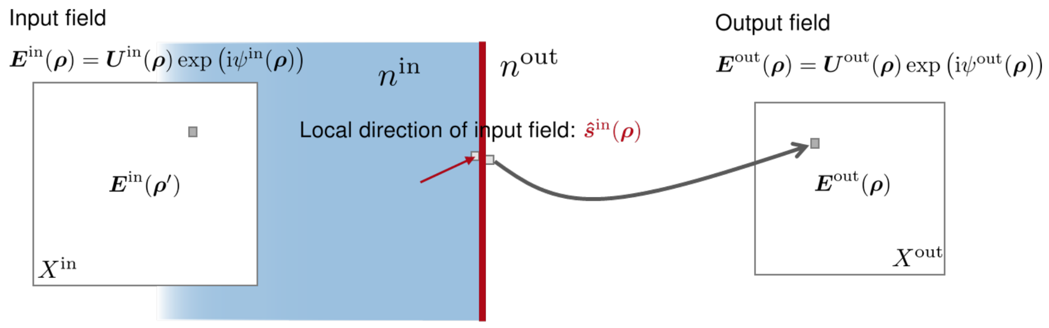
Transmission: $\Delta\psi(\alpha)$ (TE mode)



w/o layer

Incident angle α

Wavefront Response: Surface with Coating

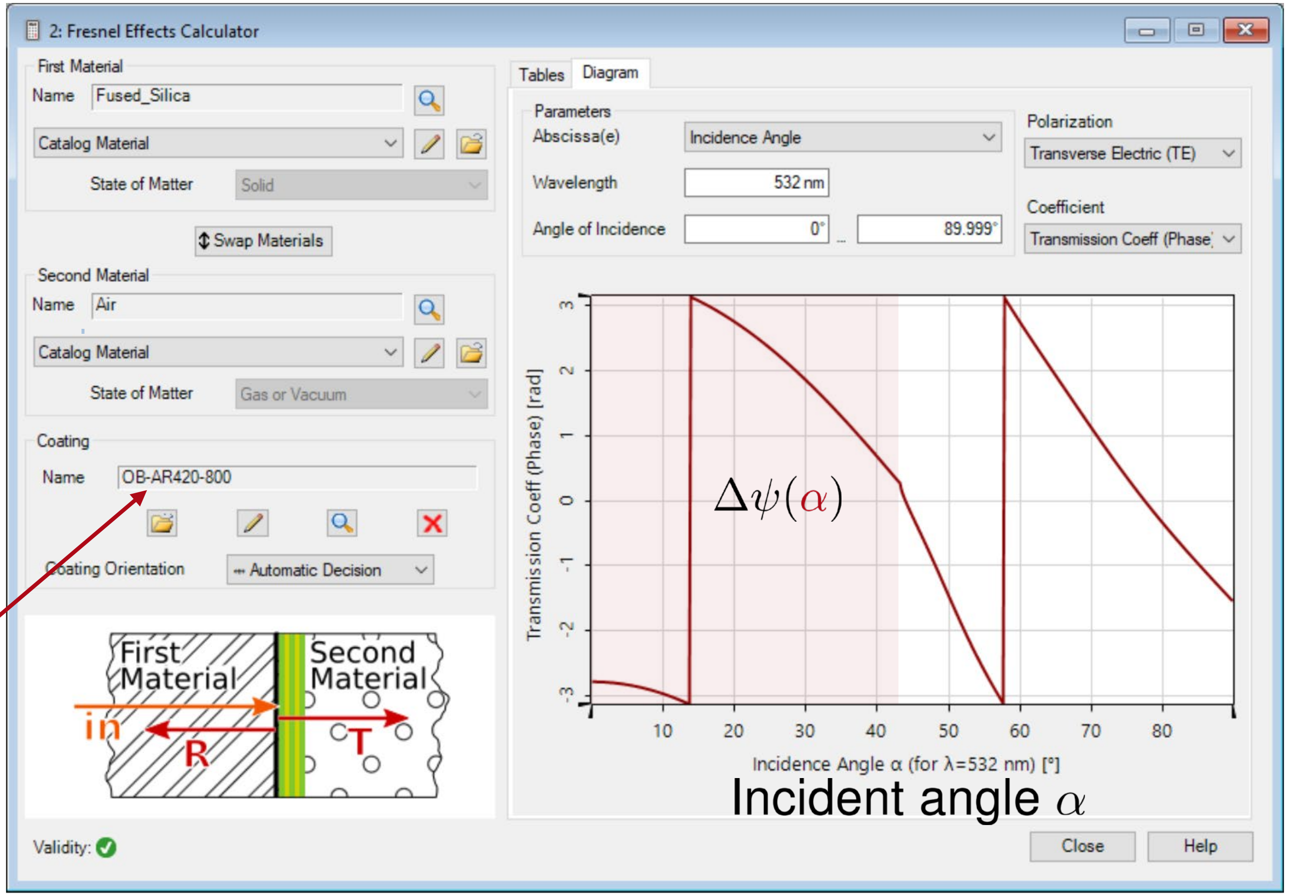


U-field response: $\underline{\mathbf{b}}(\boldsymbol{\rho}', \hat{\boldsymbol{s}}^{\text{in}}(\boldsymbol{\rho}'))\boldsymbol{U}^{\text{in}}(\boldsymbol{\rho}') \mapsto \boldsymbol{U}^{\text{out}}(\boldsymbol{\rho})$

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

Transmission: $\Delta\psi(\alpha)$ (TE mode)

With layer



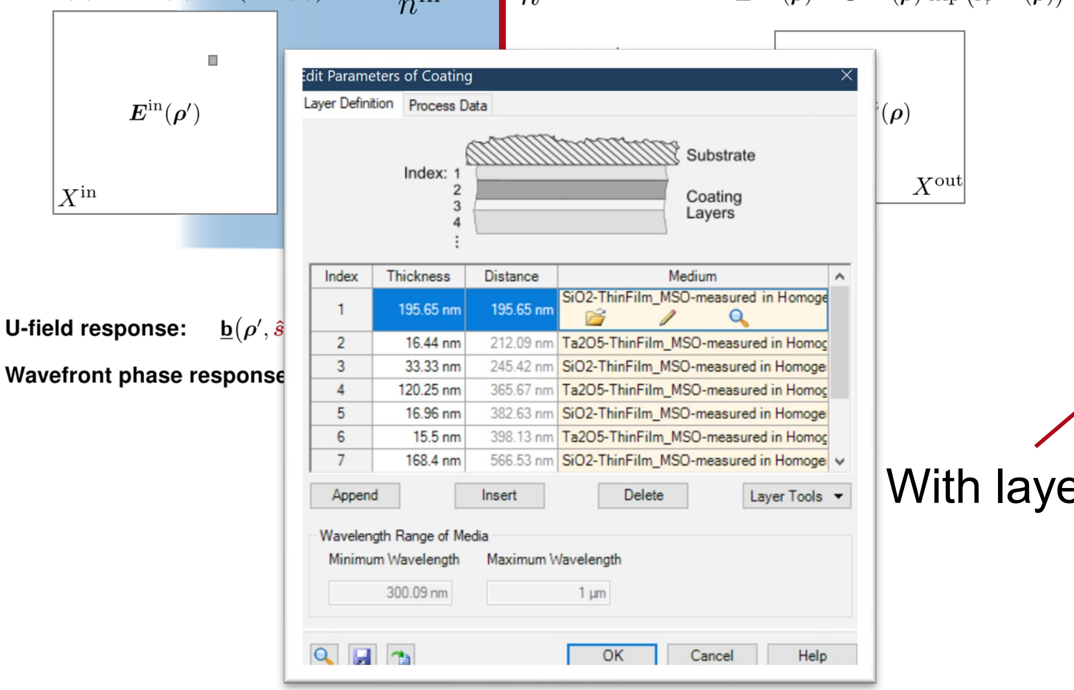
Wavefront Response: Surface with Coating

Input field

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

Output field

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

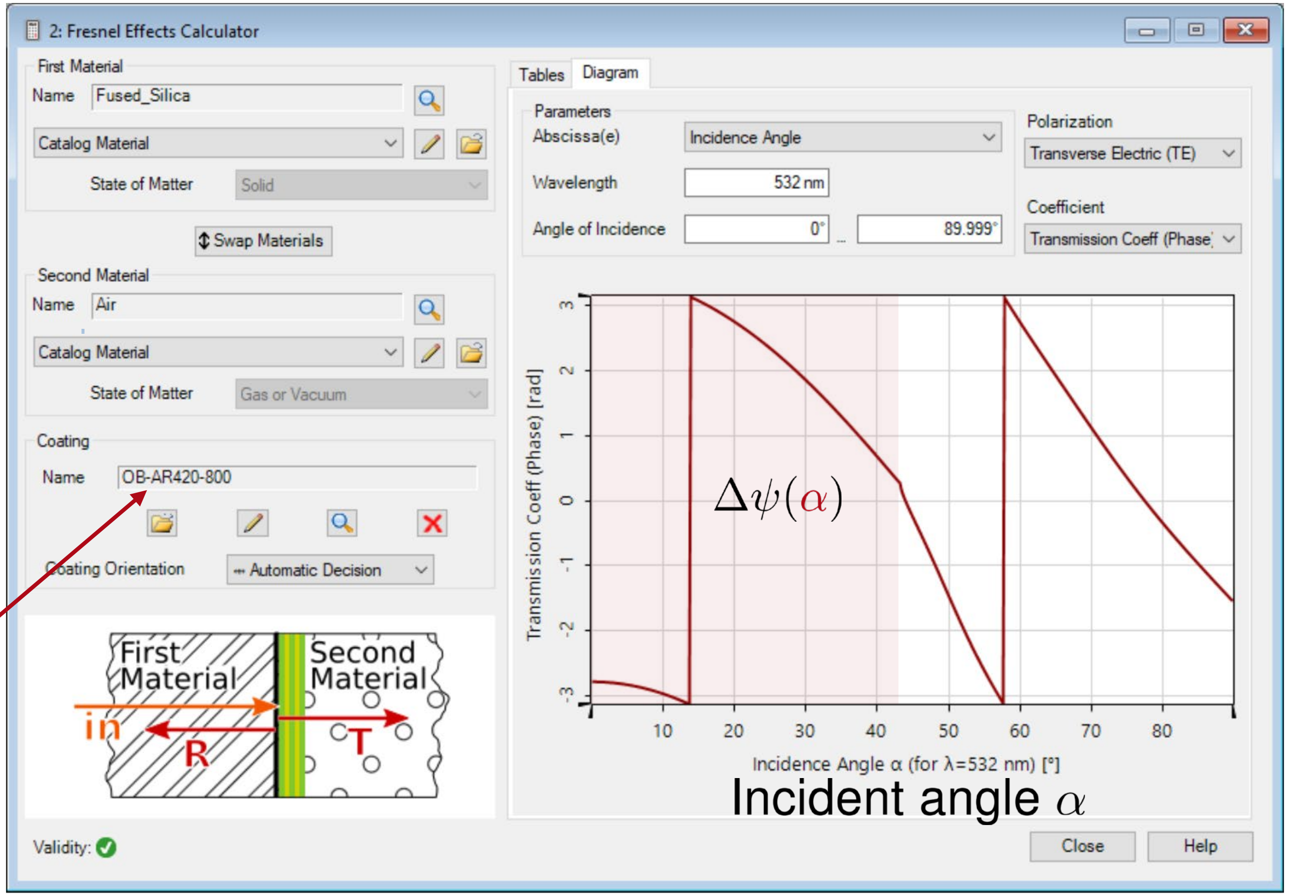


U-field response: $\underline{\mathbf{b}}(\rho', \hat{s}$

Wavefront phase response

With layer

Transmission: $\Delta\psi(\alpha)$ (TE mode)

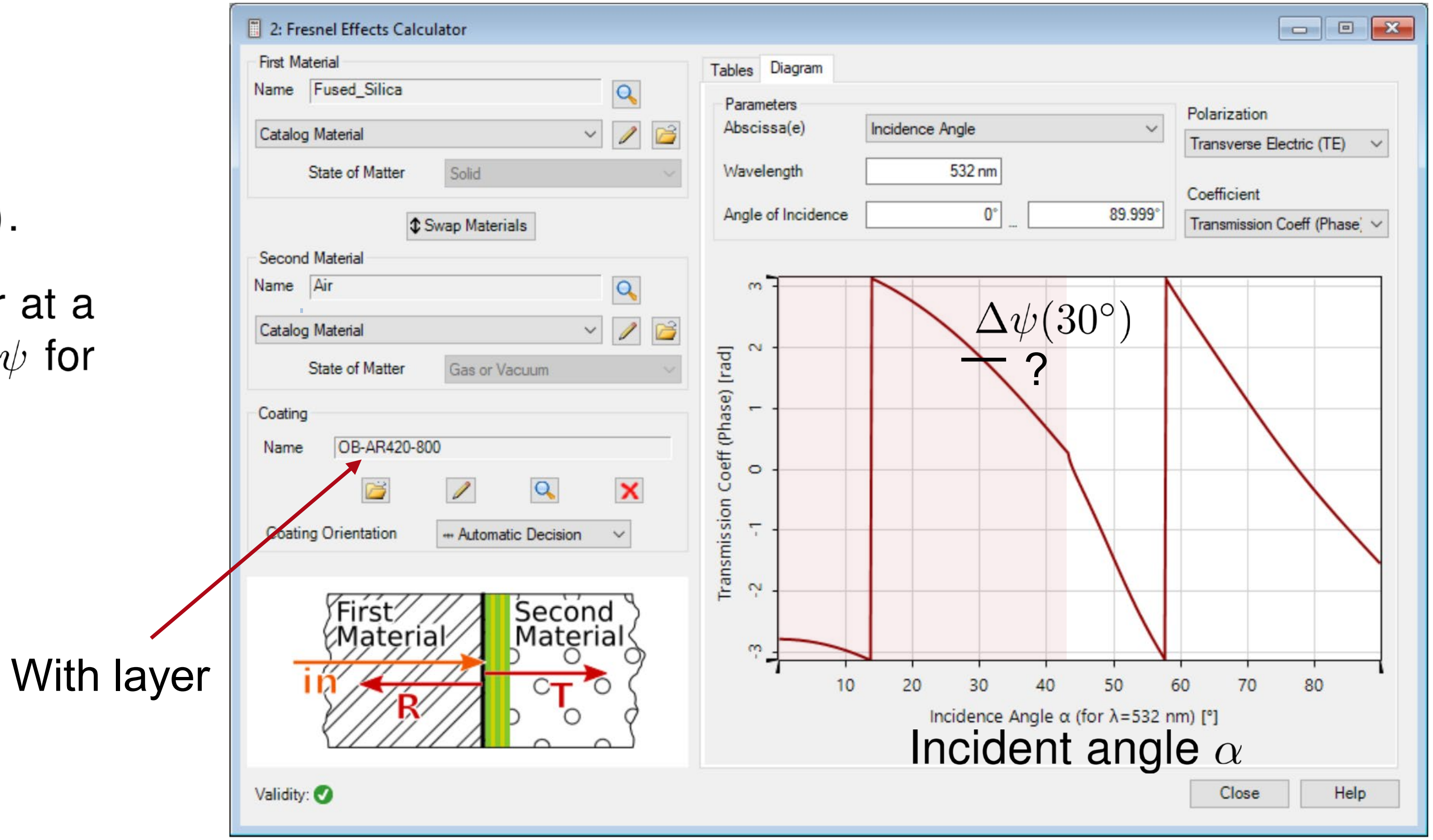


Incident angle α

Wavefront Response: Surface with Coating

- Functional design provides $\Delta\psi(\boldsymbol{\rho}, \hat{\boldsymbol{s}}^{\text{in}}(\boldsymbol{\rho}))$.
- **Structure design**: Search for local layer at a location $\boldsymbol{\rho}$, which provides demanded $\Delta\psi$ for local incident direction $\hat{\boldsymbol{s}}^{\text{in}}(\boldsymbol{\rho})$.

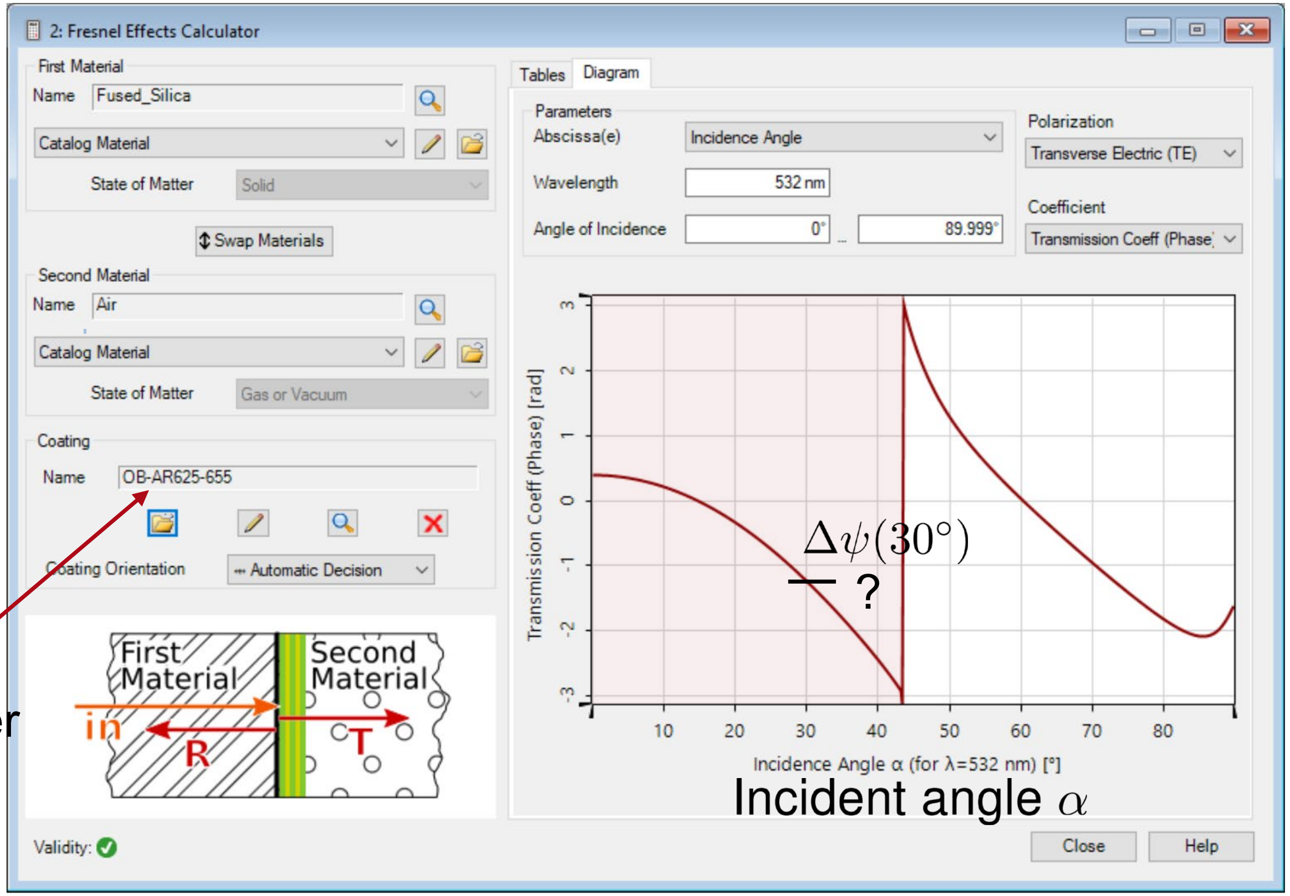
Transmission: $\Delta\psi(\alpha)$ (TE mode)



Wavefront Response: Surface with Coating

- Functional design provides $\Delta\psi(\boldsymbol{\rho}, \hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho}))$.
- **Structure design**: Search for local layer at a location $\boldsymbol{\rho}$, which provides demanded $\Delta\psi$ for local incident direction $\hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho})$.

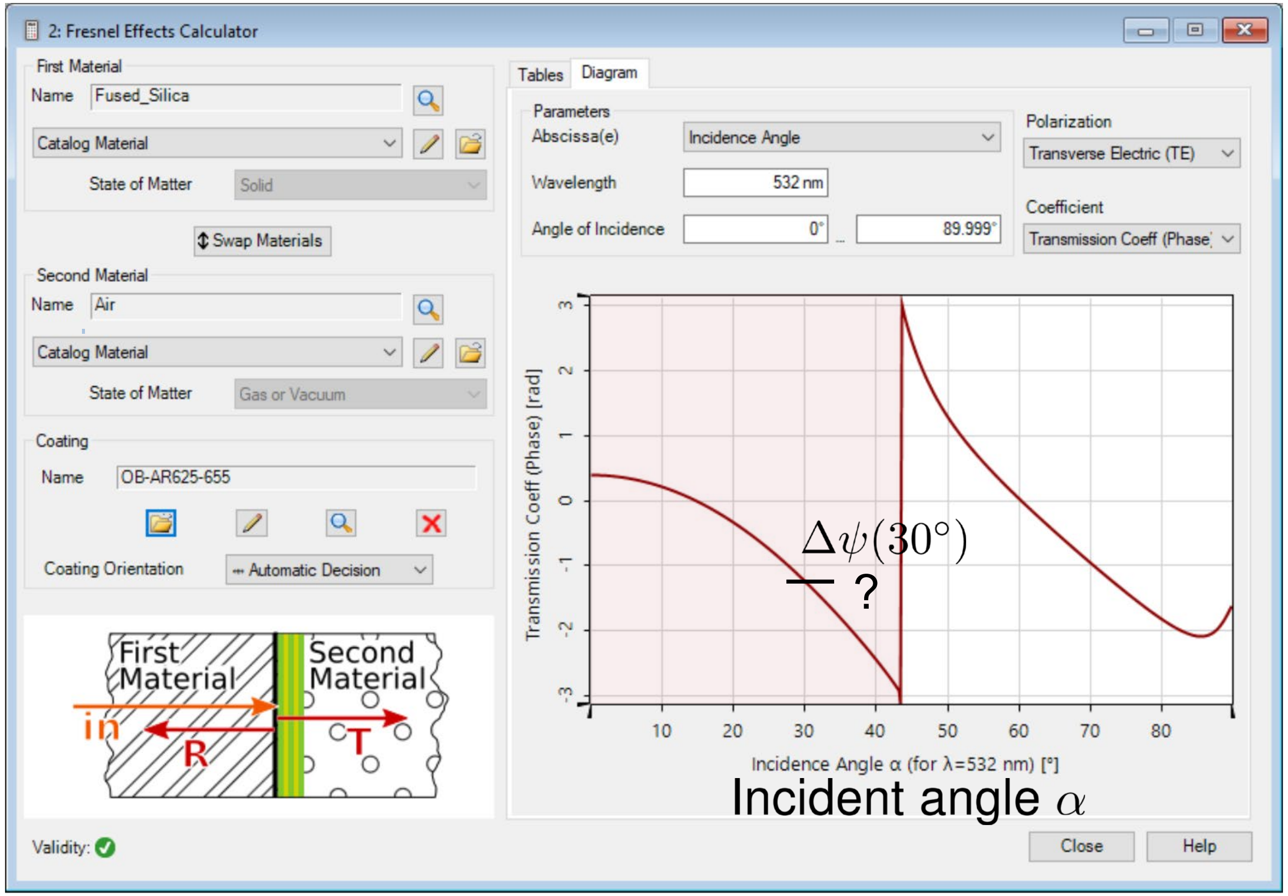
Transmission: $\Delta\psi(\alpha)$ (TE mode)



Changed layer

Wavefront Response: Surface with Coating

Transmission: $\Delta\psi(\alpha)$ (TE mode)



- Functional design provides $\Delta\psi(\boldsymbol{\rho}, \hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho}))$.
- **Structure design**: Search for local layer at a location $\boldsymbol{\rho}$, which provides demanded $\Delta\psi$ for local incident direction $\hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho})$.
- Per location a suitable layer must be found. Fabrication not practical!
- Metasurfaces: Phase effect by layer which consists of laterally modulated local cells.

Wavefront Response: Metasurface

- Functional design provides $\Delta\psi\big(\boldsymbol{\rho}, \hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho})\big)$.
- **Structure design**: Search for local layer at a location $\boldsymbol{\rho}$, which provides demanded $\Delta\psi$ for local incident direction $\hat{\boldsymbol{s}}^{\mathrm{in}}(\boldsymbol{\rho})$.
- Per location a suitable layer must be found. Fabrication not practical!
- Metasurfaces: Phase effect by layer which consists of laterally modulated local cells.

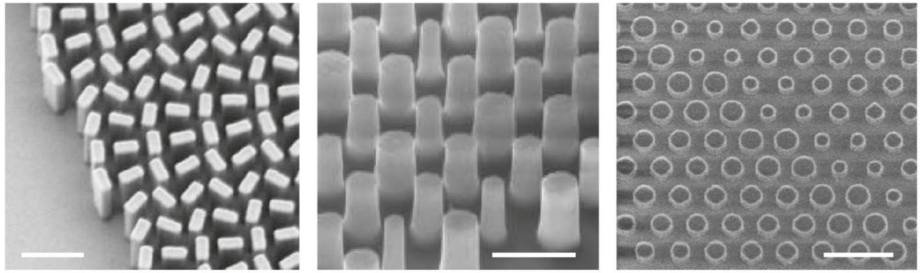
COMMENT

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

The advantages of metalenses over diffractive lenses

Jacob Engelberg[1] & Uriel Levy[1]

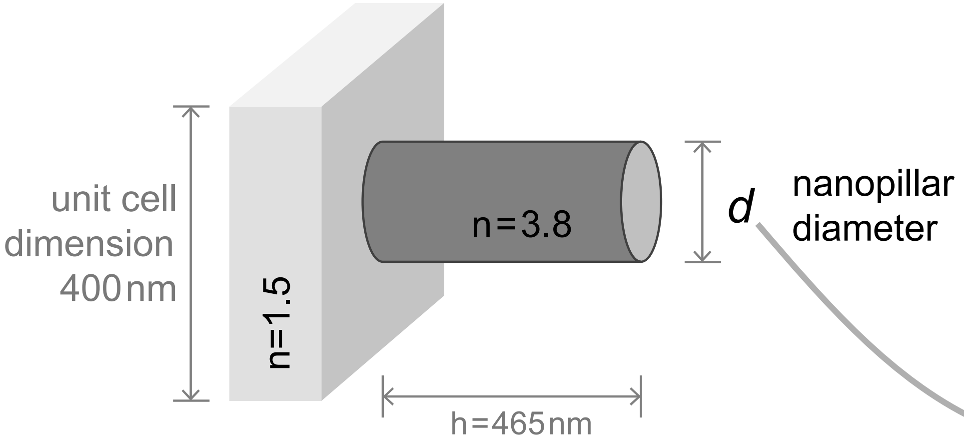
Nature Communication, April 2020

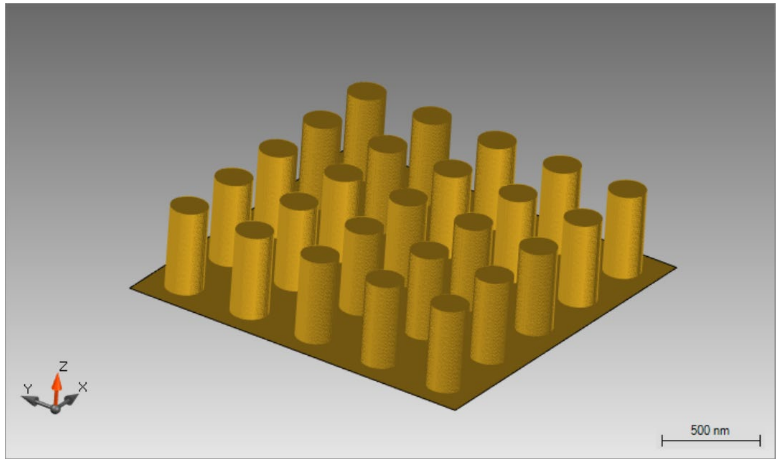


a b c

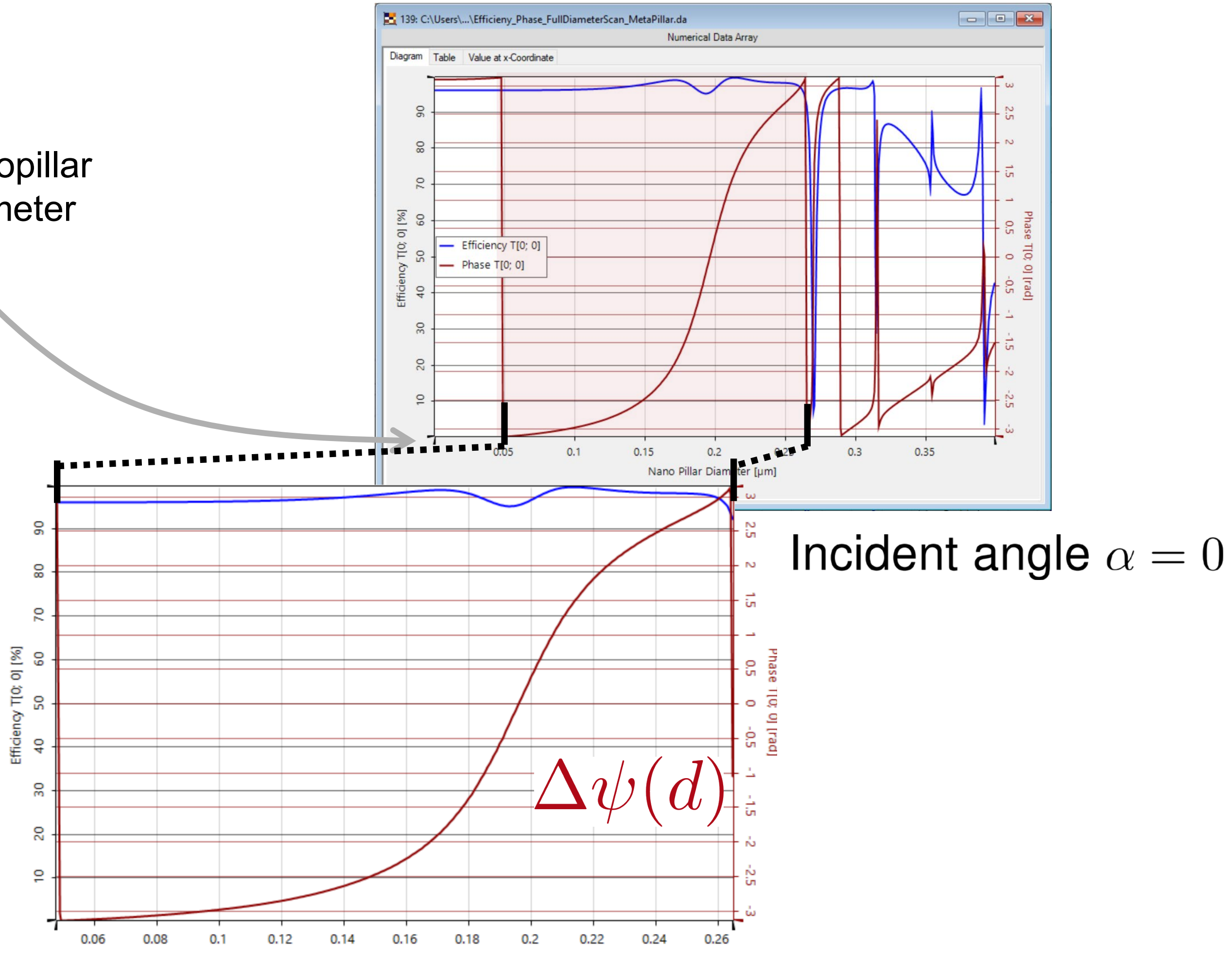
Fig. 2 Scanning electron microscope (SEM) images of several metalens antenna forms. a Nano-fins used for geometrical phase, reproduced with permission from ref. [9], Copyright 2016 AAAS. (**b**) Nano-rods used as truncated waveguides, reproduced with permission from ref. [7], Springer Nature and **c** Nano-disks used for Huygens metalens, reproduced with permission from ref. [12], De Gruyter. Scale bar is 1 µm.

Analysis of Phase Response of Metasurface Unit Cell

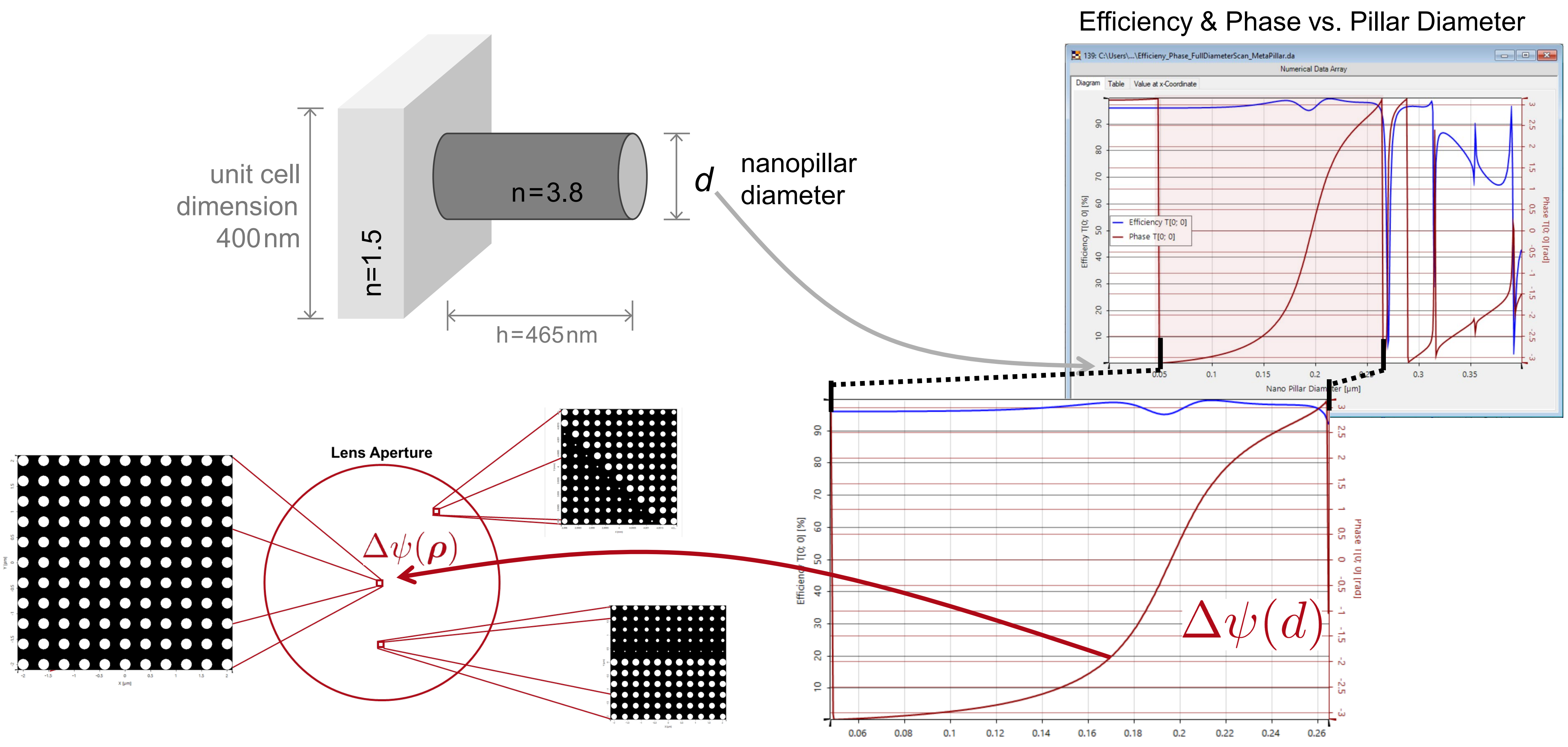




Efficiency & Phase vs. Pillar Diameter



Design of Metasurface for Specified Phase Response



Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and flat optics components.

- Freeform design
- Segmented components
- Fresnel lenses
- HOE
- Metasurfaces

MODELING & EVALUATION

detectors and merit functions.

FURTHER OPTIMIZATION

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.

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and 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 t… techn… furthe… the sy… param… optim…

SYSTEM TOLERANCING

… system.

FABRICATION DATA

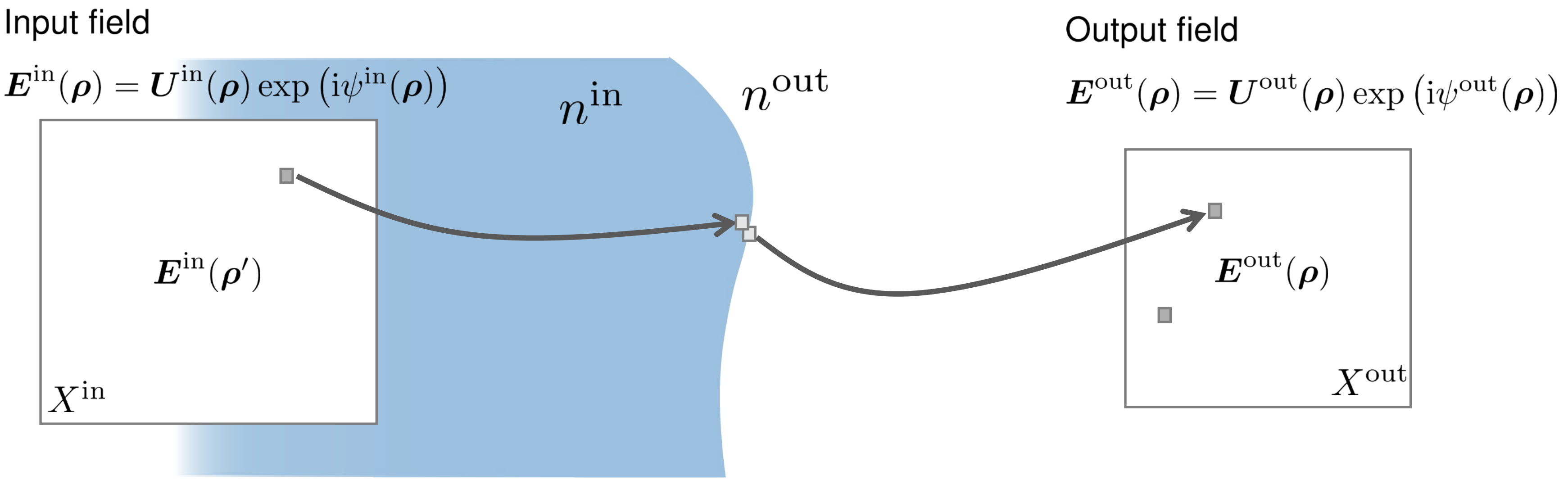
Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

- Freeform design
- Segmented components
- Fresnel lenses
- HOE
- Metasurfaces

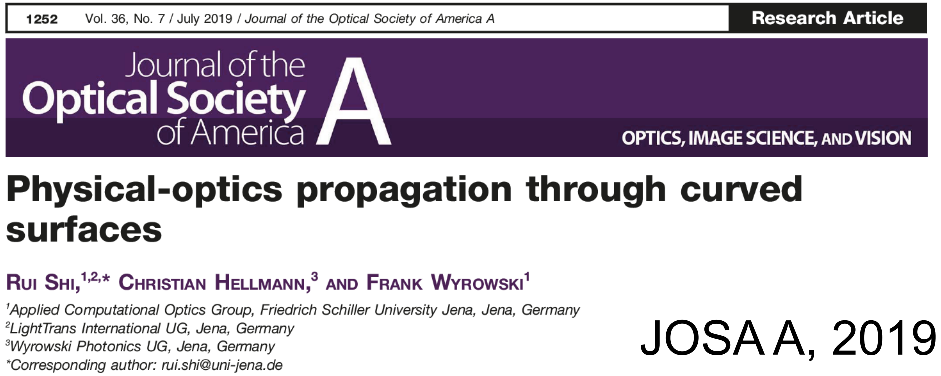
Modeling

Modeling and evaluation of performance of surfaces which are obtained by structure design

Freeform Surface: Modeling



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



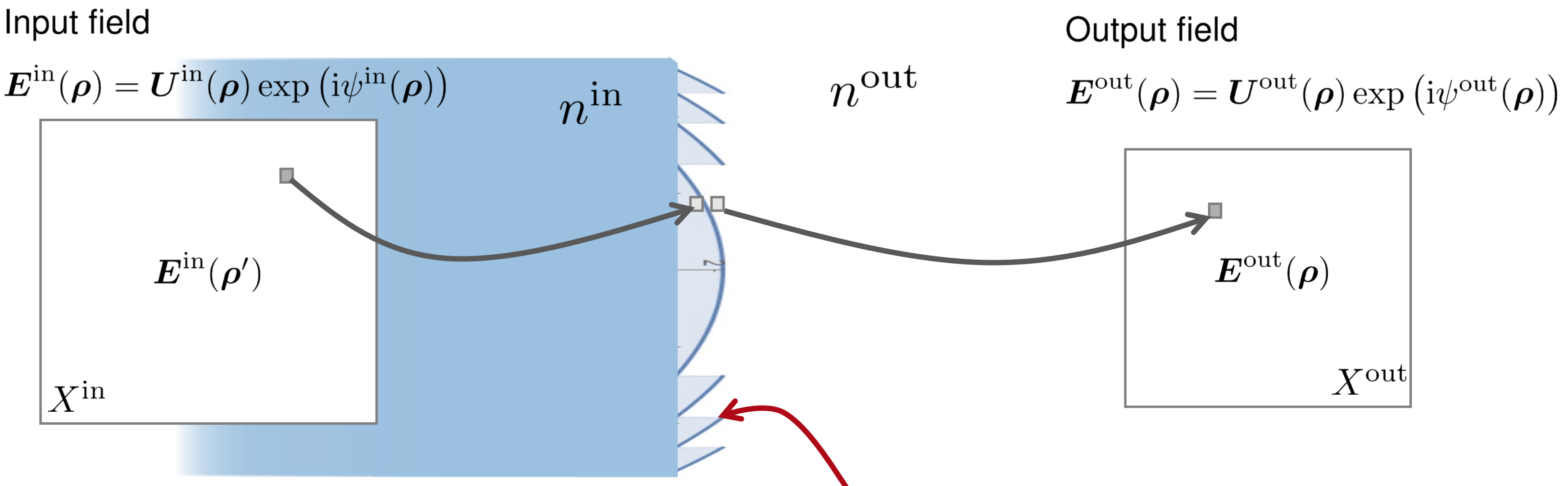
1252 Vol. 36, No. 7 / July 2019 / Journal of the Optical Society of America A Research Article
Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

Physical-optics propagation through curved surfaces

Rui Shi,[1,2,*] Christian Hellmann,[3] and Frank Wyrowski[1]
[1]Applied Computational Optics Group, Friedrich Schiller University Jena, Jena, Germany
[2]LightTrans International UG, Jena, Germany
[3]Wyrowski Photonics UG, Jena, Germany
*Corresponding author: rui.shi@uni-jena.de

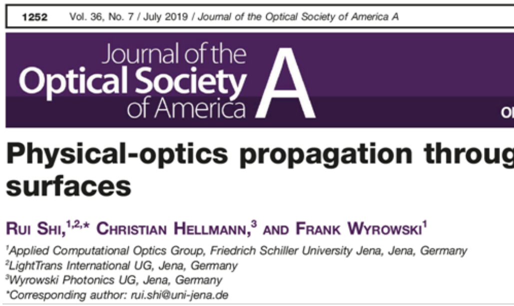
JOSA A, 2019

Segmented Surface: Modeling



Include diffraction at jumps of profile.

- 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

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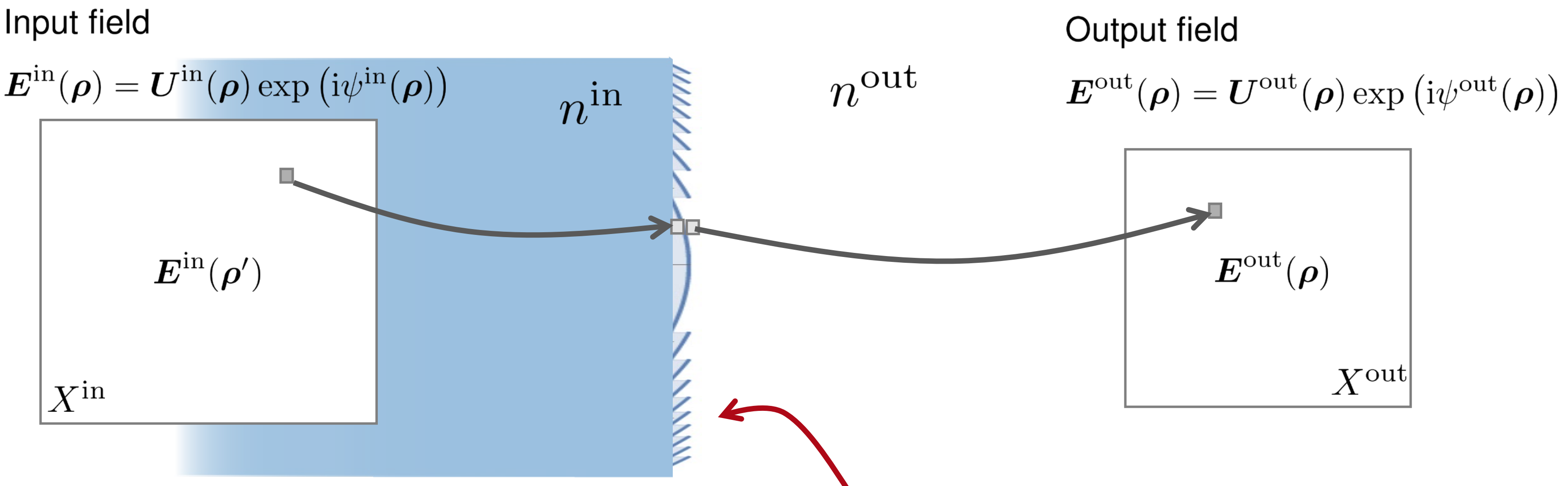
*Corresponding author: rui.shi@uni-jena.de

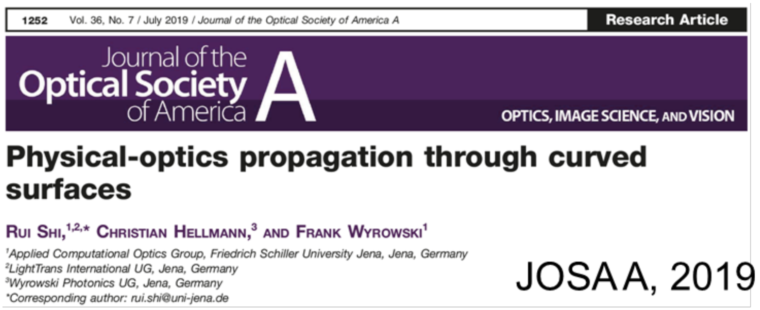
JOSAA, 2019

Holographic Optical Element: Modeling



Include diffraction at jumps of profile.

- Local application of S-matrix for curved surfaces: Local Plane Interface Approximation (LPIA).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Journal of the Optical Society of America A — OPTICS, IMAGE SCIENCE, AND VISION

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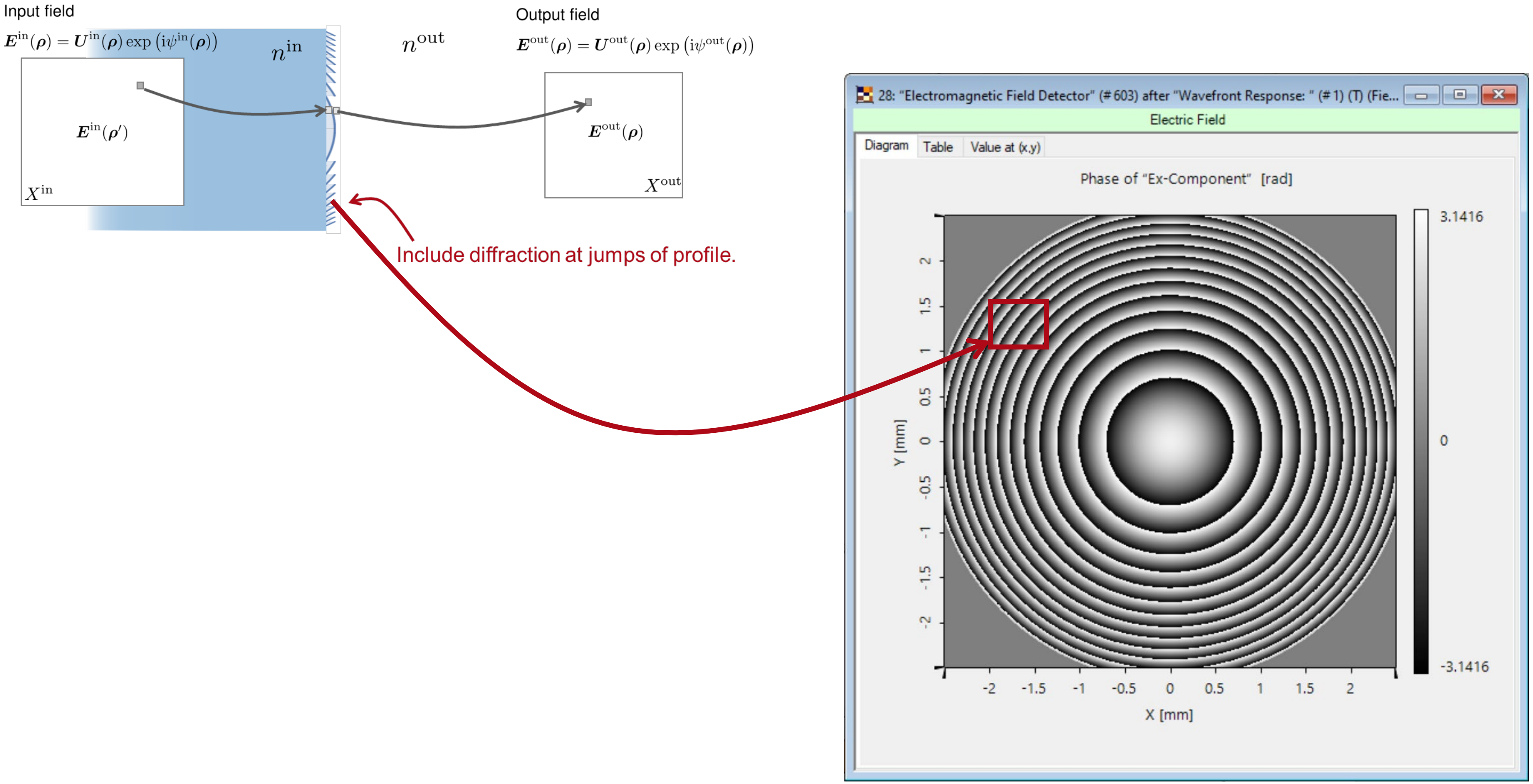
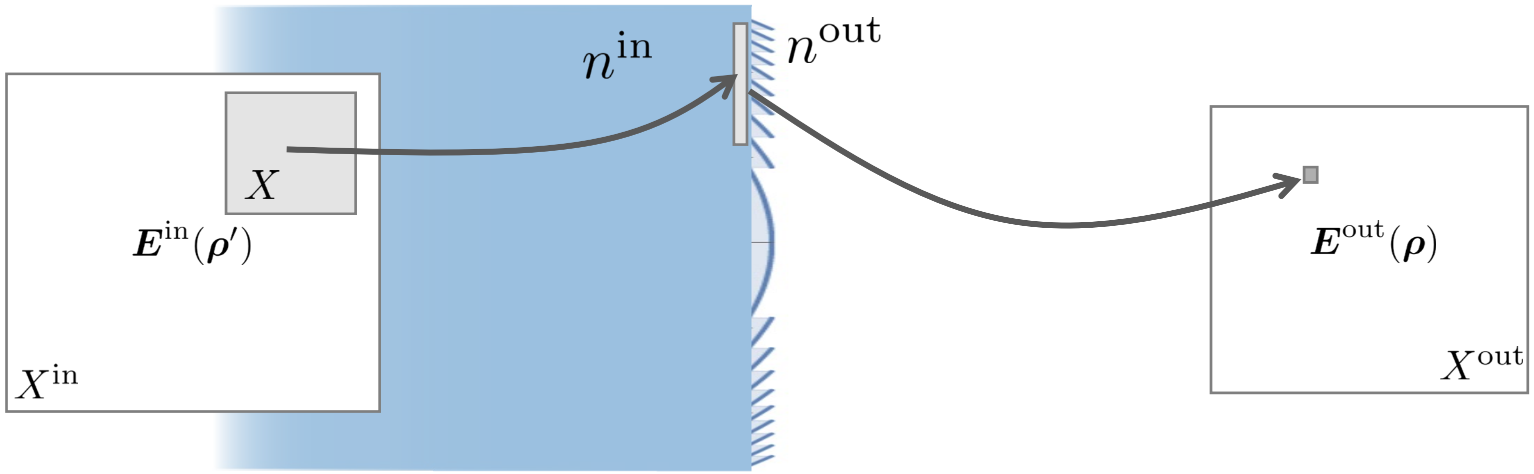
JOSAA, 2019

Holographic Optical Element: Modeling



HOE Modeling: Local Integration

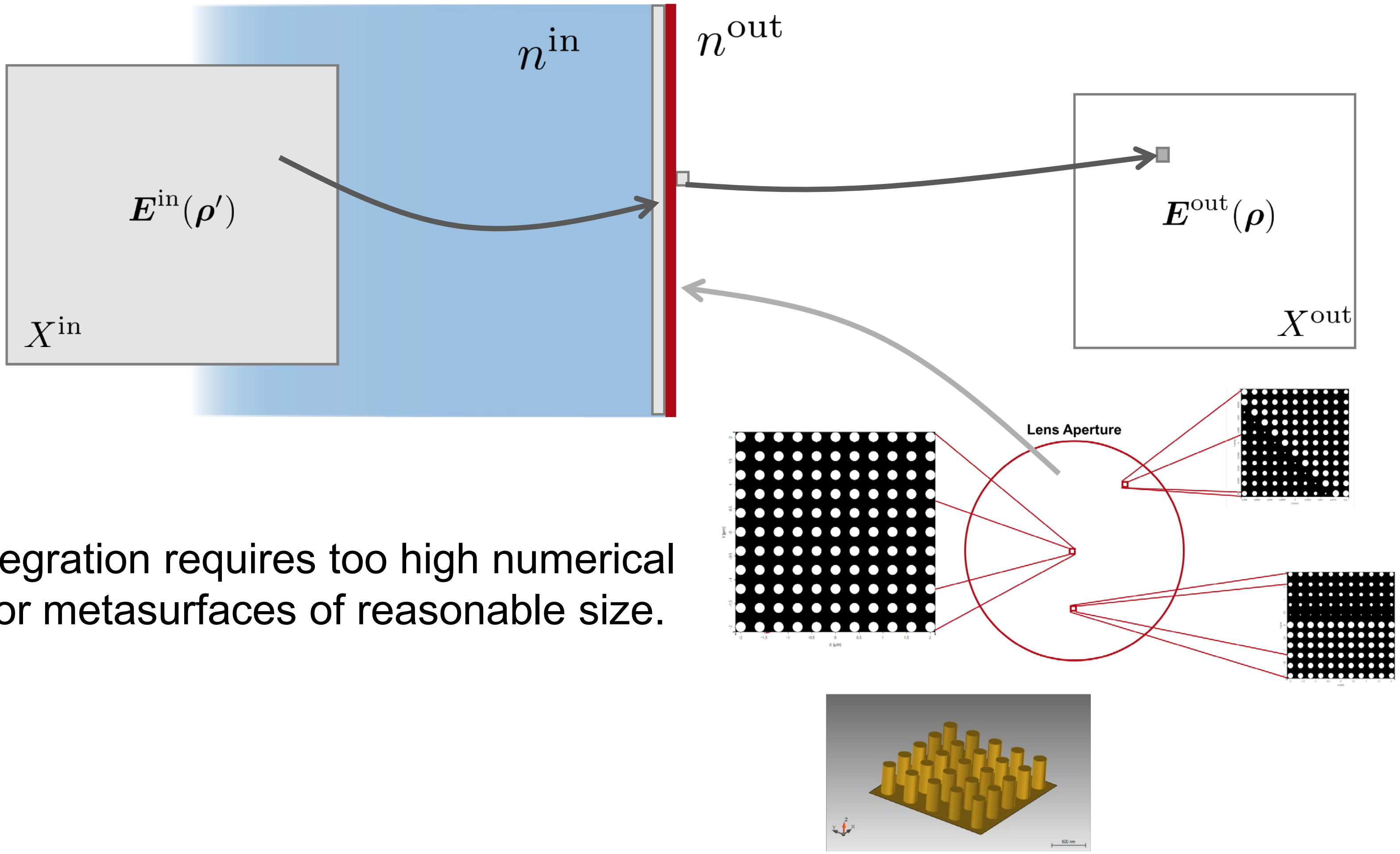


U-field response in outer zones is affected by the neighborhood in structure: **local grating**

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

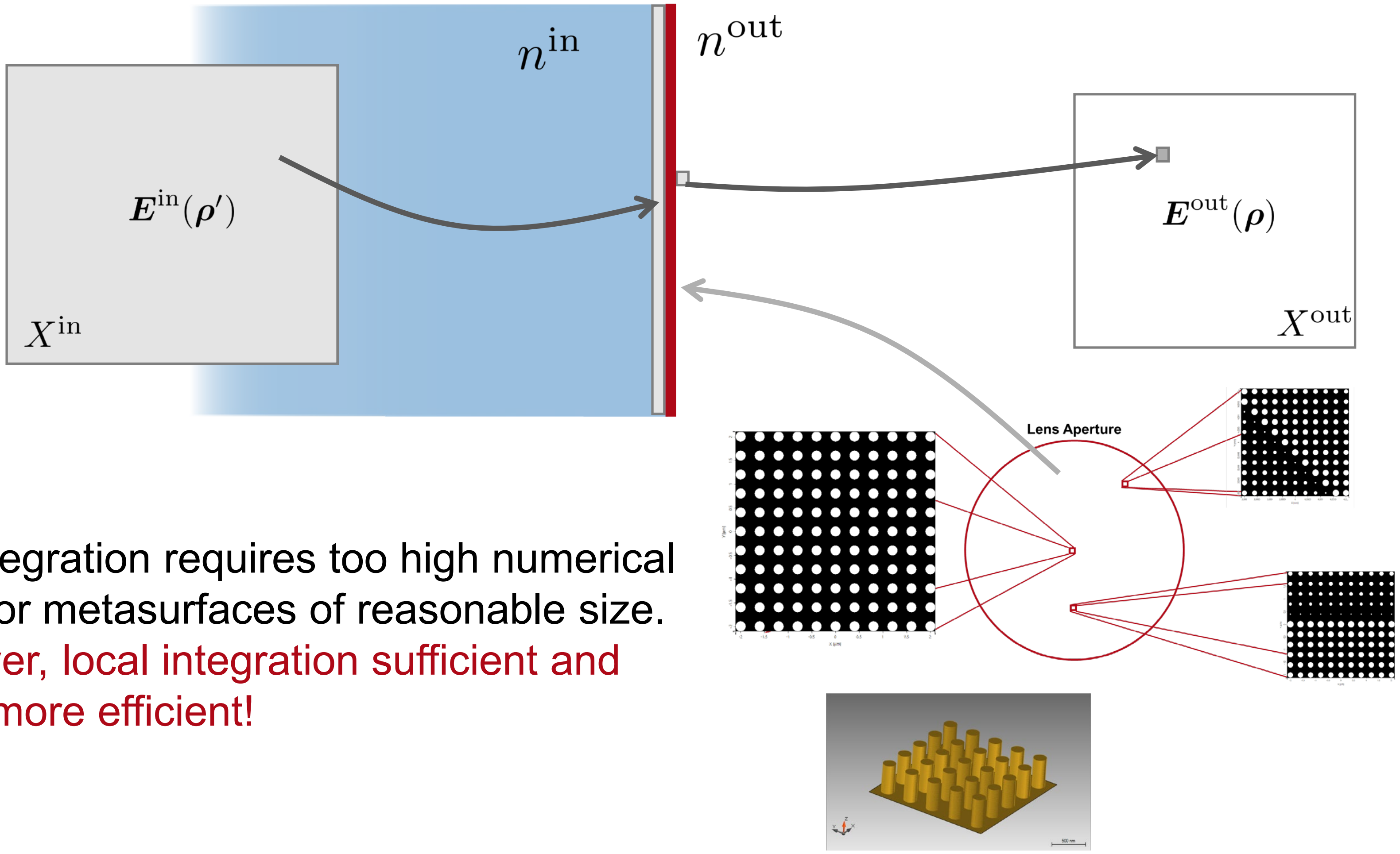
VirtualLab Fusion 2021

Metasurface Modeling: Full Integration Over Lens Diameter



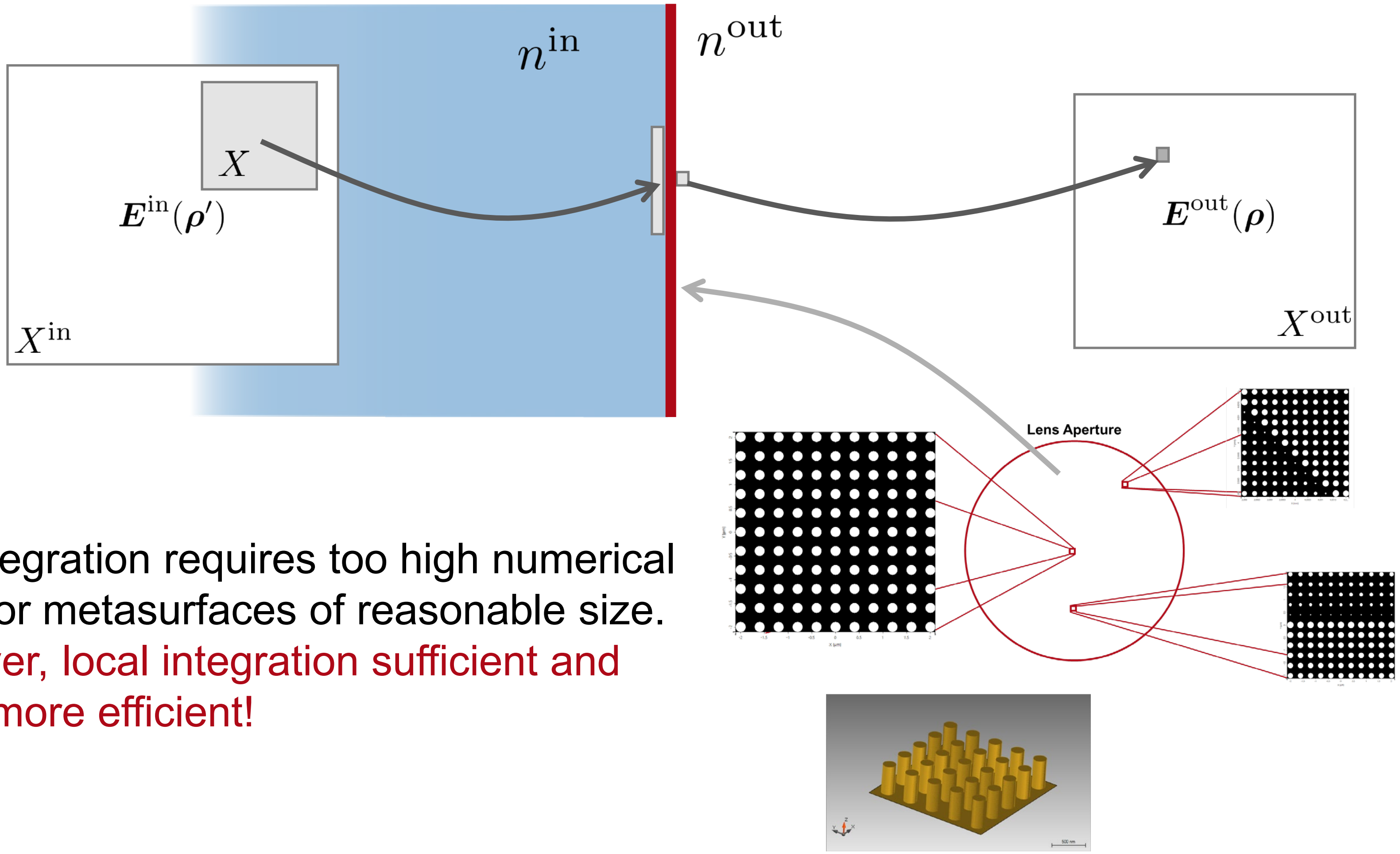
- Full integration requires too high numerical effort for metasurfaces of reasonable size.

Metasurface Modeling: Full Integration Over Lens Diameter



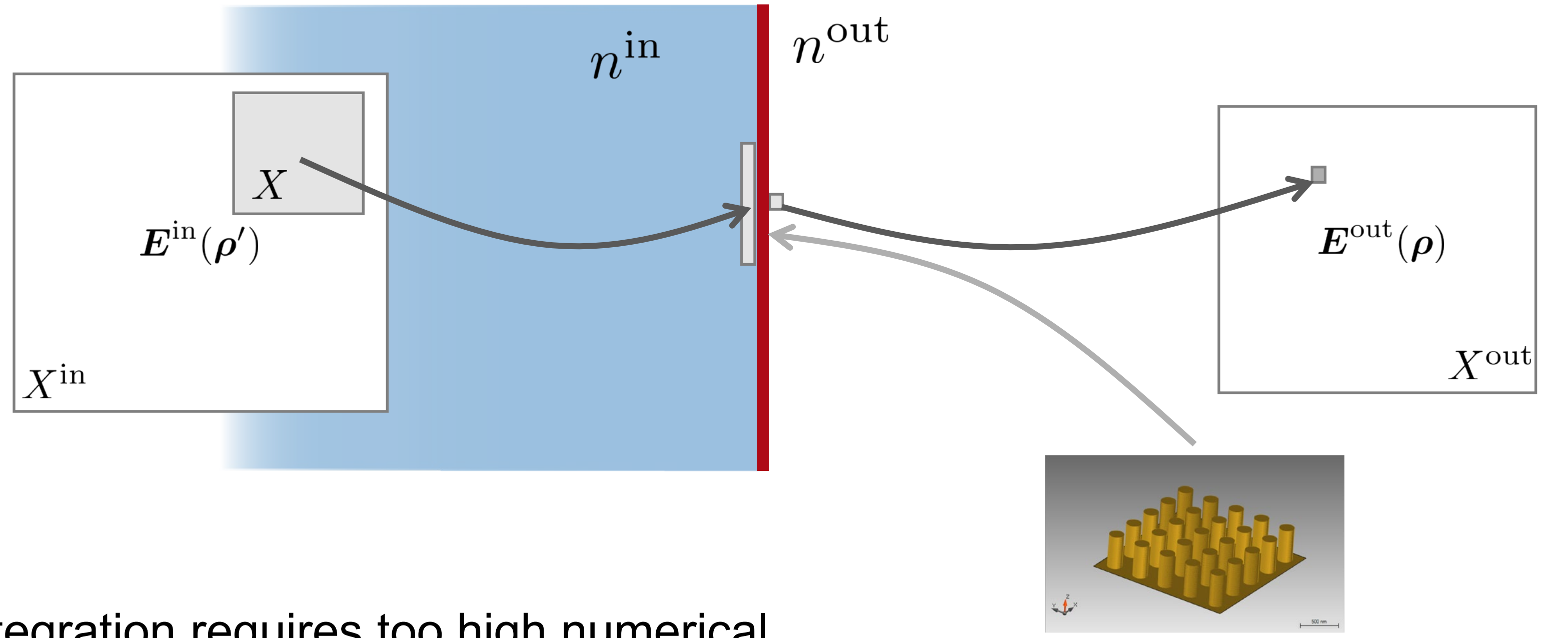
- Full integration requires too high numerical effort for metasurfaces of reasonable size.
- However, local integration sufficient and much more efficient!

Metasurface Modeling: Local Integration



- Full integration requires too high numerical effort for metasurfaces of reasonable size.
- However, local integration sufficient and much more efficient!

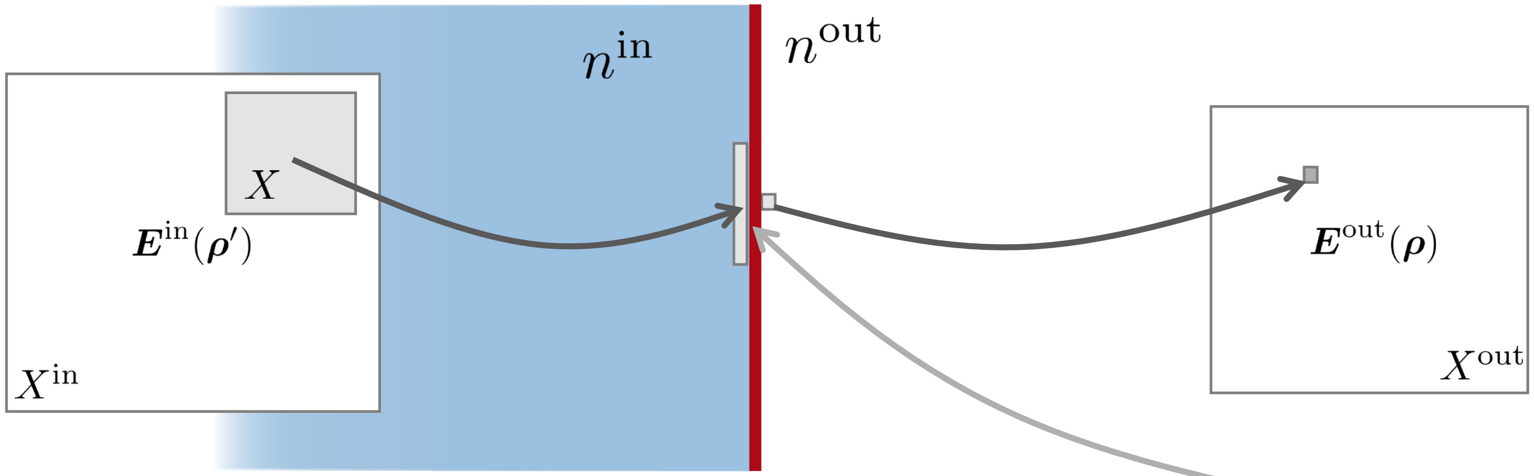
Metasurface Modeling: Local Integration Level I



- Full integration requires too high numerical effort for metasurfaces of reasonable size.
- However, local integration sufficient and much more efficient!

Locally we assume subwavelength grating with local pillar size.

Metasurface Modeling: Local Integration Level II



- Full integration requires too high numerical effort for metasurfaces of reasonable size.
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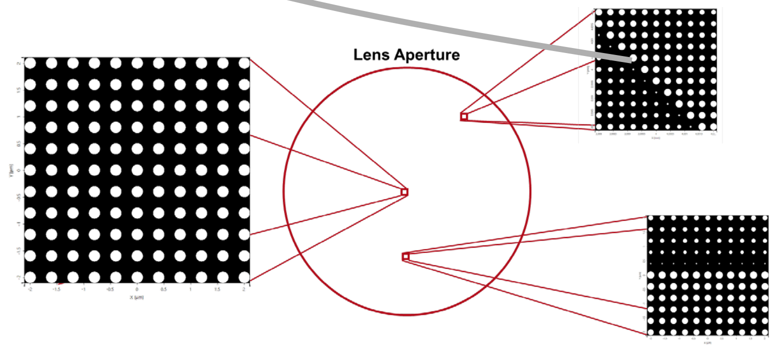
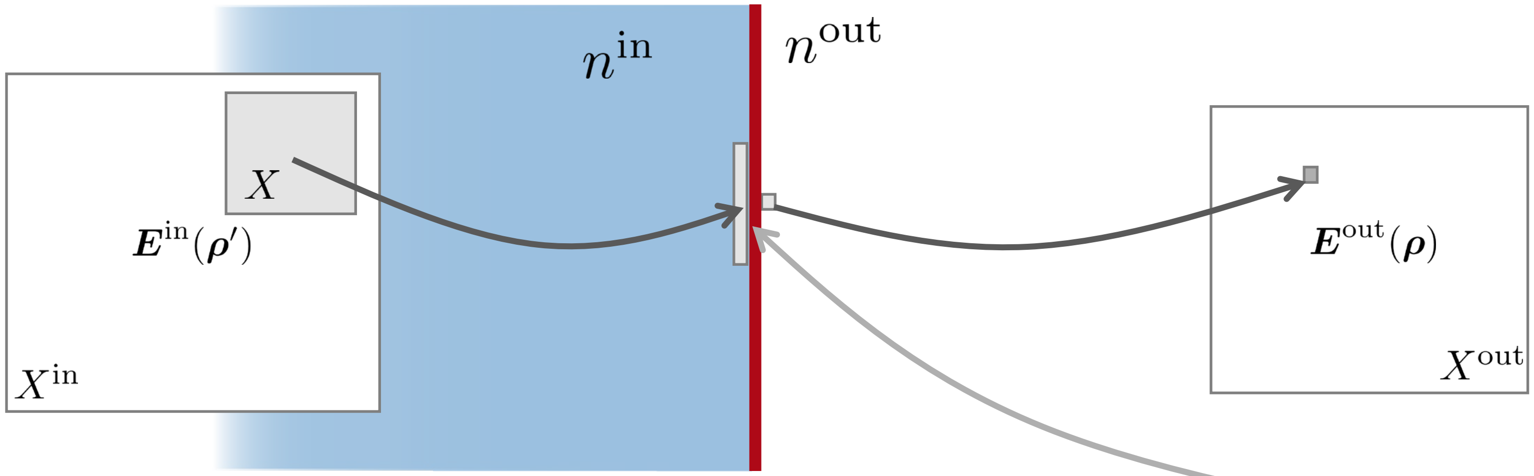


Stitching method by benefiting from local reach of evanescent fields.

Metasurface Modeling: Local Integration Level II

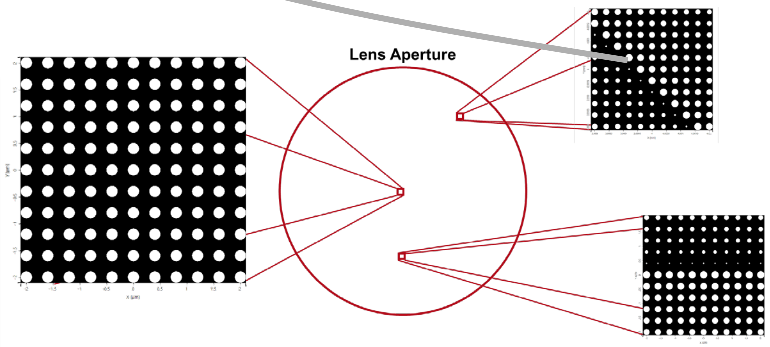


J. Opt. Soc. Am. A/Vol. 14, No. 7/July 1997 **JOSA A, 1997** B. Layet and M. R. Taghizadeh

Electromagnetic analysis of fan-out gratings and diffractive cylindrical lens arrays by field stitching

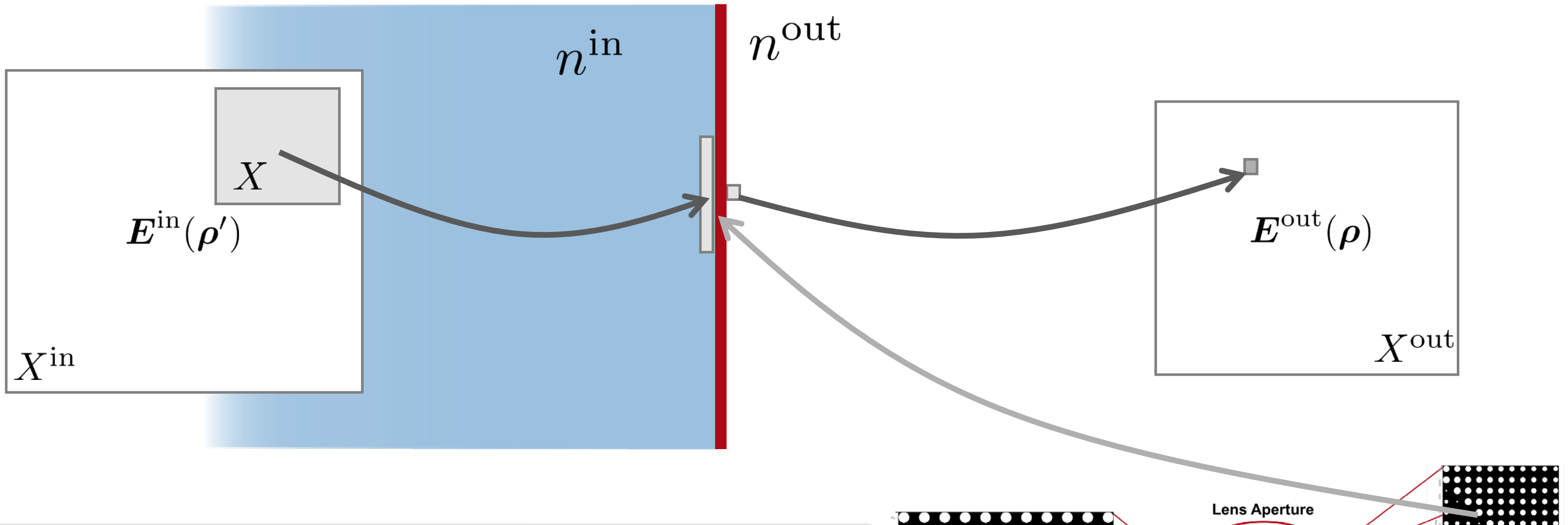
Ben Layet and Mohammad R. Taghizadeh

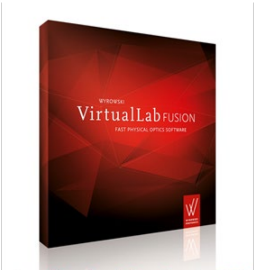
Department of Physics, Heriot-Watt University, Edinburgh EH14 4AS, UK



Stitching method by benefiting from local reach of evanescent fields.

Metasurface Modeling: Local Integration Level II





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J. Opt. Soc. Am. A/Vol. 14, No. 7/July 1997 JOSA A, 1997 B. Layet and M. R. Taghizadeh

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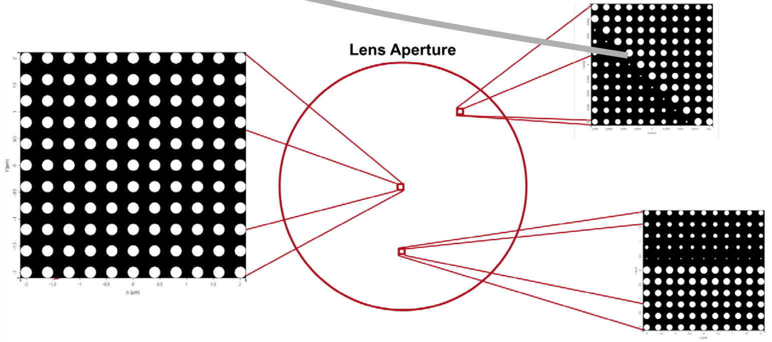

Stitching method by benefiting from local reach of evanescent fields.

Proposed Design Workflow

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

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

FURTHER OPTIMIZATION

Use t
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param
optim

SYSTEM TOLERANCING

system.

FABRICATION DATA

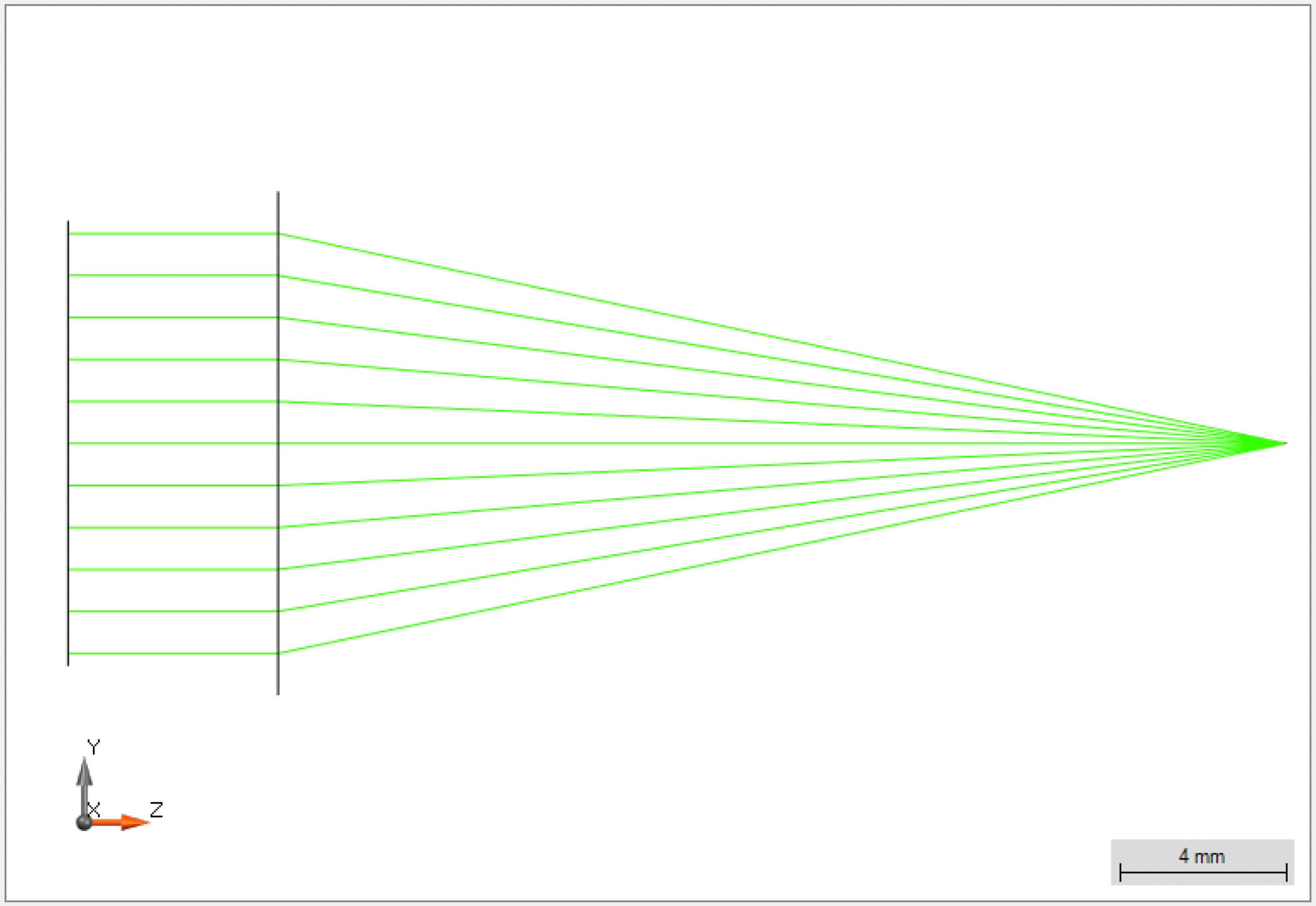
Jse the modeling echniques to urther optimize he system by, e.g. parametric optimization.

- Freeform design
- Segmented components
- Fresnel lenses
- HOE
- Metasurfaces

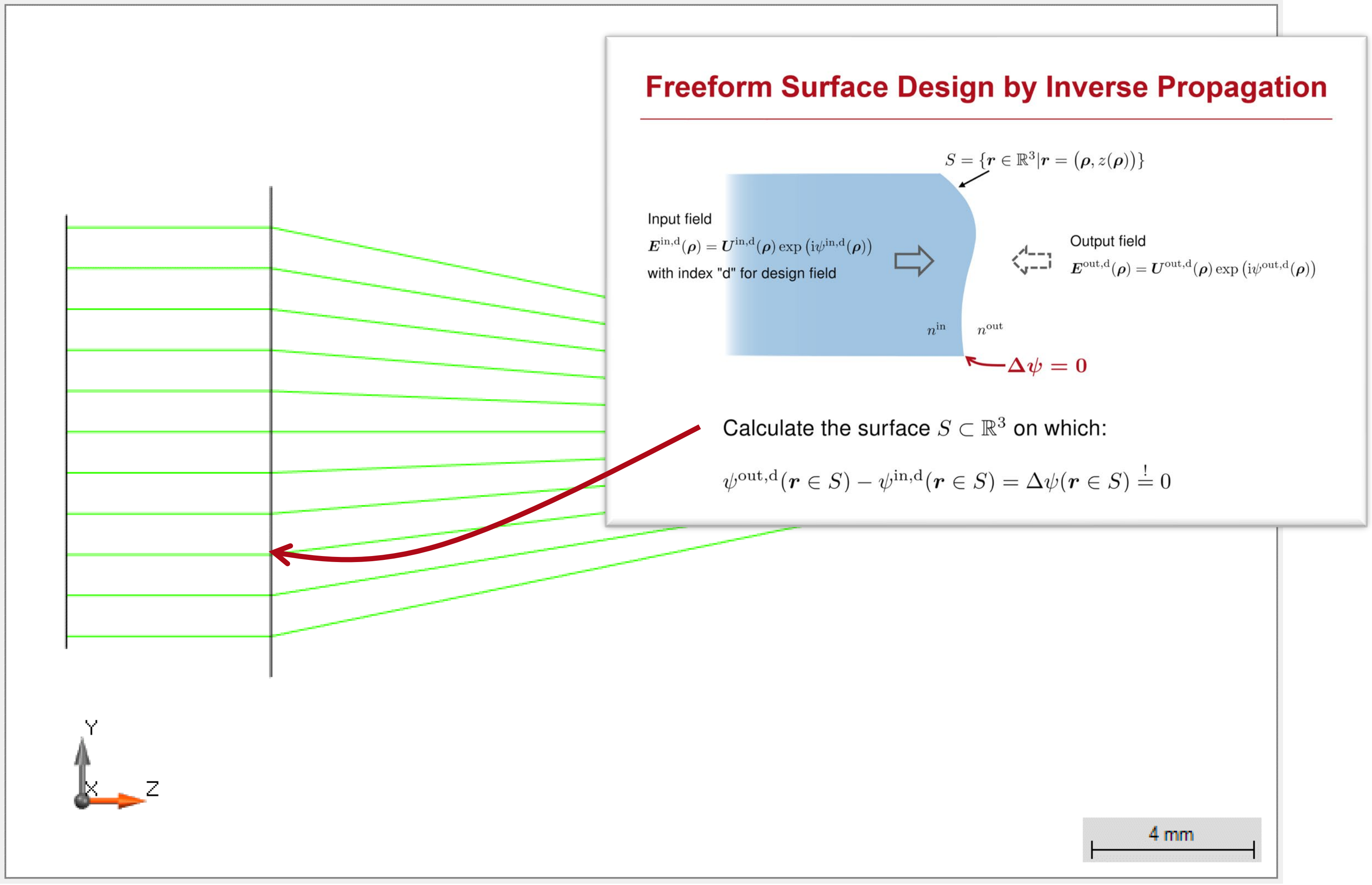
Example Focusing

Structural Design

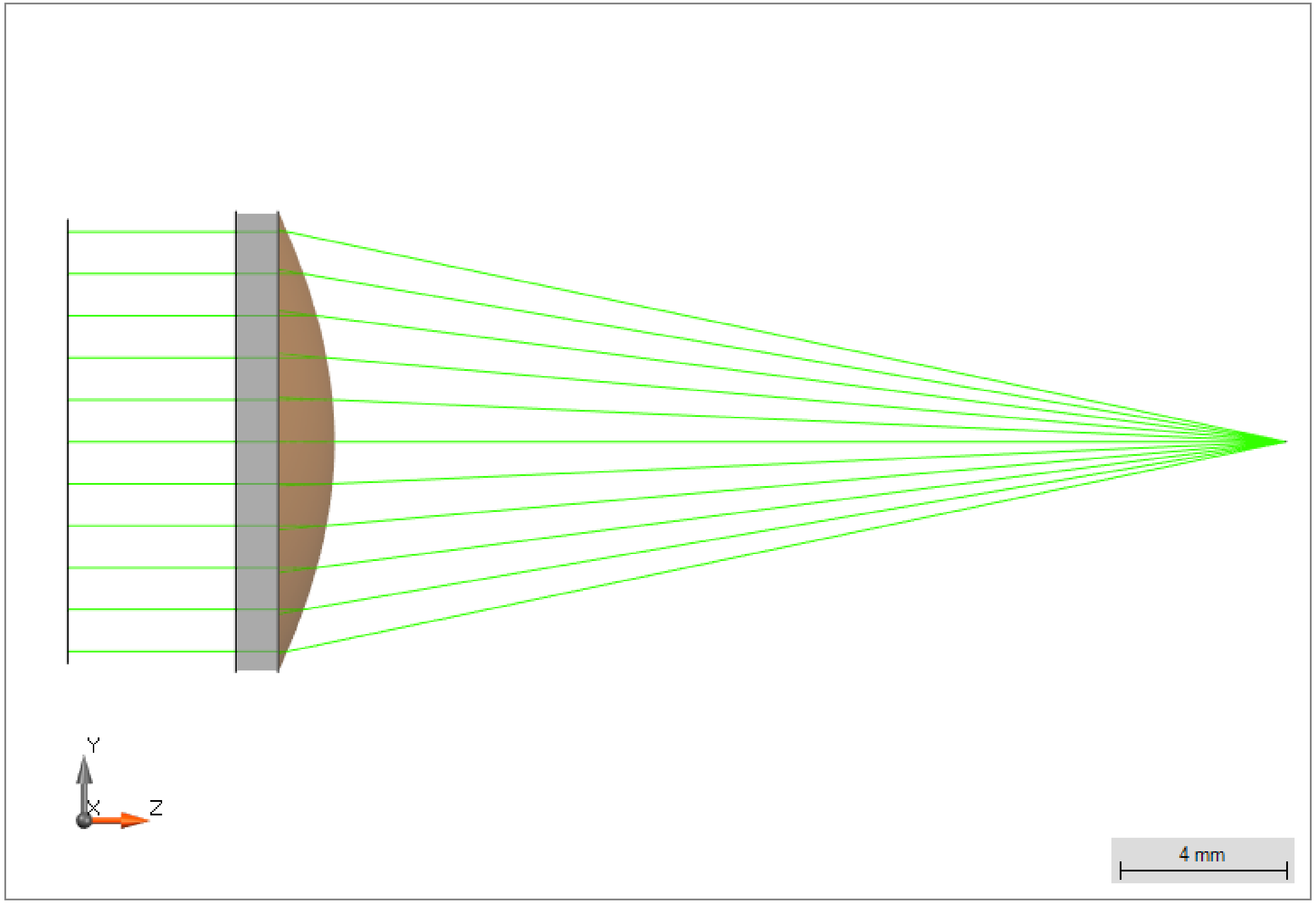
Functional Design: Focusing (NA = 0.2) – Ray Tracing



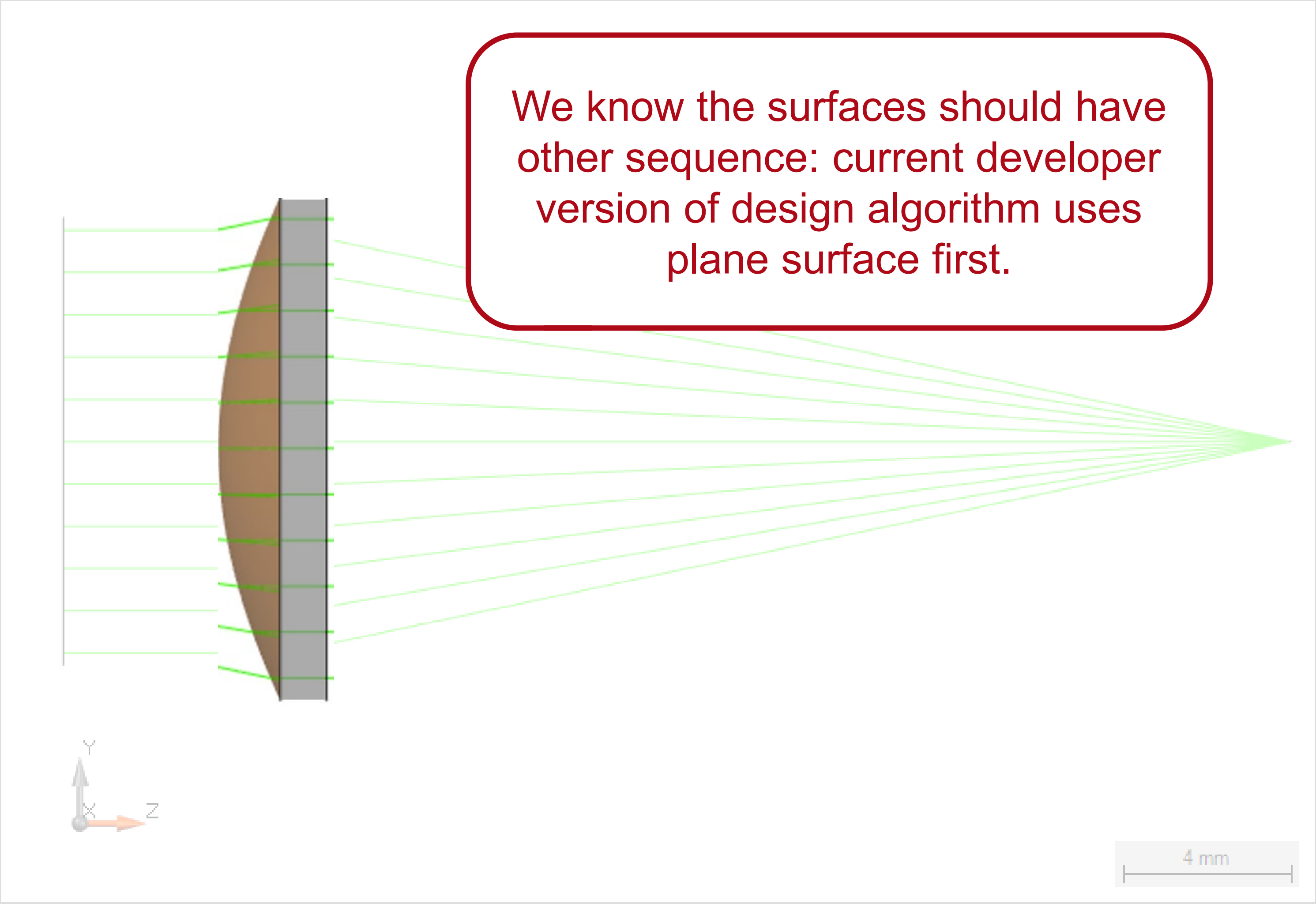
Structural Design Freeform: Focusing (NA = 0.2)



Focusing (NA = 0.2) Lens: Ray Tracing

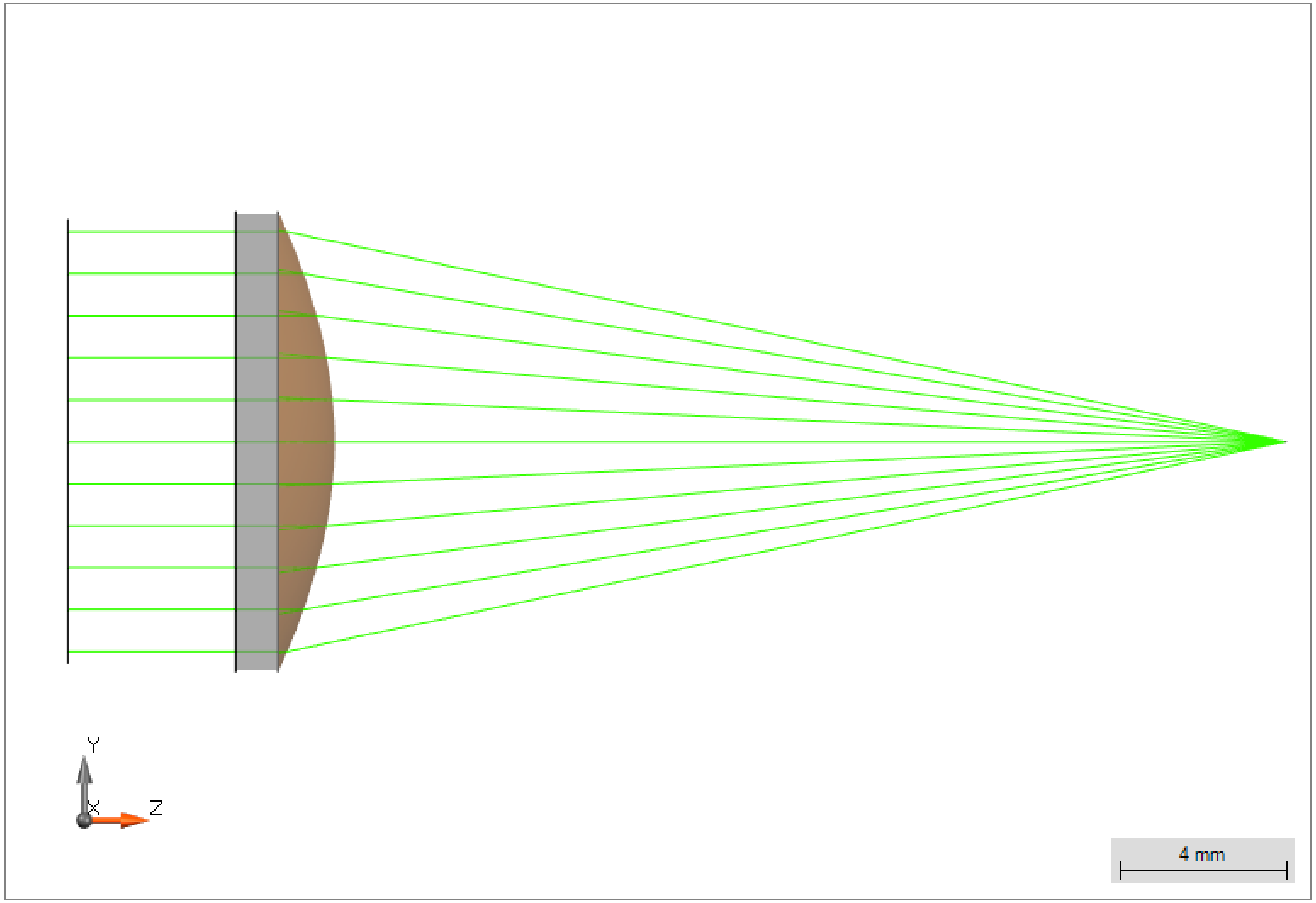


Remark

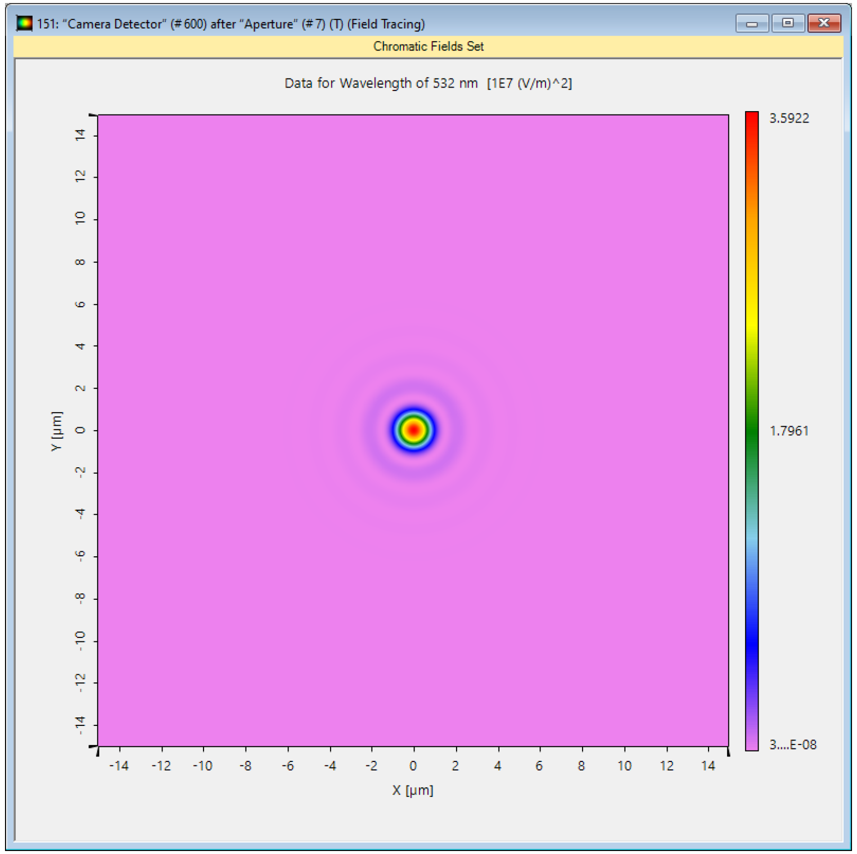


We know the surfaces should have other sequence: current developer version of design algorithm uses plane surface first.

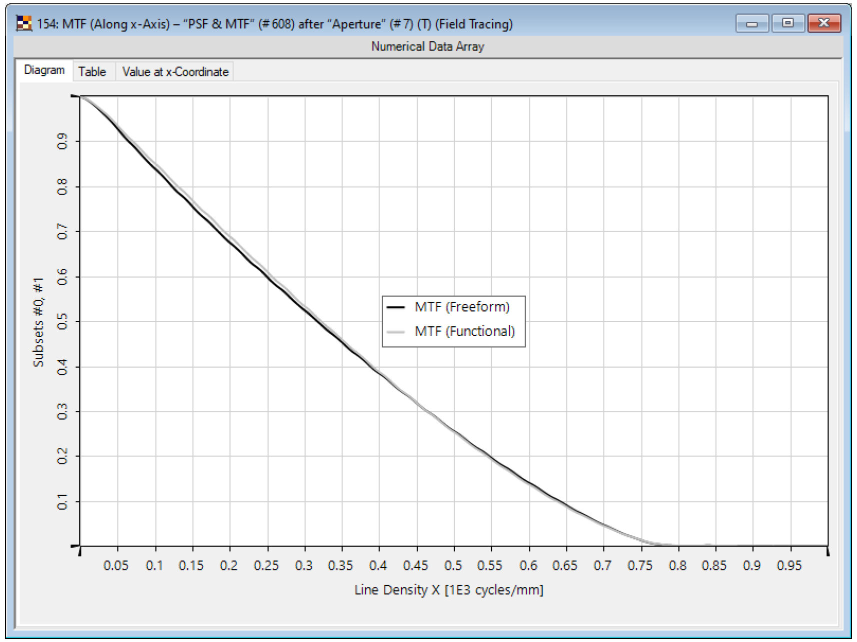
Focusing (NA = 0.2) Lens: Ray Tracing



Focusing (NA = 0.2) Lens: Field Tracing



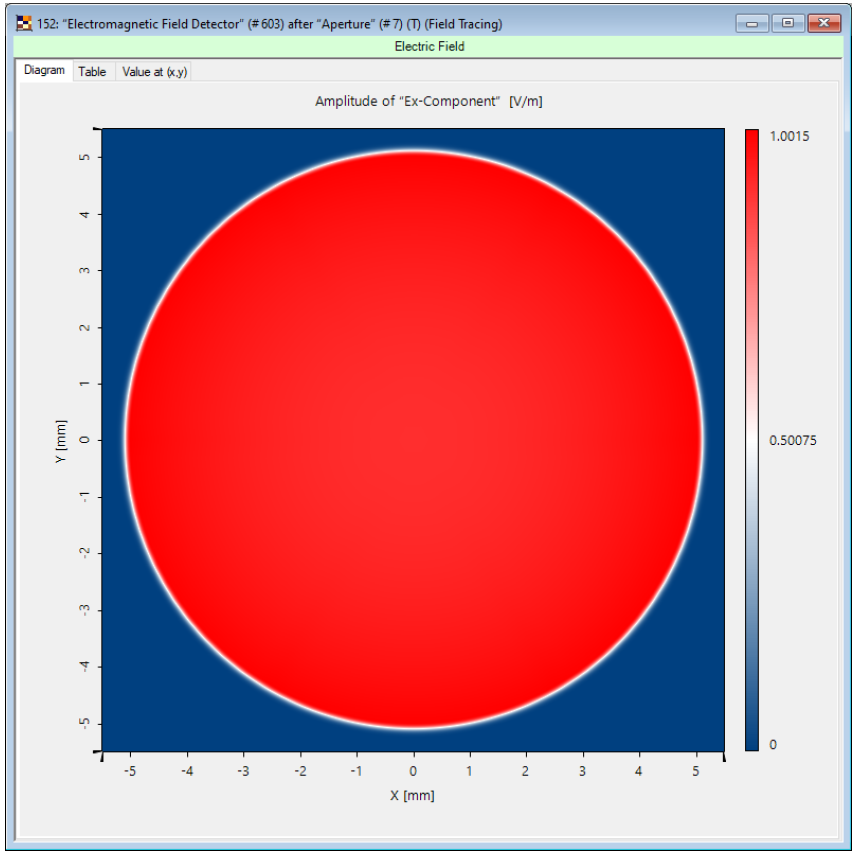
Energy Density in Focus (False Color)



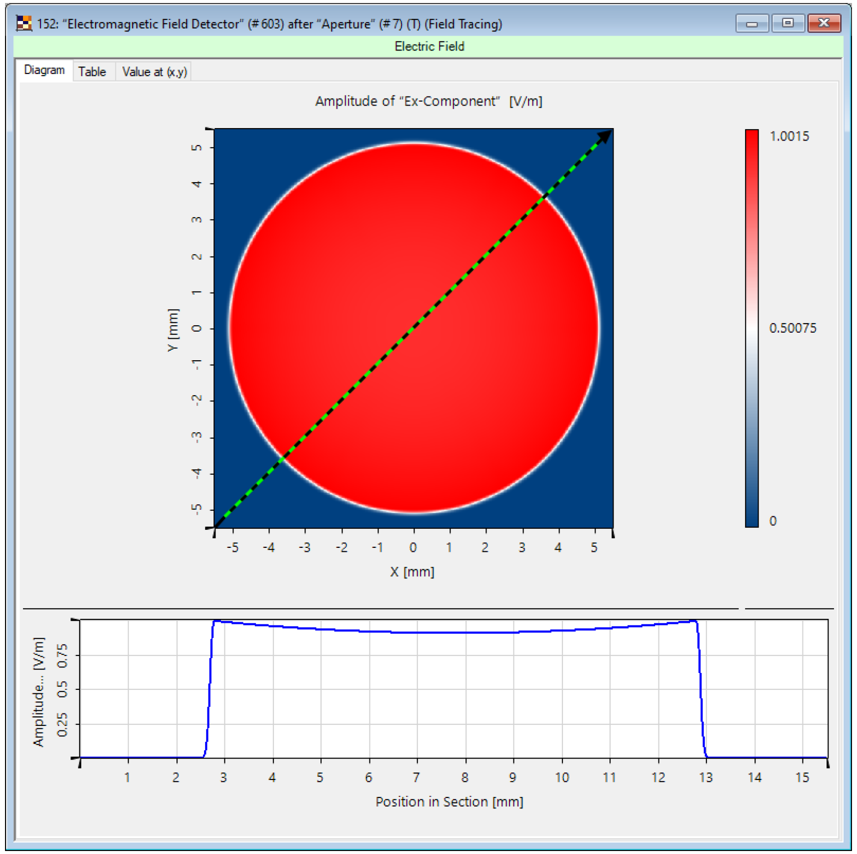
MTF

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

Focusing (NA = 0.2) Lens: Field Tracing

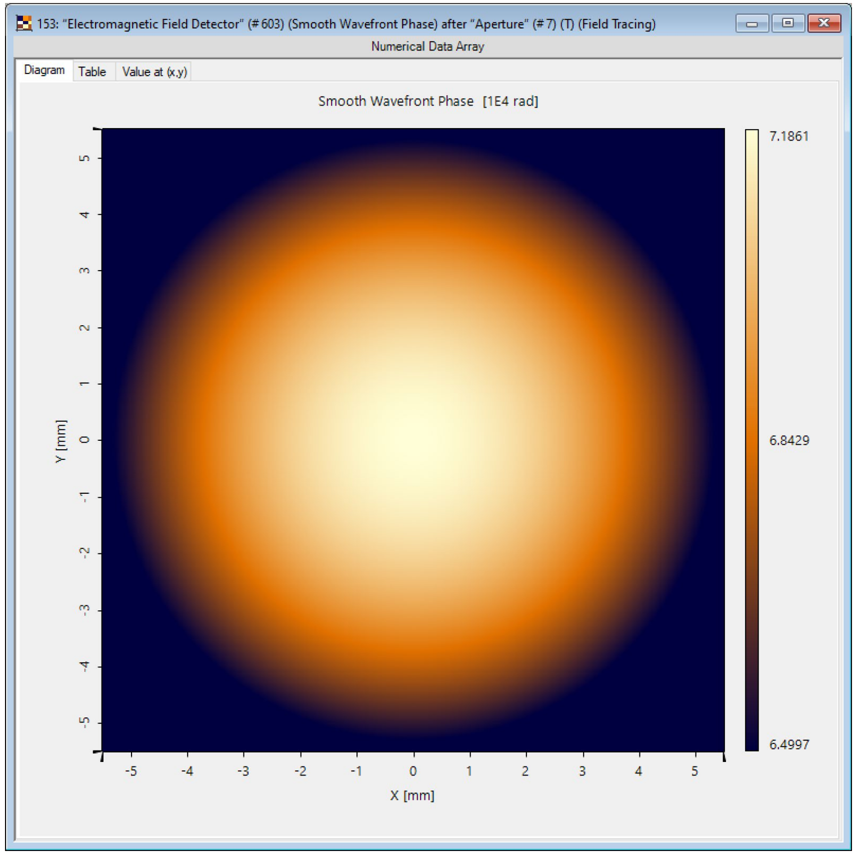


Amplitude after lens

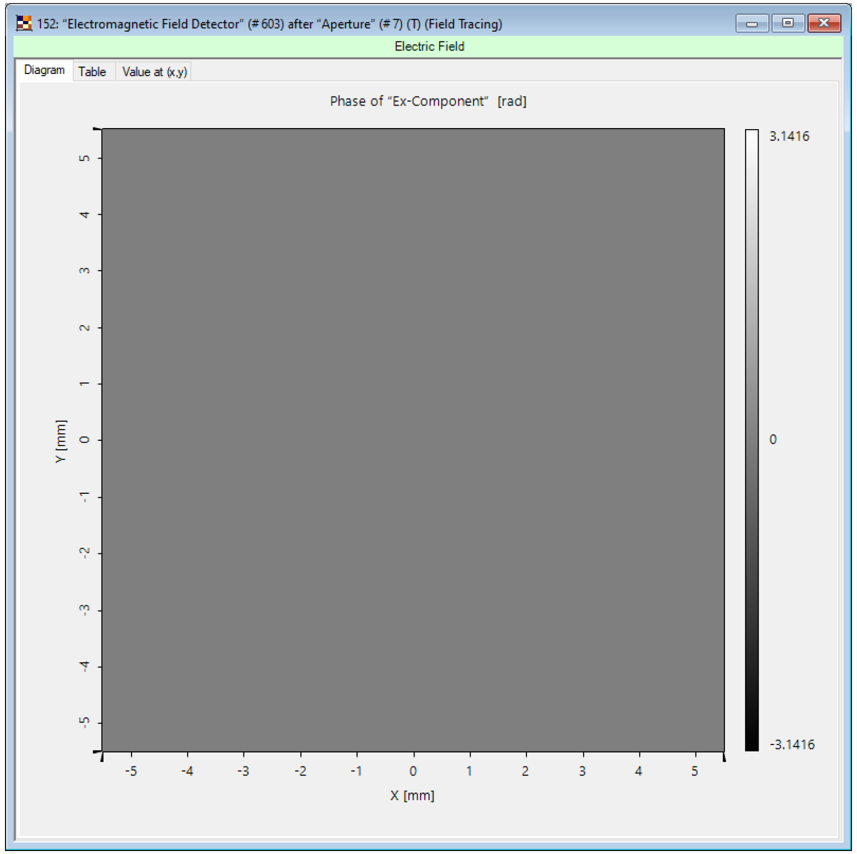


Amplitude after lens

Focusing (NA = 0.2) Lens: Field Tracing

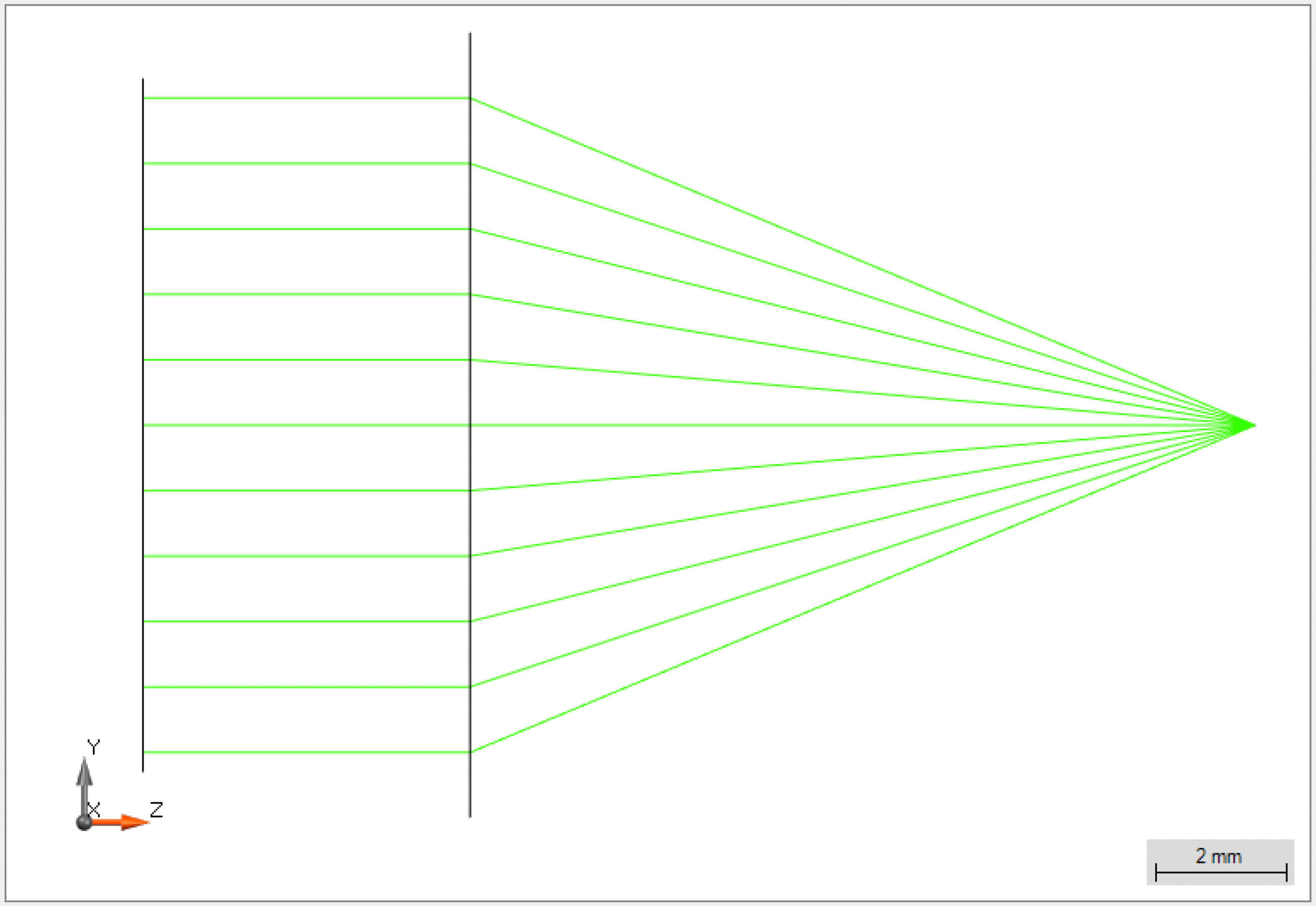


Wavefront phase after lens

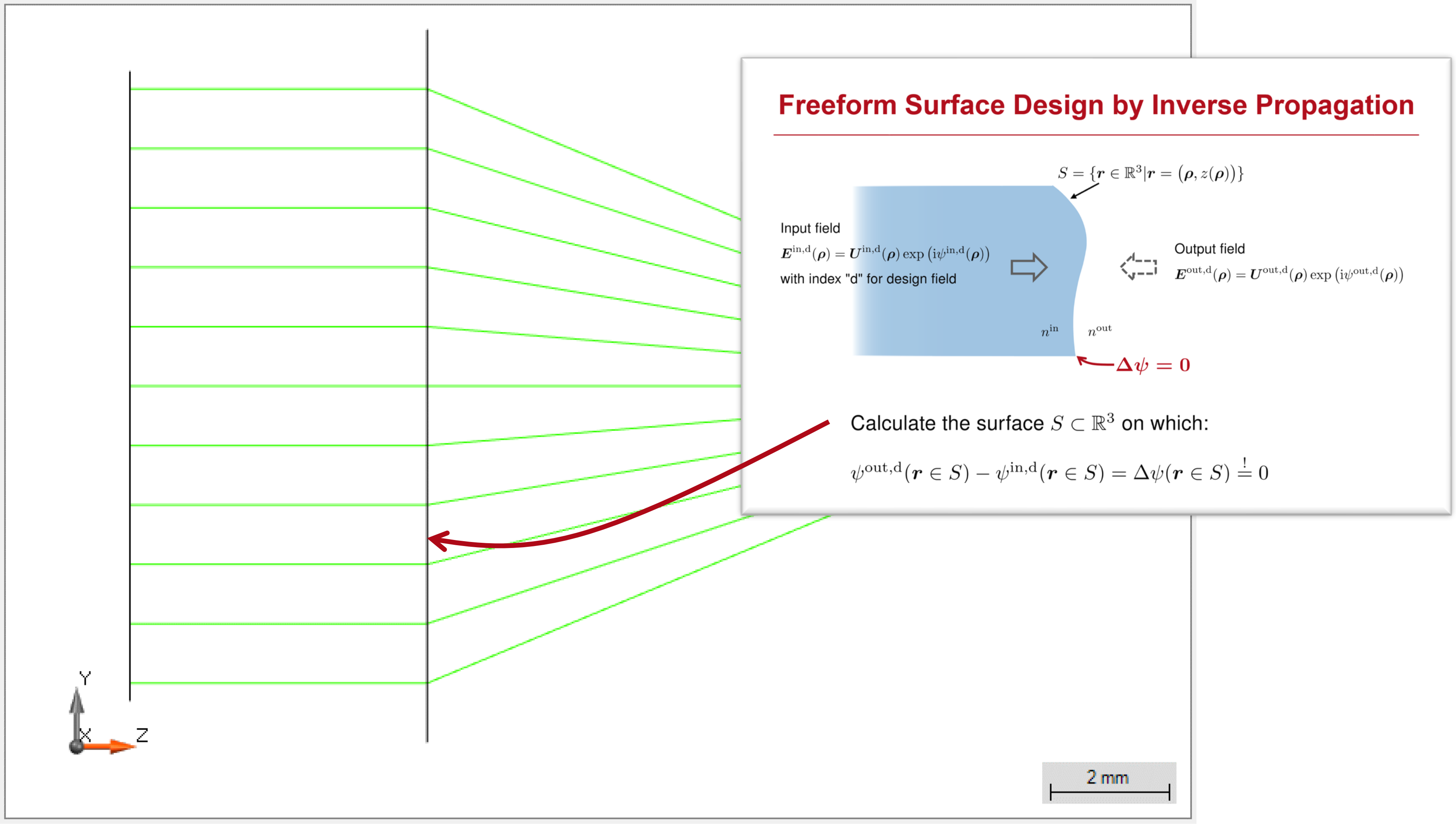


Wavefront phase error after lens

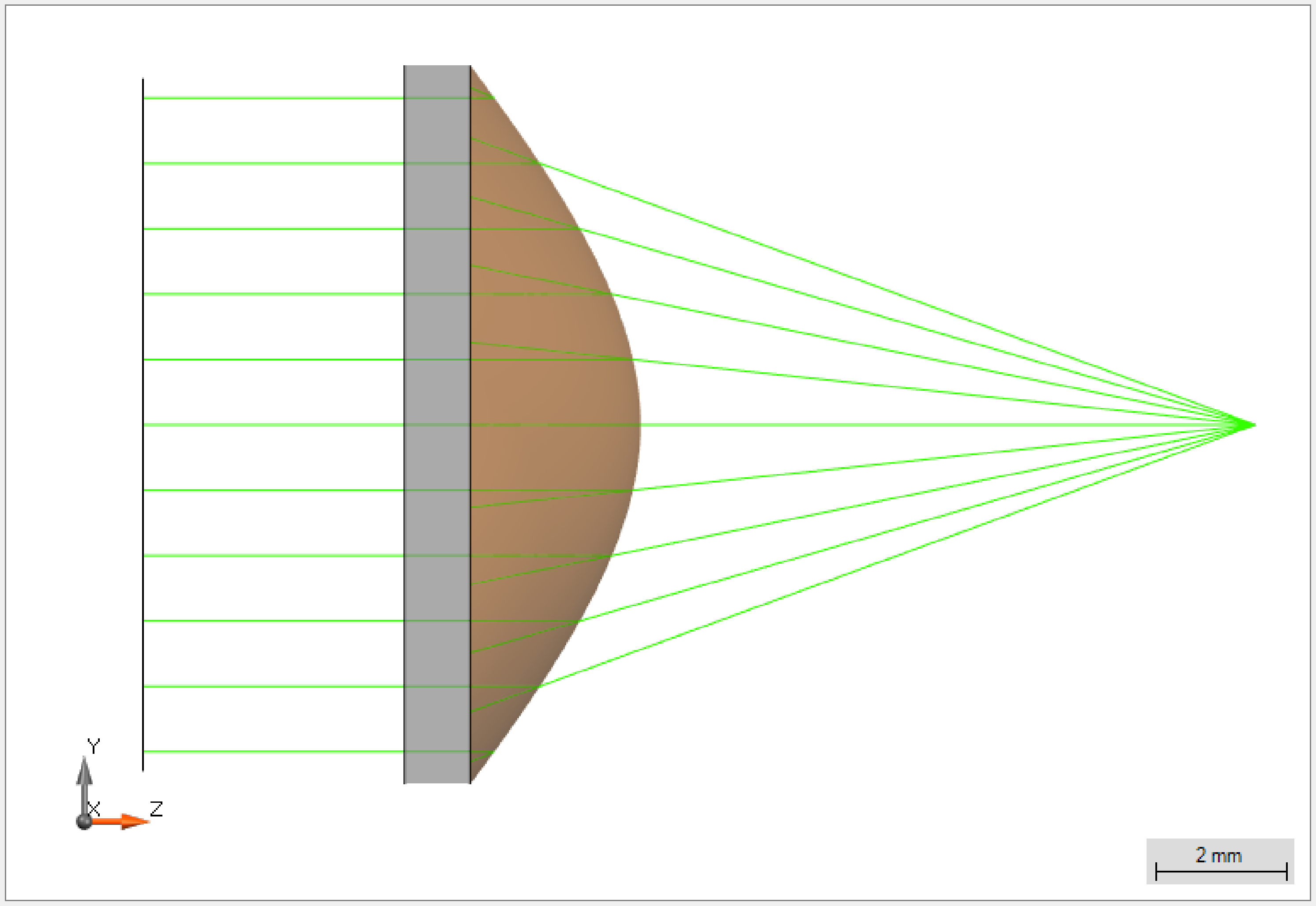
Focusing (NA = 0.4) – Functional Design



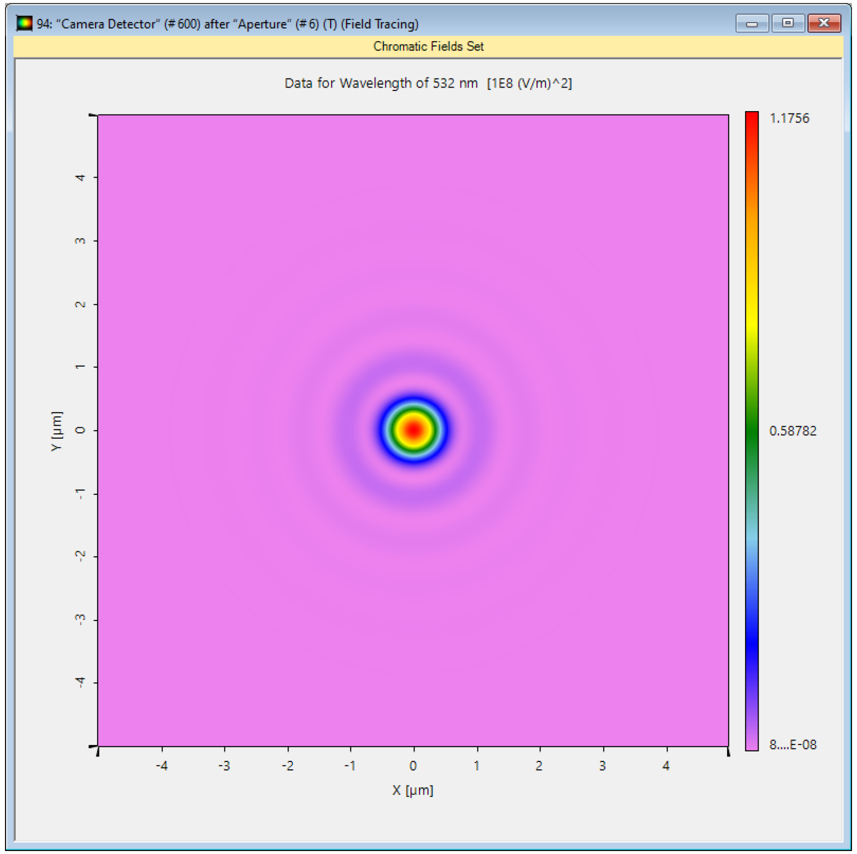
Structural Design Freeform: Focusing (NA = 0.4)



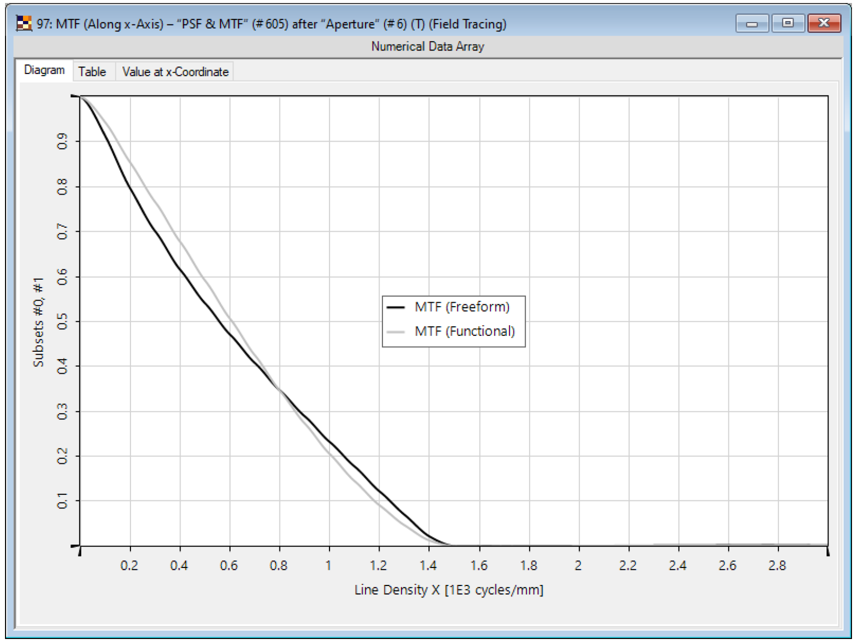
Focusing (NA = 0.4) Lens: Ray Tracing



Focusing (NA = 0.4) Lens: Field Tracing



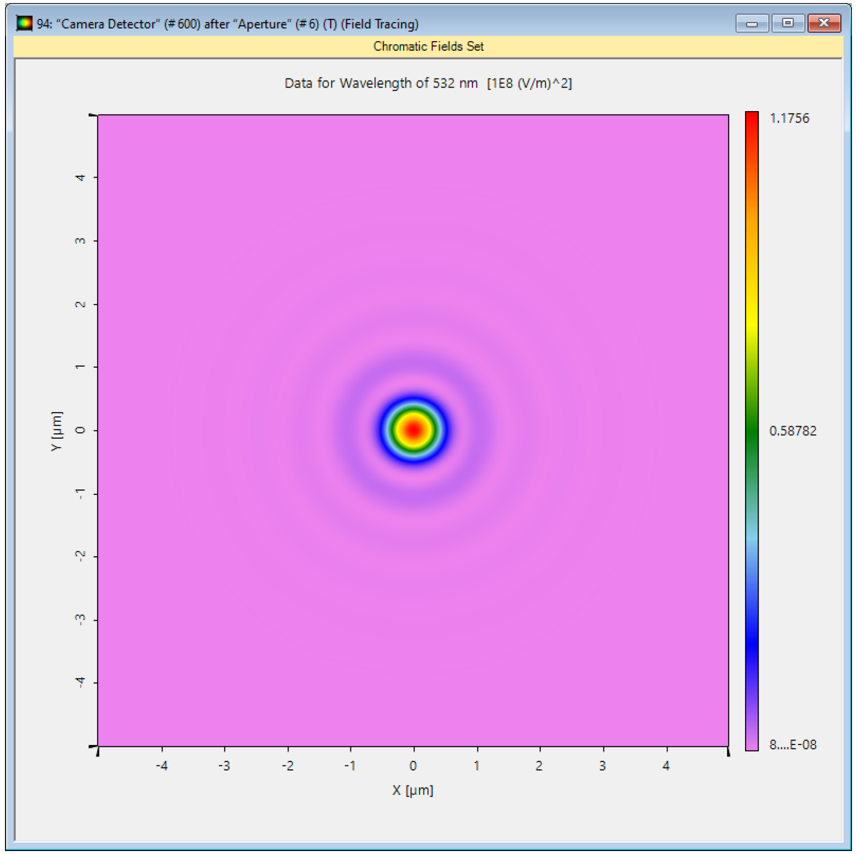
Energy Density in Focus (False Color)



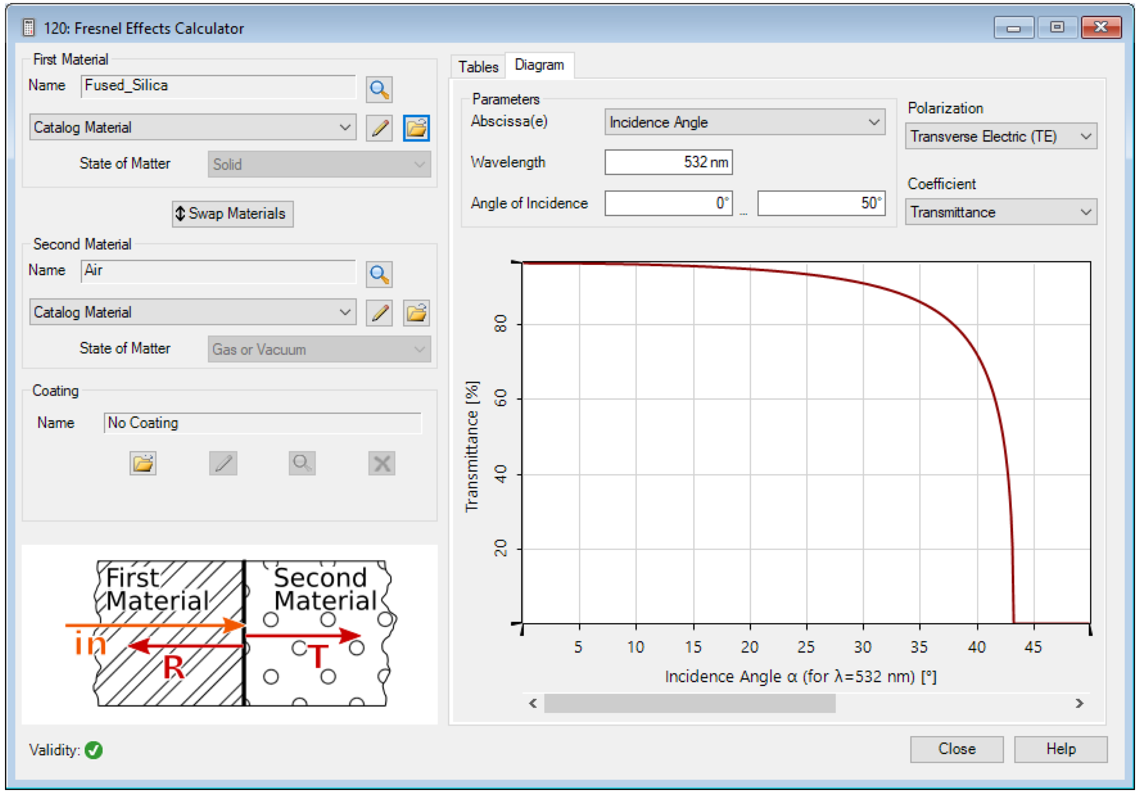
MTF

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

Focusing (NA = 0.4) Lens: Field Tracing



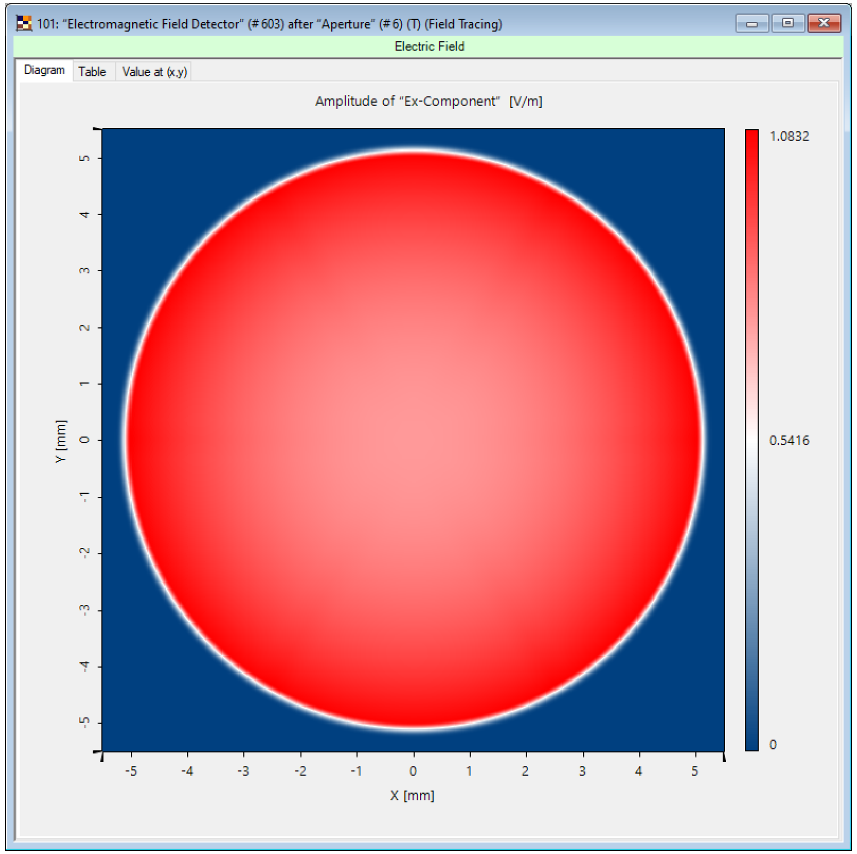
Energy Density in Focus (False Color)



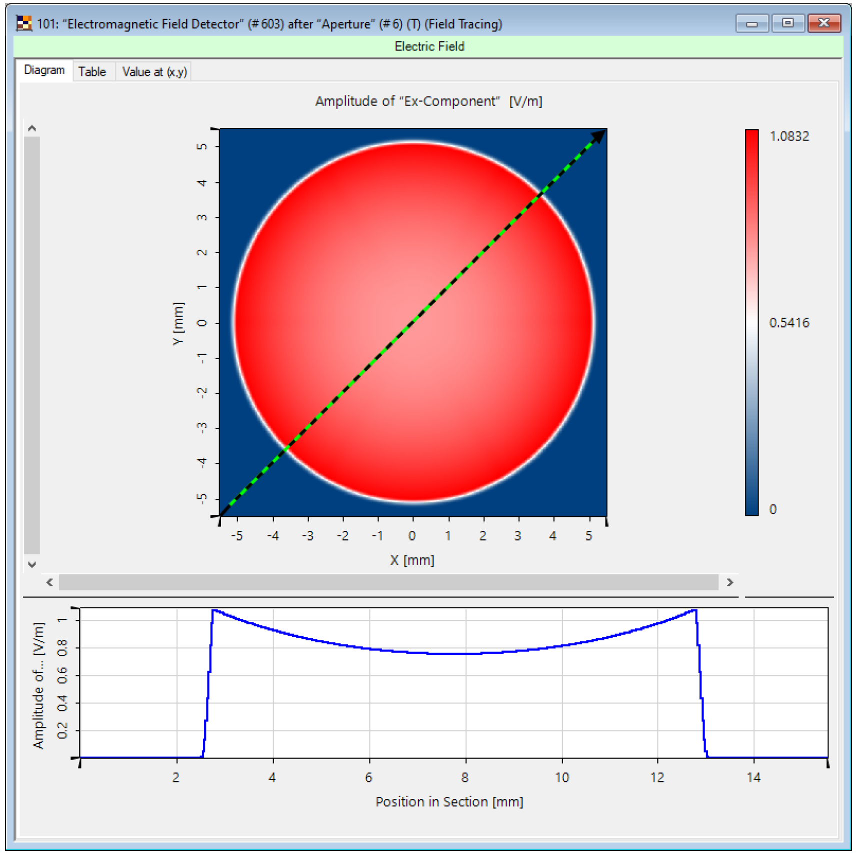
Fresnel effect at surface

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

Focusing (NA = 0.4) Lens: Field Tracing

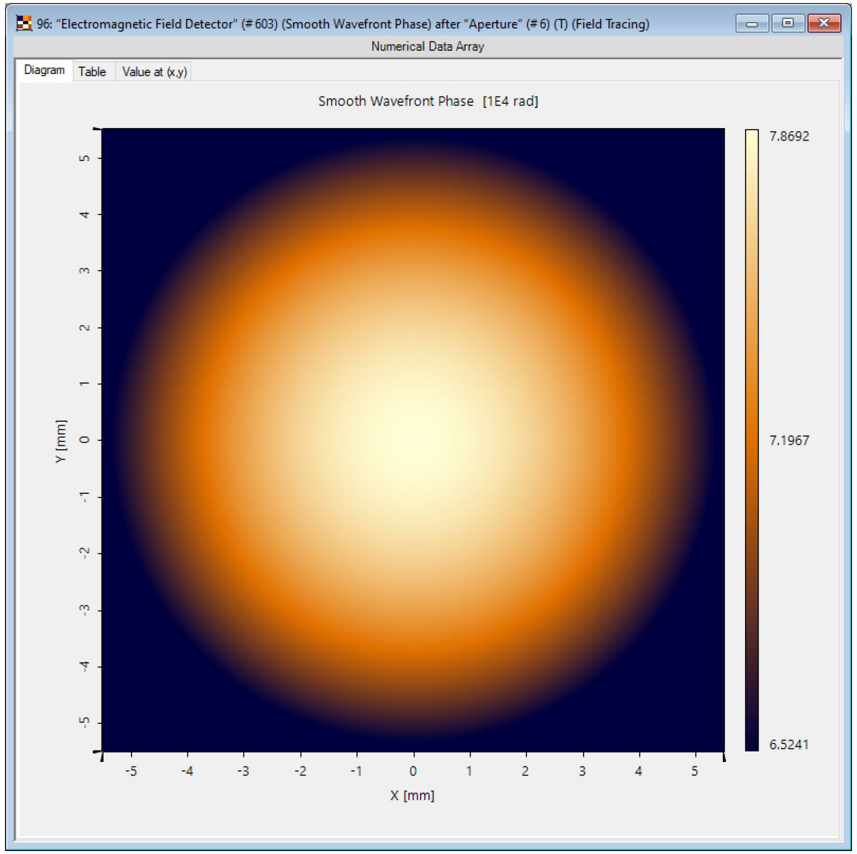


Amplitude after lens

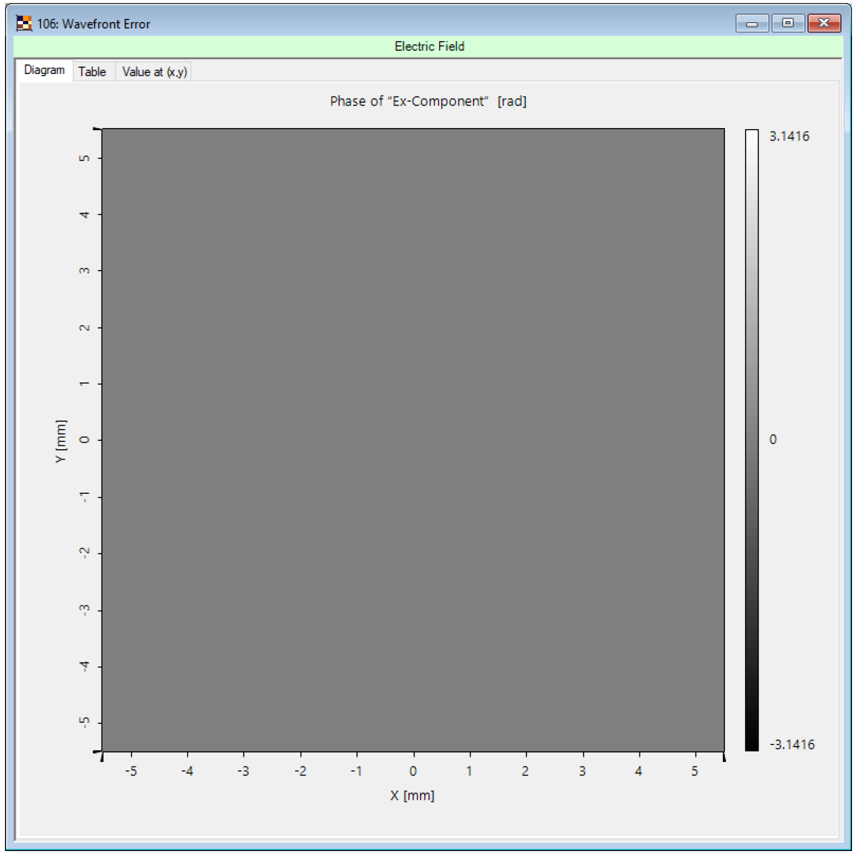


Amplitude after lens

Focusing (NA = 0.4) Lens: Field Tracing

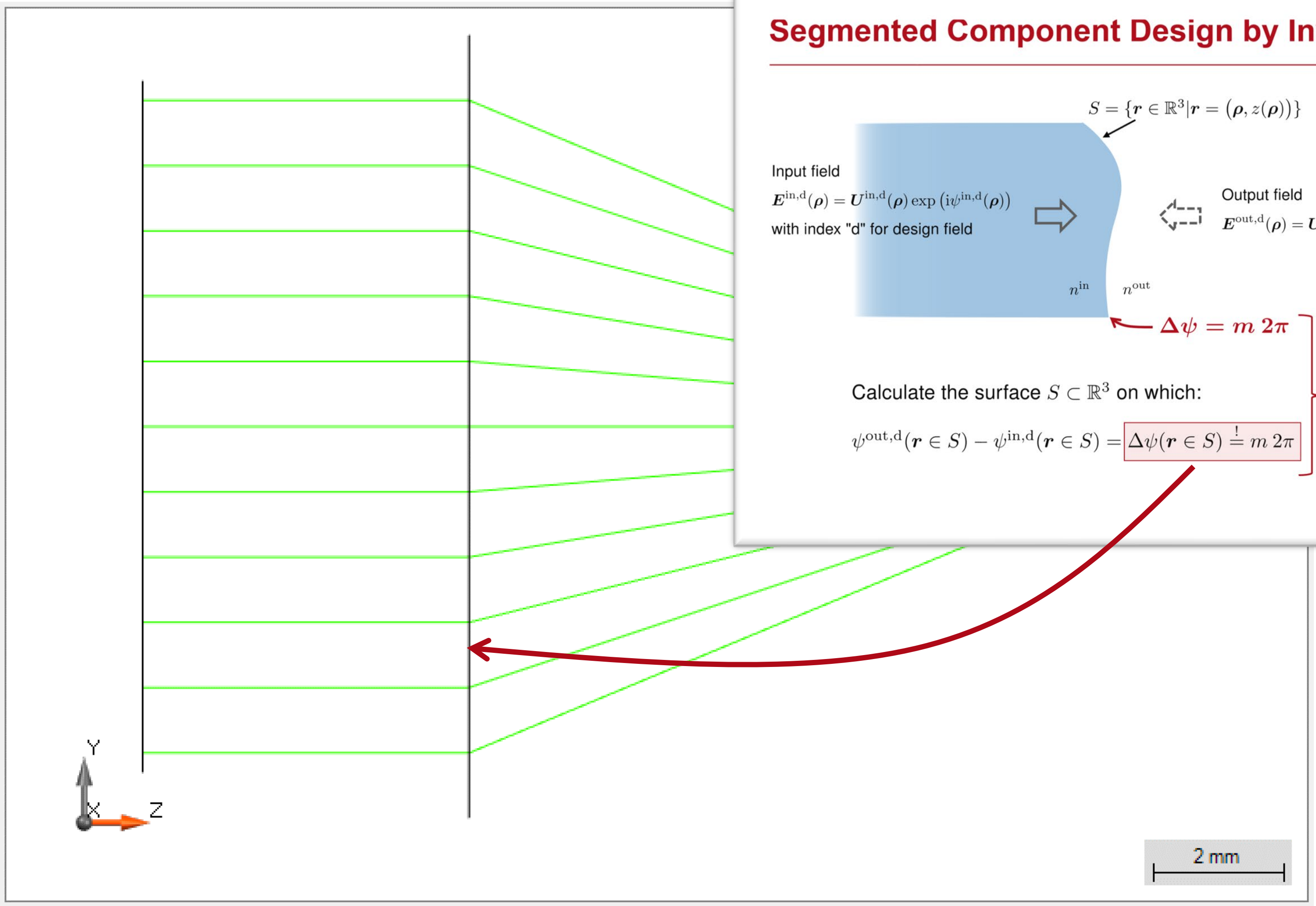


Wavefront phase after lens



Wavefront phase error after lens

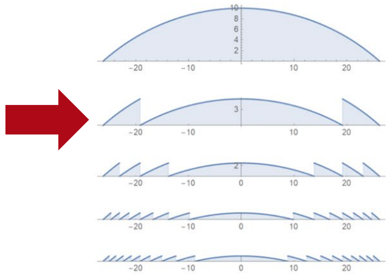
Structural Design Segmented: Focusing (NA = 0.4)



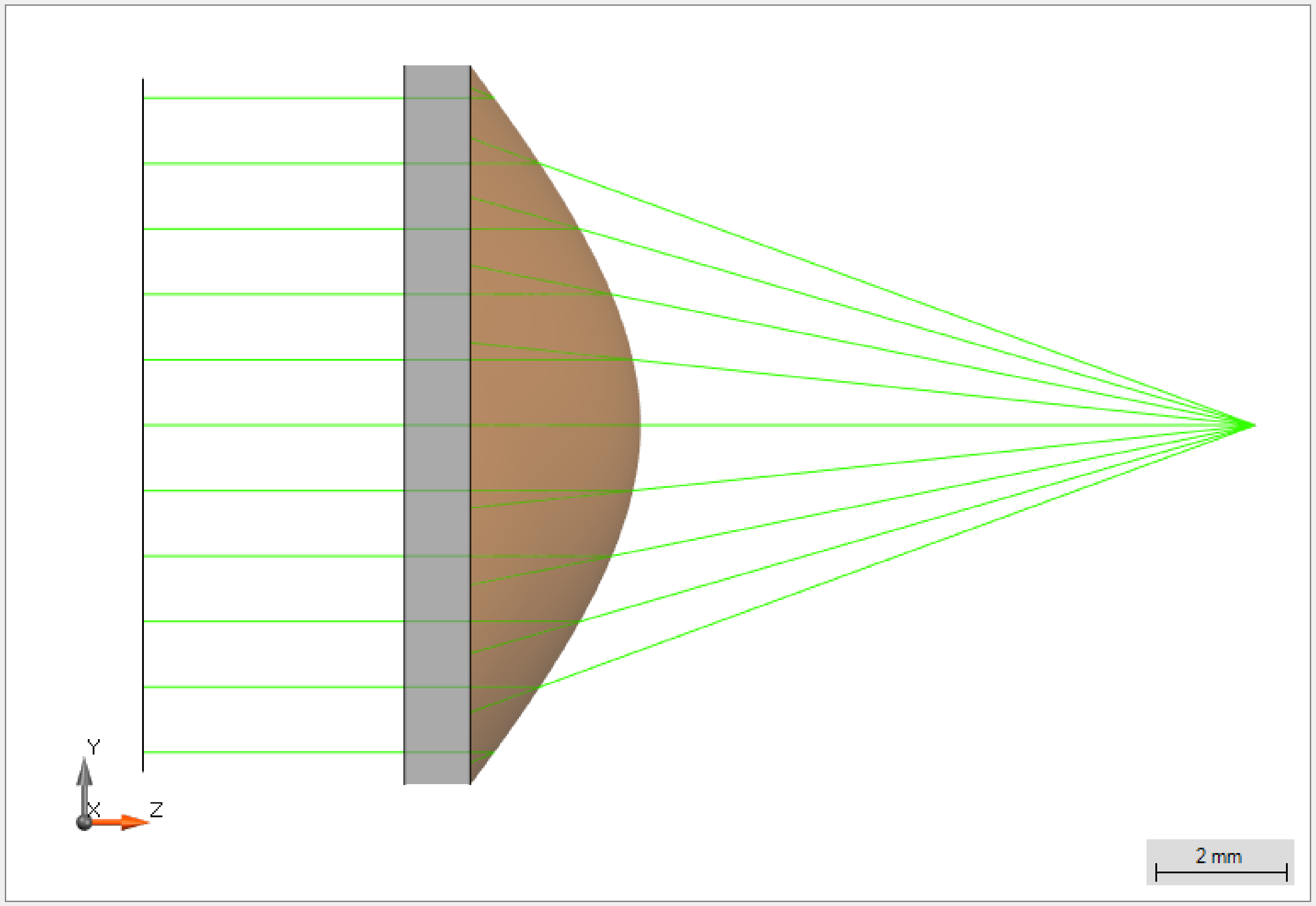
Segmented Component Design by Inverse Propagation

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

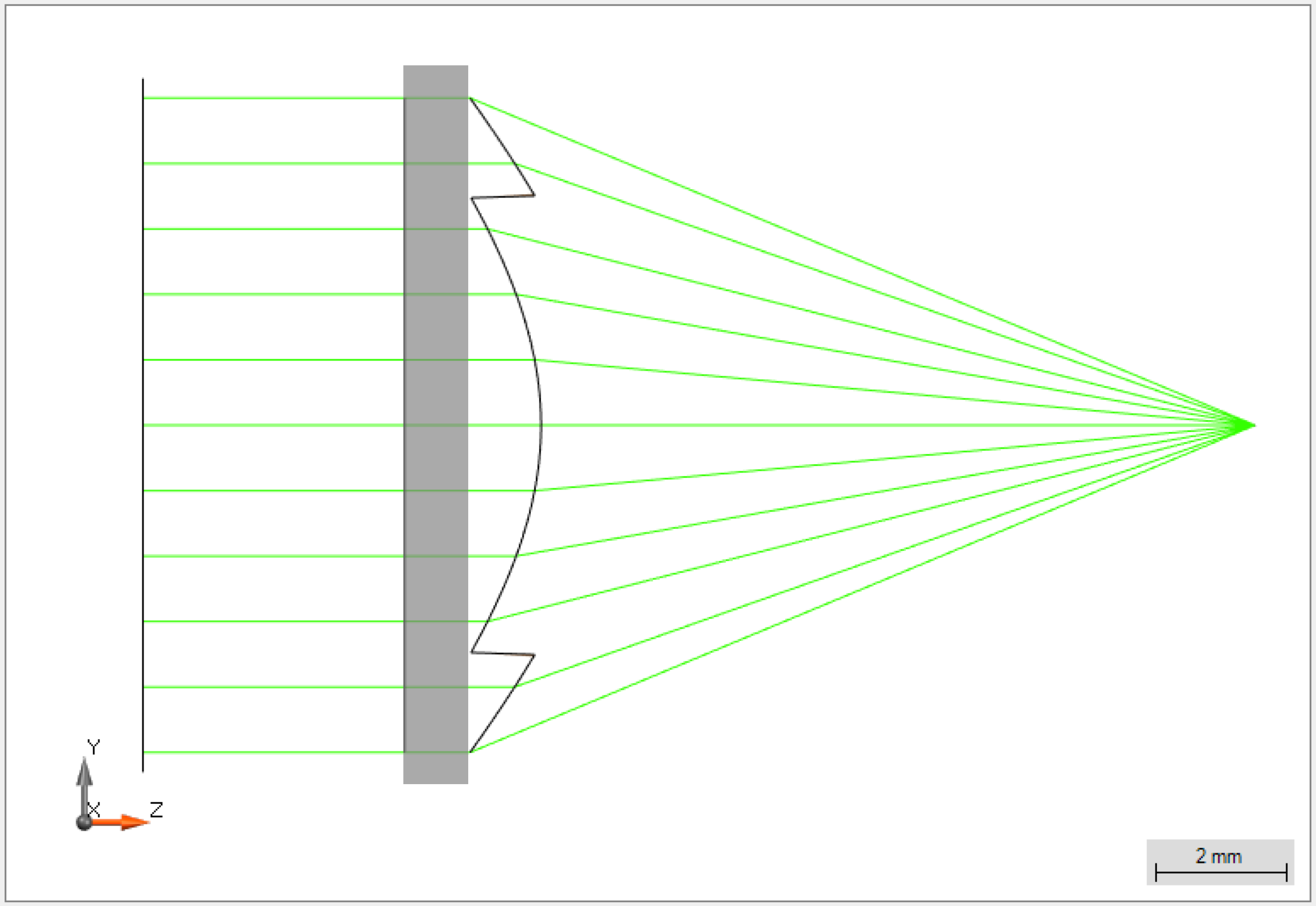
$$\psi^{\mathrm{out,d}}(\boldsymbol{r} \in S) - \psi^{\mathrm{in,d}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} m\,2\pi$$



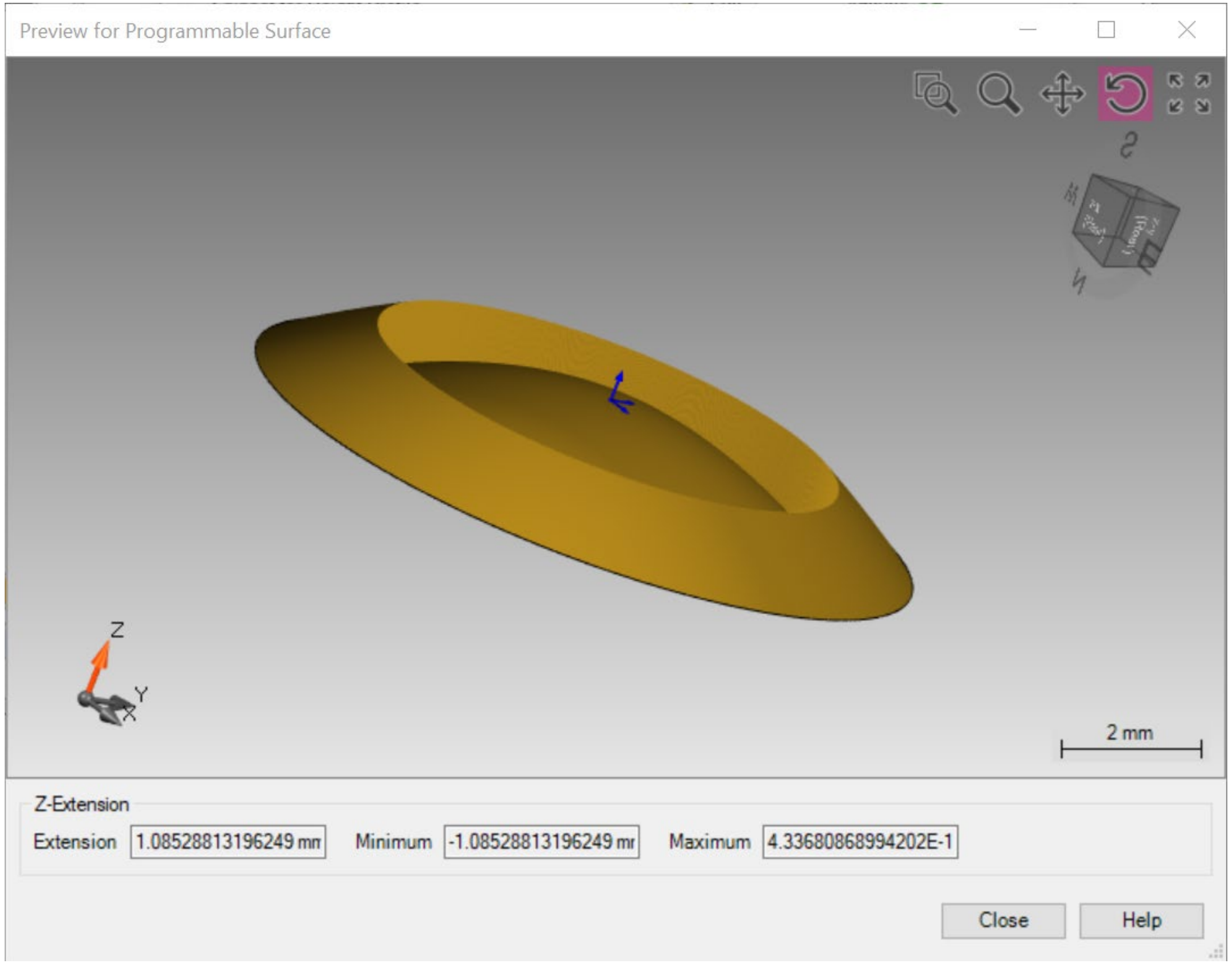
Focusing (NA = 0.4) Lens: Ray Tracing



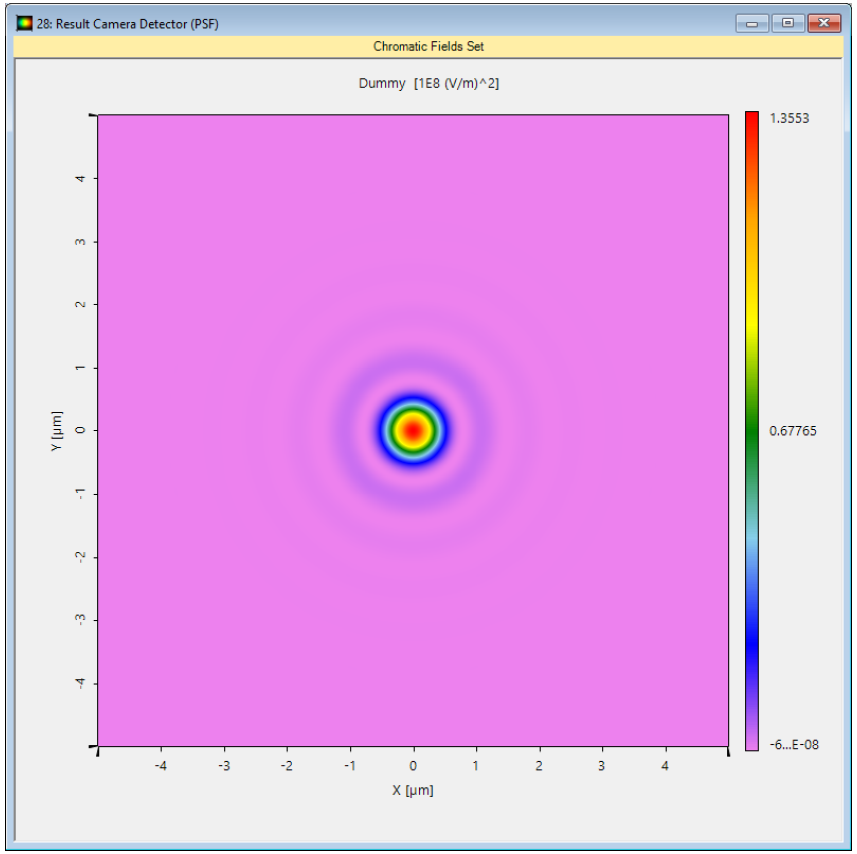
Focusing (NA = 0.4) Segmented Lens: Ray Tracing



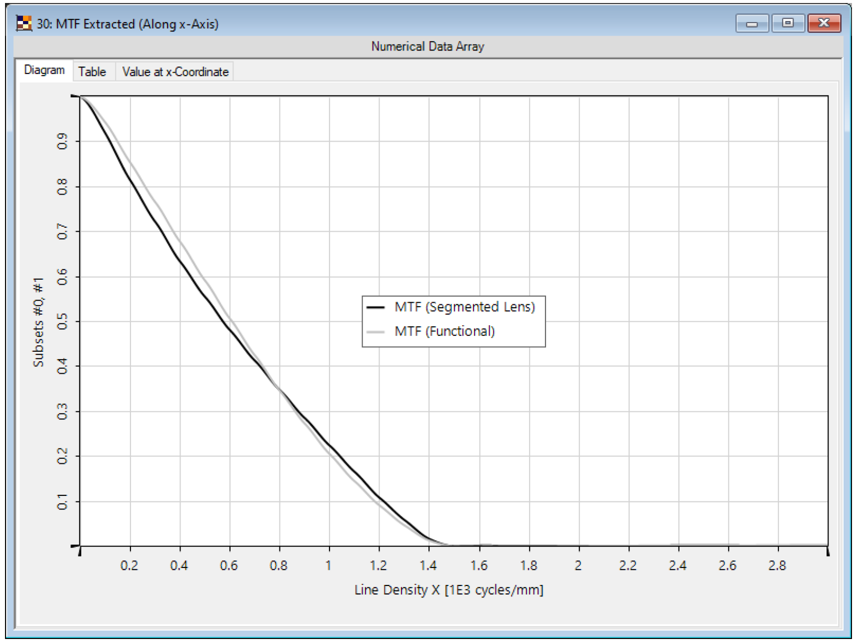
Structural Design Segmented Lens: Focusing NA 0.4



Focusing (NA = 0.4) Segmented Lens: Field Tracing

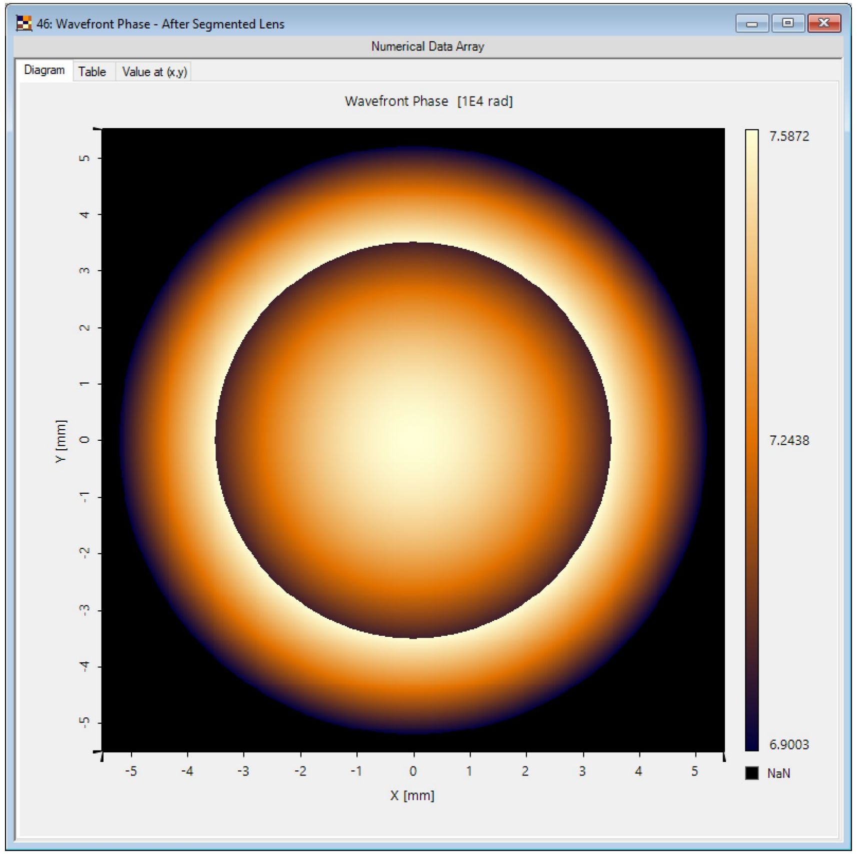


Energy Density in Focus (False Color)

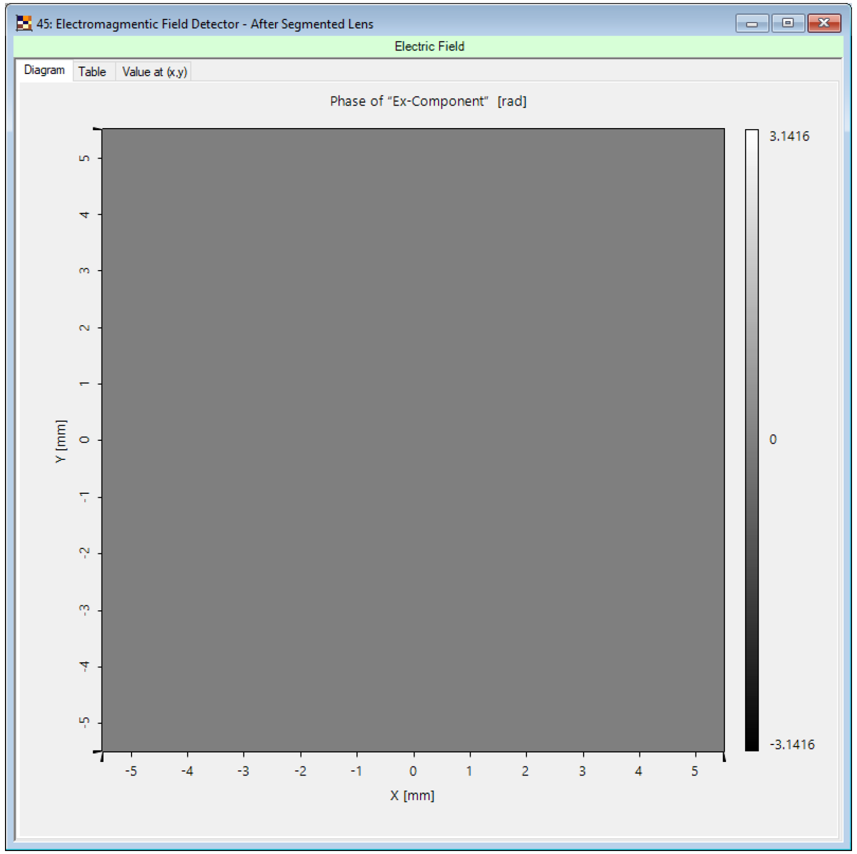


MTF

Focusing (NA = 0.4) Segmented Lens: Field Tracing



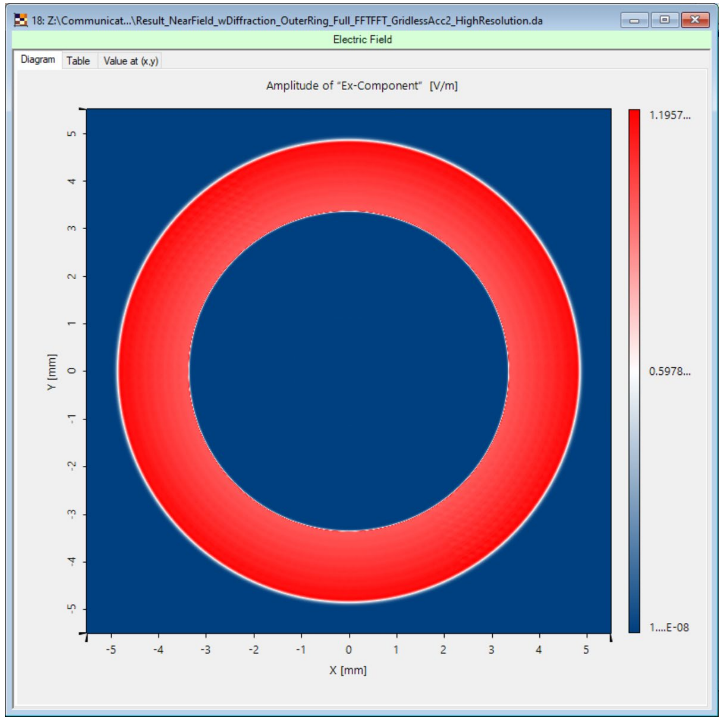
Wavefront Phase after Segmented Lens



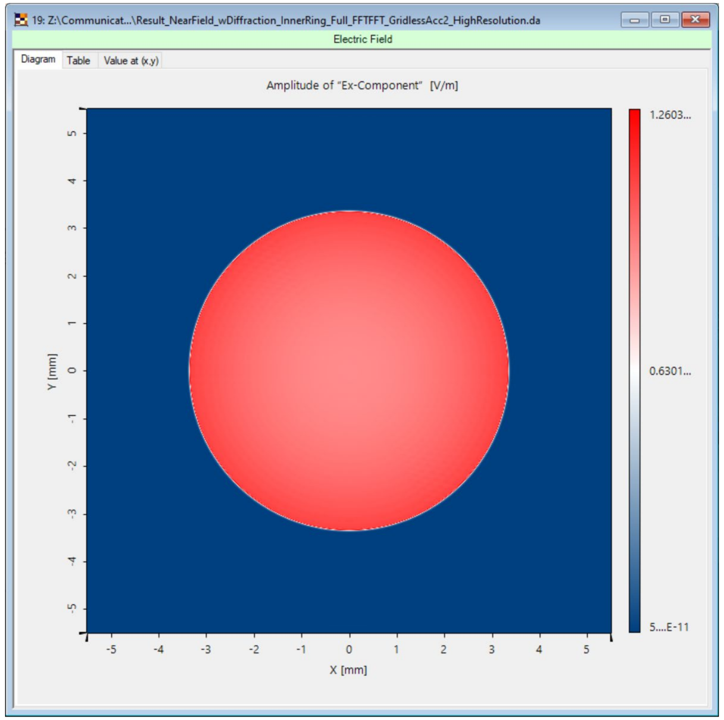
Wavefront Error after Segmented Lens

Focusing (NA = 0.4) Segmented Lens: Field Tracing

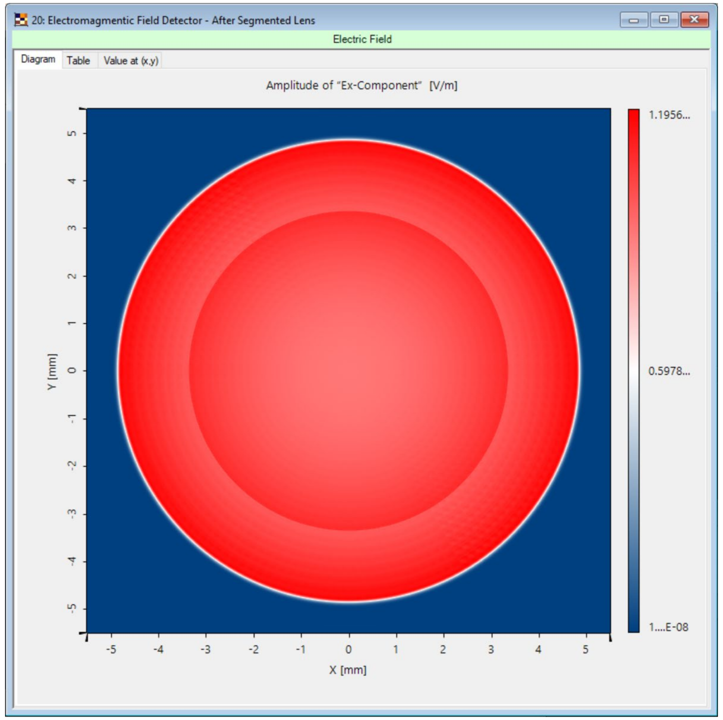
Near Field Analysis – 500µm after Segmented Lens:



Field (Ex) @ 500µm after Lens (Outer Segment)



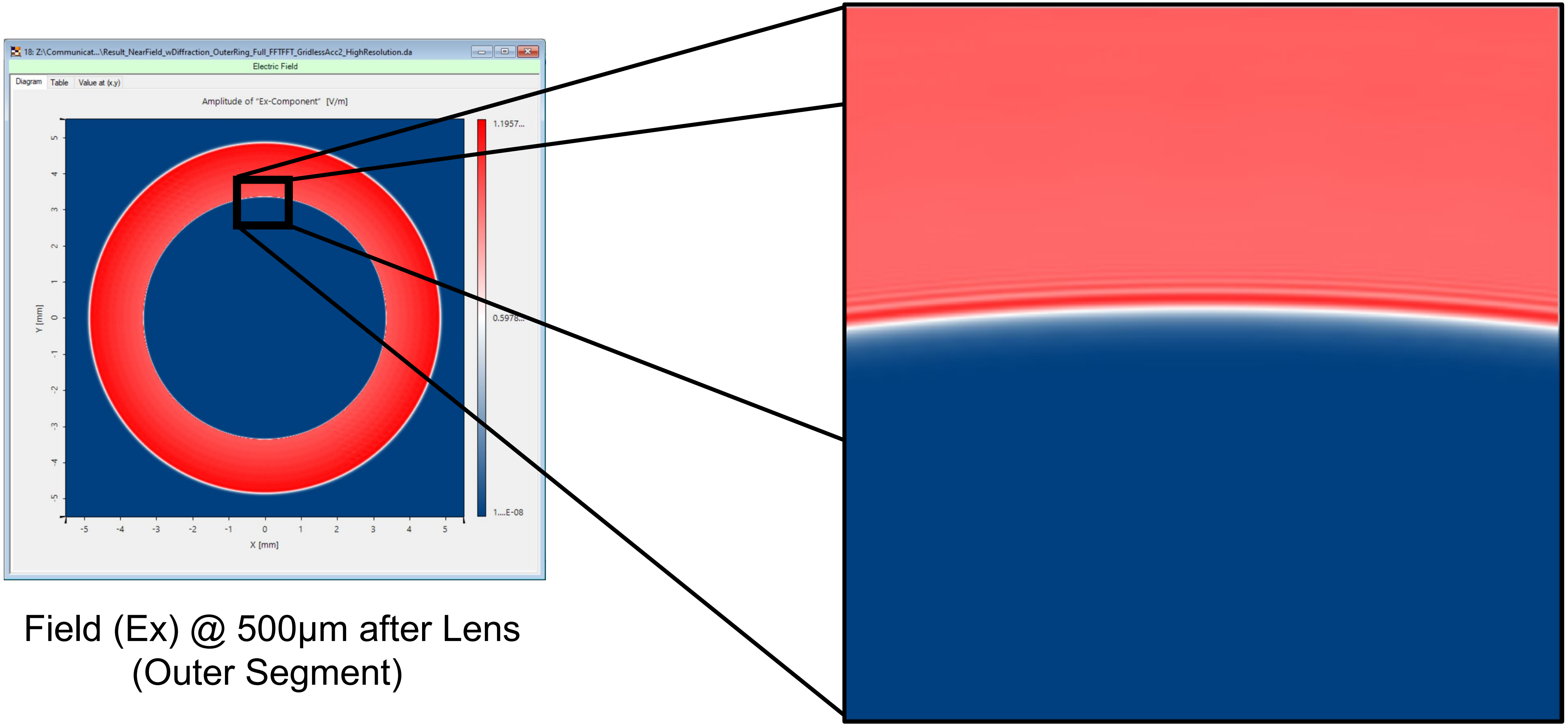
Field (Ex) @ 500µm after Lens (Inner Segment)



Field (Ex) @ 500µm after Lens (Combined)

Focusing (NA = 0.4) Segmented Lens: Field Tracing

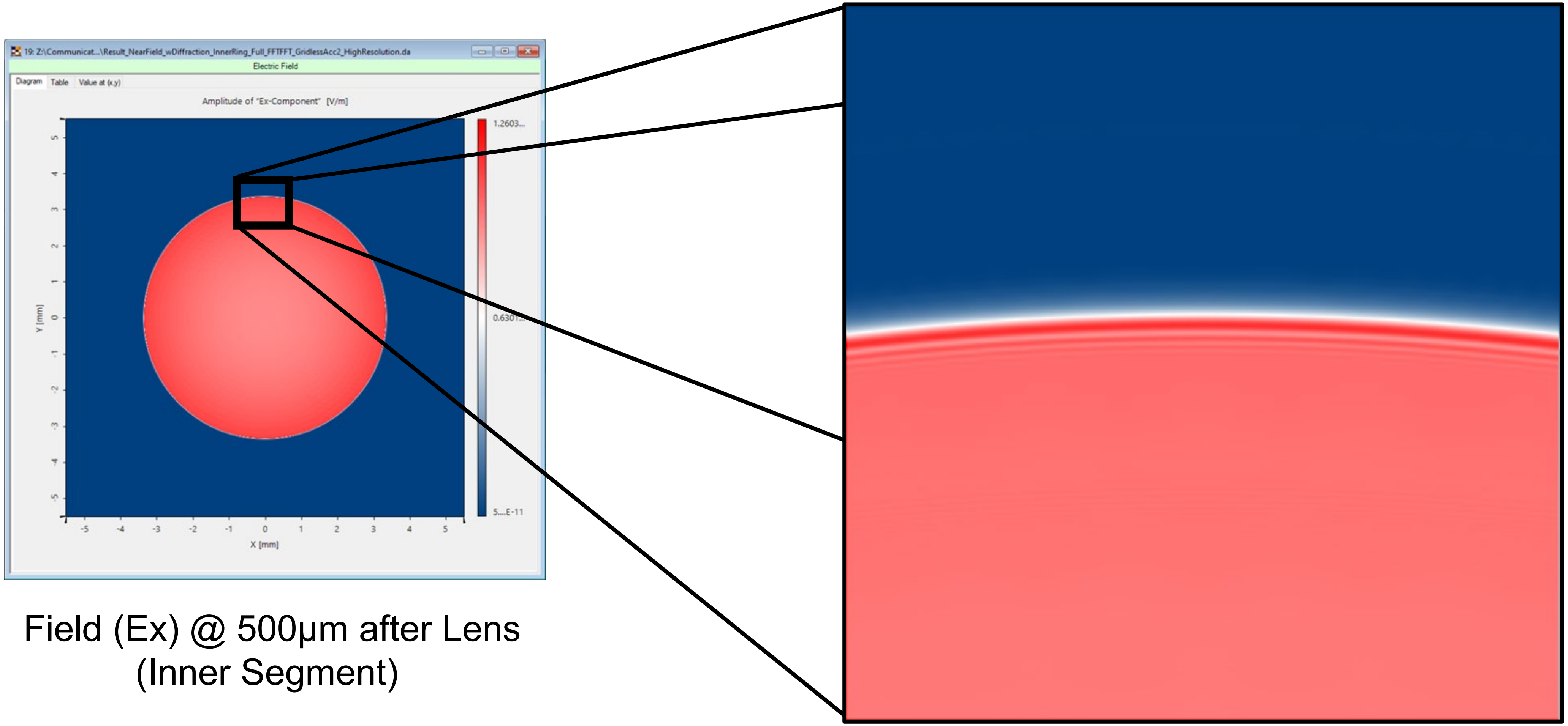
Near Field Analysis – 500µm after Segmented Lens:



Field (Ex) @ 500µm after Lens
(Outer Segment)

Focusing (NA = 0.4) Segmented Lens: Field Tracing

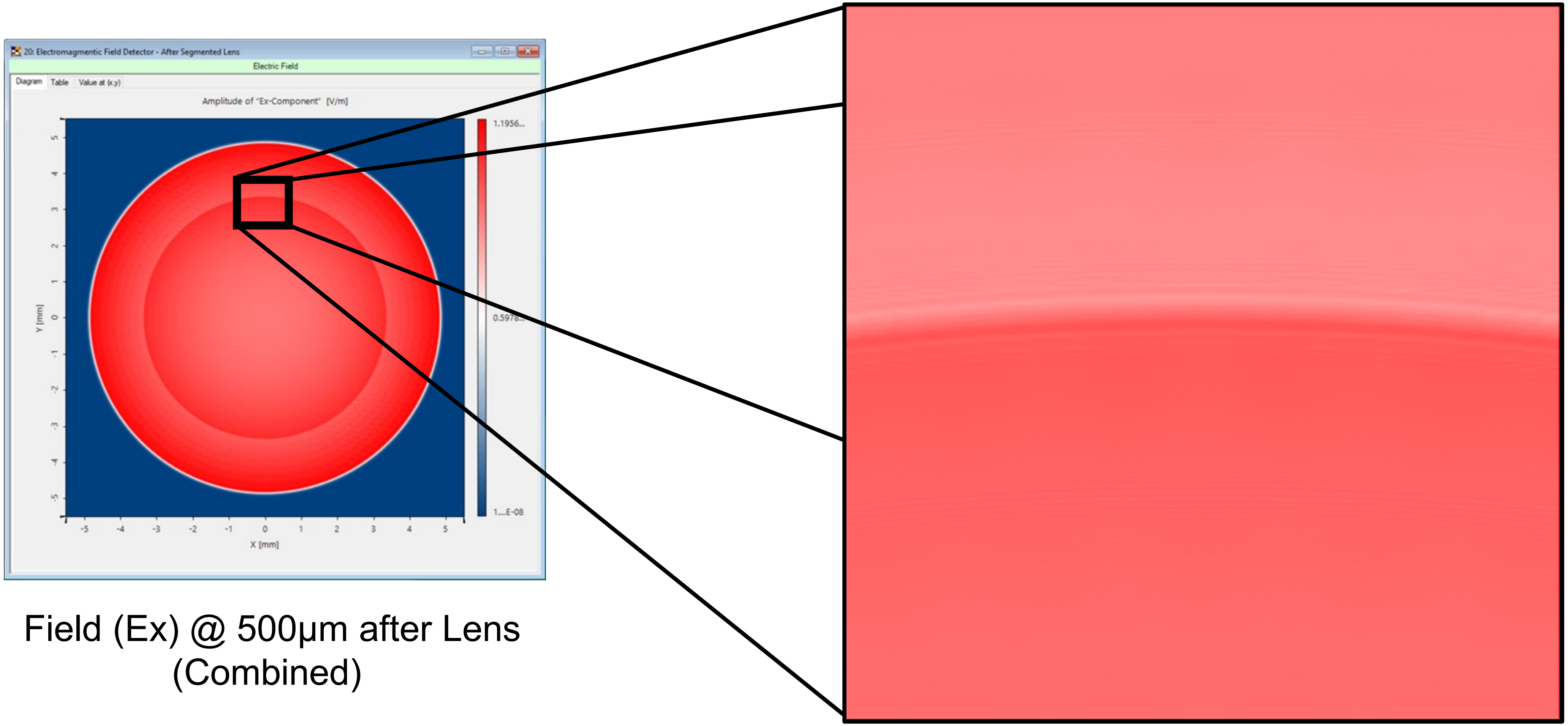
Near Field Analysis – 500µm after Segmented Lens:



Field (Ex) @ 500µm after Lens
(Inner Segment)

Focusing (NA = 0.4) Segmented Lens: Field Tracing

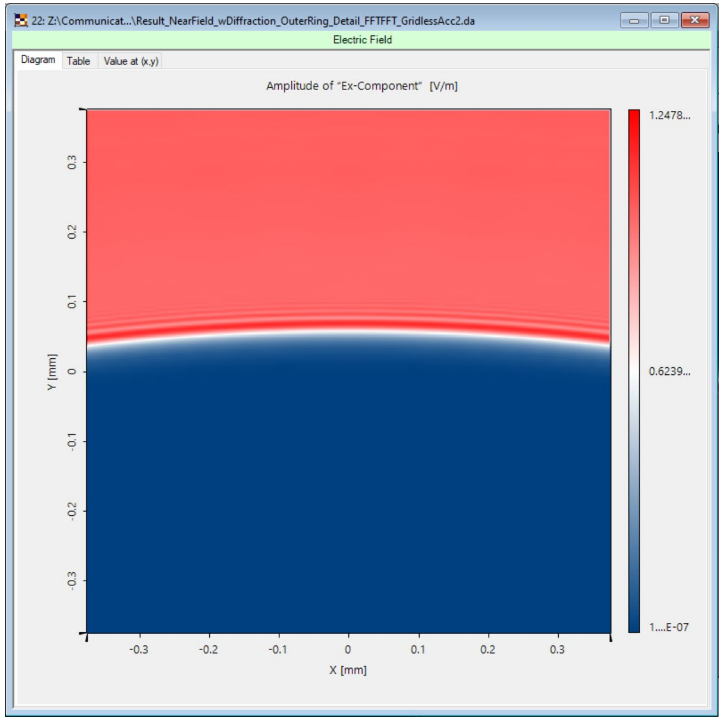
Near Field Analysis – 500µm after Segmented Lens:



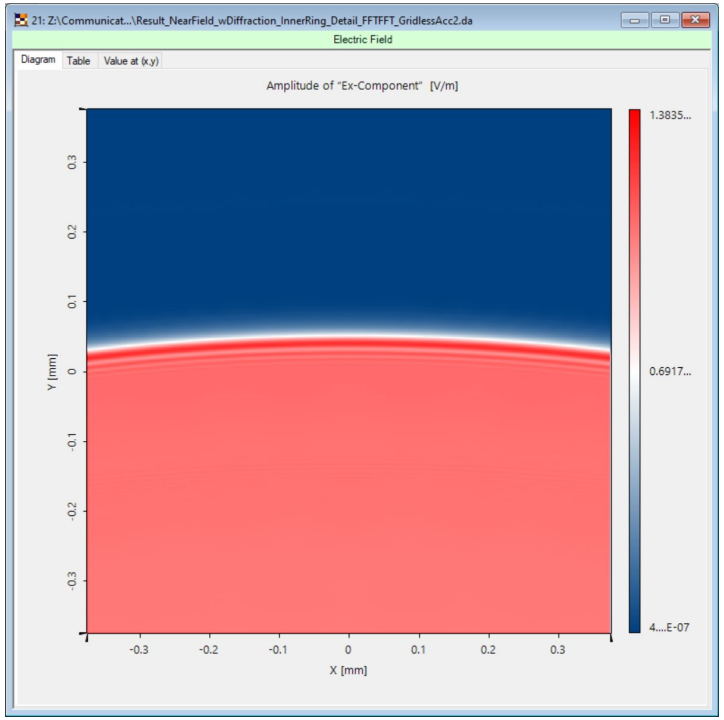
Field (Ex) @ 500µm after Lens
(Combined)

Focusing (NA = 0.4) Segmented Lens: Field Tracing

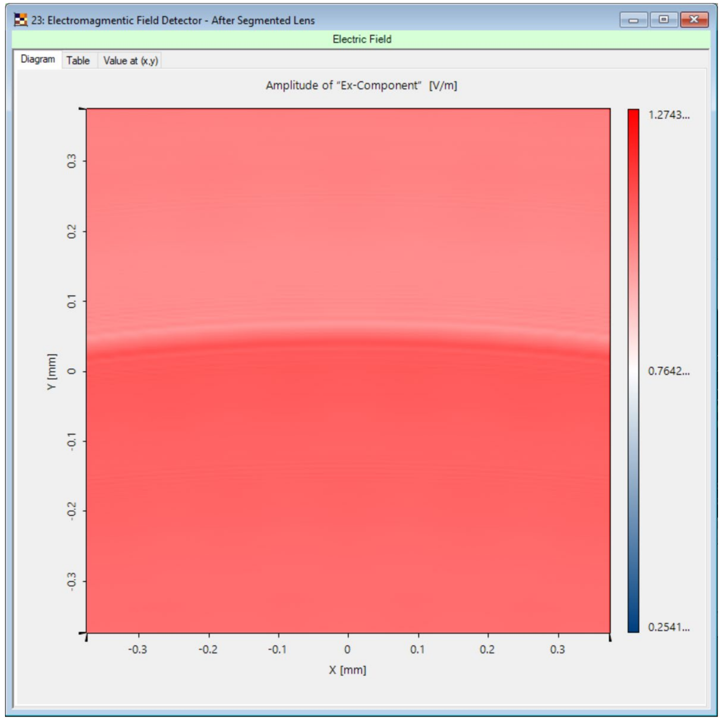
Near Field Analysis – 500µm after Segmented Lens:



Field (Ex) @ 500µm after Lens
(Outer Segment)

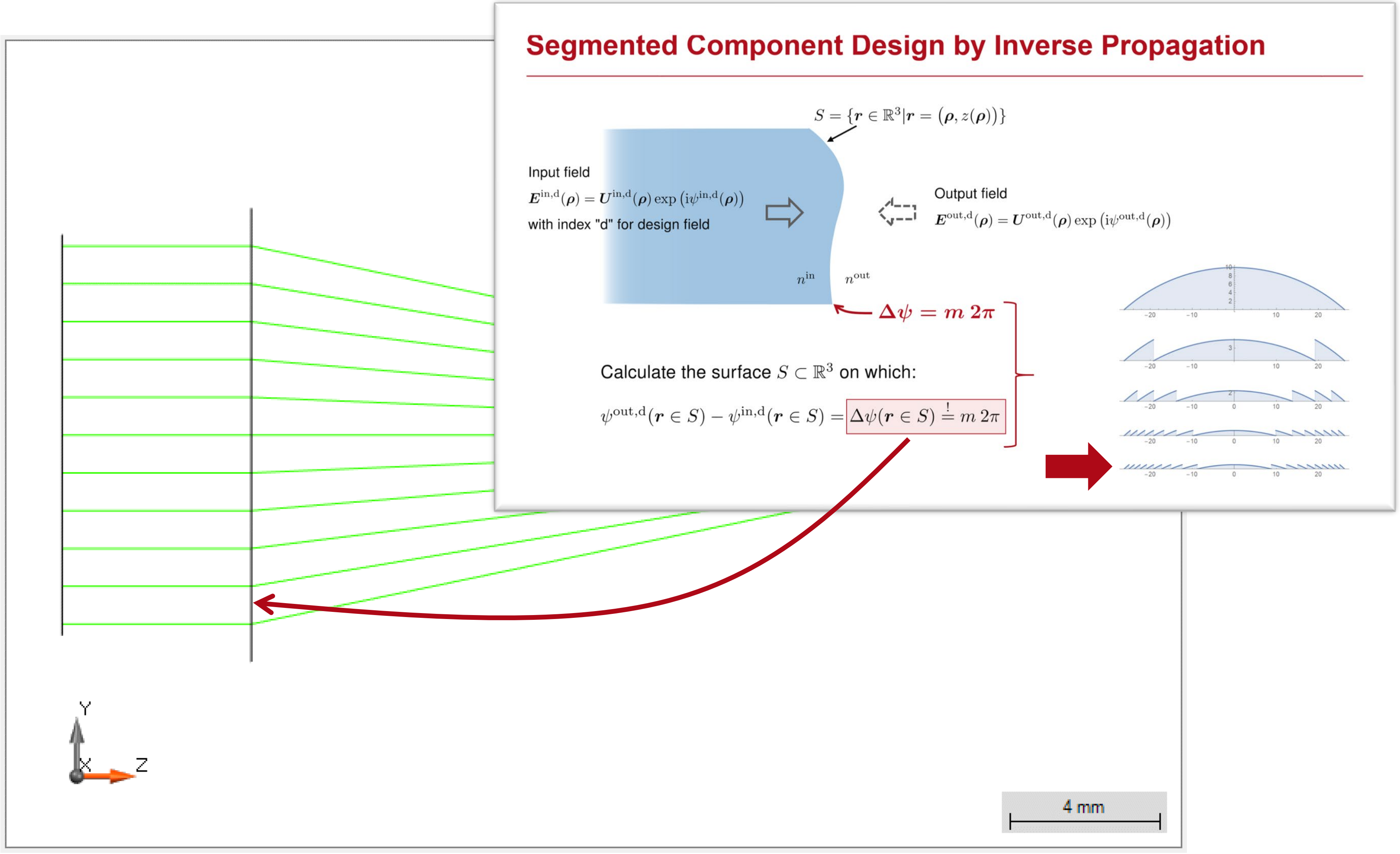


Field (Ex) @ 500µm after Lens
(Inner Segment)

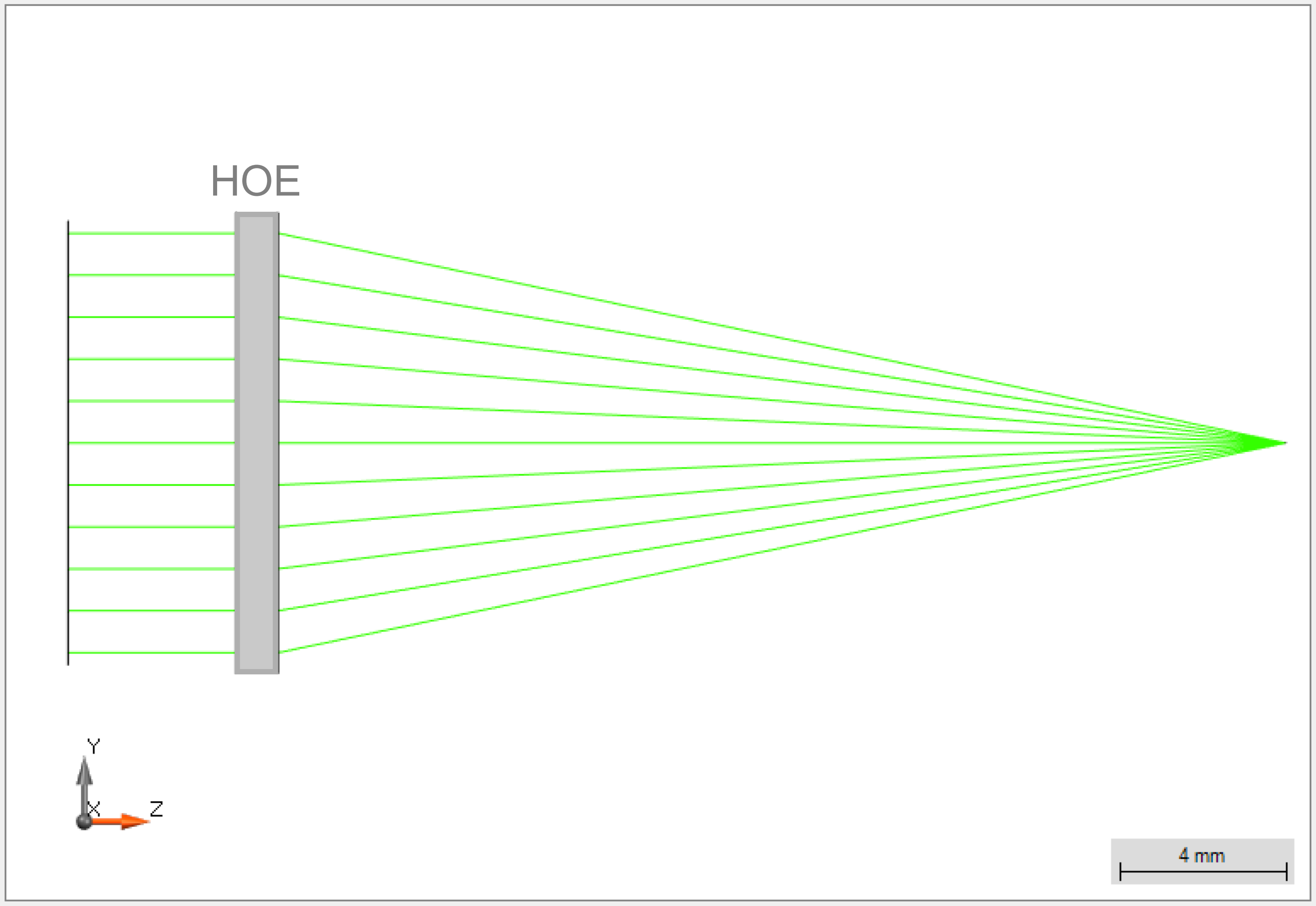


Field (Ex) @ 500µm after Lens
(Combined)

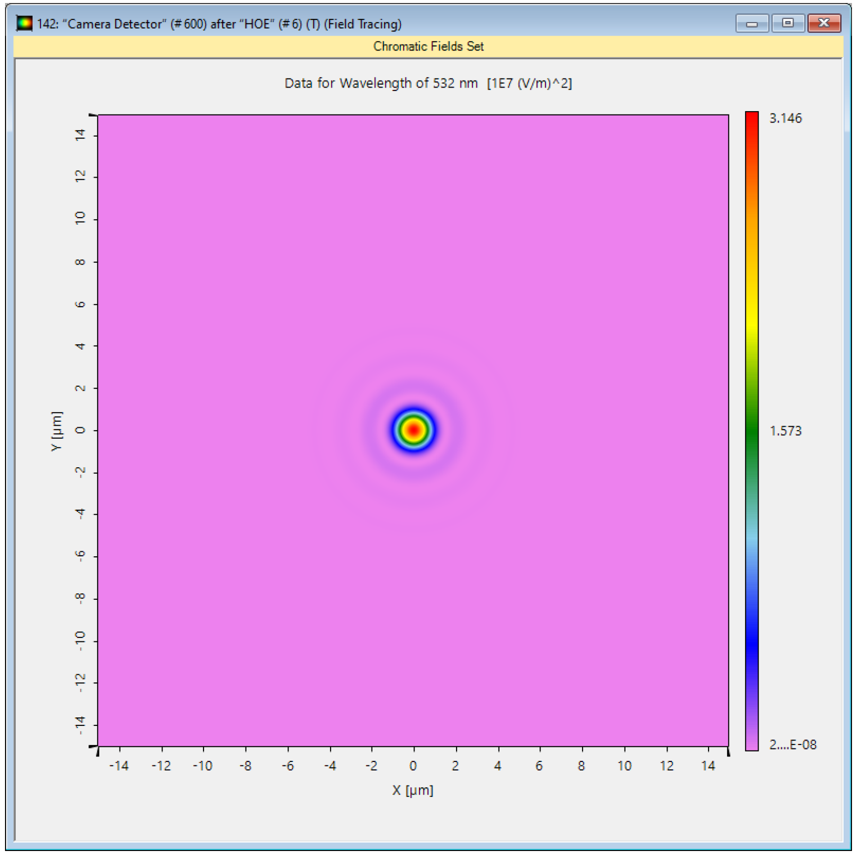
Structural Design HOE: Focusing (NA = 0.2)



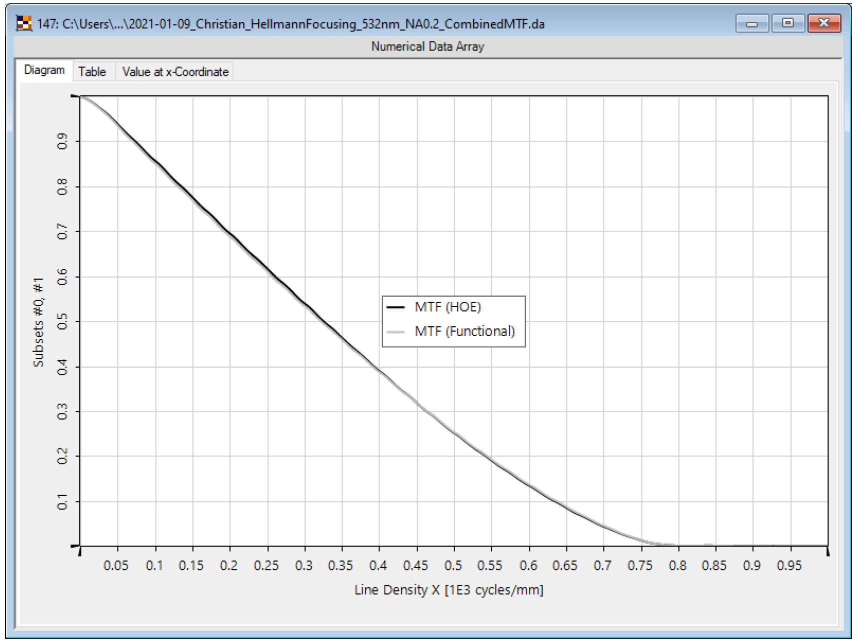
Focusing (NA = 0.2) HOE: Ray Tracing



Focusing (NA = 0.2) HOE: Field Tracing



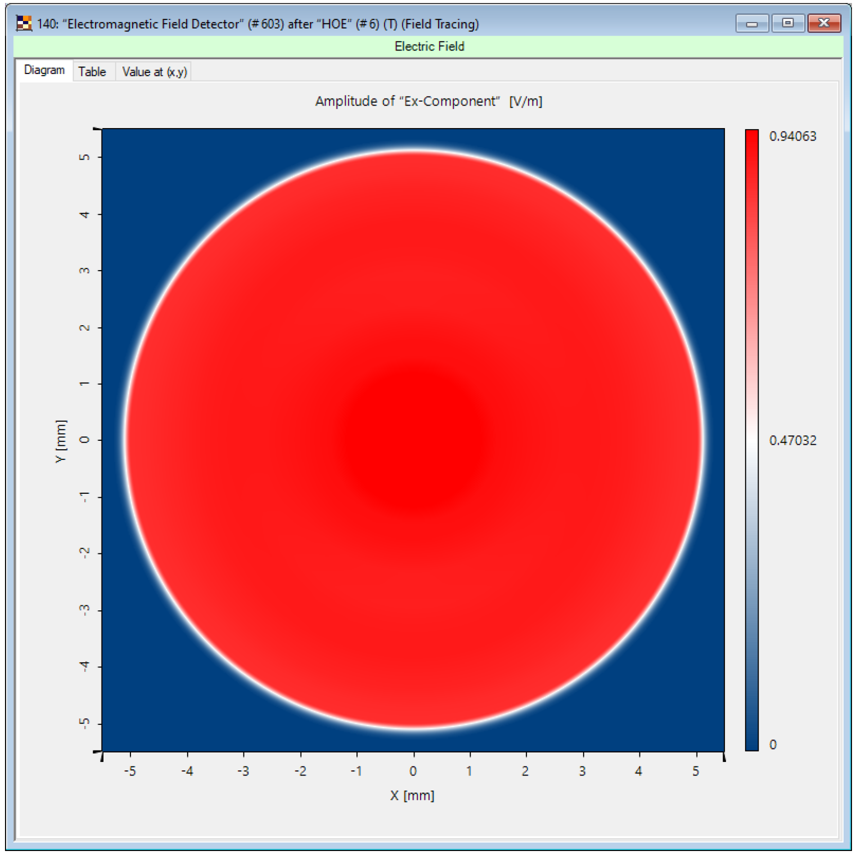
Field in Focus (False Color)



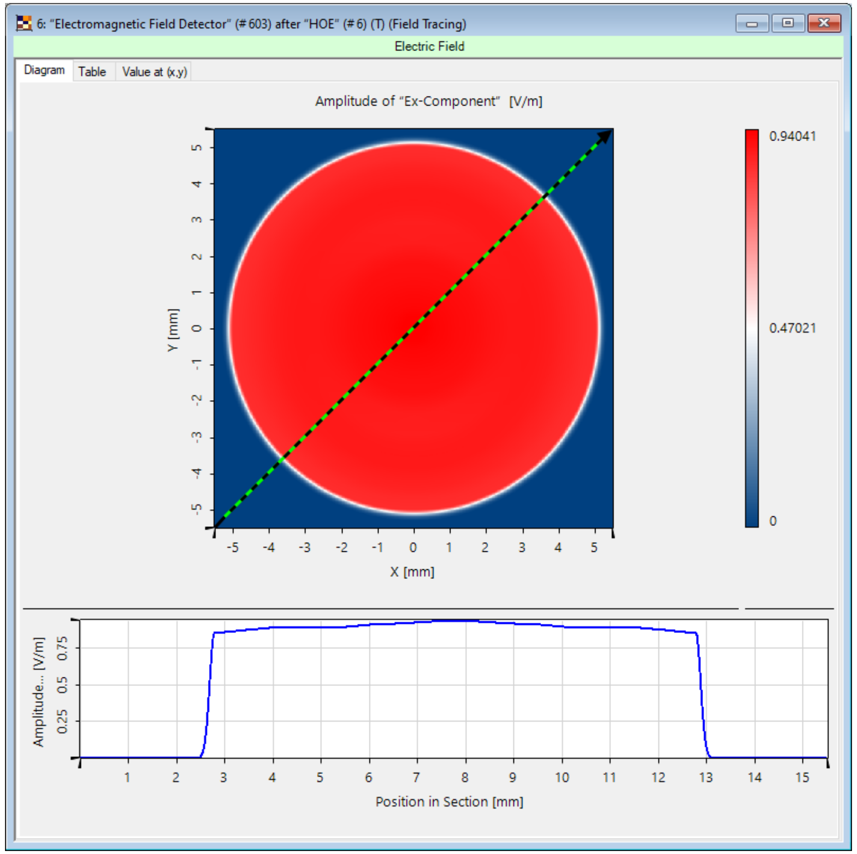
MTF

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

Focusing (NA = 0.2) HOE: Field Tracing

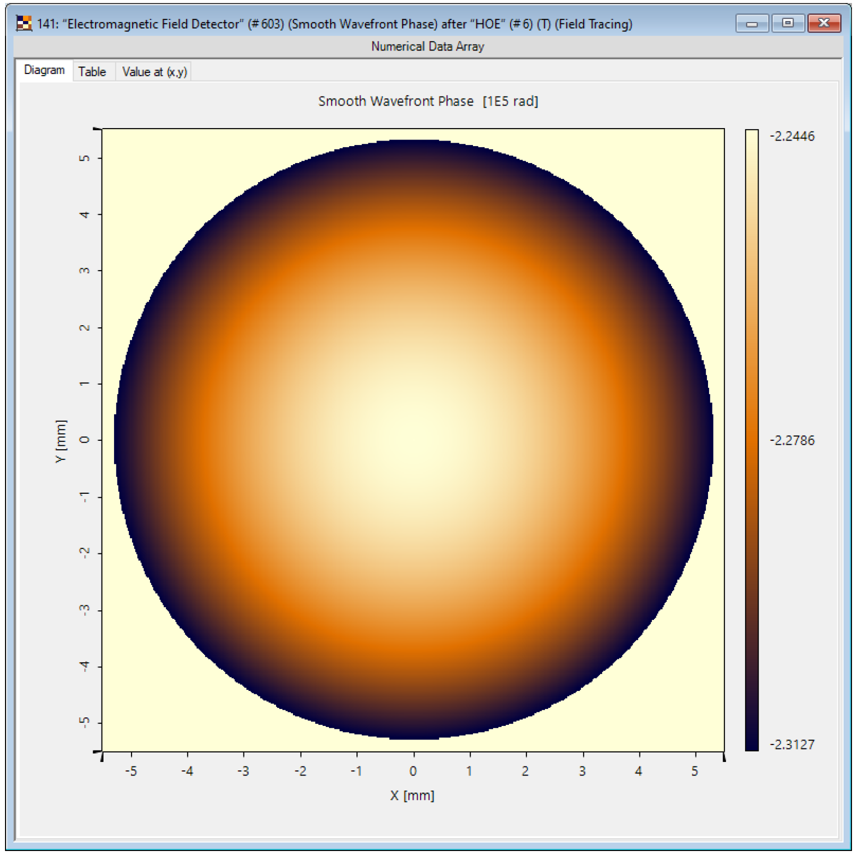


Amplitude after HOE

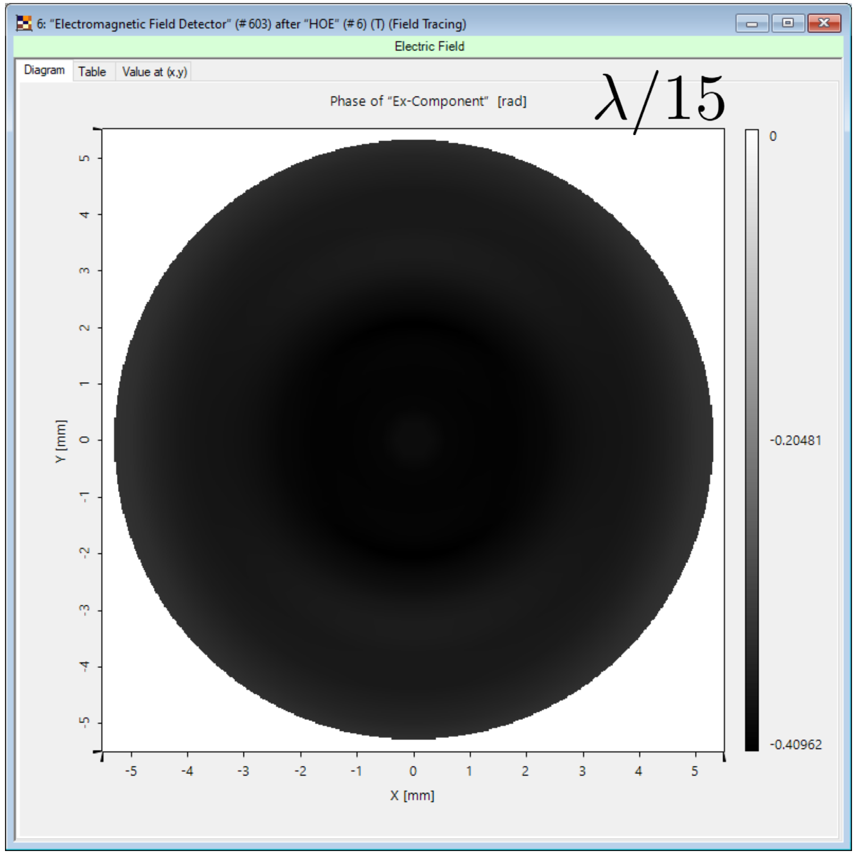


Amplitude after HOE

Focusing (NA = 0.2) HOE: Field Tracing

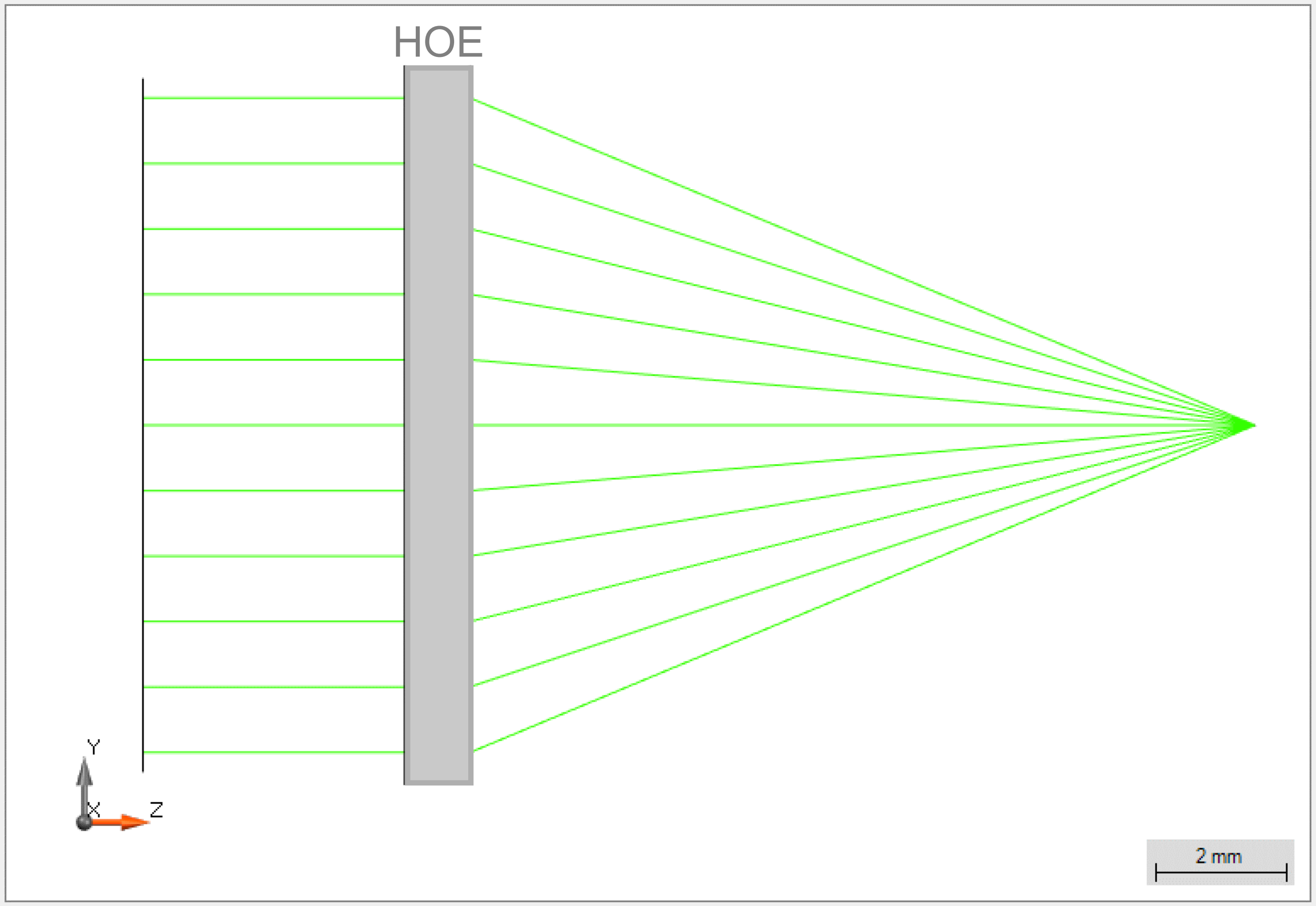


Wavefront after HOE

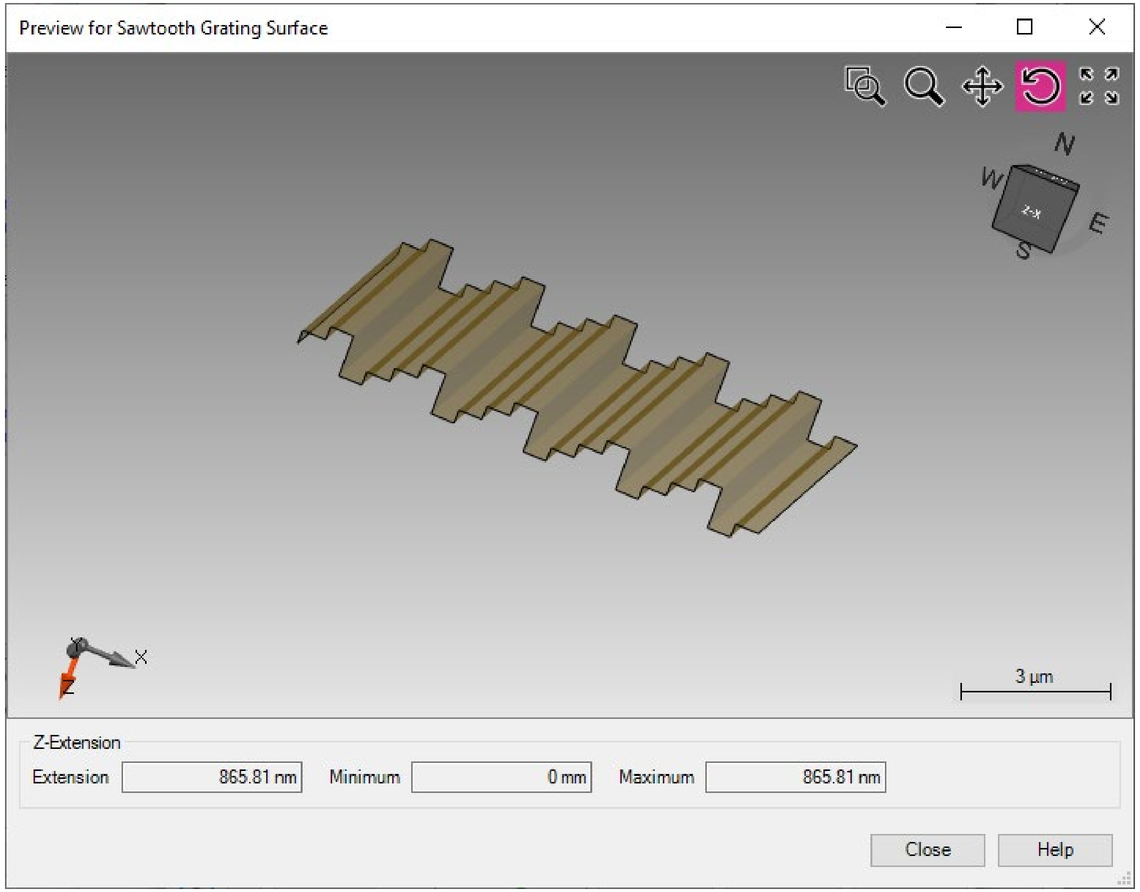


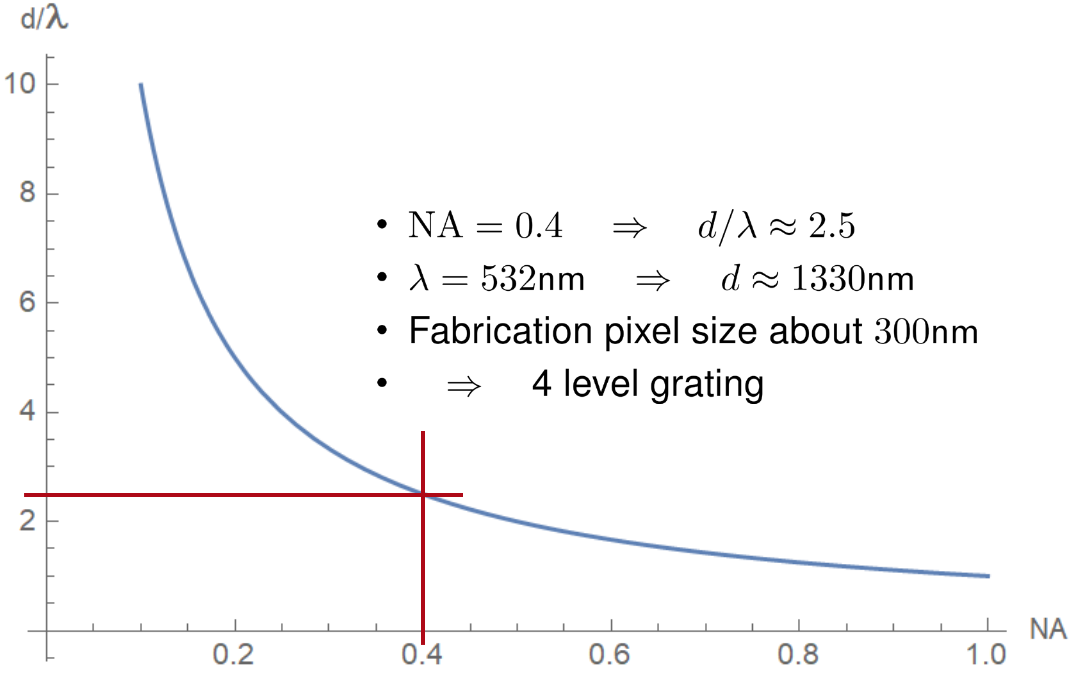
Wavefront Error after HOE

Focusing (NA = 0.4) HOE: Ray Tracing



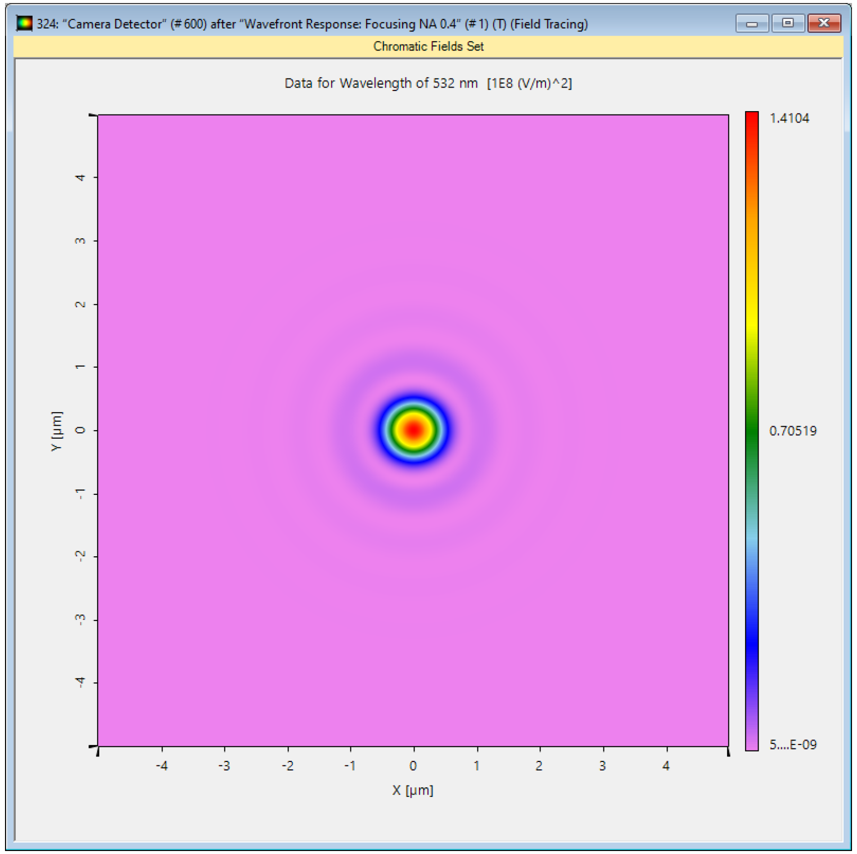
Grating Profile for HOE: Four Level



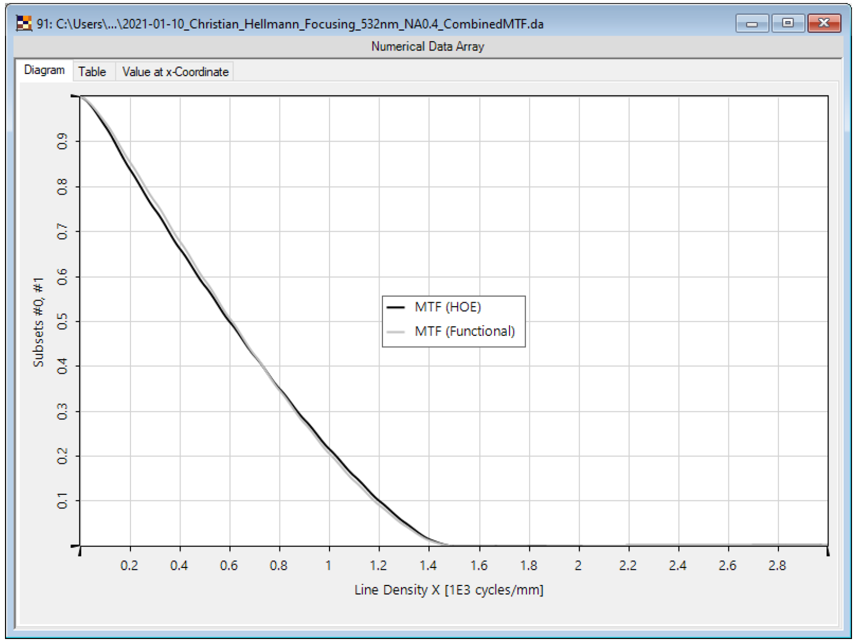


$\frac{\text{grating period at margin of lens}}{\lambda}$ vs. NA

Focusing (NA = 0.4) HOE: Field Tracing



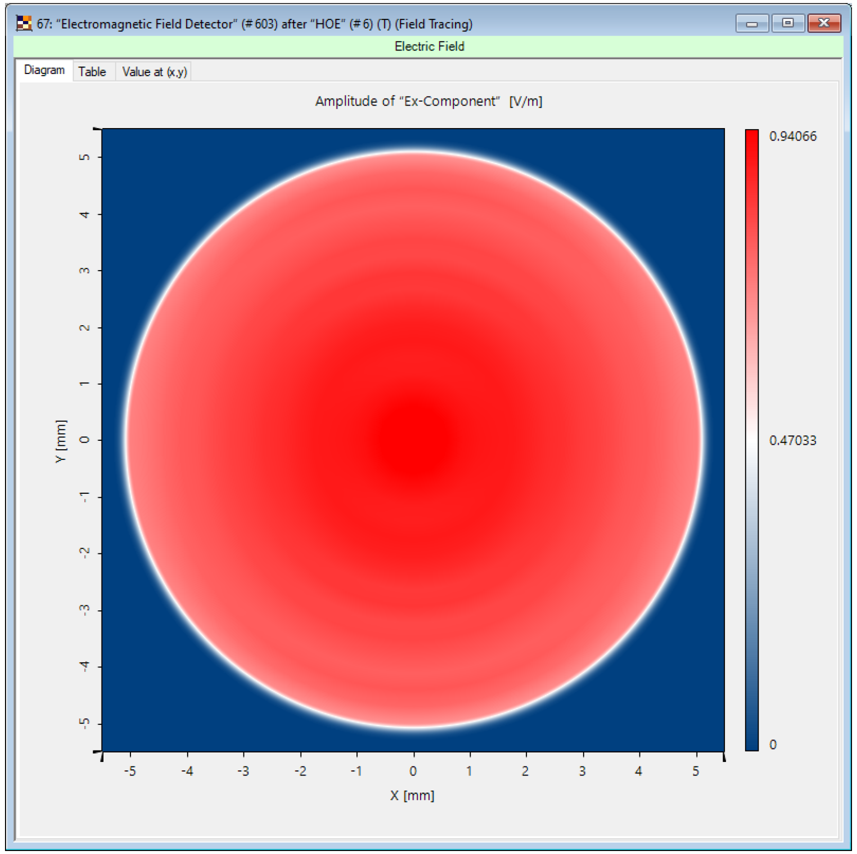
Energy Density in Focus (False Color)



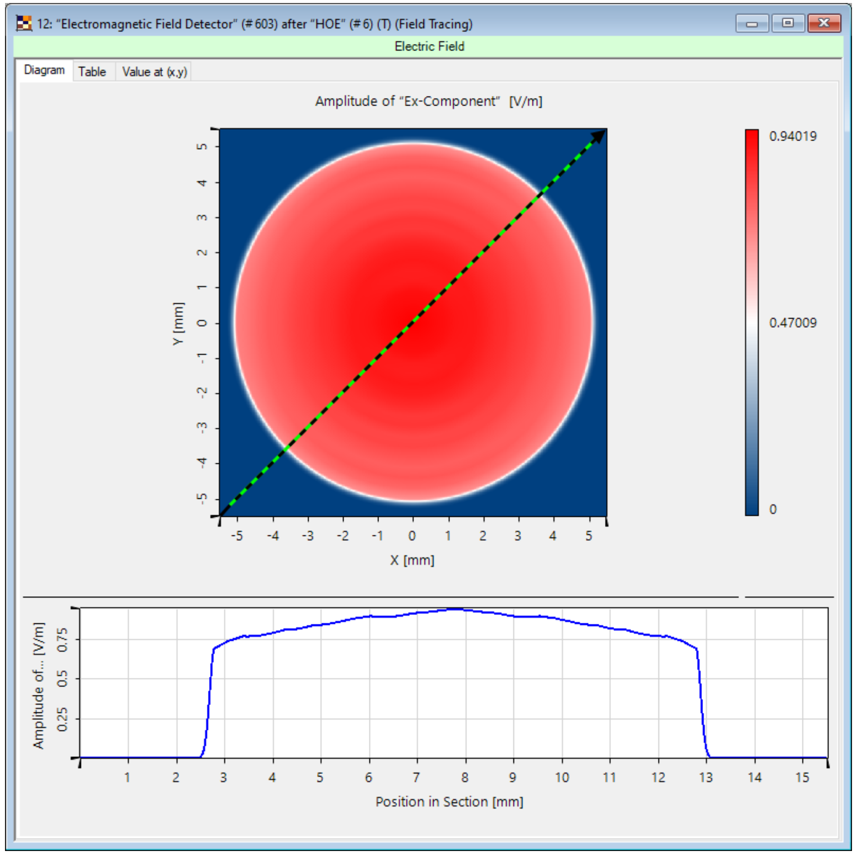
MTF

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

Focusing (NA = 0.4) HOE: Field Tracing

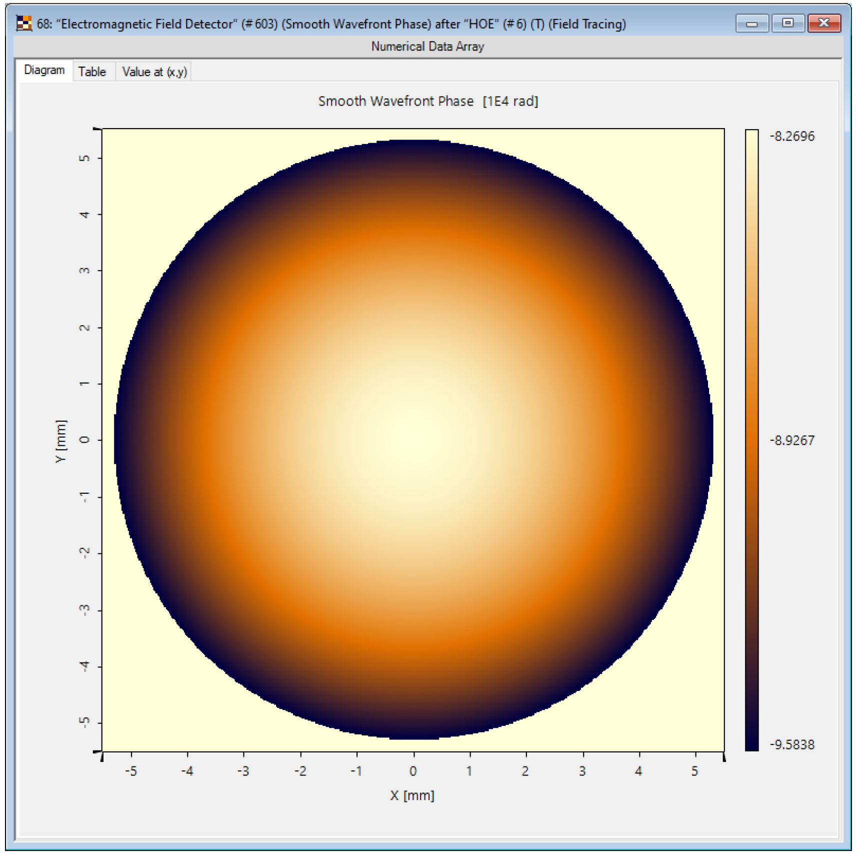


Amplitude after HOE

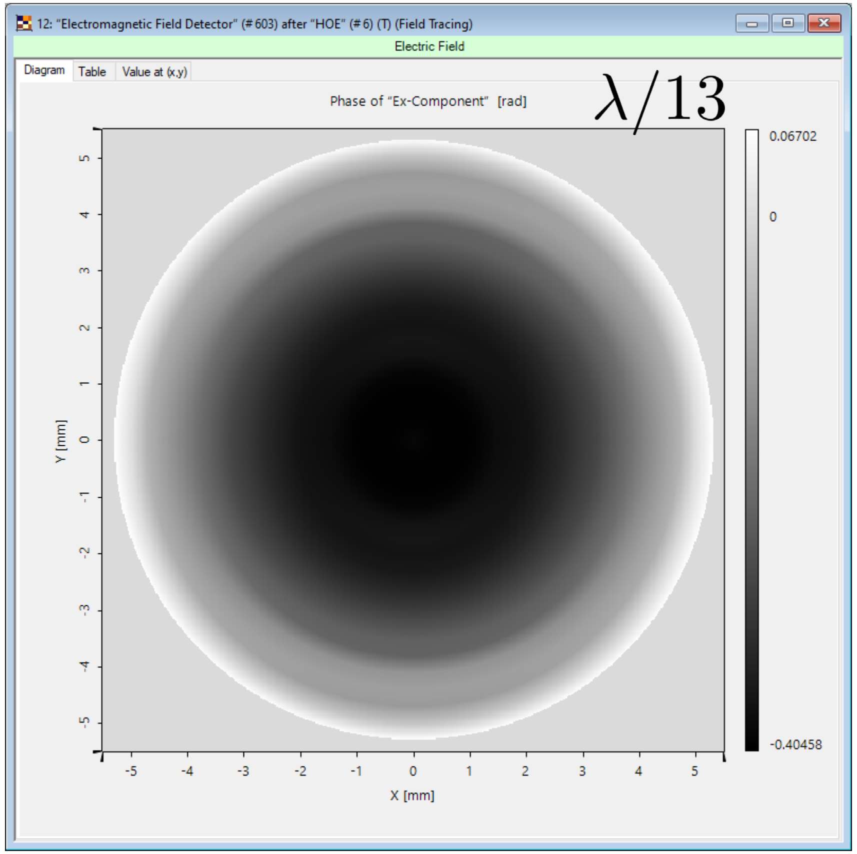


Amplitude after HOE

Focusing (NA = 0.4) HOE: Field Tracing

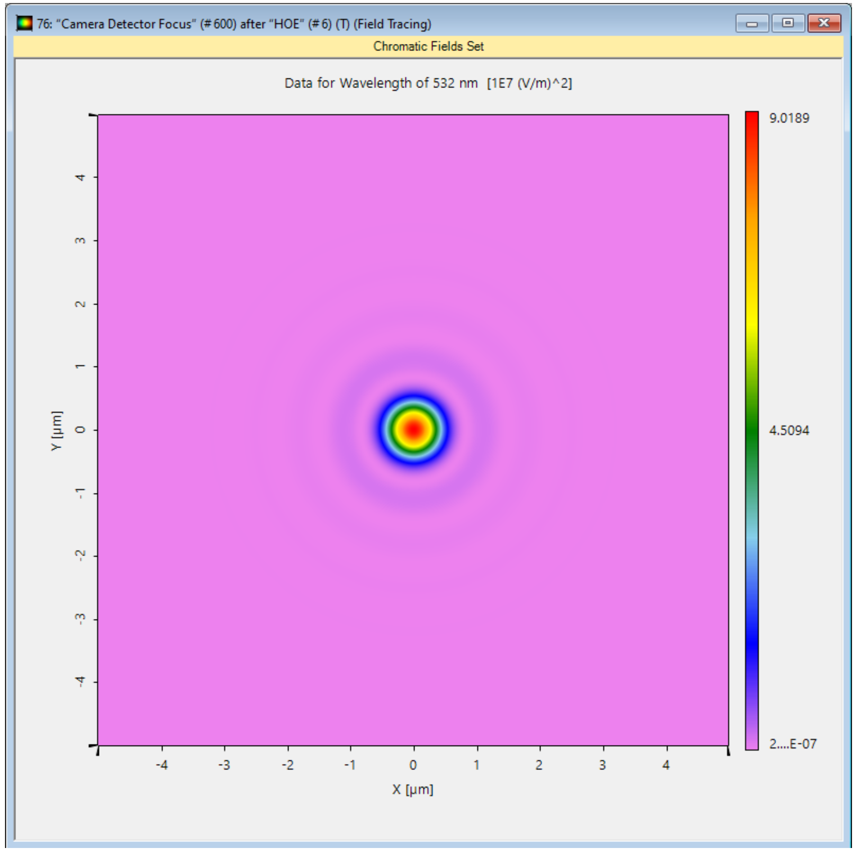


Wavefront after HOE



Wavefront Error after HOE

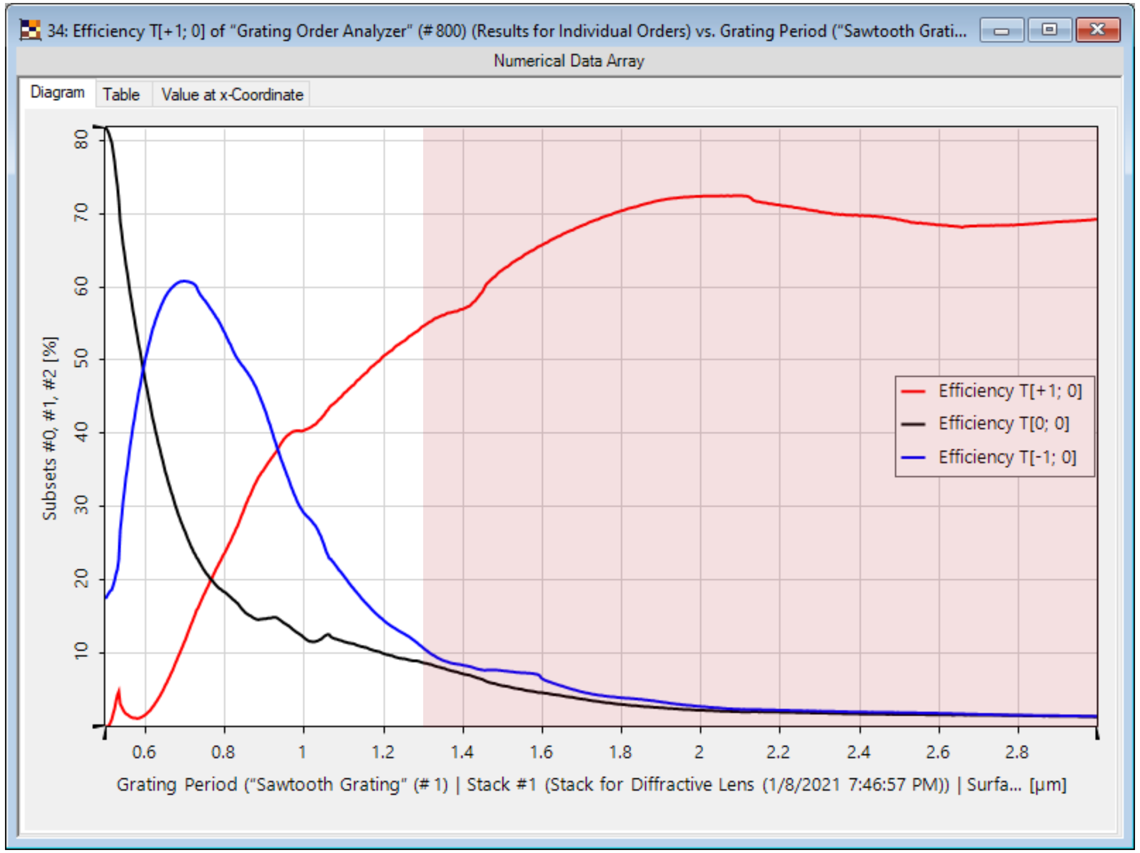
Focusing (NA = 0.4) HOE: Field Tracing → -1st, 0th, +1st



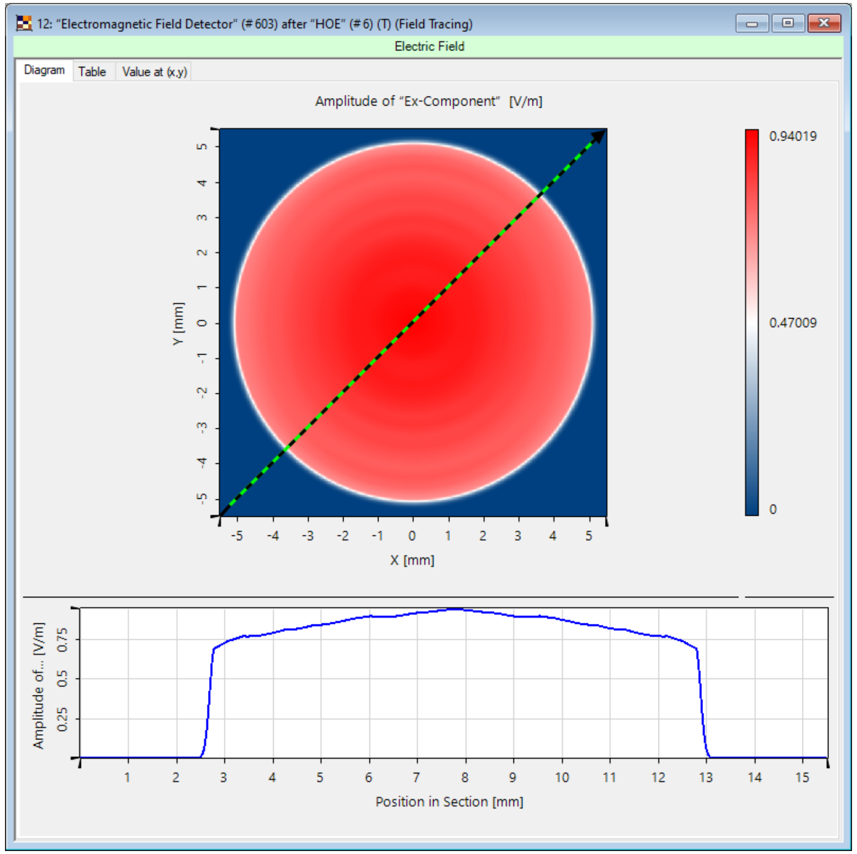
Energy Density in Focus (False Color)

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

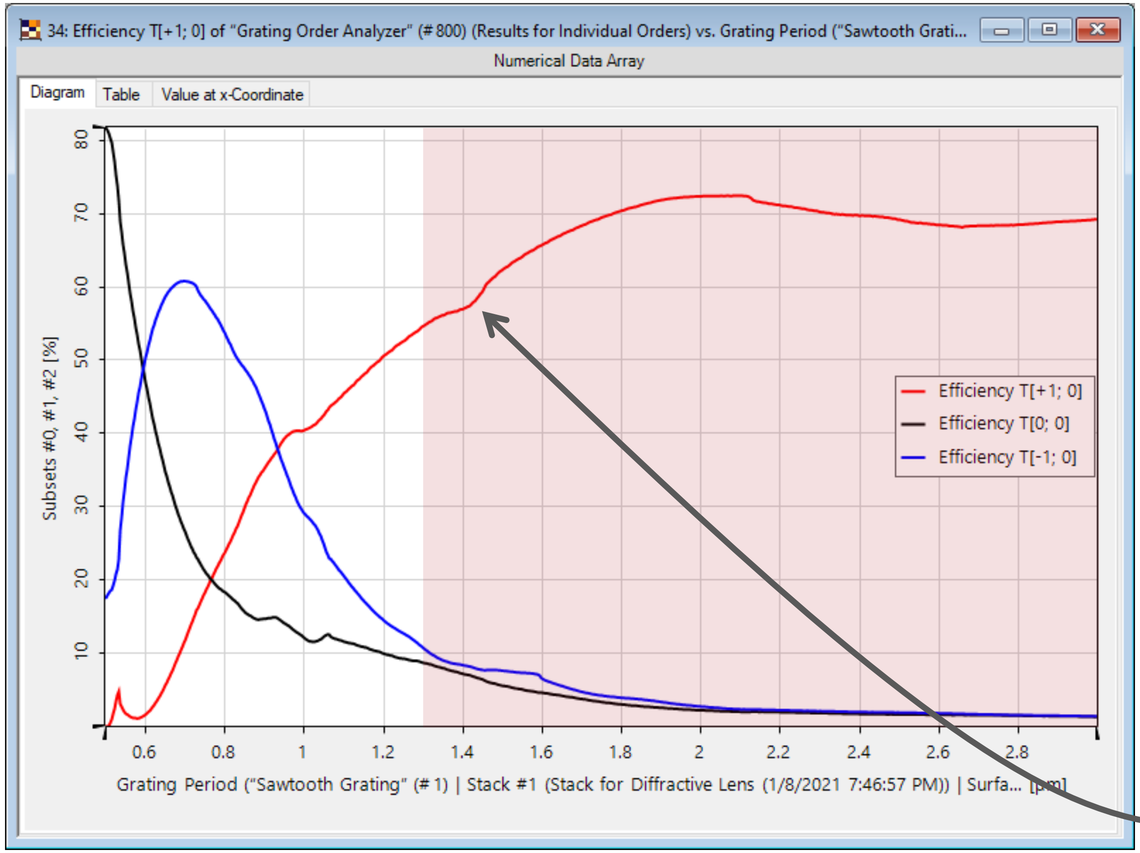


Efficiencies vs. Period

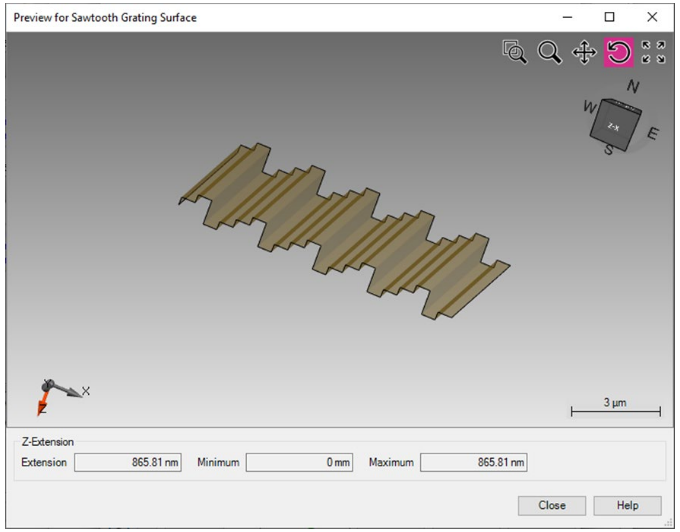


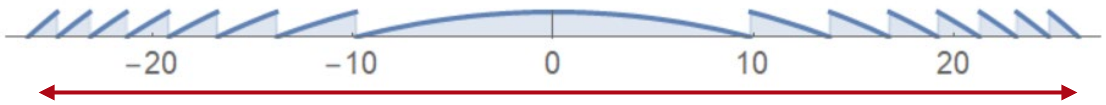
Amplitude after HOE

Focusing (NA = 0.4) HOE: Field Tracing



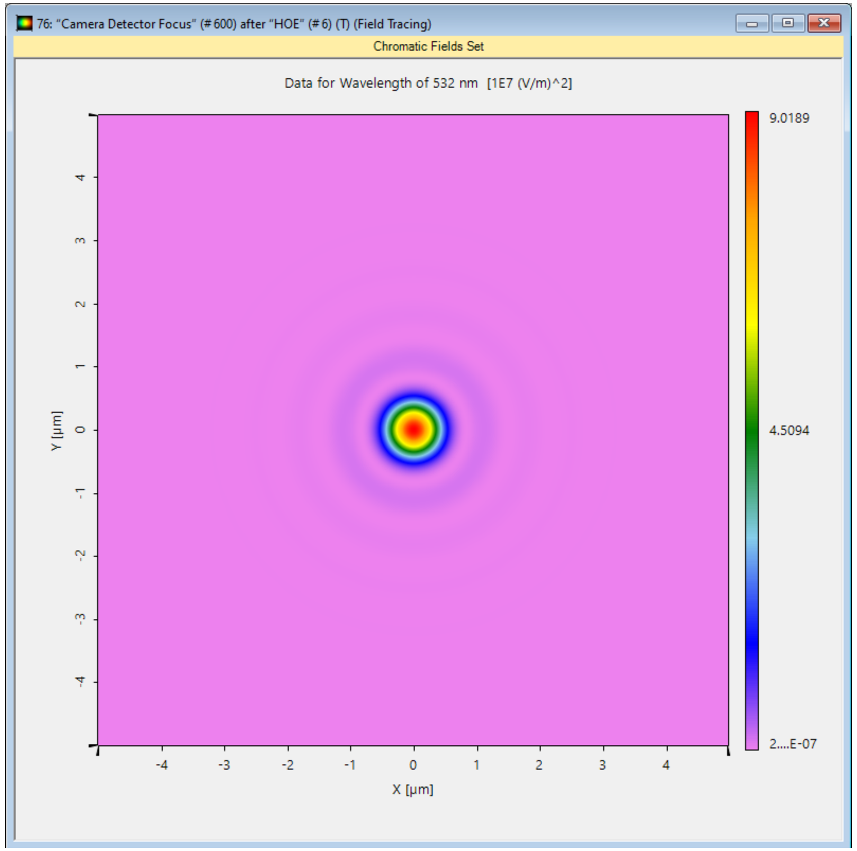
Efficiencies vs. Period



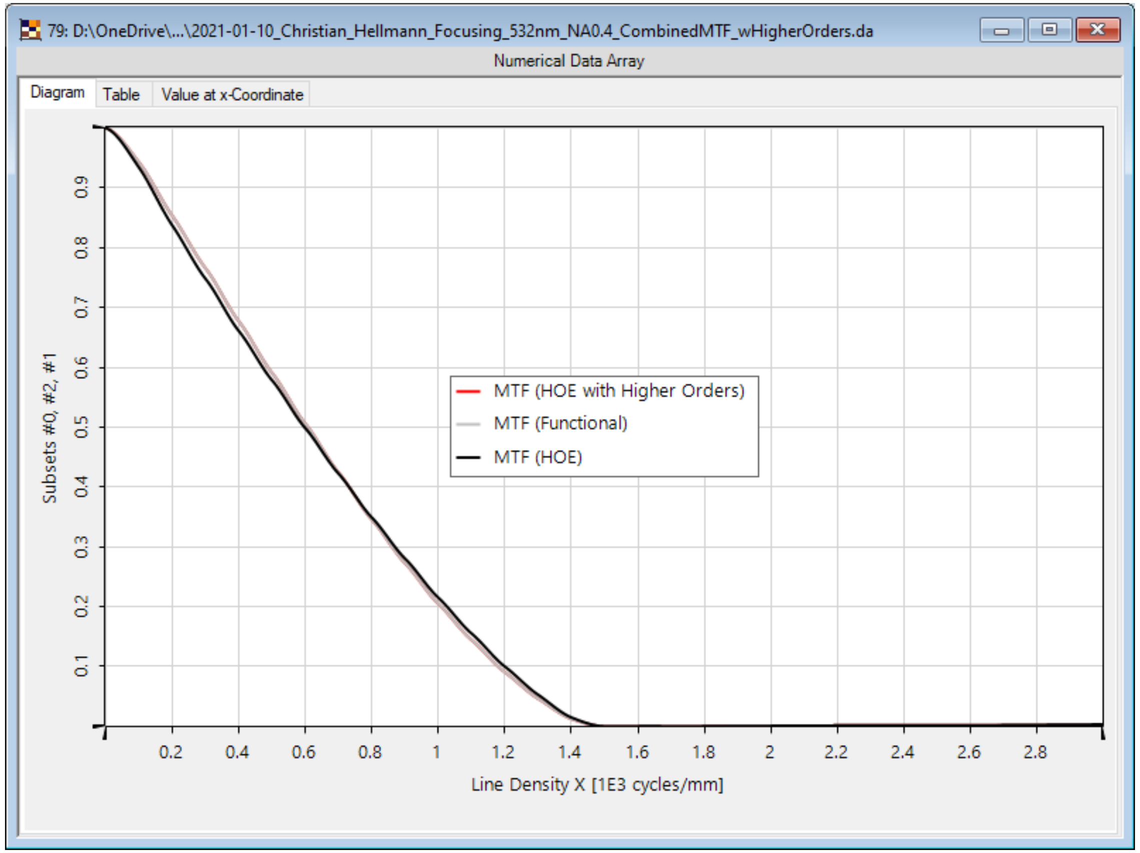


Applied fabrication constraint: no height modulation over lens diameter

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

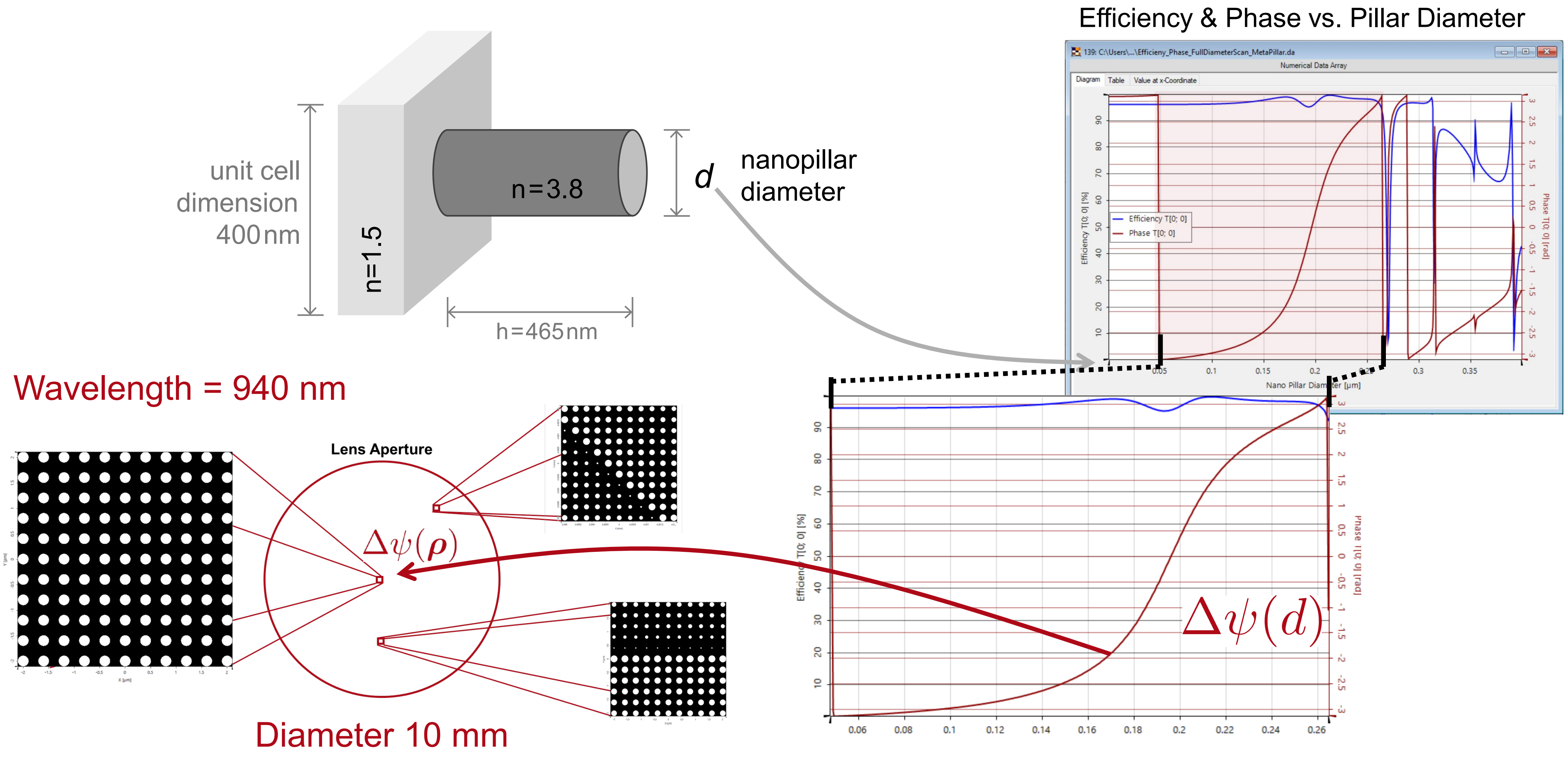


Energy Density in Focus (False Color)

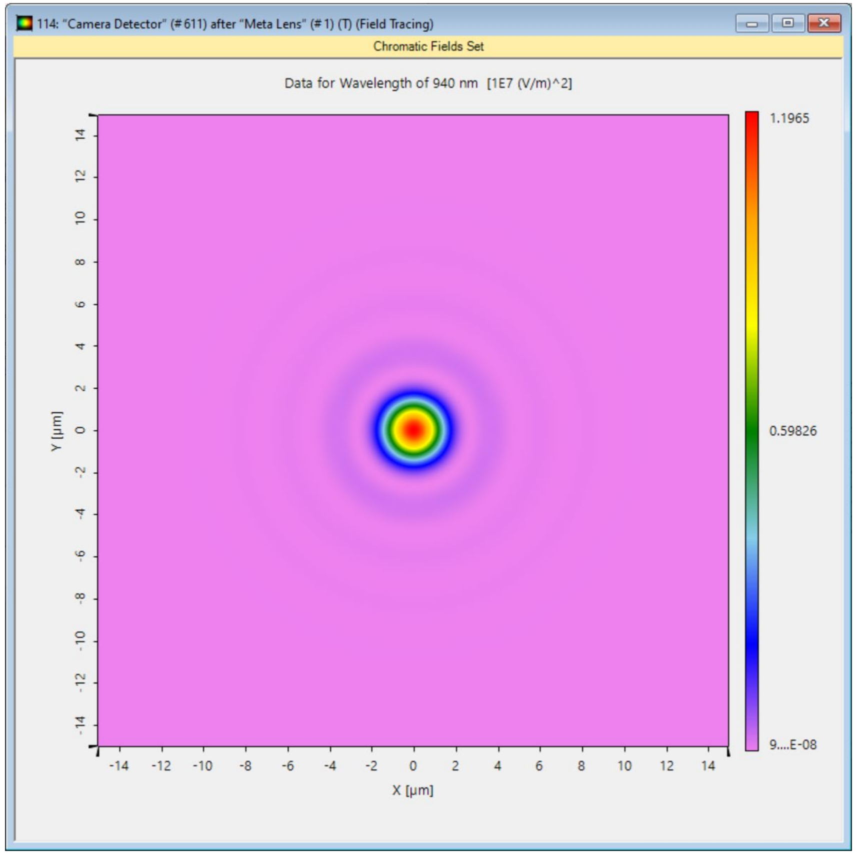


MTF

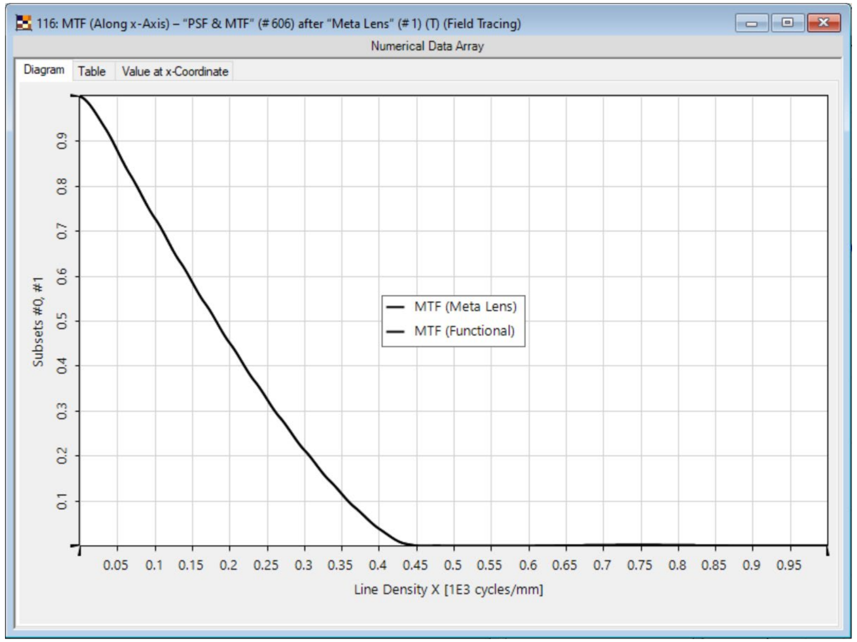
Design of Metasurface for Specified Phase Response



Focusing (NA = 0.2) Metalens: Field Tracing (Level I)



Energy Density in Focus (False Color)

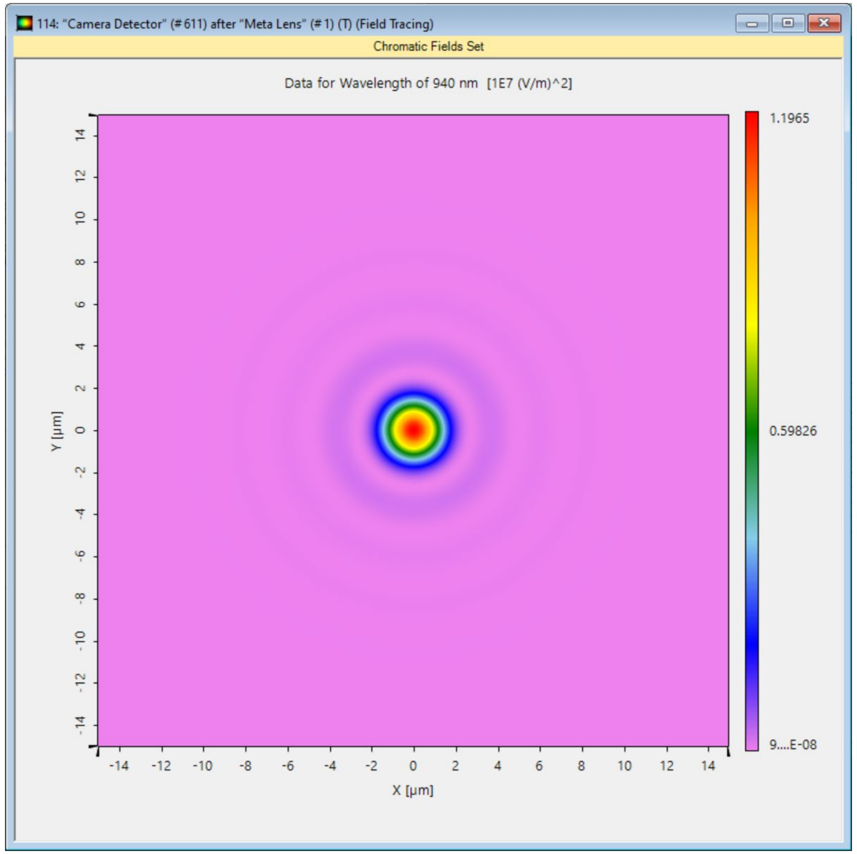


MTF

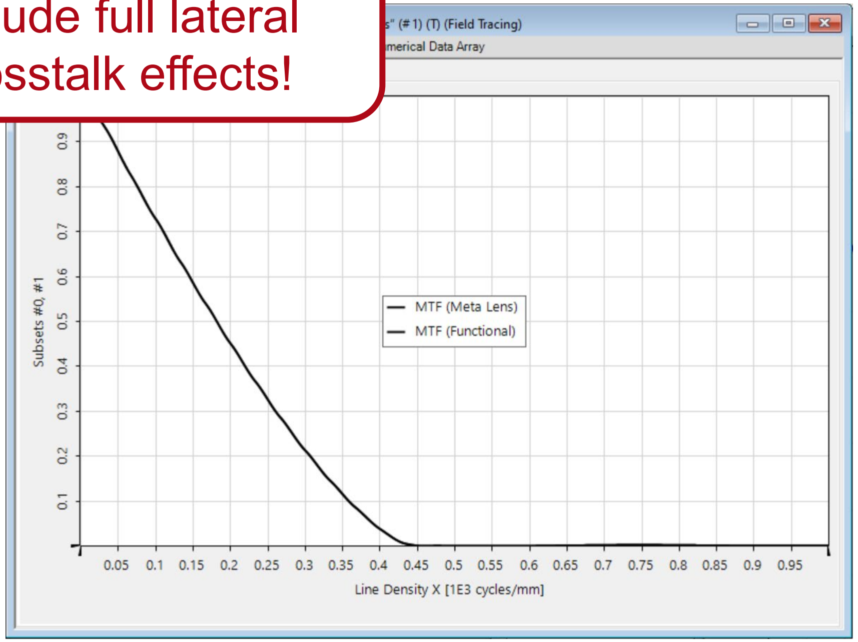
Efficiency: 93.64% (Efficiency after First Plane: 96.5%)

Focusing (NA = 0.2) Metalens: Field Tracing (Level I)

Modeling does not include full lateral crosstalk effects!



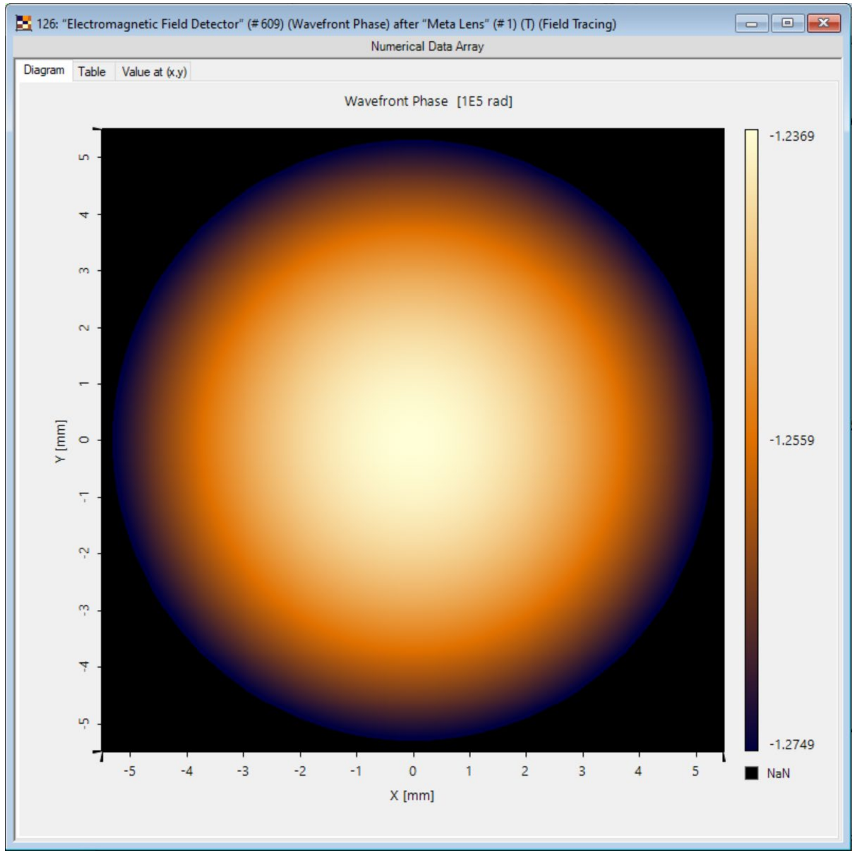
Energy Density in Focus (False Color)



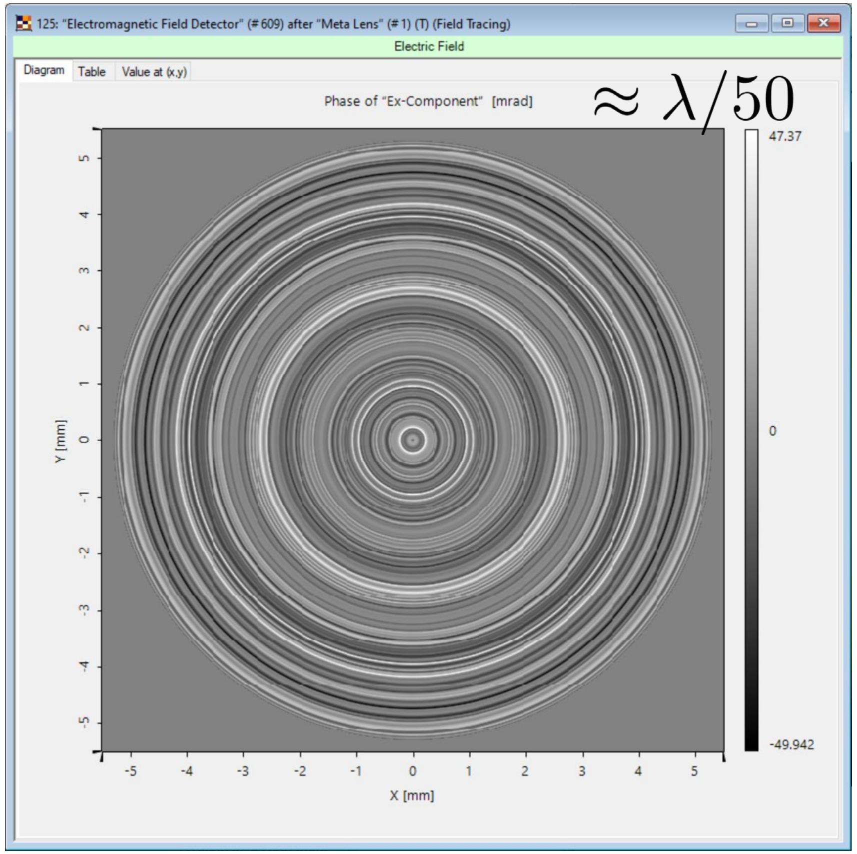
MTF

Efficiency: 93.64% (Efficiency after First Plane: 96.5%)

Focusing (NA = 0.2) Metalens: Field Tracing (Level I)

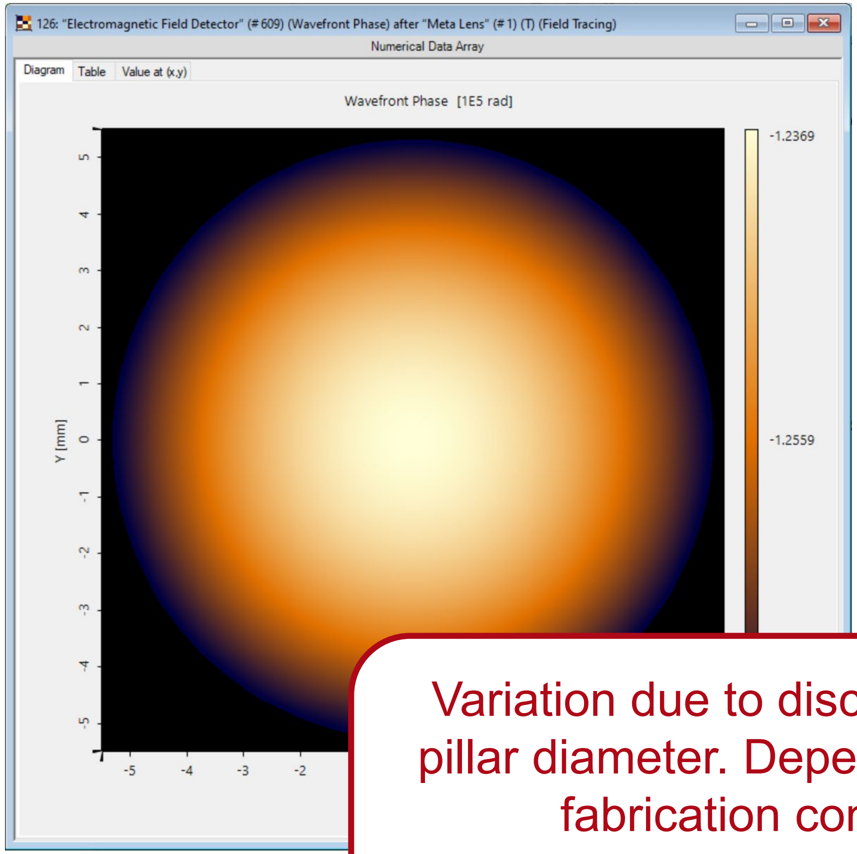


Wavefront after Meta Lens

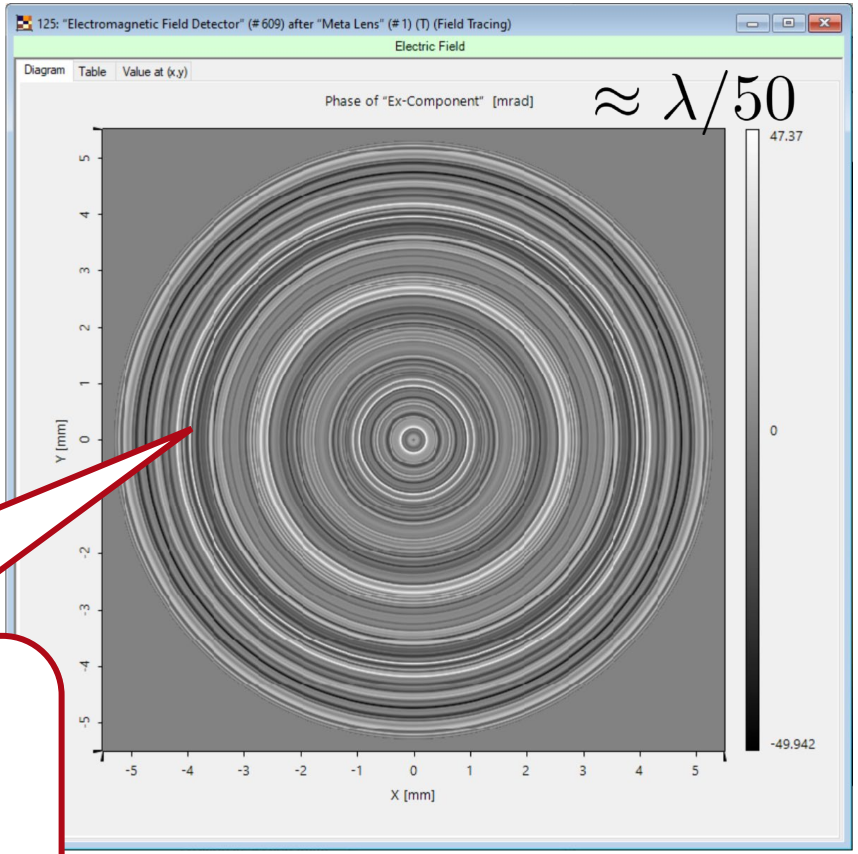


Wavefront Error after Meta Lens

Focusing (NA = 0.2) Metalens: Field Tracing (Level I)



Wavefron



Wavefront Error after Meta Lens

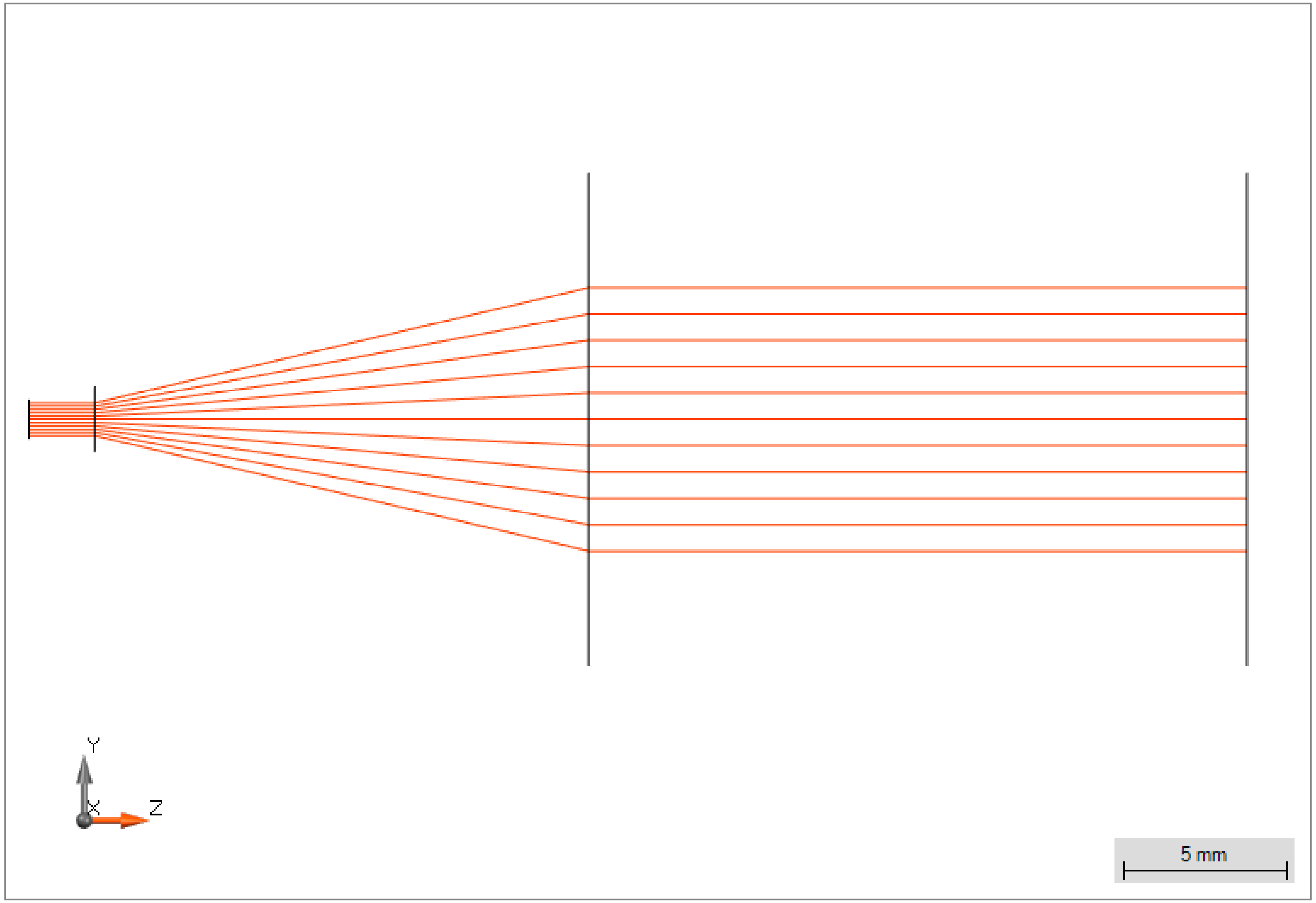
Variation due to discrete change of pillar diameter. Depends strongly on fabrication constraints.

Level II modeling smooths the result.

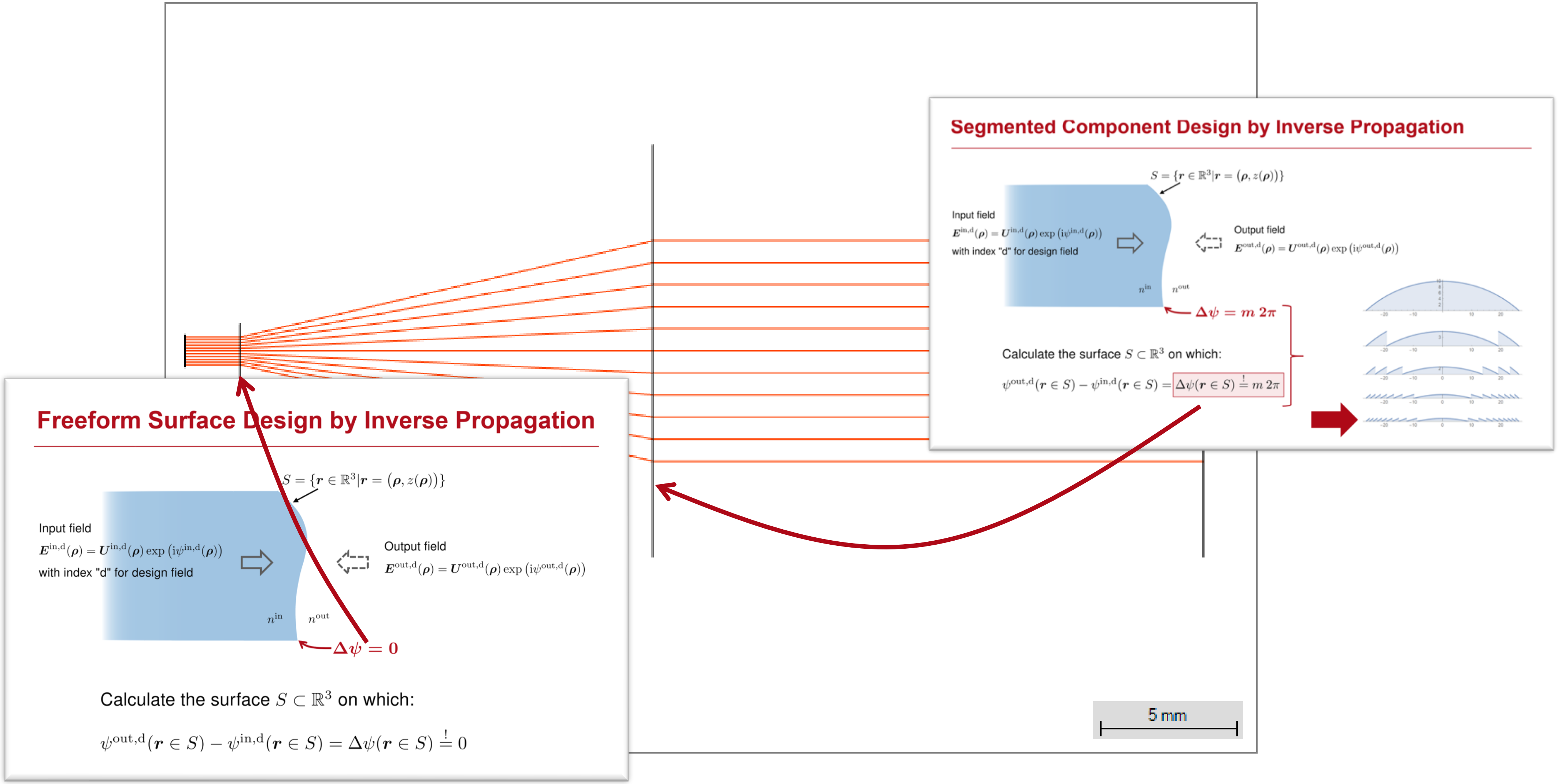
Example Expander

Structural Design

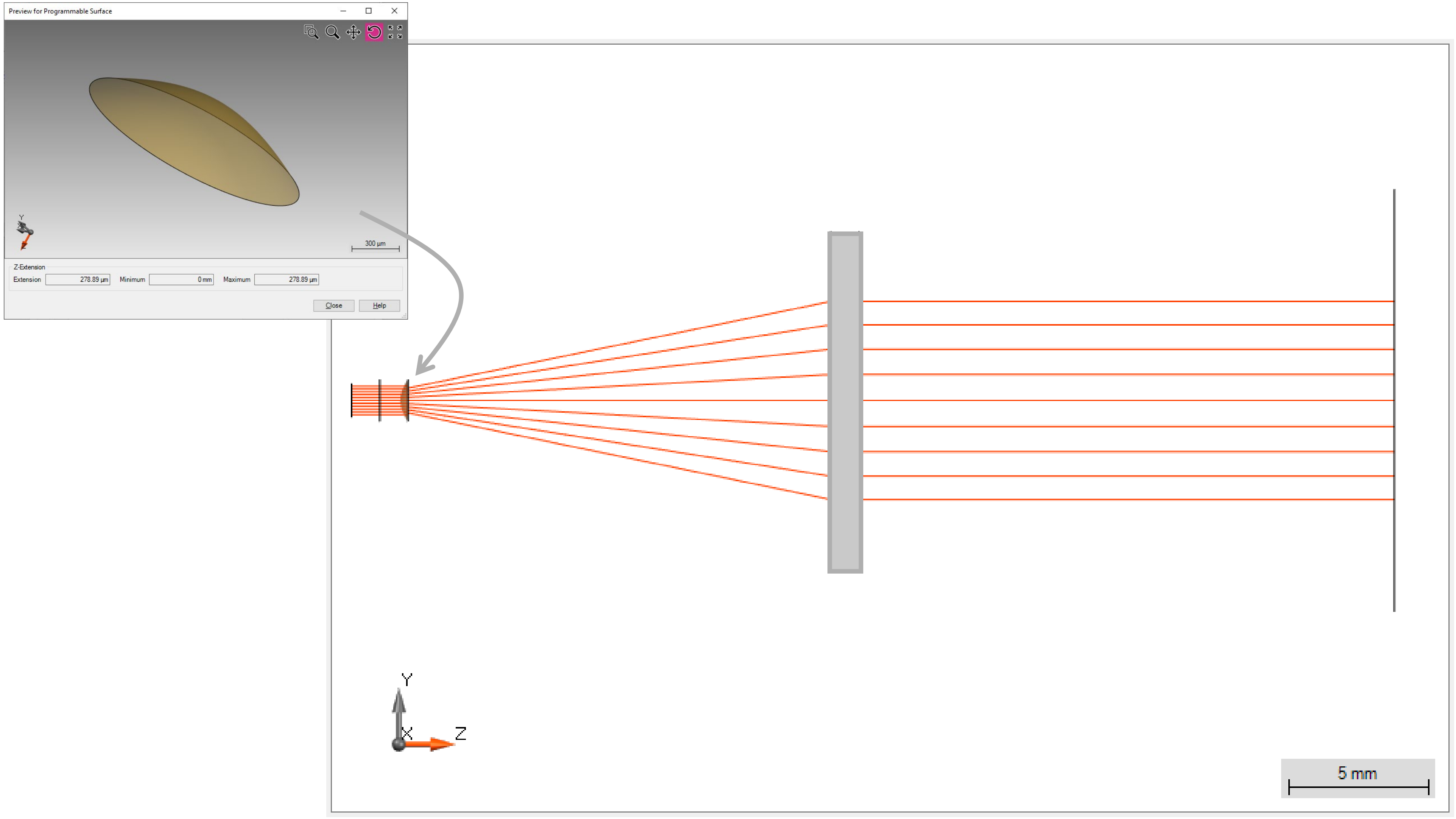
Structural Design Beam Expander (1:5): Freeform + HOE



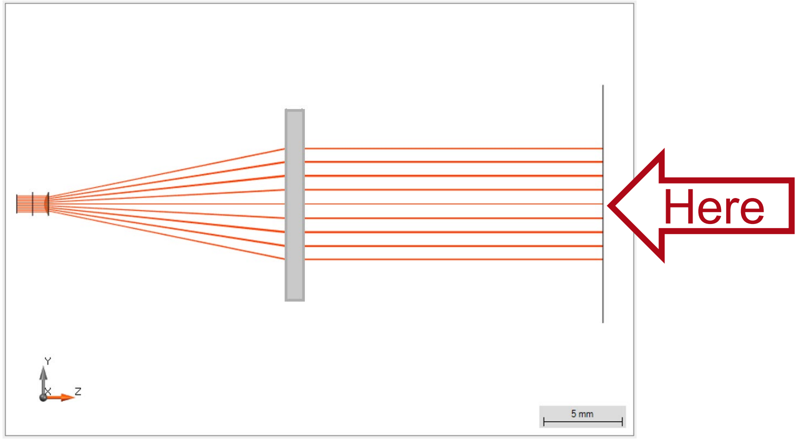
Structural Design Beam Expander (1:5): Freeform + HOE

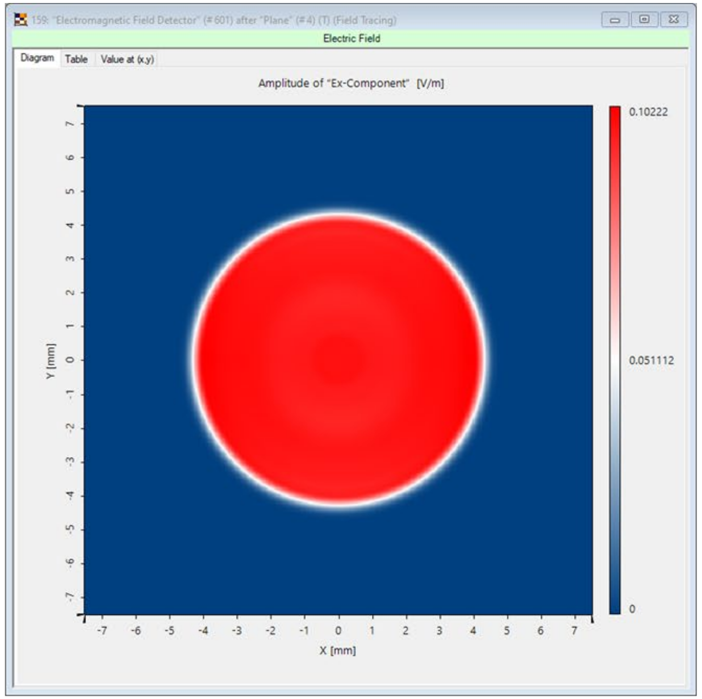


Beam Expander (1:5) Lens + HOE: Ray Tracing

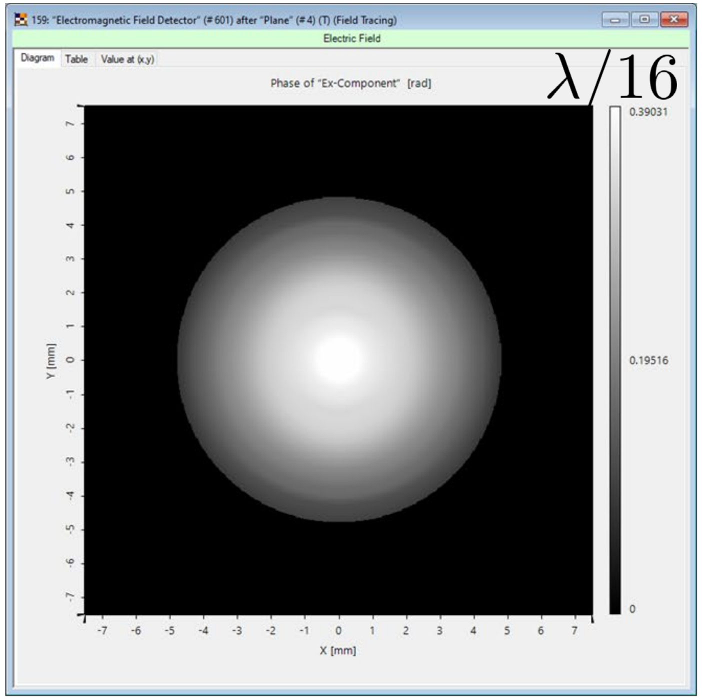


Beam Expander (1:5) Lens + HOE: Field Tracing





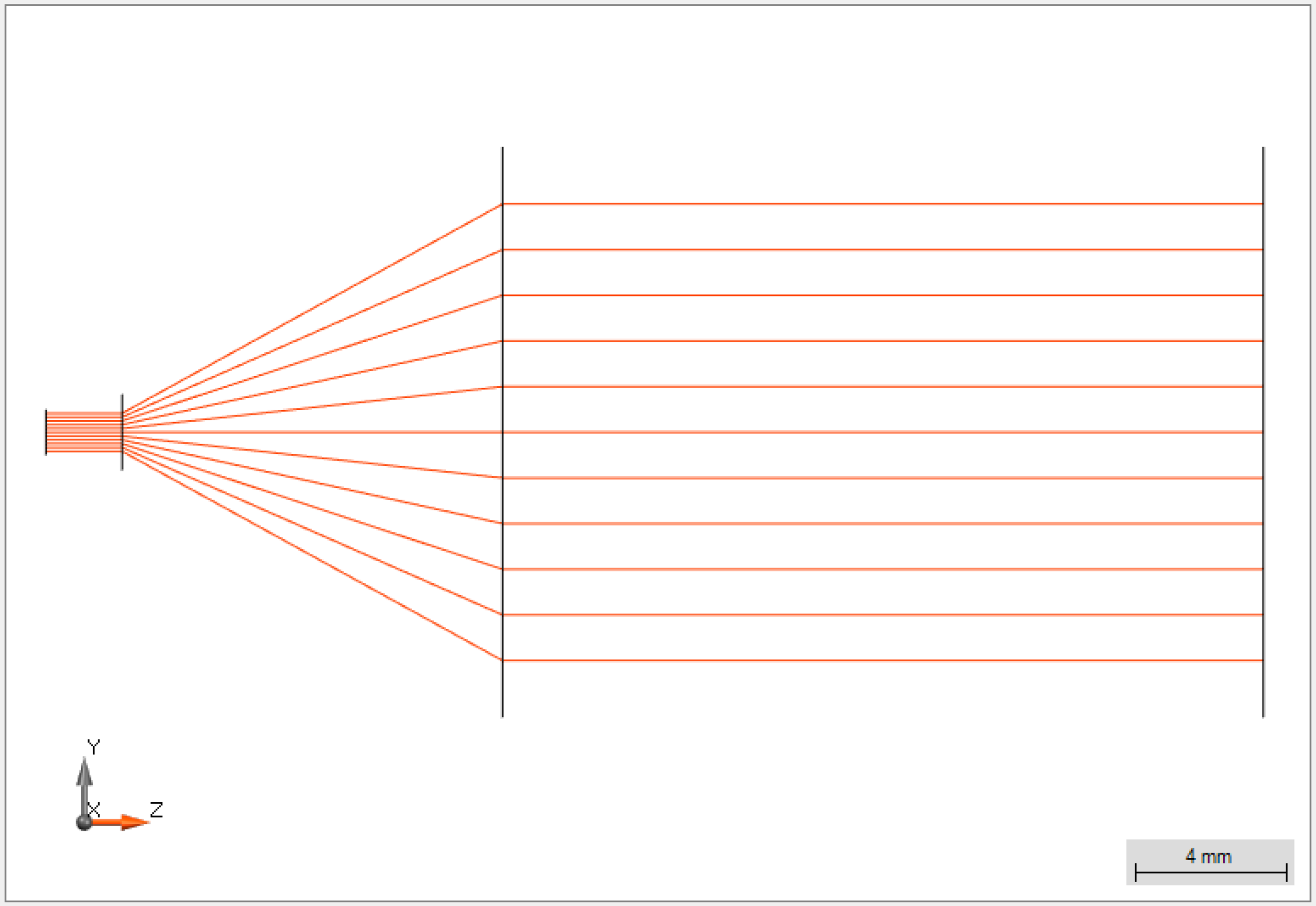
Amplitude after Beam Expander



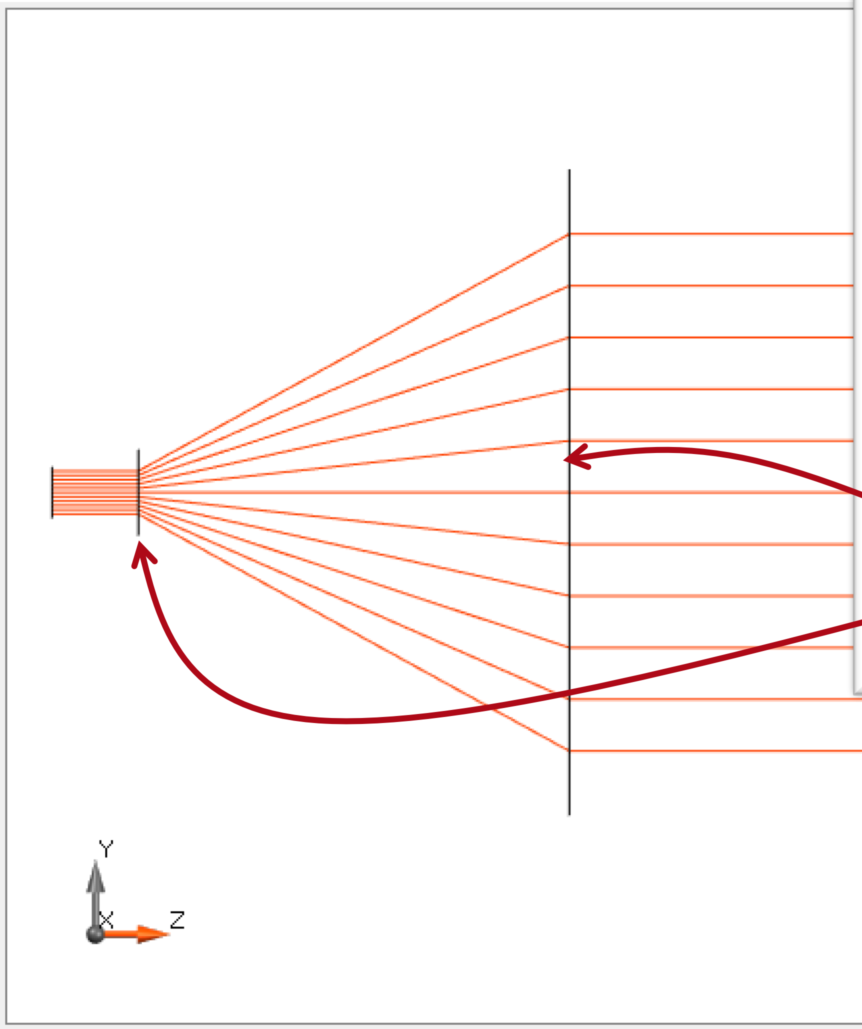
Phase after Beam Expander

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

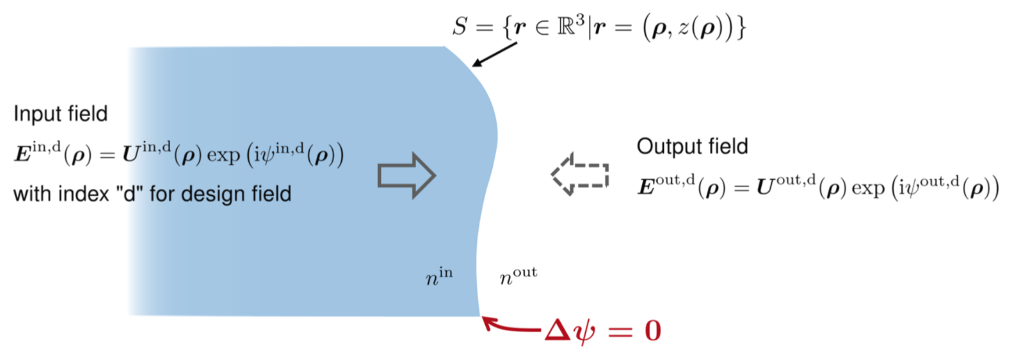
Beam Expander (1:10) – Functional Design: Ray Tracing



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



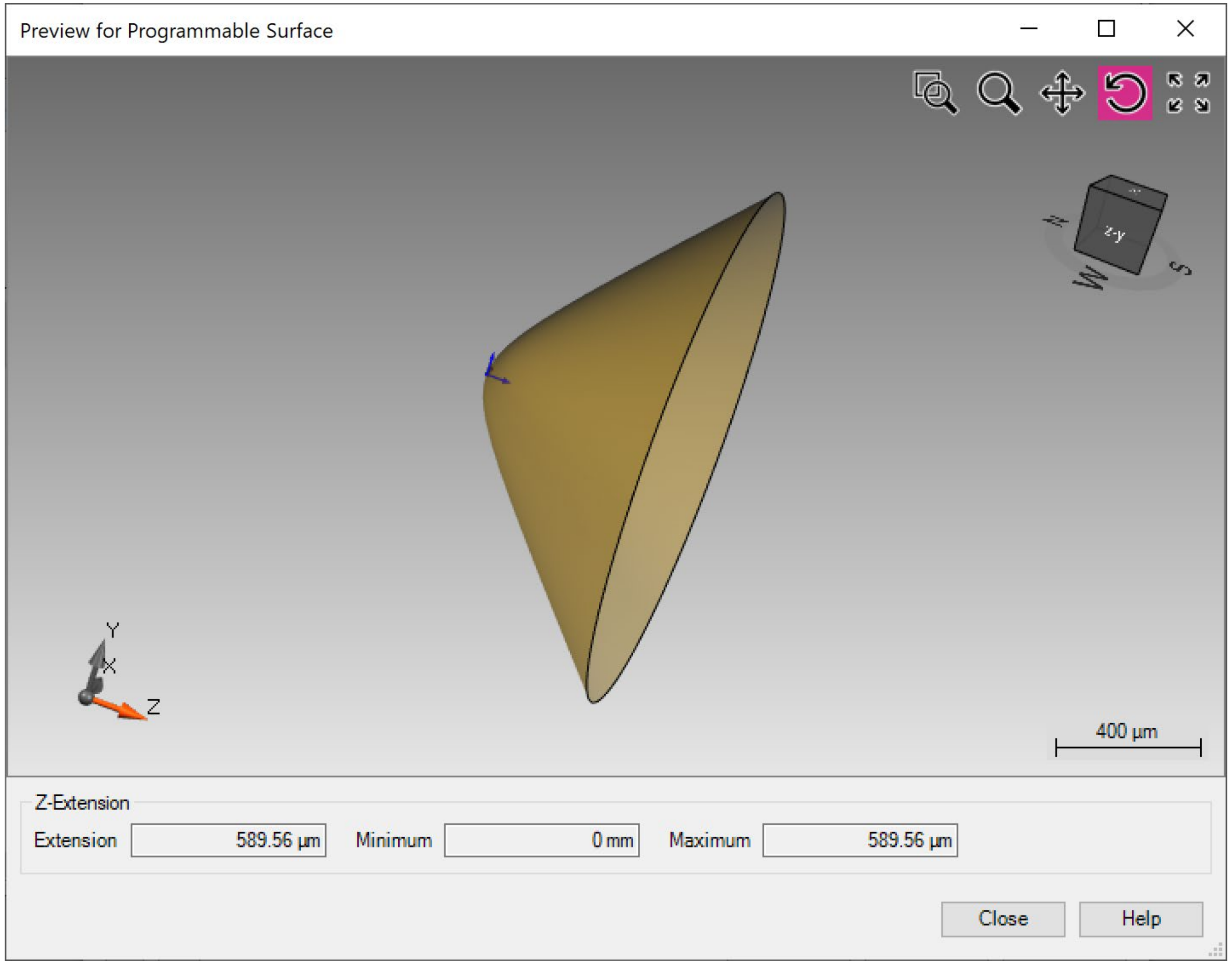
Freeform Surface Design by Inverse Propagation



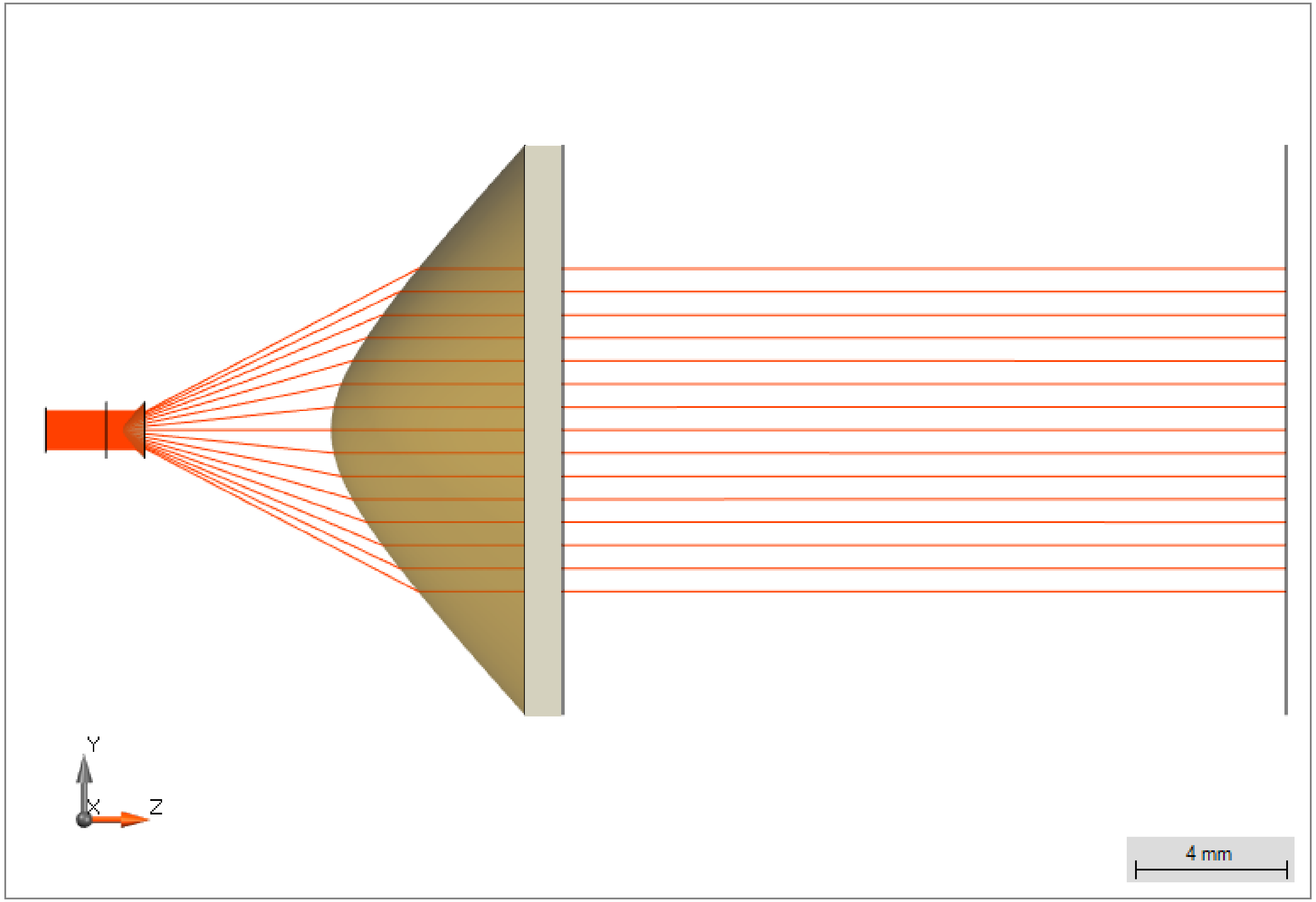
Calculate the surface $S \subset \mathbb{R}^3$ on which:

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

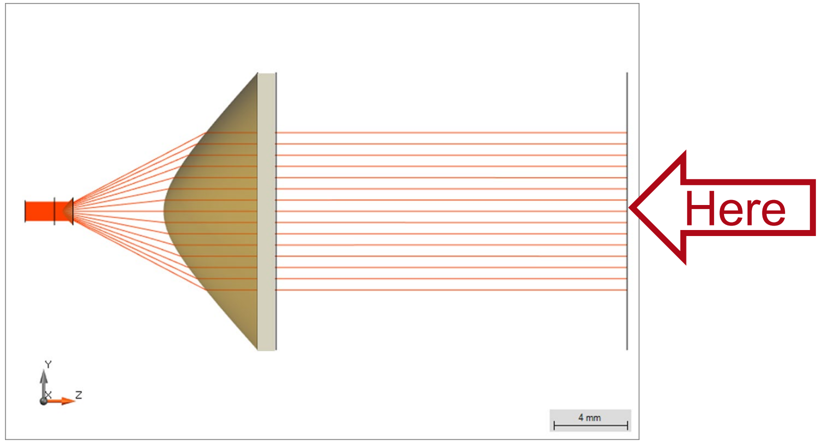
Beam Expander (1:10) – Structural Design: Lens

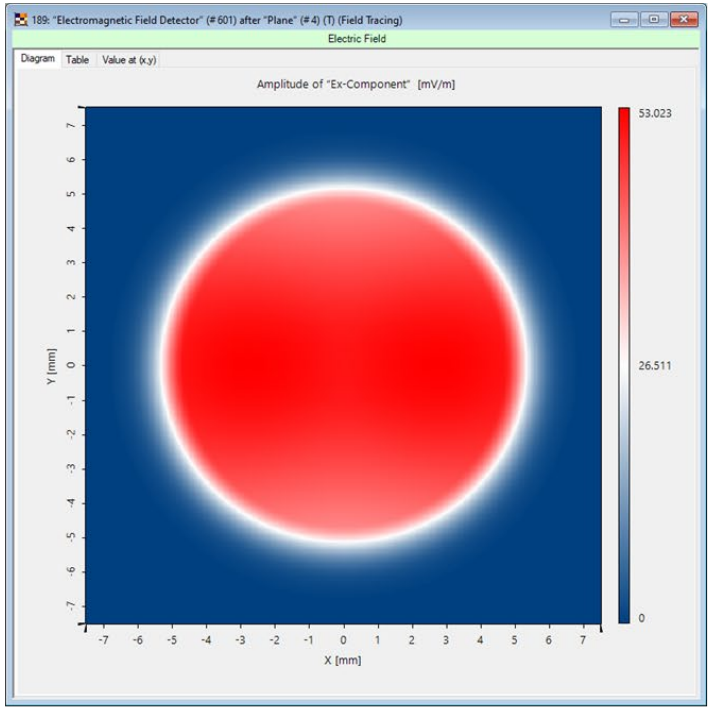


Beam Expander (1:10) Lens + Lens: Ray Tracing

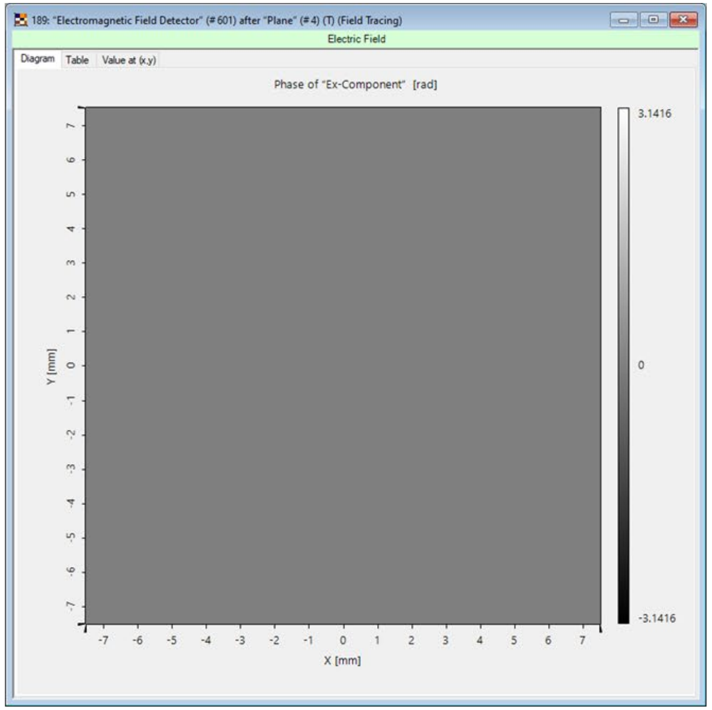


Beam Expander (1:10) Lens + Lens: Field Tracing





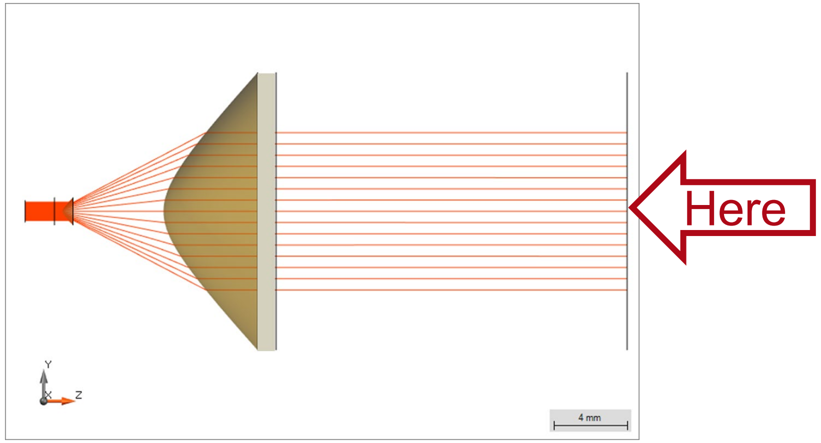
Amplitude after Beam Expander

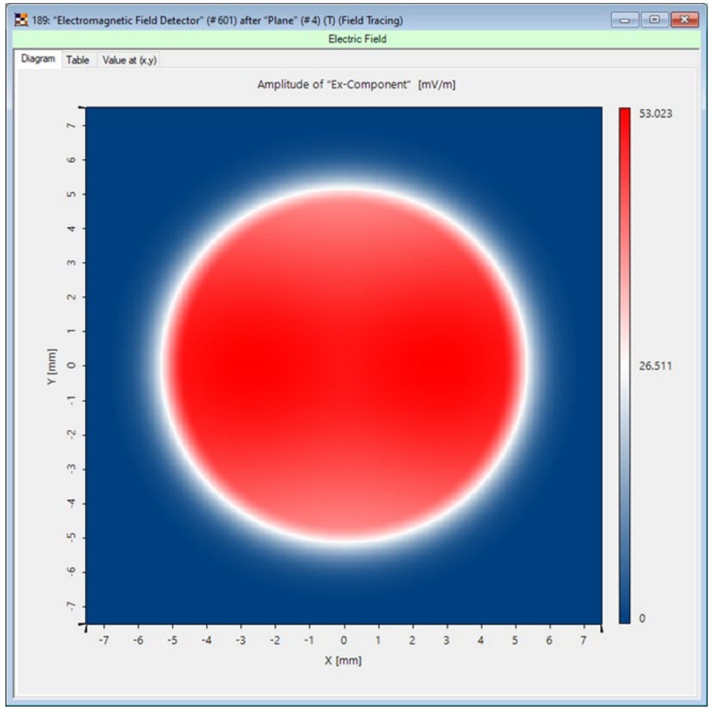


Phase after Beam Expander

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

Beam Expander (1:10) Lens + Lens: Field Tracing





Amplitude after Beam Expander

Irradiance shaping satisfying because of symmetric situation.

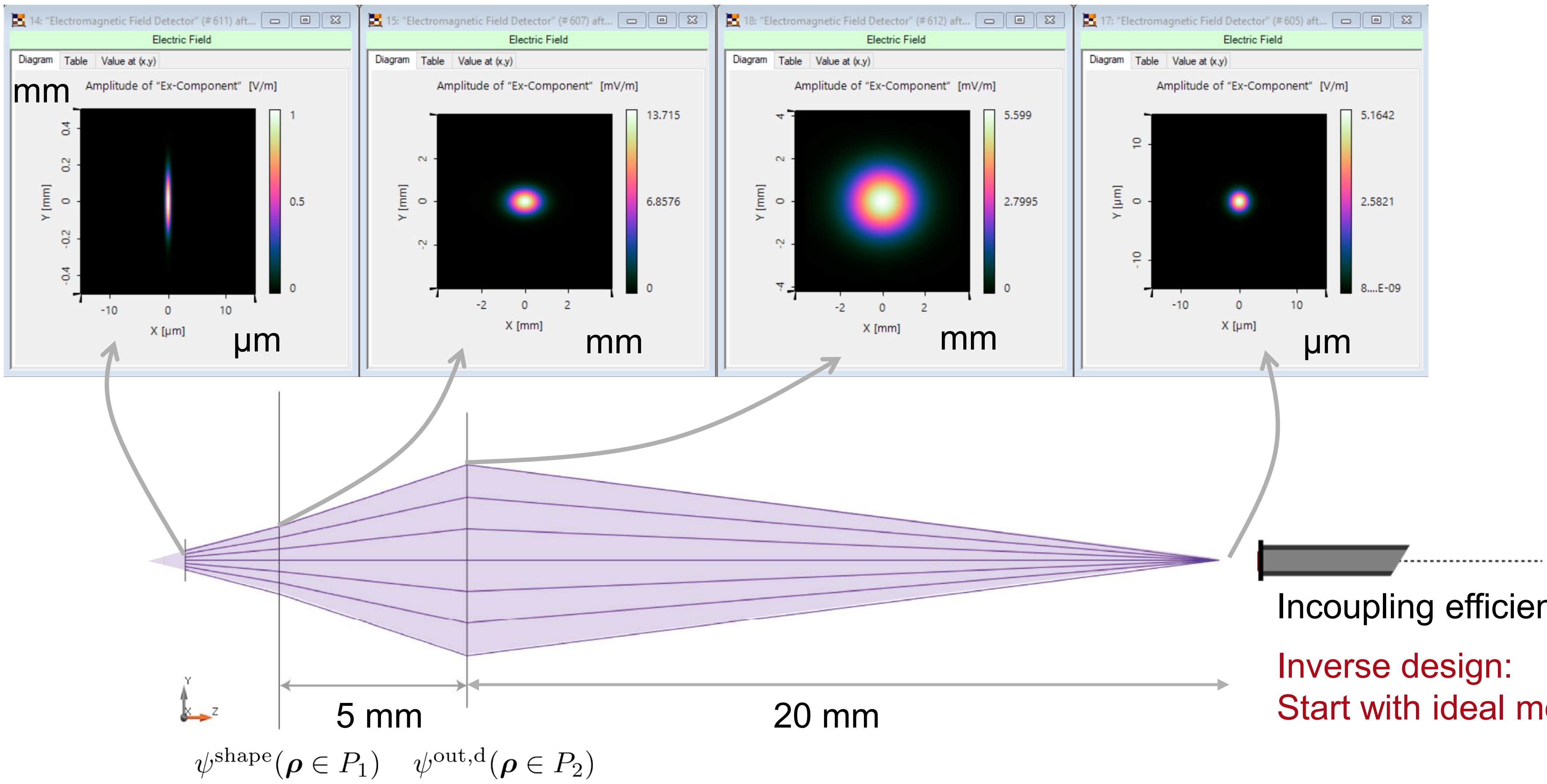
Iterative design not needed.

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

Example Fiber Coupling

Structural Design

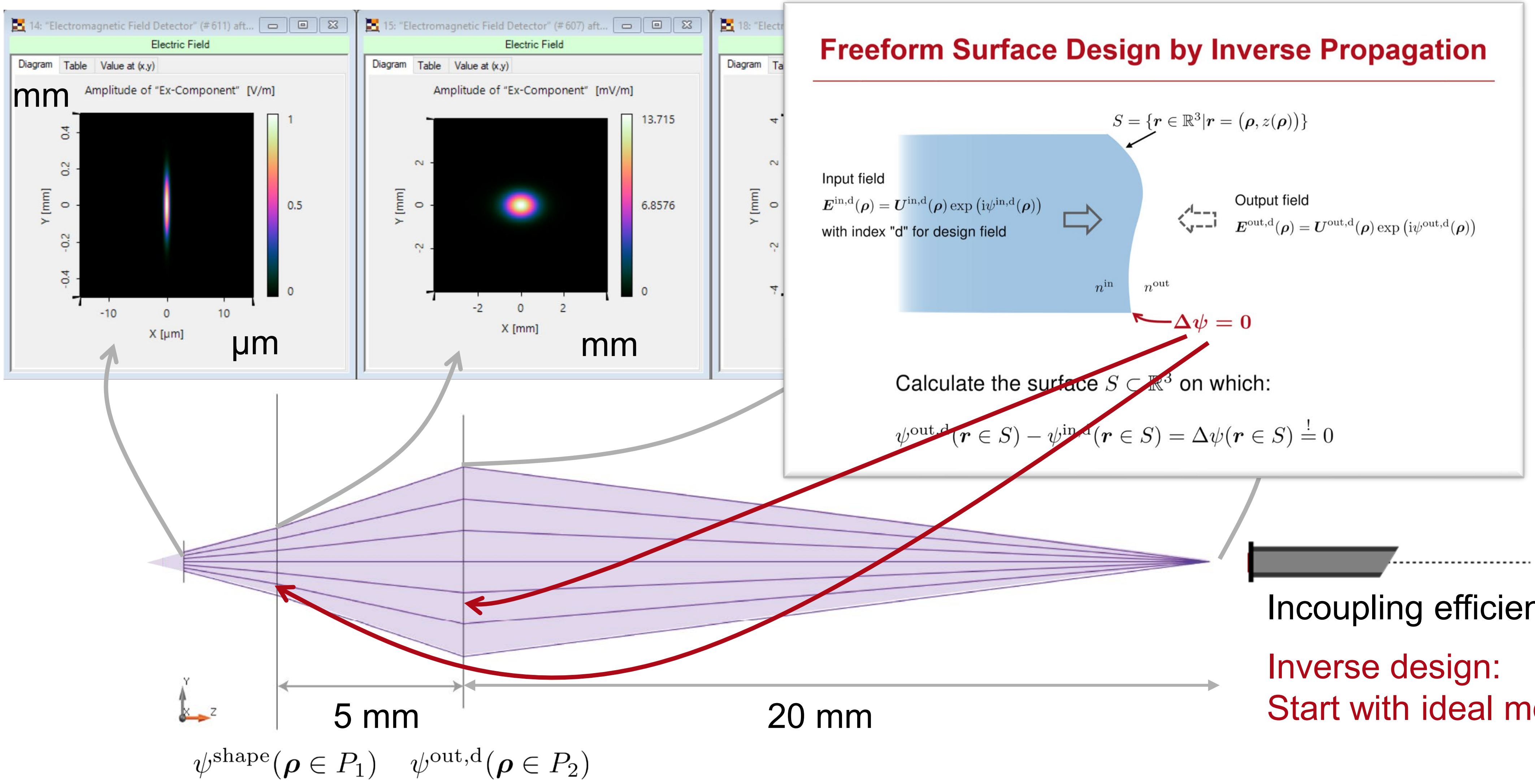
Laser Diode Coupling Into Fiber: Functional Design



Incoupling efficiency : 99%

Inverse design:
Start with ideal mode

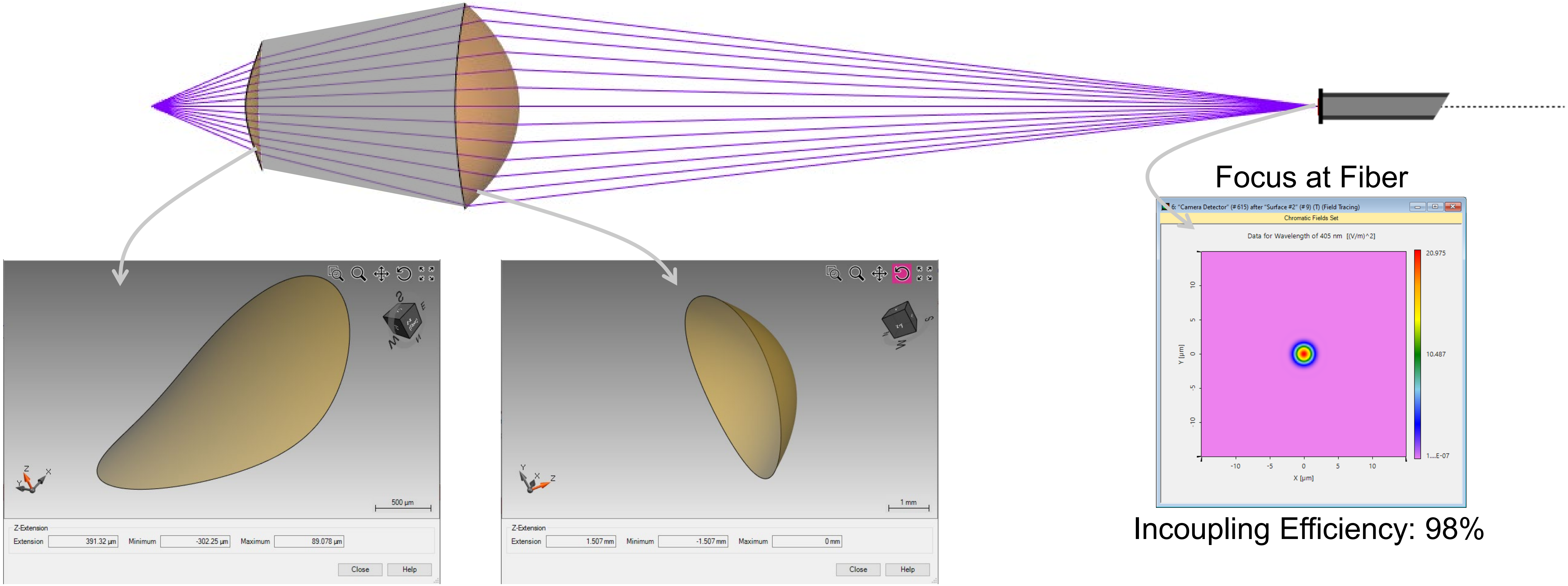
Laser Diode Coupling Into Fiber: Freeform Design



Incoupling efficiency : 99%

Inverse design:
Start with ideal mode

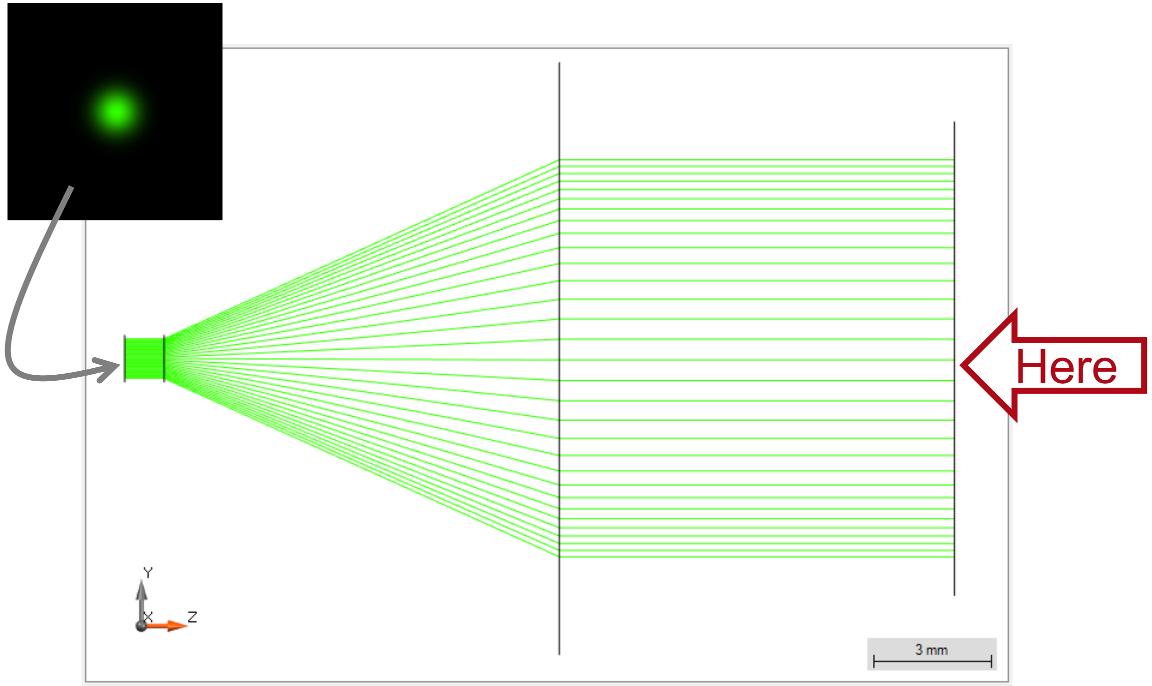
Laser Diode Coupling Into Fiber: Ray and Field Tracing

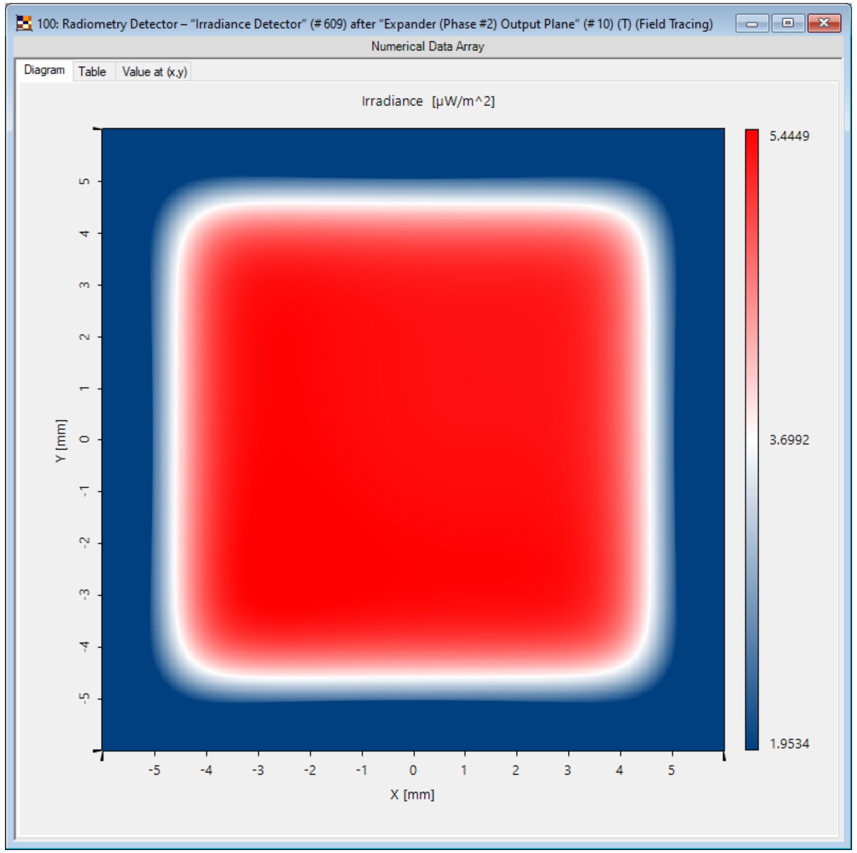


Example Shaping Expander

Structural Design

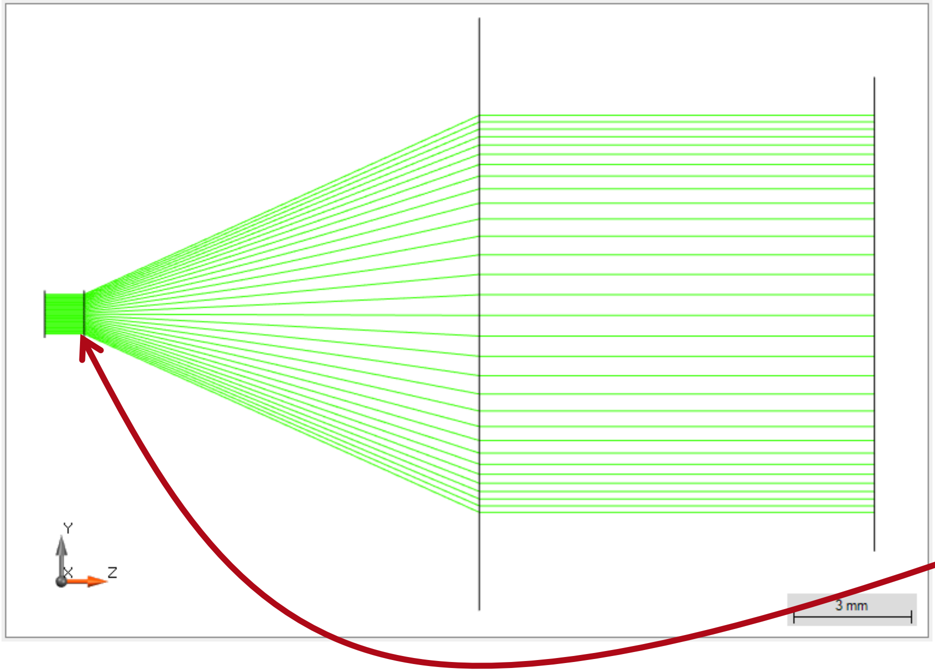
Shaping Beam Expander: Functional Design



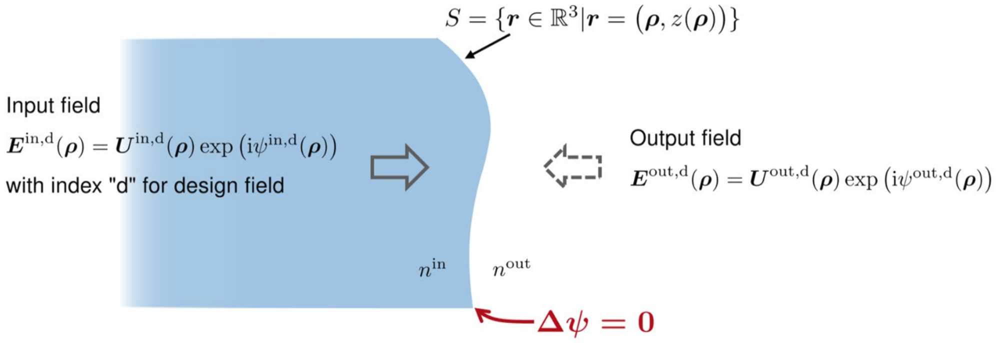


Irradiance (by field tracing)

Structural Design Shaping Expander: One Freeform



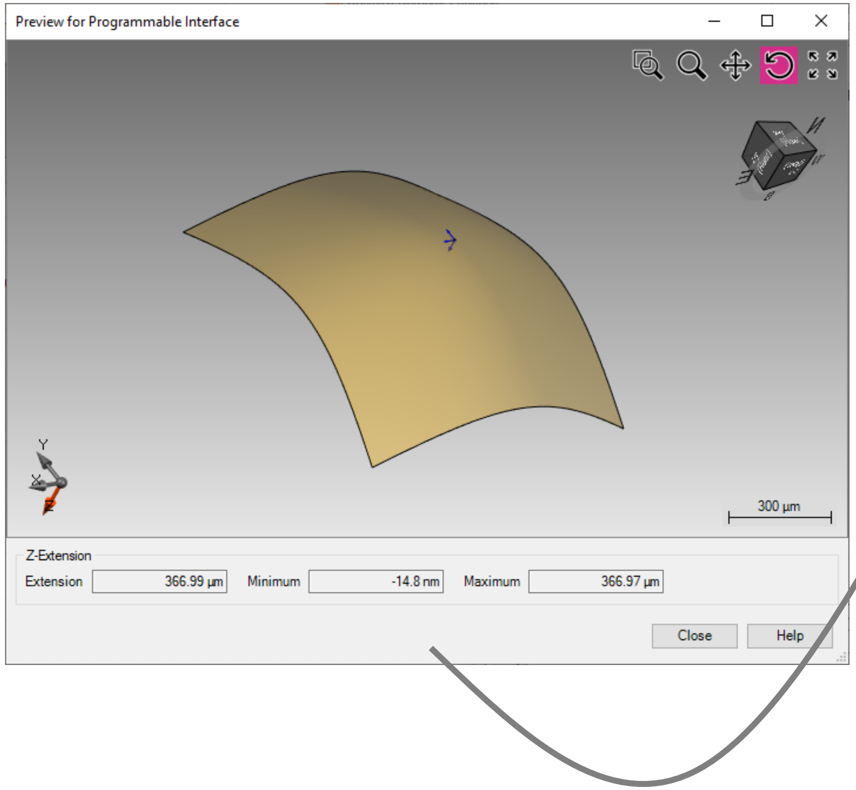
Freeform Surface Design by Inverse Propagation

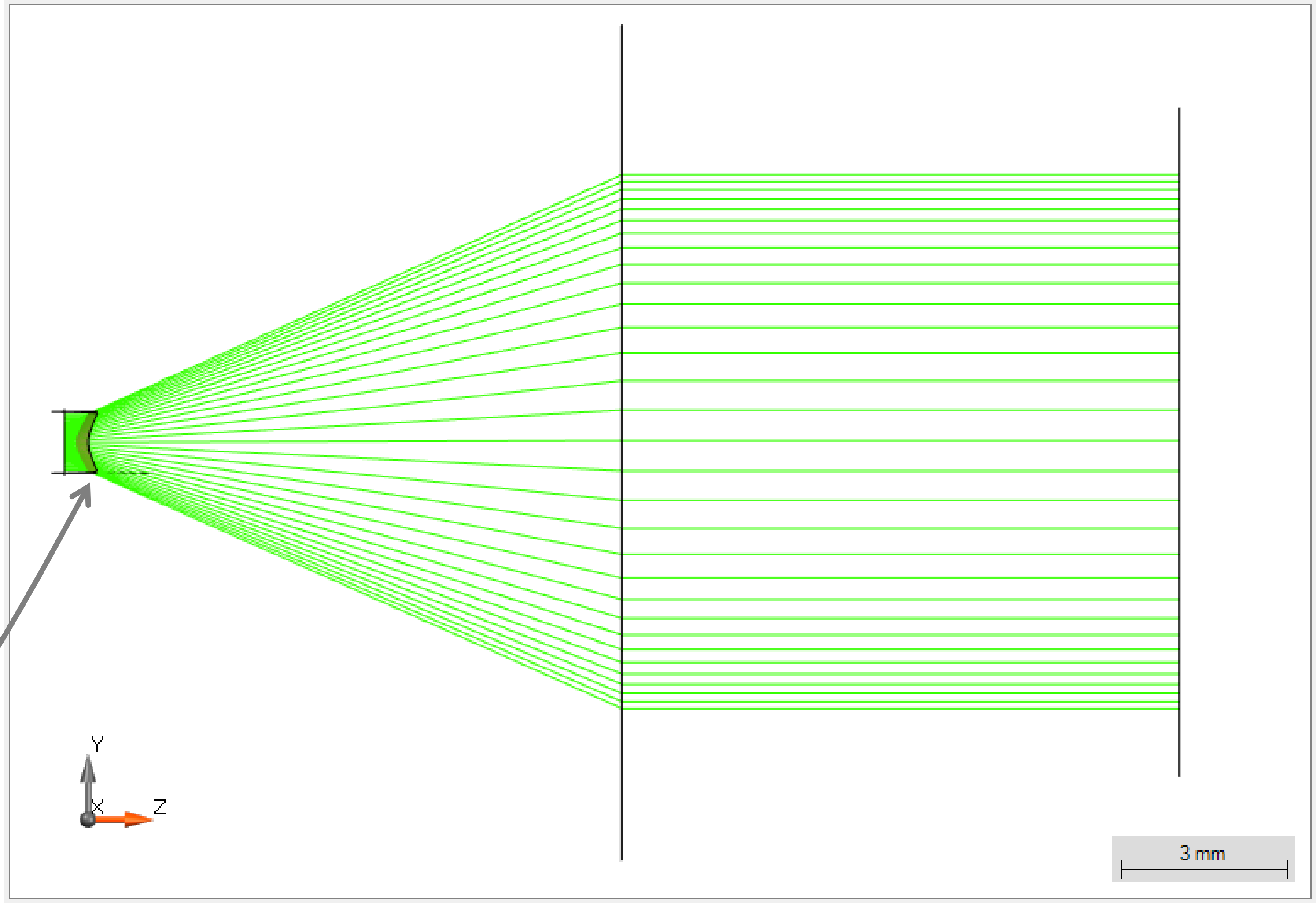


Calculate the surface $S \subset \mathbb{R}^3$ on which:

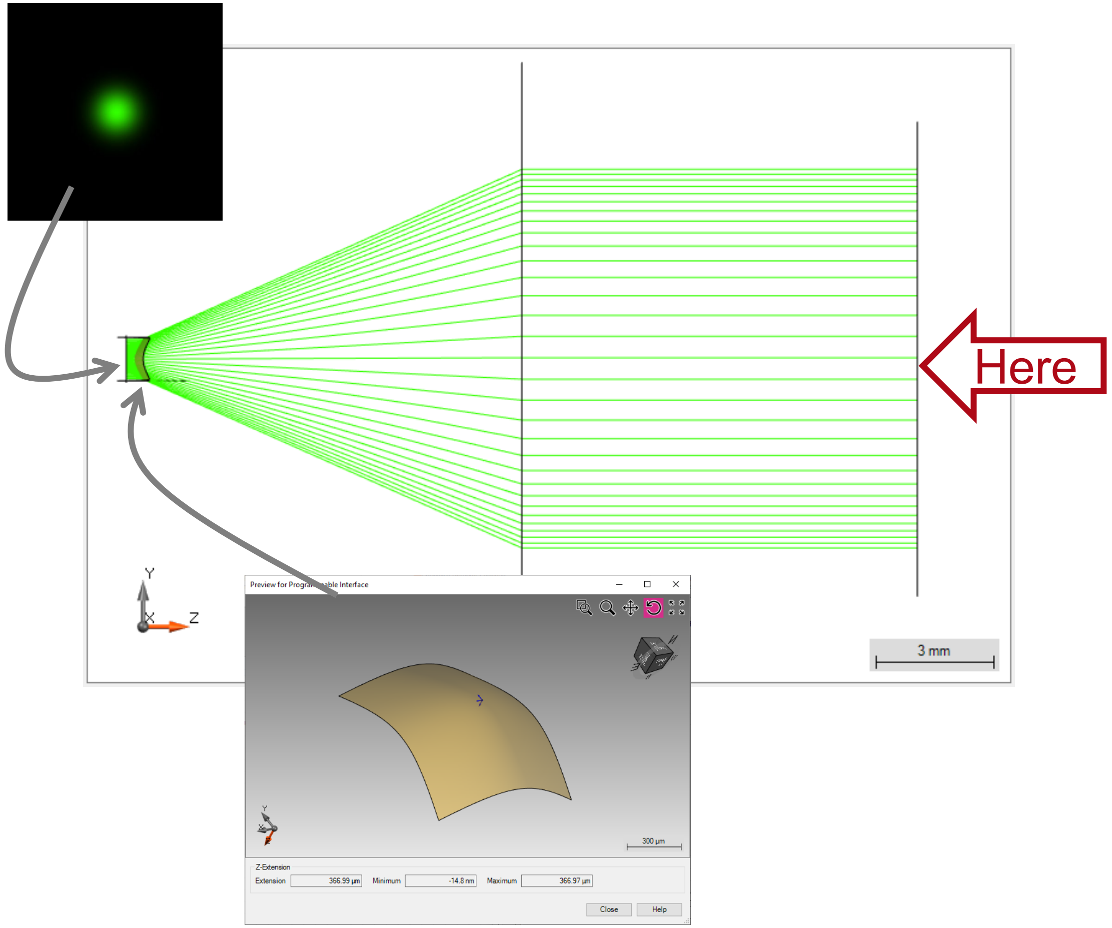
$$\psi^{\text{out,d}}(\boldsymbol{r} \in S) - \psi^{\text{in,d}}(\boldsymbol{r} \in S) = \Delta\psi(\boldsymbol{r} \in S) \stackrel{!}{=} 0$$

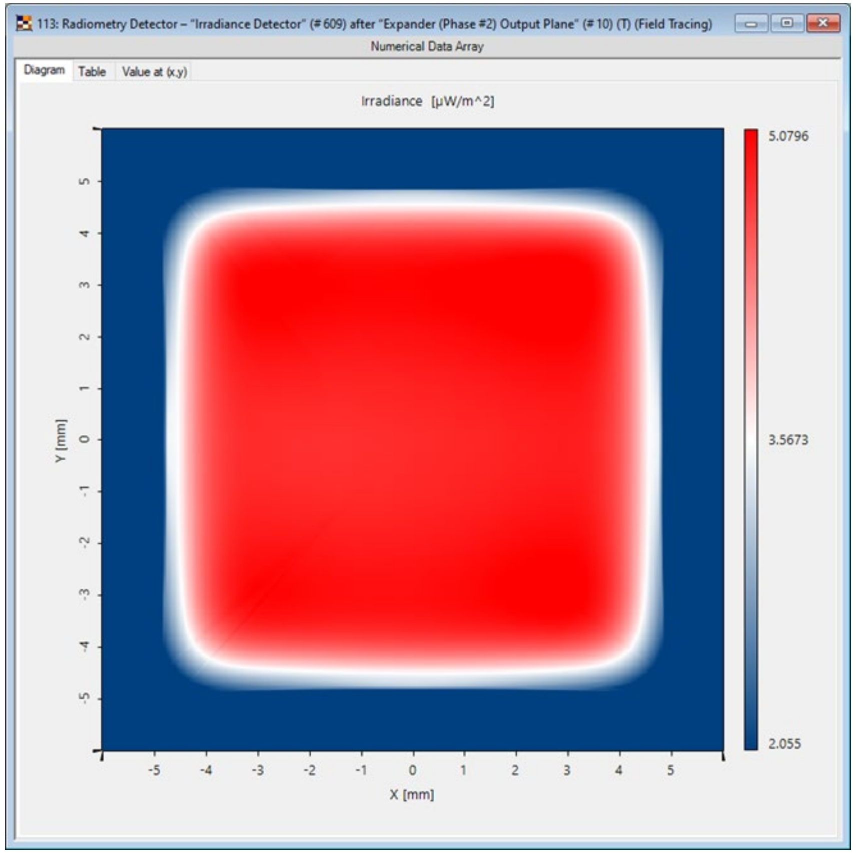
Shaping Beam Expander Freeform + Functional: Ray Tracing





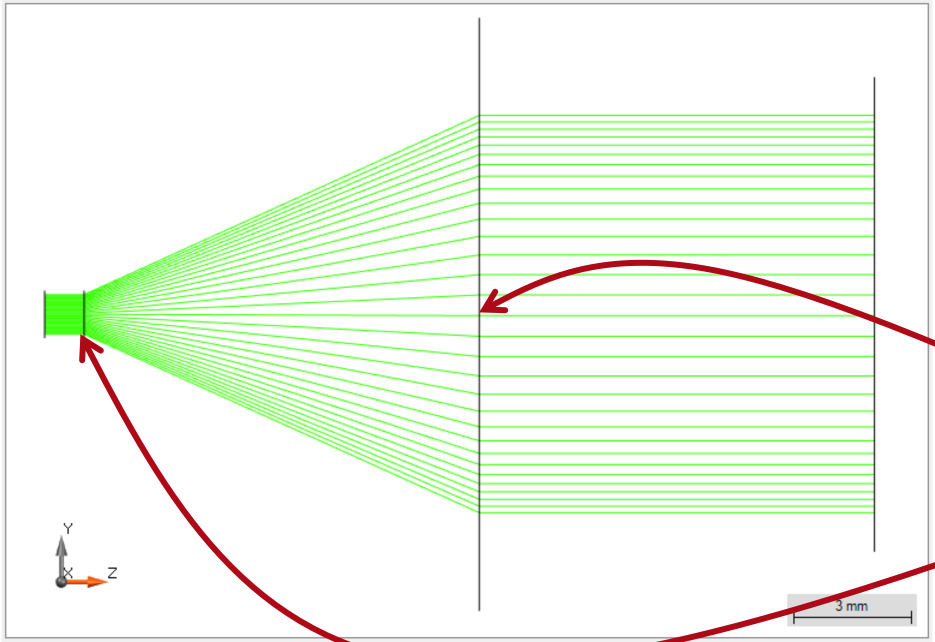
Shaping Beam Expander Freeform + Functional: Field Tracing





Irradiance (by field tracing)

Structural Design Shaping Expander: Two Freeforms



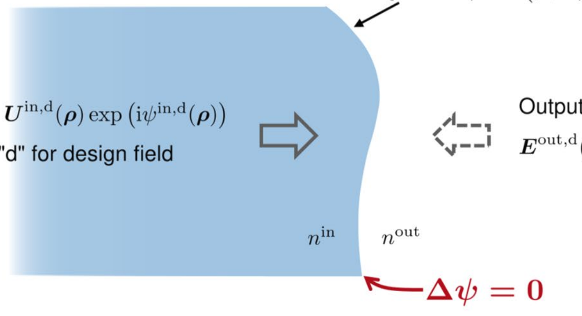
Freeform Surface Design by Inverse Propagation

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

Input field

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

with index "d" for design field



Output field

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

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

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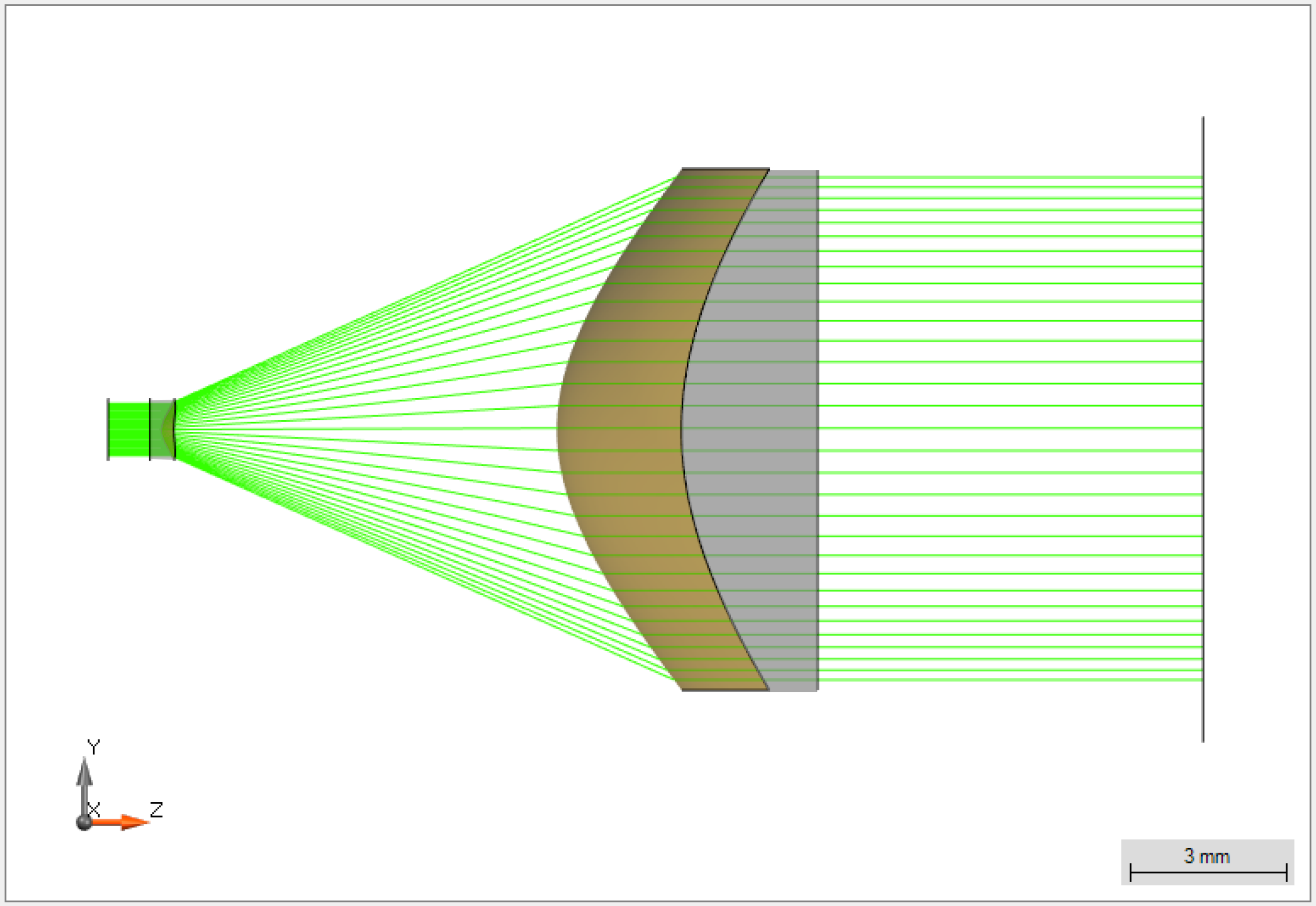
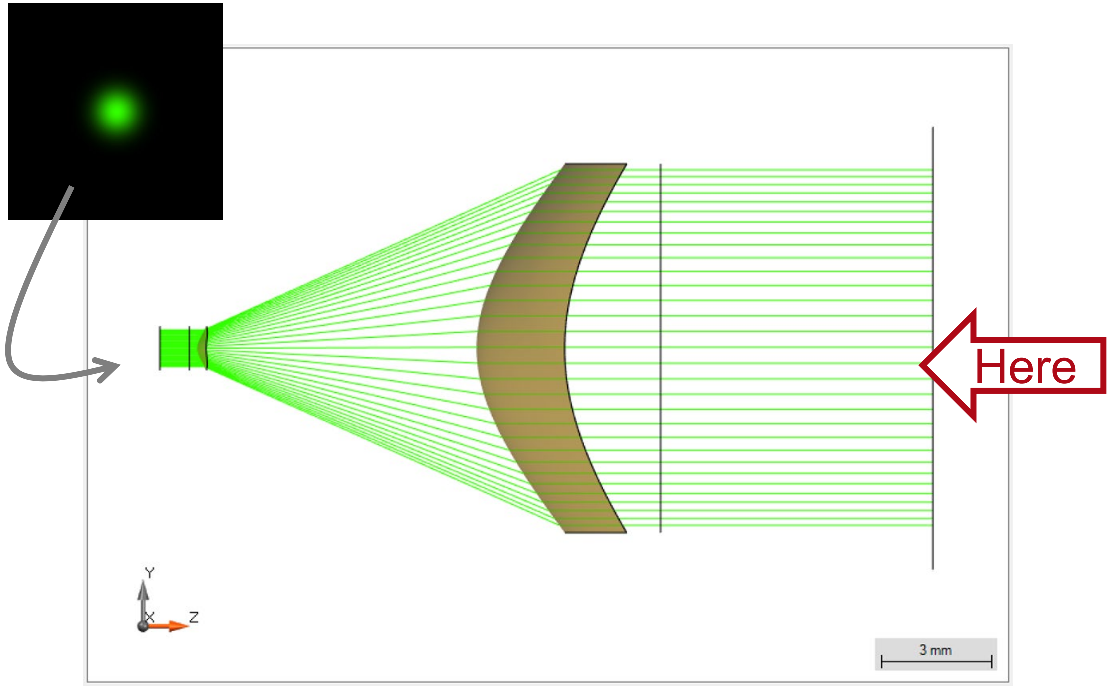
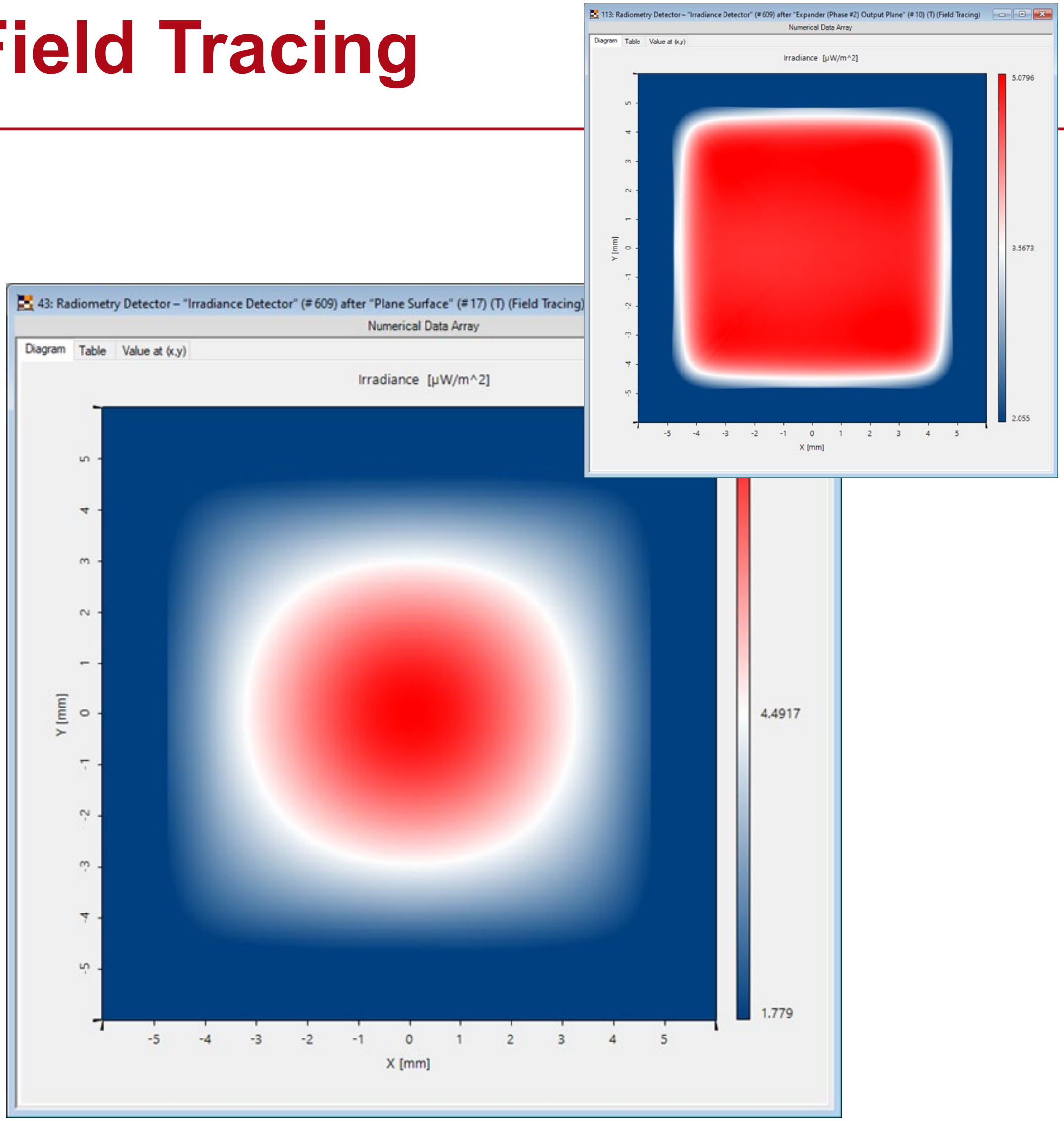
Shaping Expander Two Freeforms: Ray Tracing



Shaping Expander Two Freeforms: Field Tracing

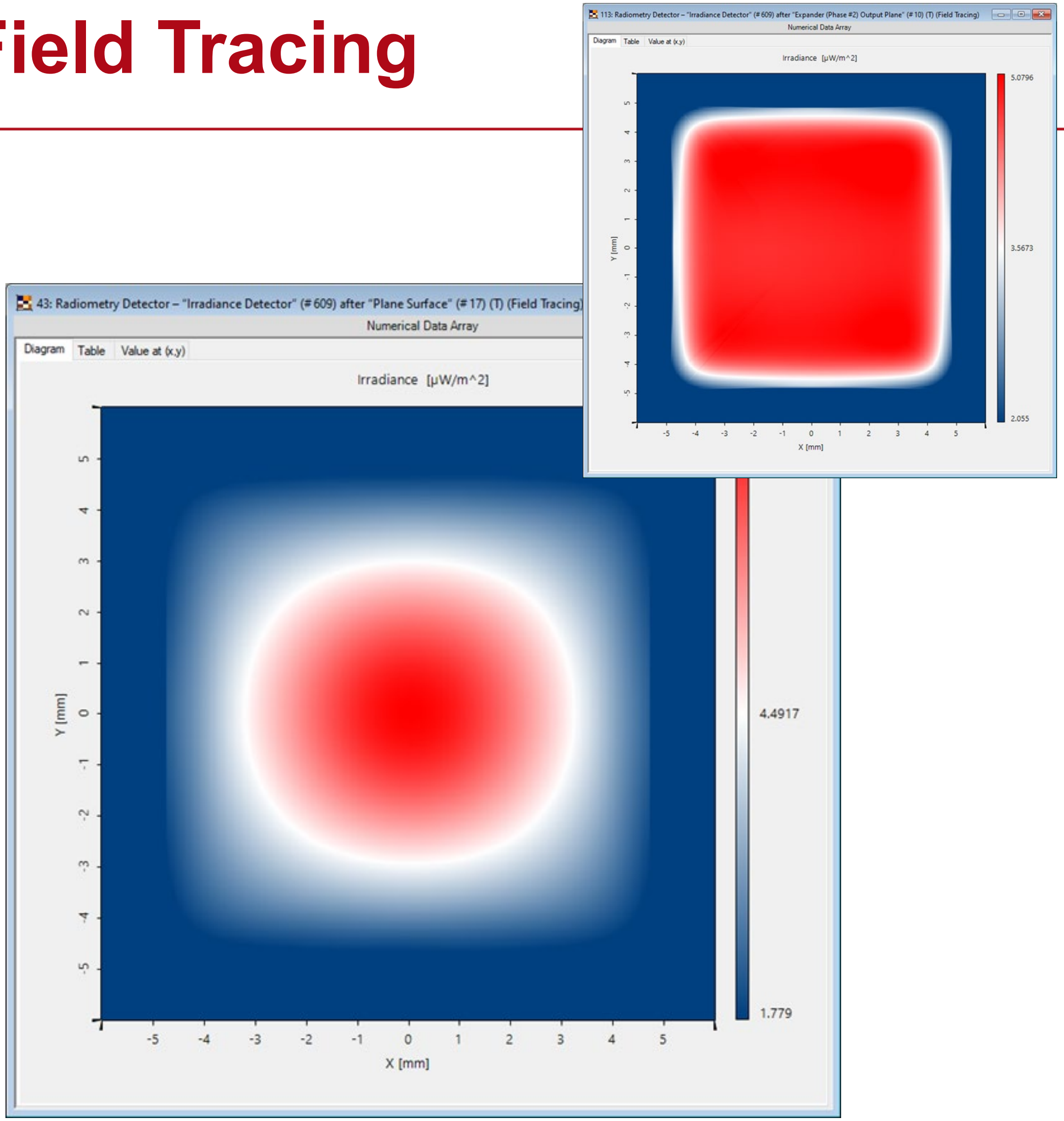




Irradiance (by field tracing)

Shaping Expander Two Freeforms: Field Tracing

Significant irradiance shaping often requires iterative optimization by several cycles of design workflow.



Irradiance (by field tracing)

Proposed Design Workflow

FUNCTIONAL DESIGN

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

STRUCTURAL DESIGN

Replace functional components by freeform or/and 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

Calculate and export fabrication data from the surfaces which result from structural design and optimization.

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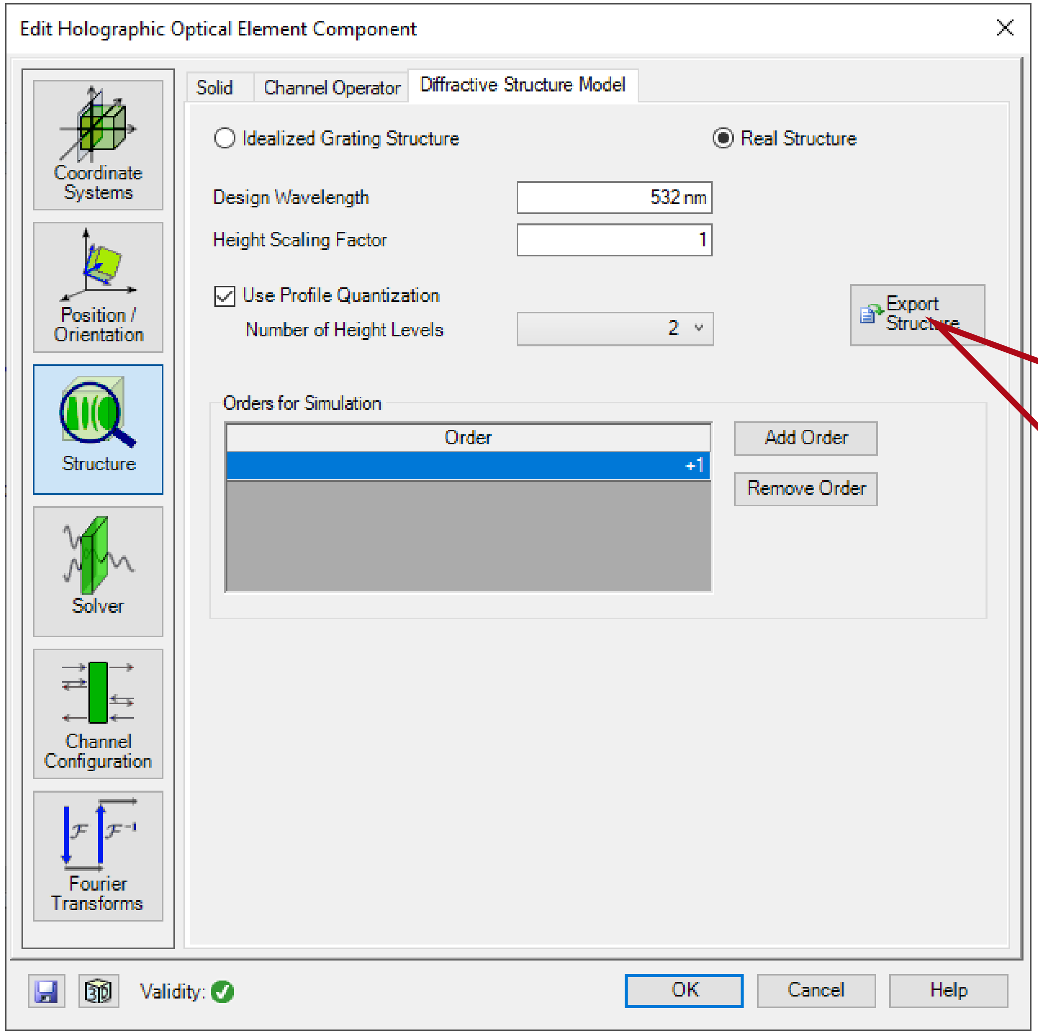
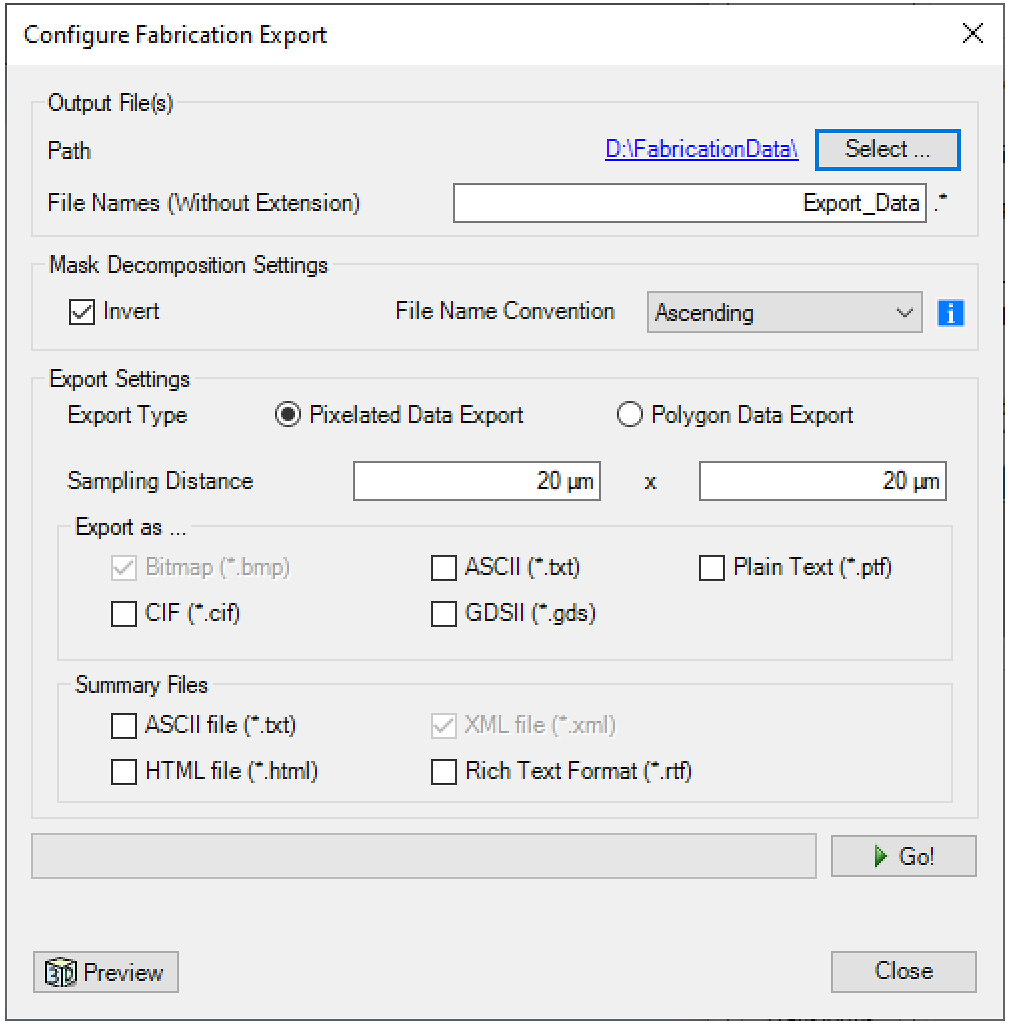
HOE Fabrication Data Export



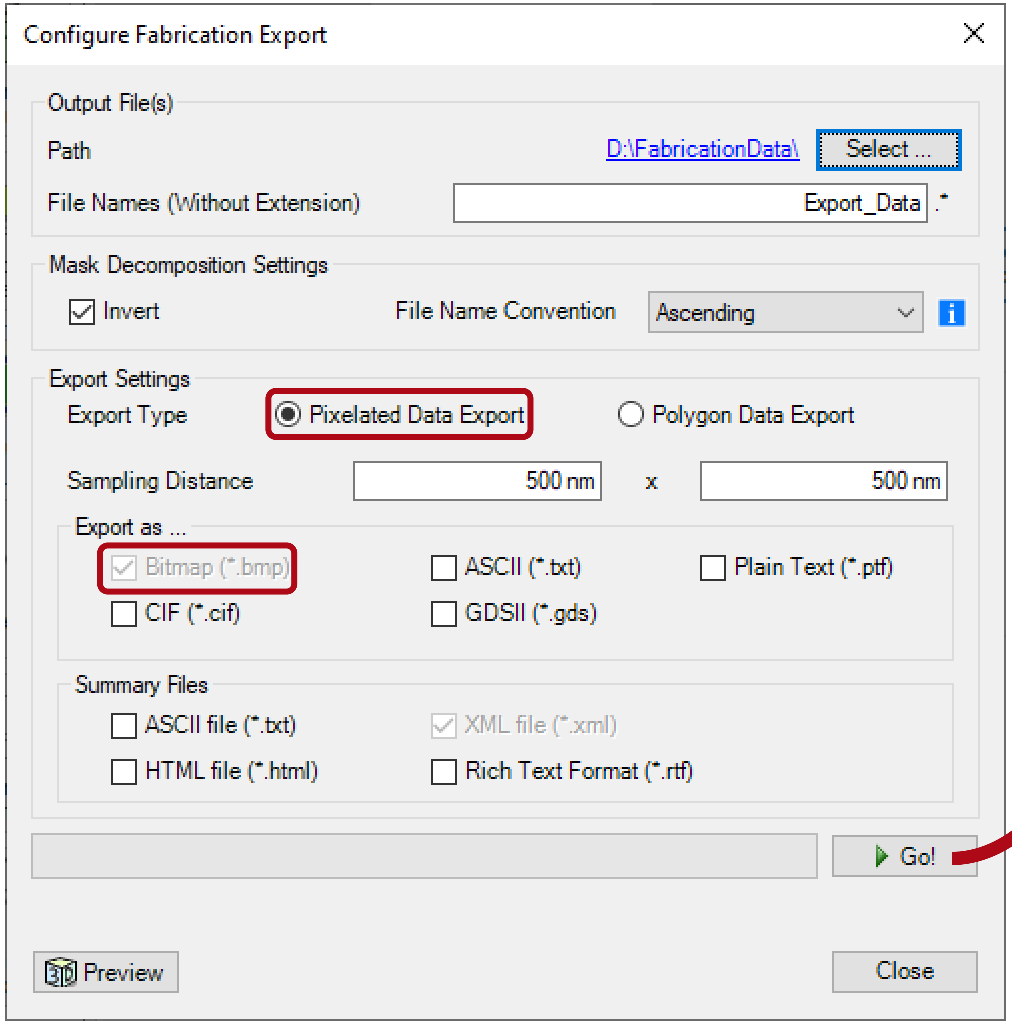
Structure export for quantized height structures can be performed by clicking on the corresponding button in the edit dialog of the HOE.

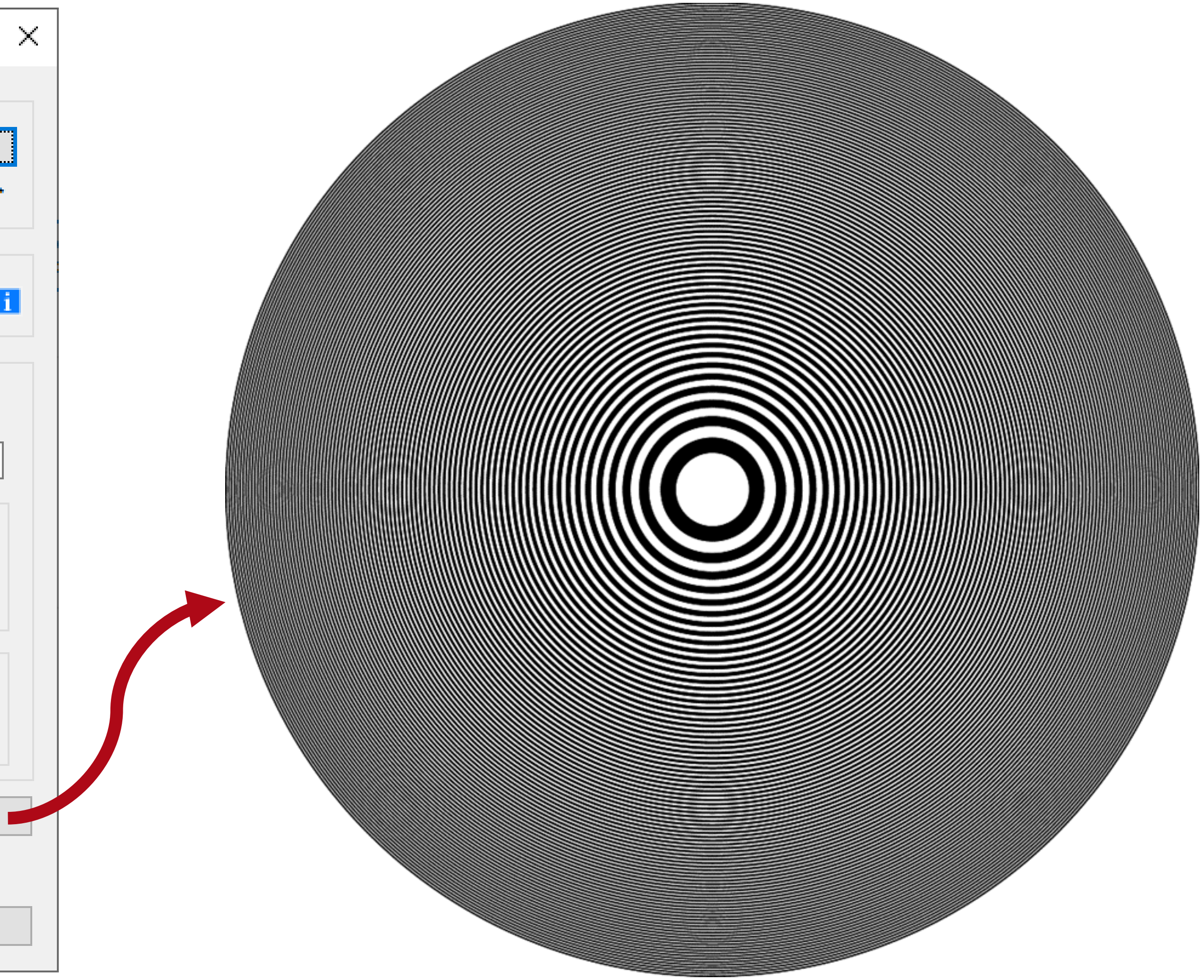
HOE Fabrication Data Export



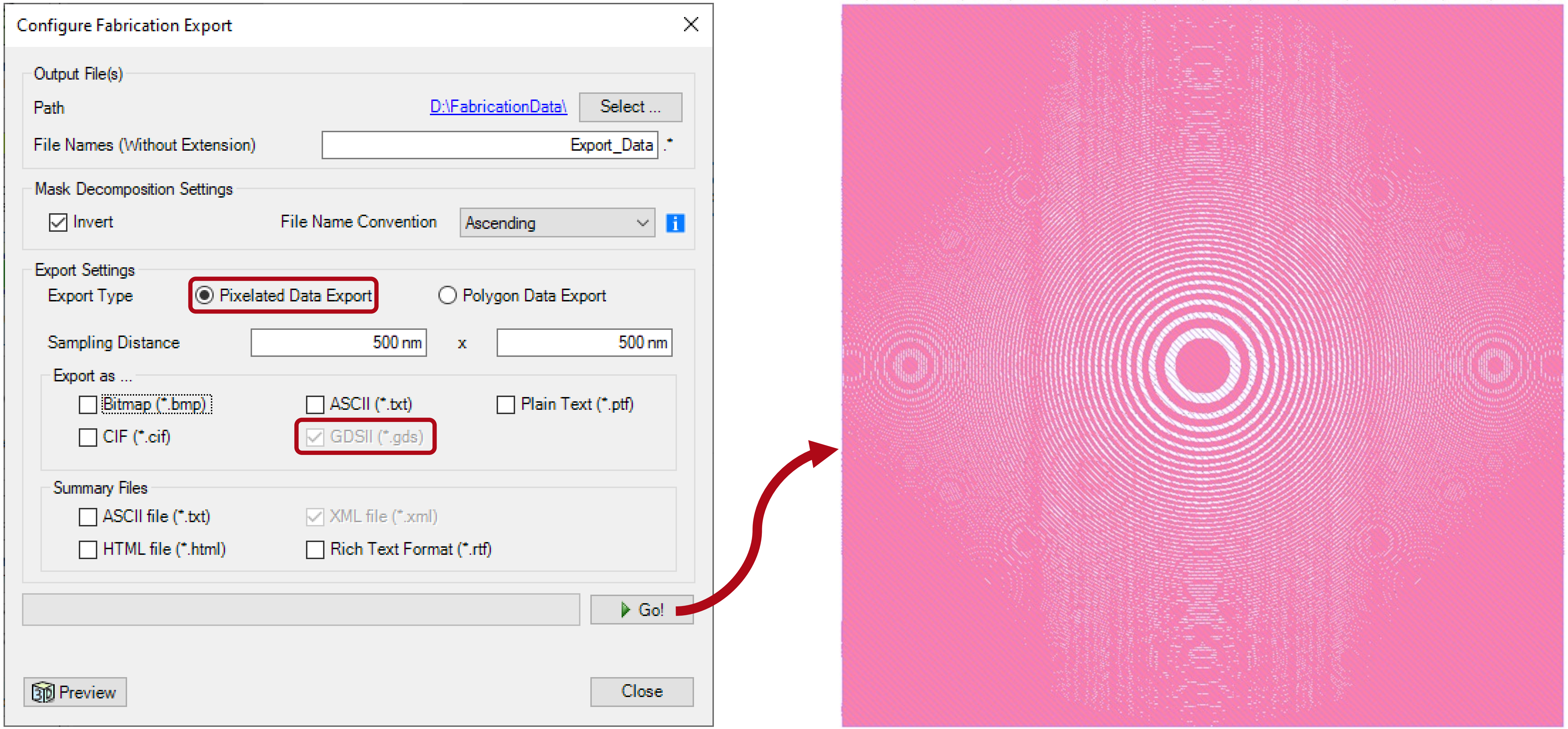
- Fabrication export supports specification of
  - Target directory
  - Parameters for mask decomposition
  - Pixelated or polygon data export (+ export accuracy parameters)
  - File format (supported formats: bitmap, text files, GDISII or CIF)

HOE Fabrication Data Export – Sample Data Pixelated Bitmap

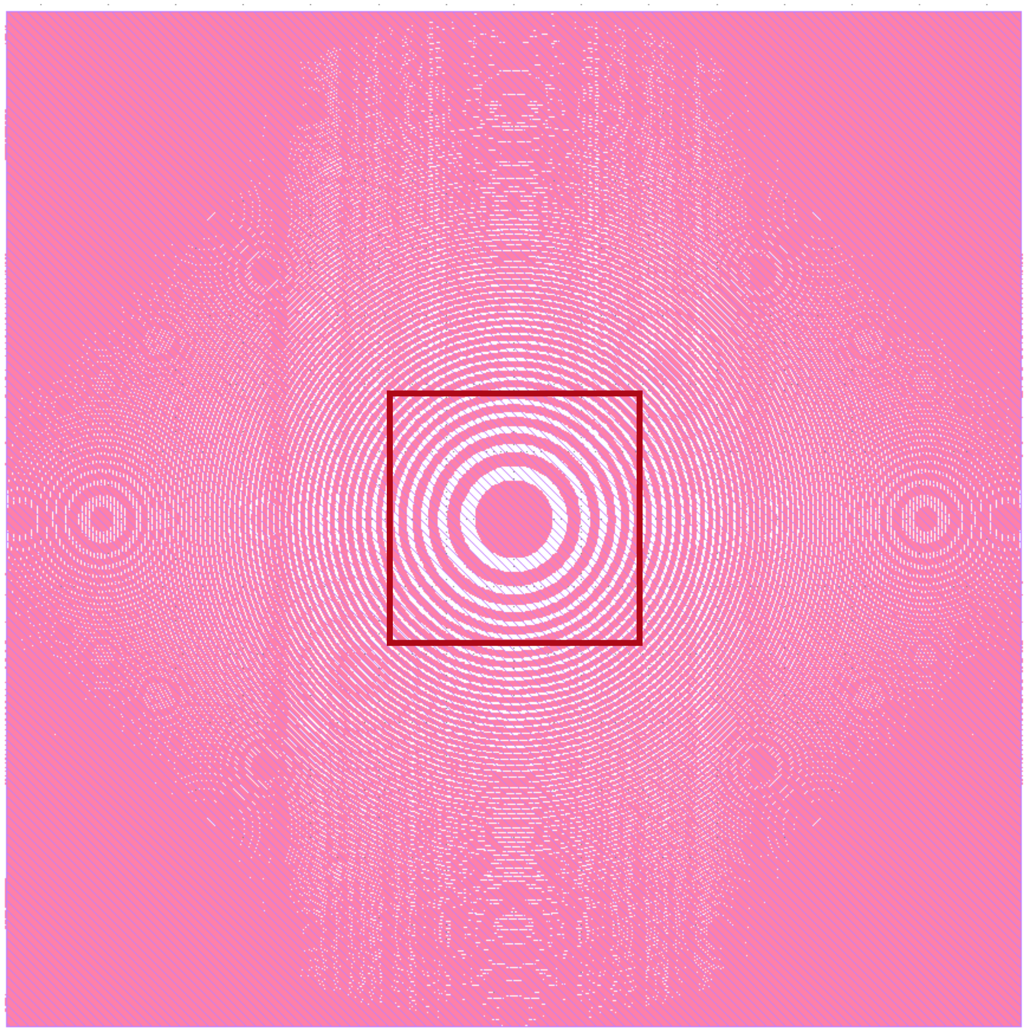


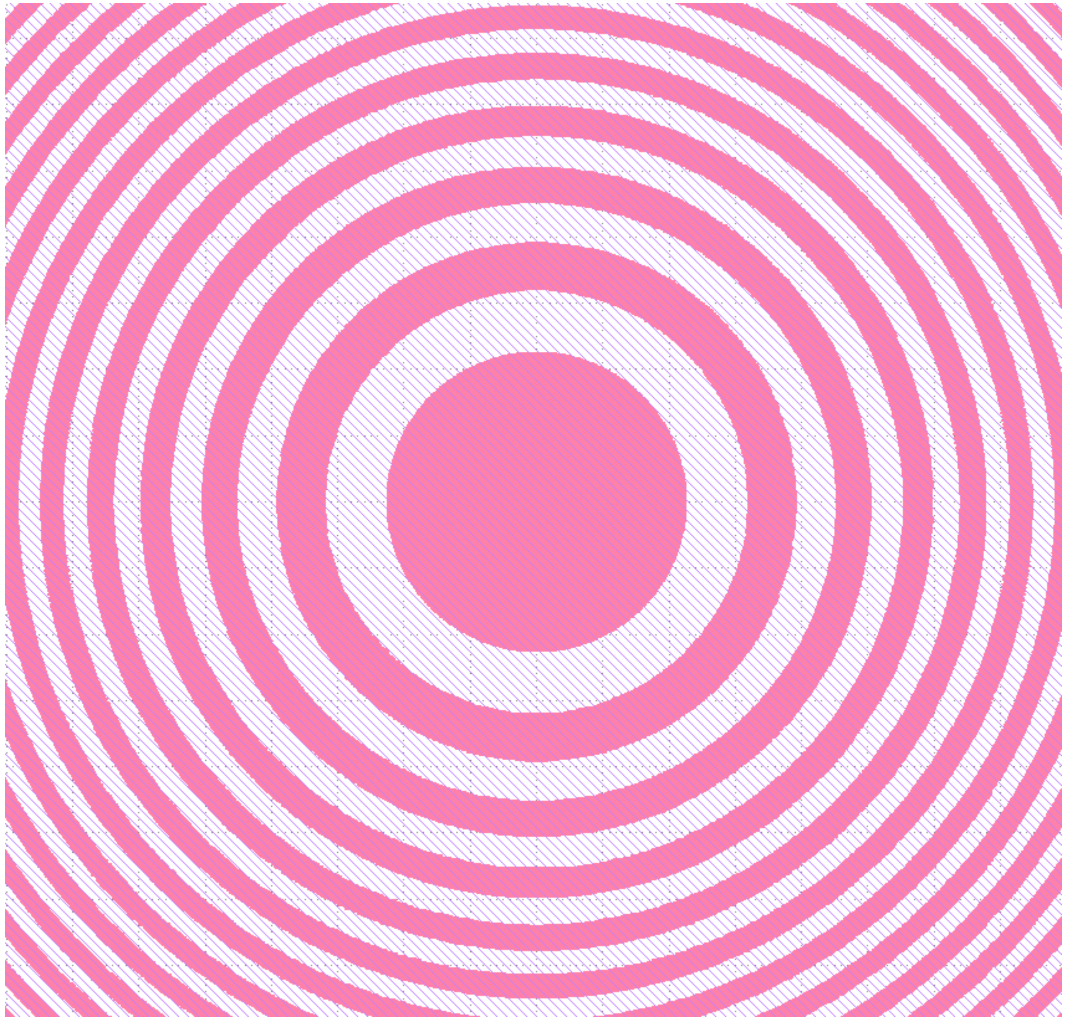


HOE Fabrication Data Export – Sample Data Pixelated GDSII

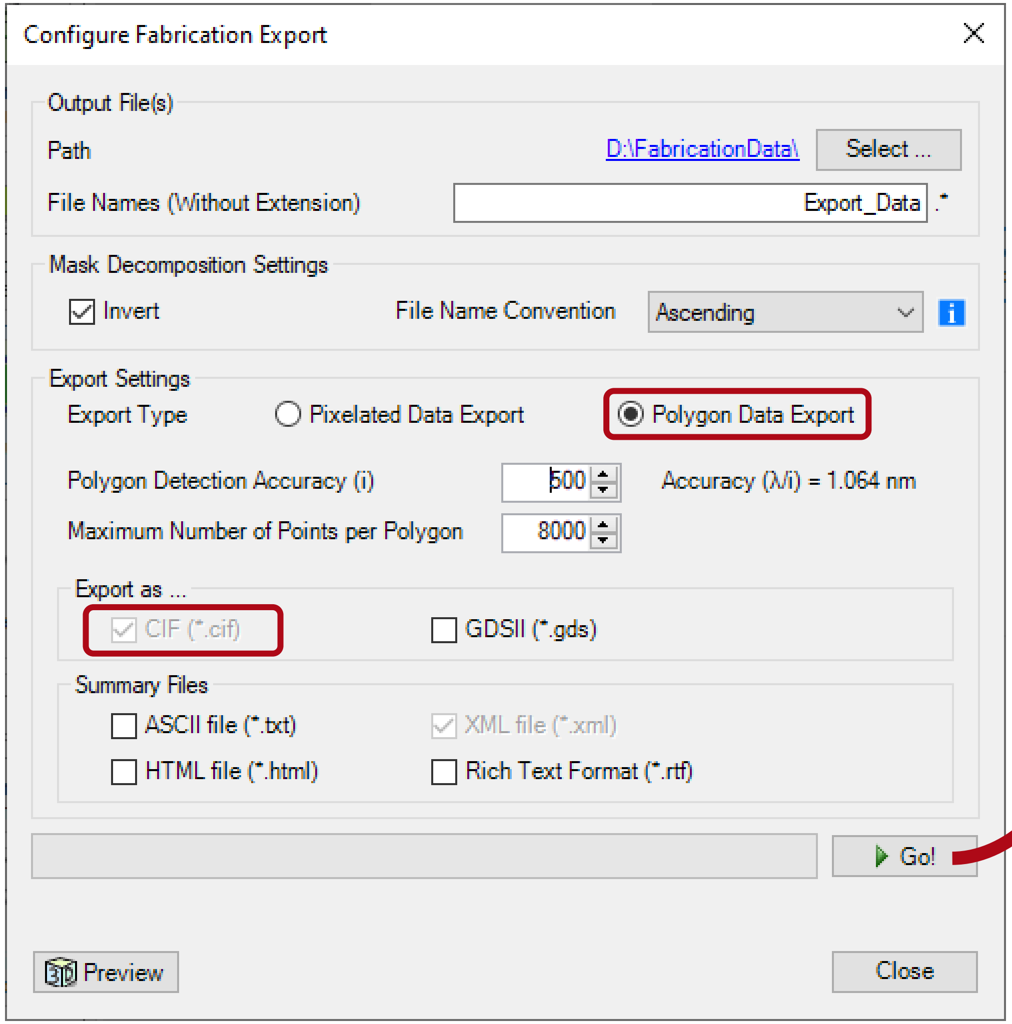


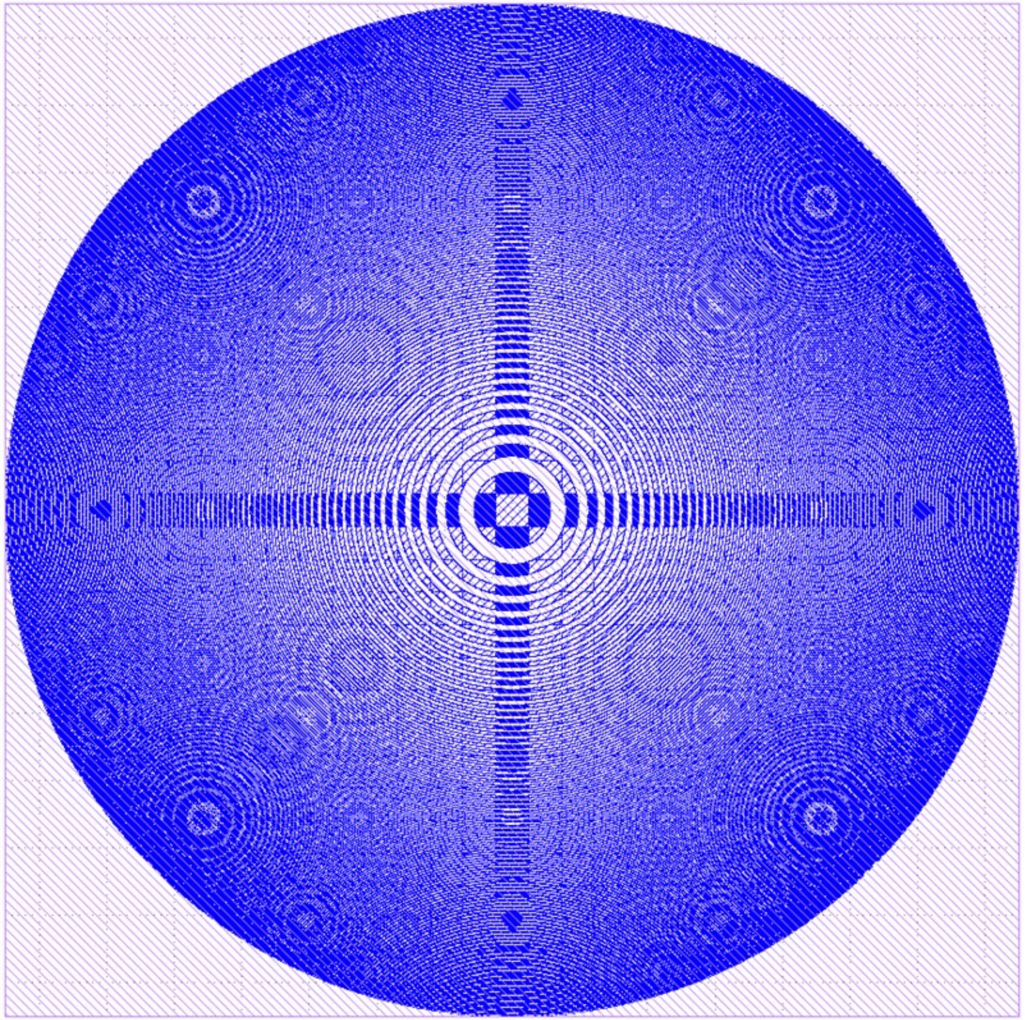
HOE Fabrication Data Export – Sample Data Pixelated GDSII



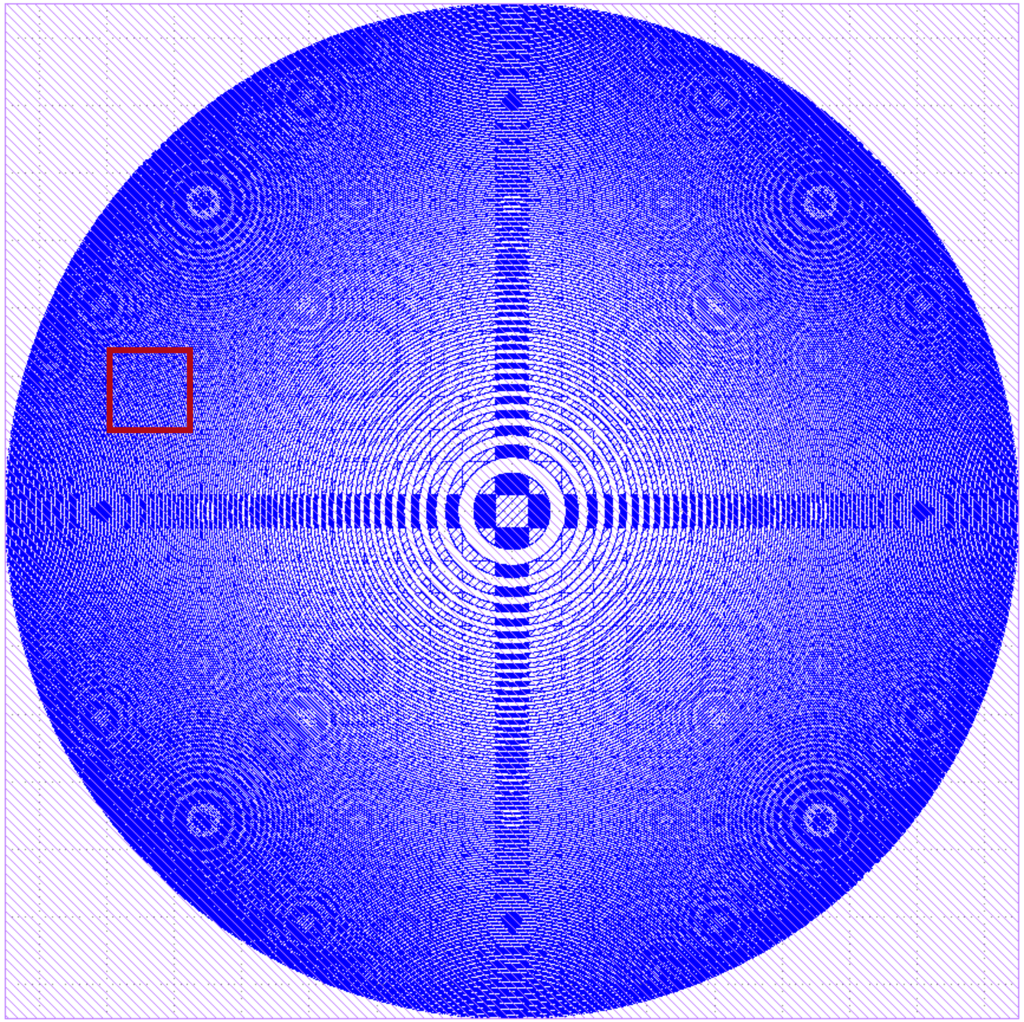


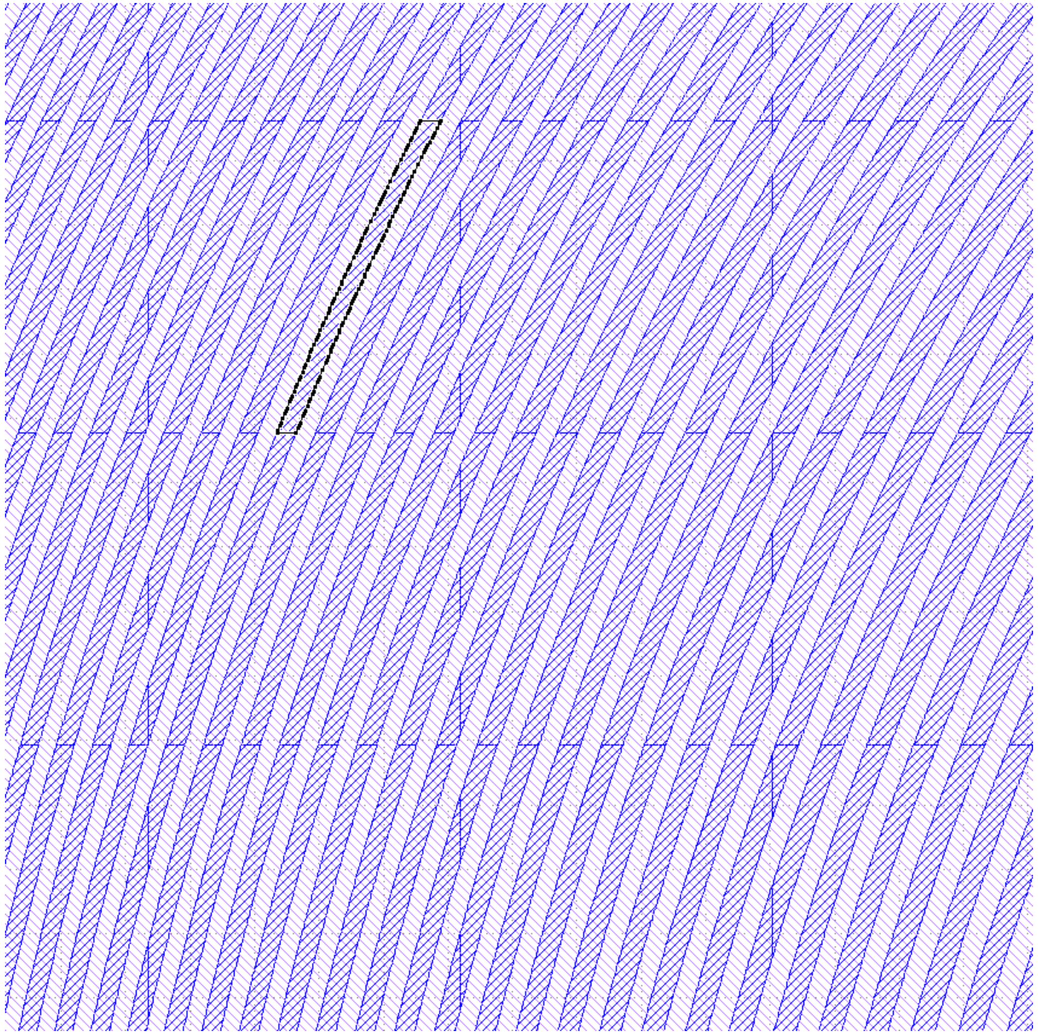
HOE Fabrication Data Export – Sample Data Polygon CIF



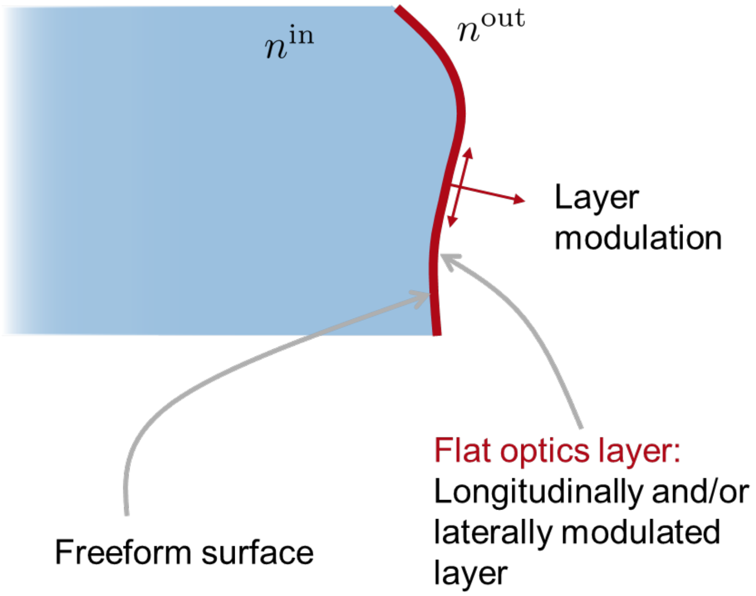


HOE Fabrication Data Export – Sample Data Polygon CIF





Freeform and Flat Optics: Why?



Freeform and flat optics introduce new design freedoms:

- Improve performance
- Reduce size and weight
- Less components
- Cost reduction
- Add new functionality, e.g., bifocal lenses, polarization dependency, …

"Is it possible to replace a bulky glass system by one meta lens" ?

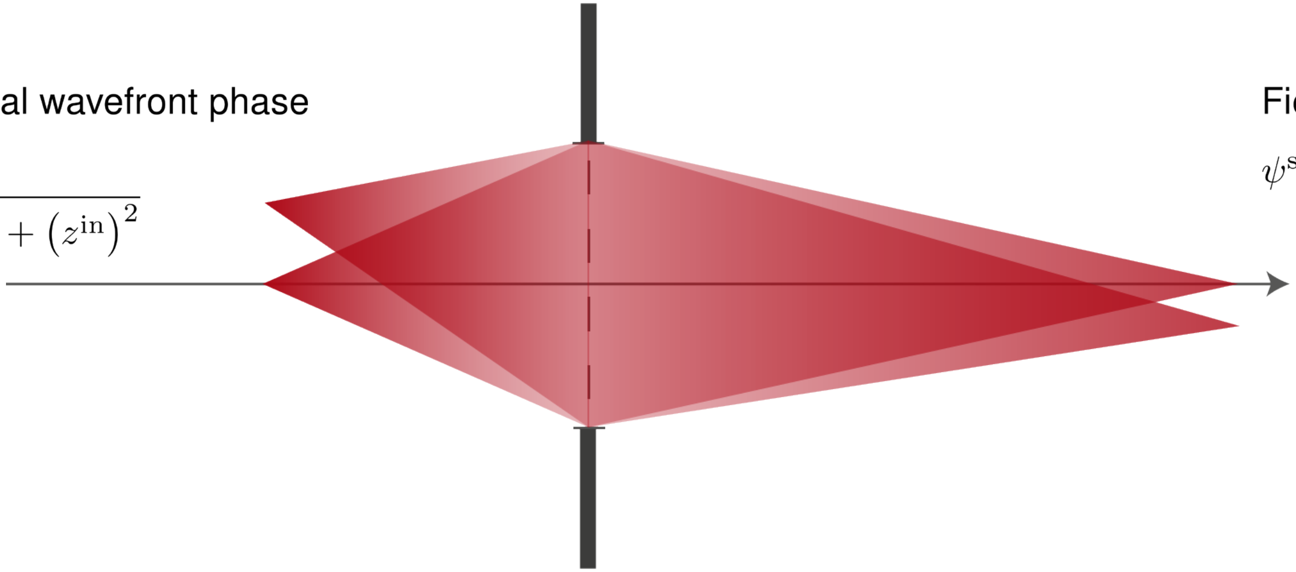
Imaging With One Component

Multifield scenario!

Imaging with One Component: Scenario

Input fields with spherical wavefront phase

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



Fields with spherical wavefront phase

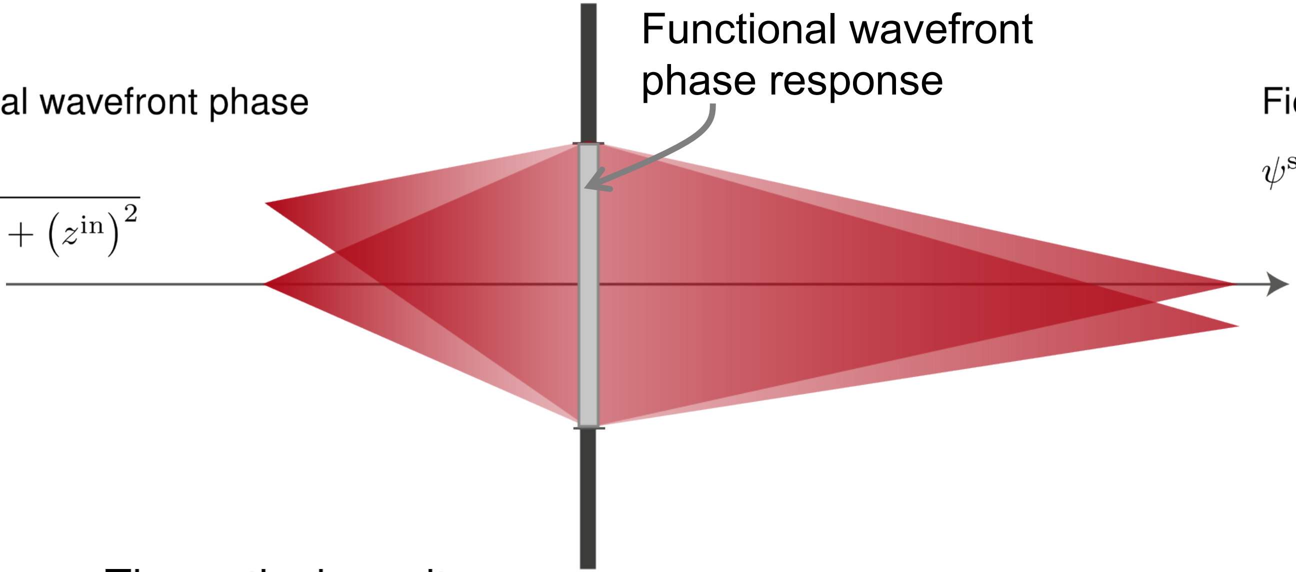
$$\psi^{\mathrm{sph,out}}(\boldsymbol{r}, \omega, j) = -k_0 n^{\mathrm{out}} \sqrt{\left\|\boldsymbol{\rho} - M\boldsymbol{\rho}_j^{\mathrm{in}}\right\|^2 + \left(z^{\mathrm{out}}\right)^2}$$

Imaging with One Component: Functional Design

Input fields with spherical wavefront phase

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

Functional wavefront phase response



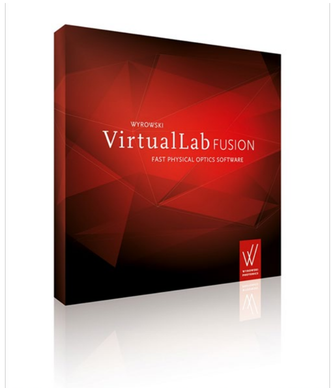
Fields with spherical wavefront phase

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

Theoretical result:

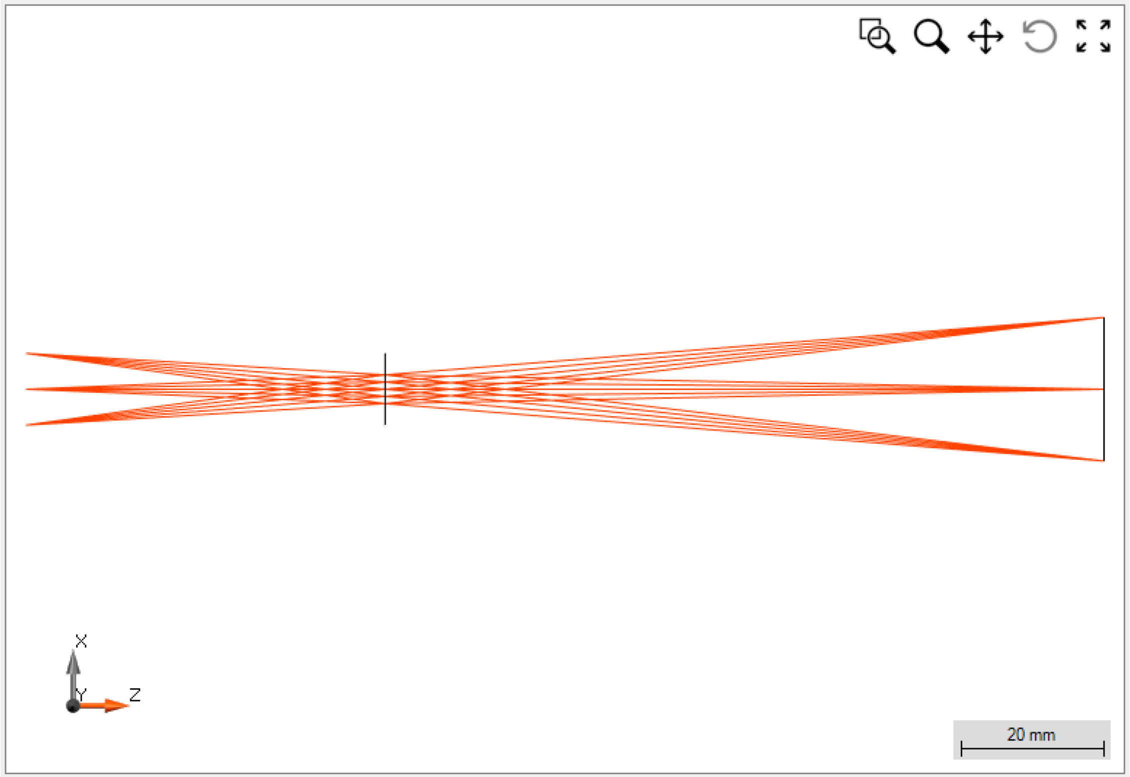
$$\Delta\psi_j(\boldsymbol{\rho},\lambda) = -k_0 n \sqrt{\left\|\boldsymbol{\rho}-M\boldsymbol{\rho}_j^{\mathrm{in}}\right\|^2 + \left(z^{\mathrm{out}}\right)^2} - k_0 n \sqrt{\left\|\boldsymbol{\rho}-\boldsymbol{\rho}_j^{\mathrm{in}}\right\|^2 + \left(z^{\mathrm{in}}\right)^2}$$

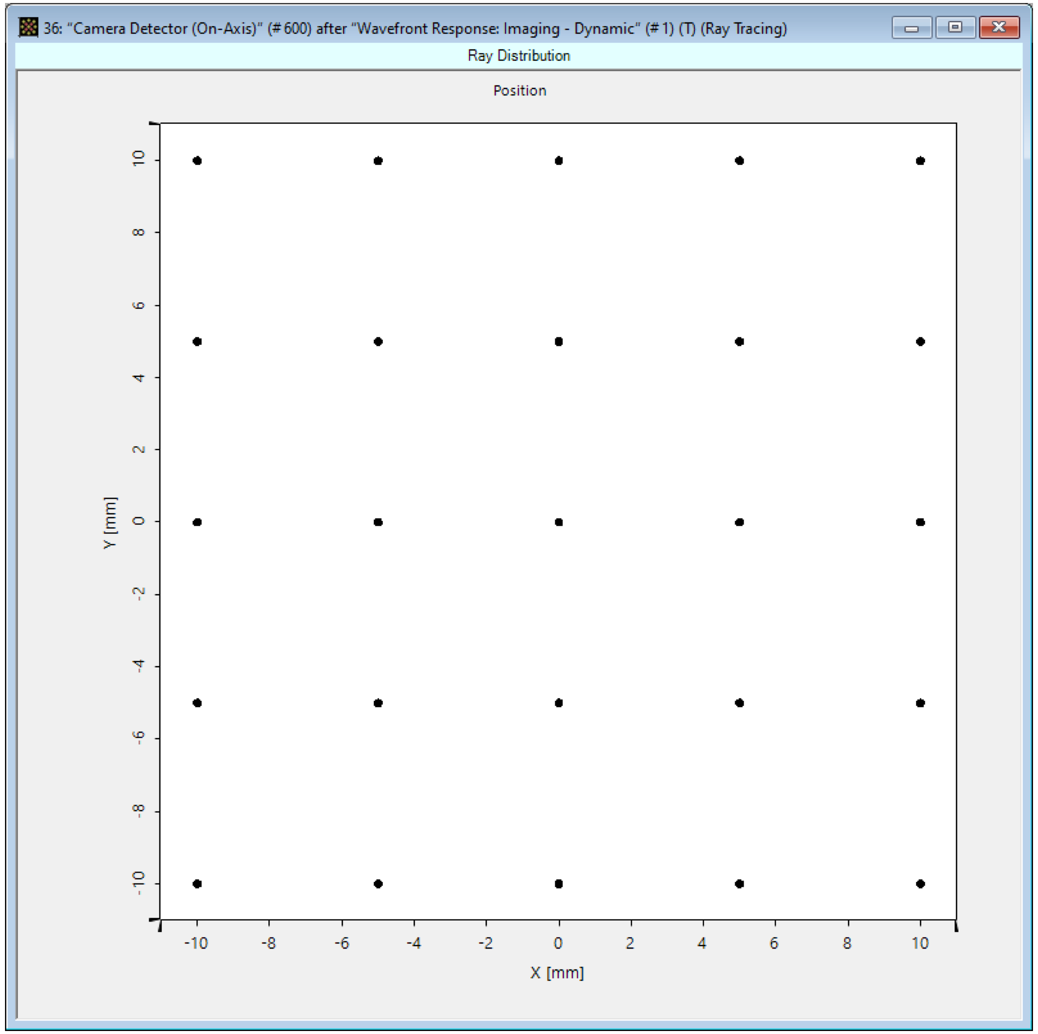
⇨ Wavefront Response Component (Multifield)



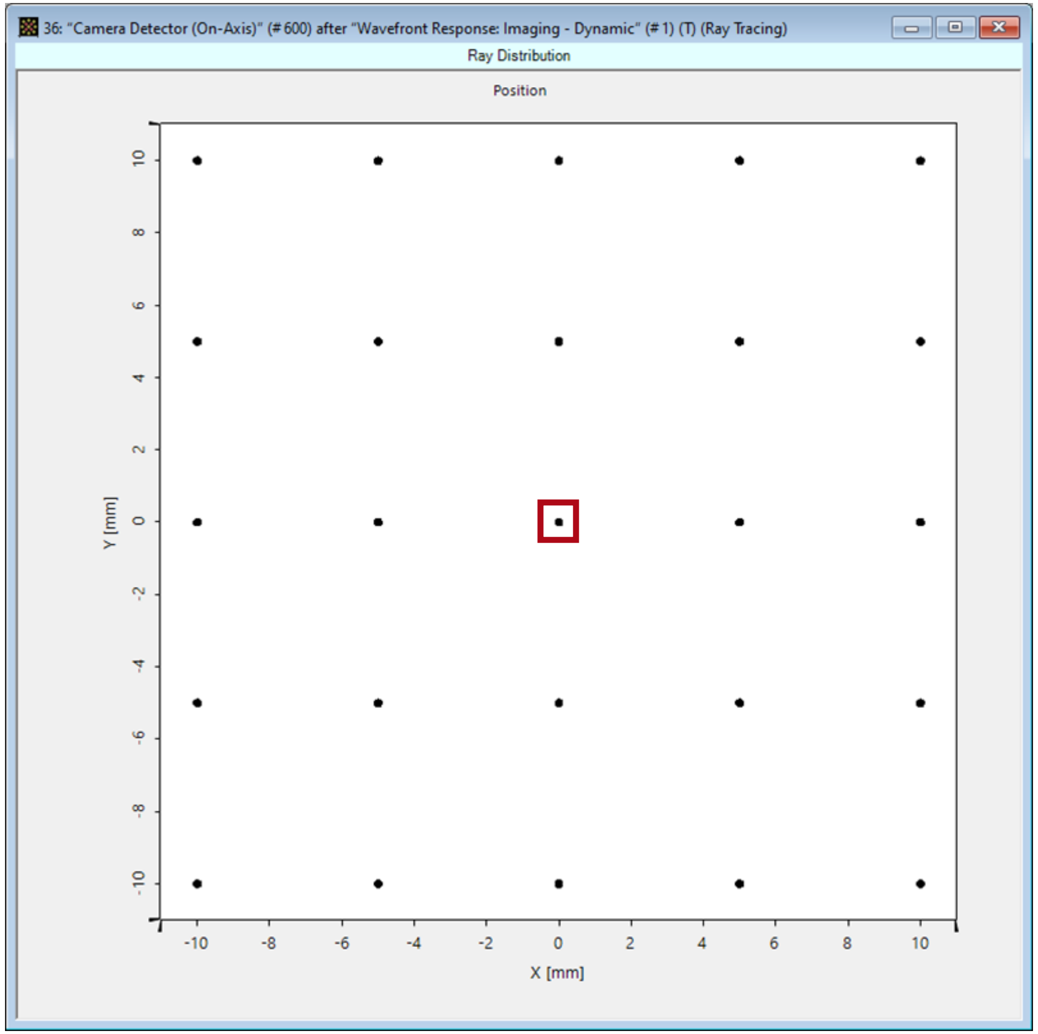
VirtualLab Fusion 2021

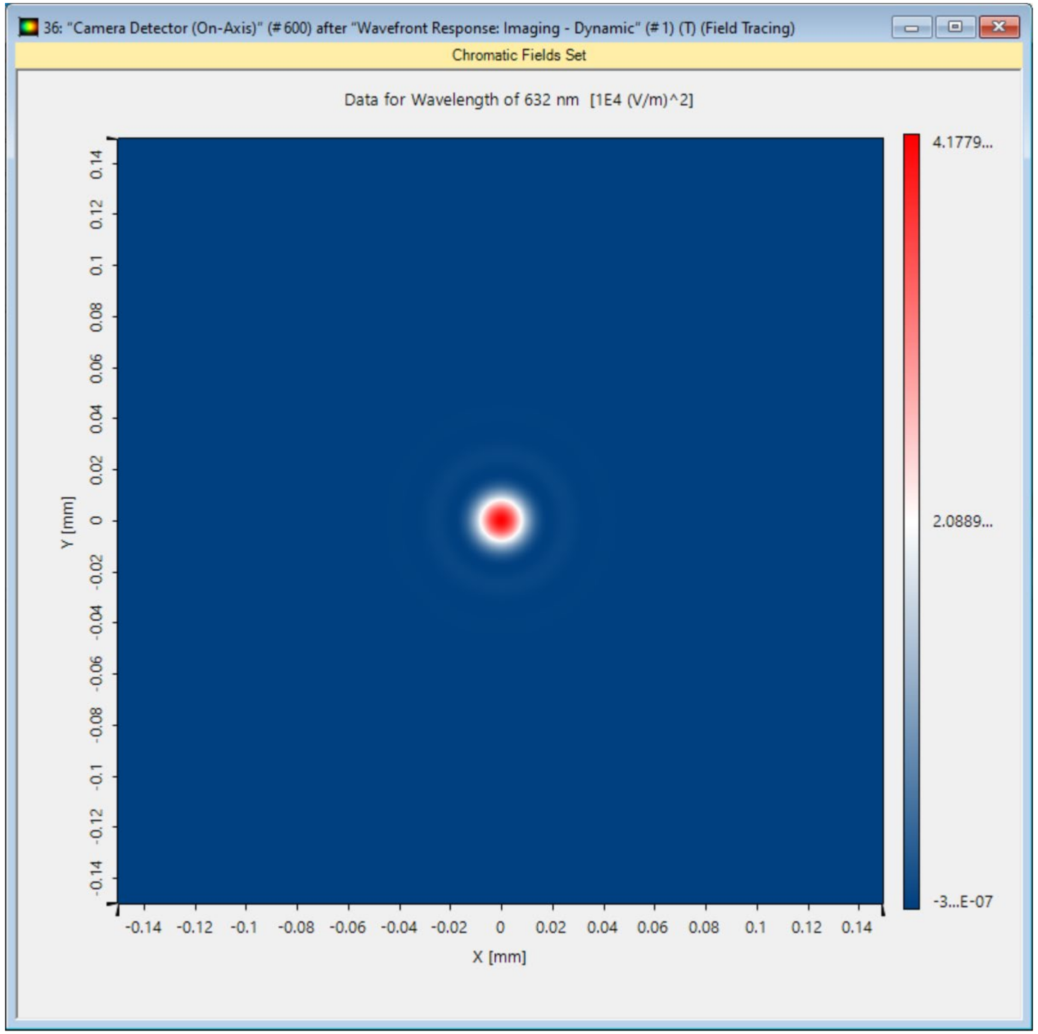
Wavefront Response Component (Multifield): Ray Tracing





Wavefront Response Component (Multifield): Field Tracing





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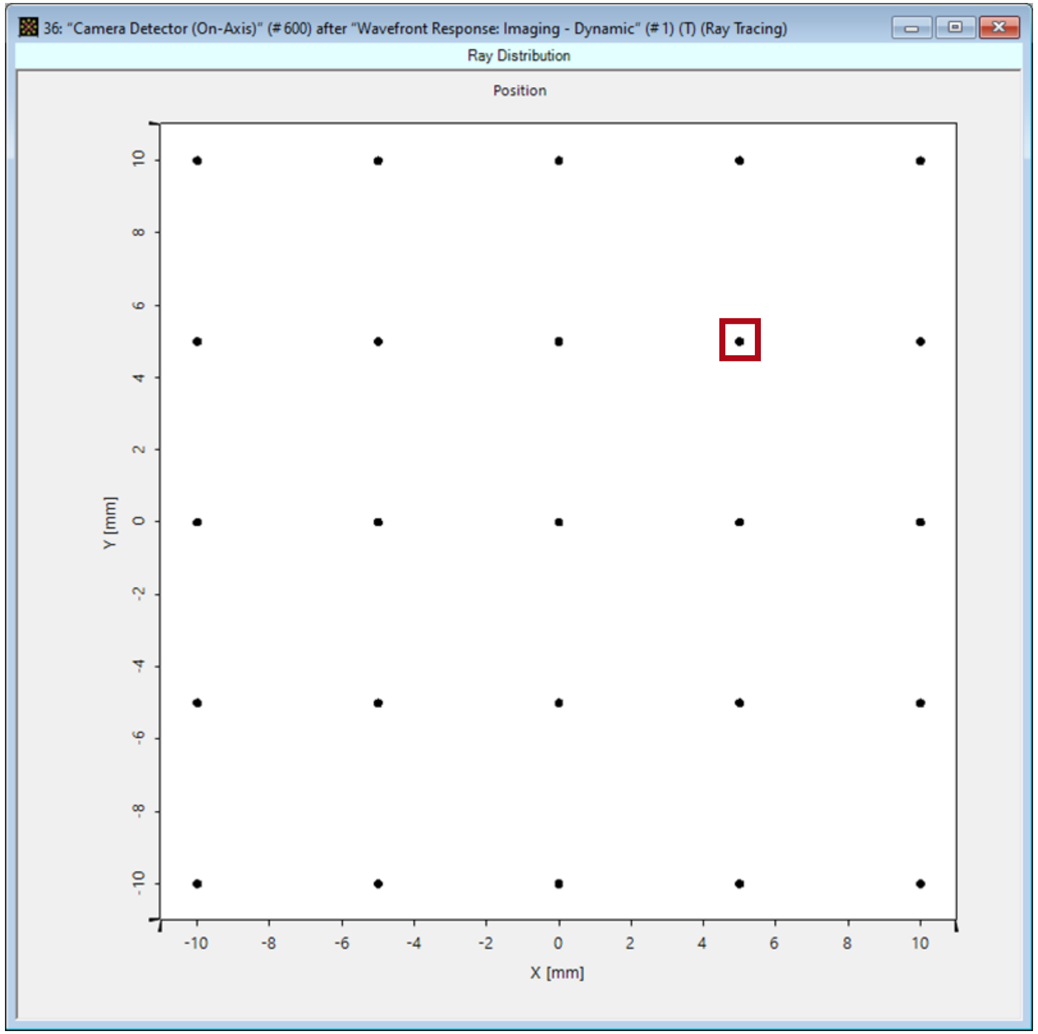

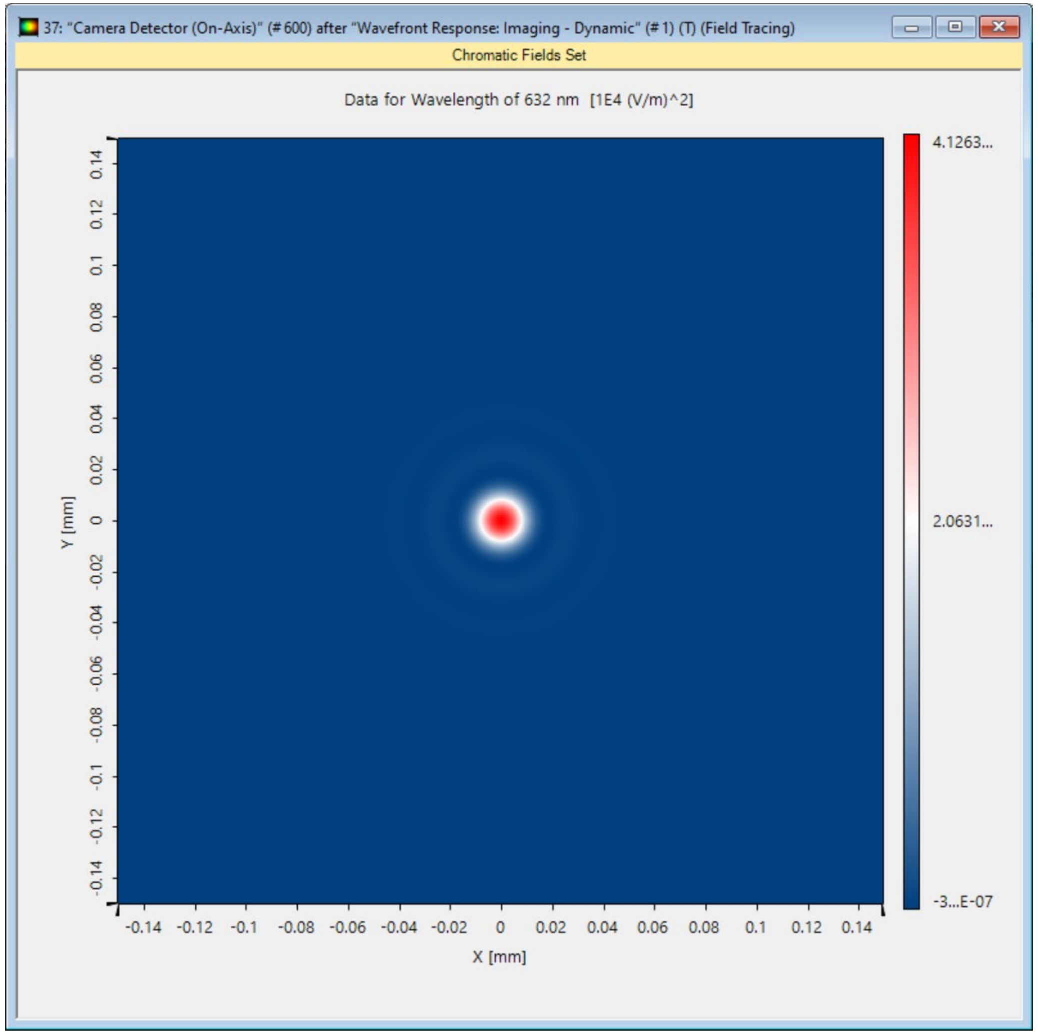

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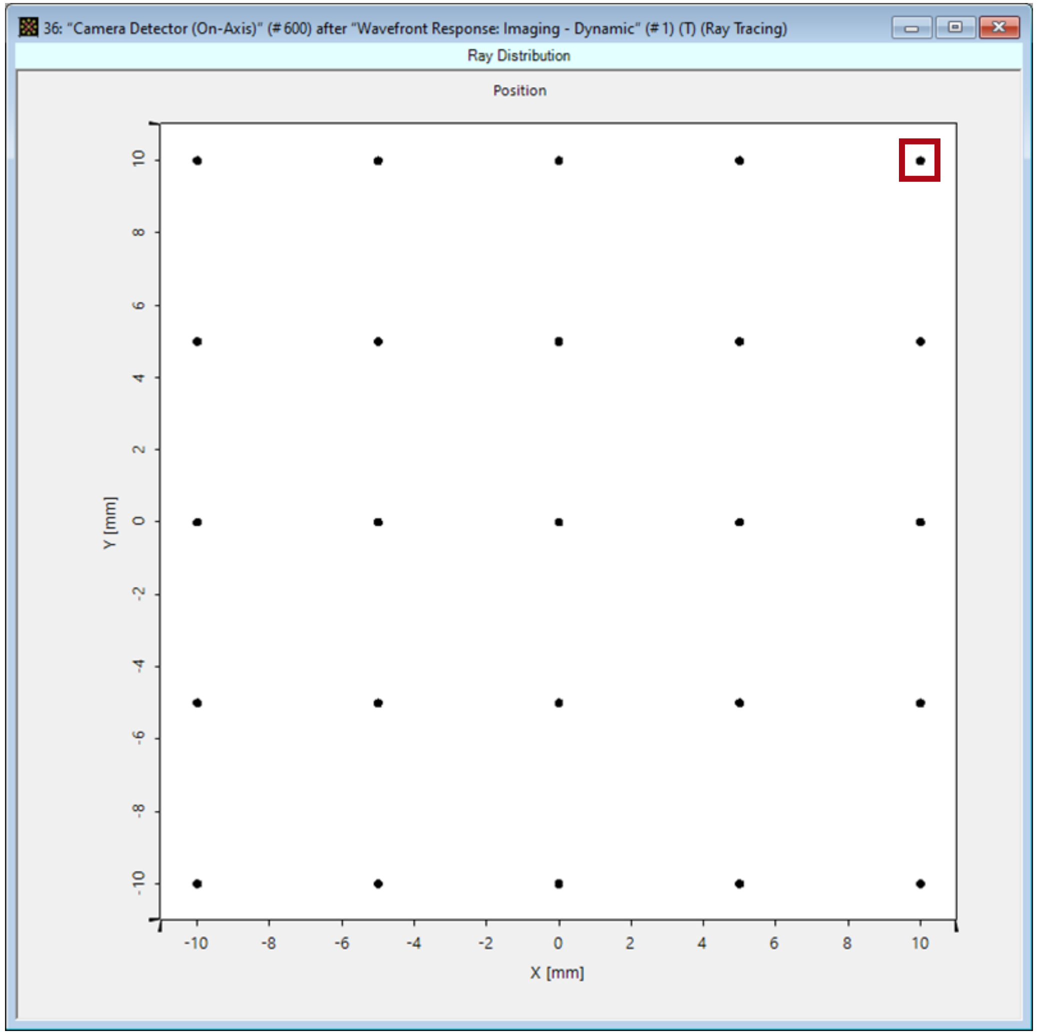
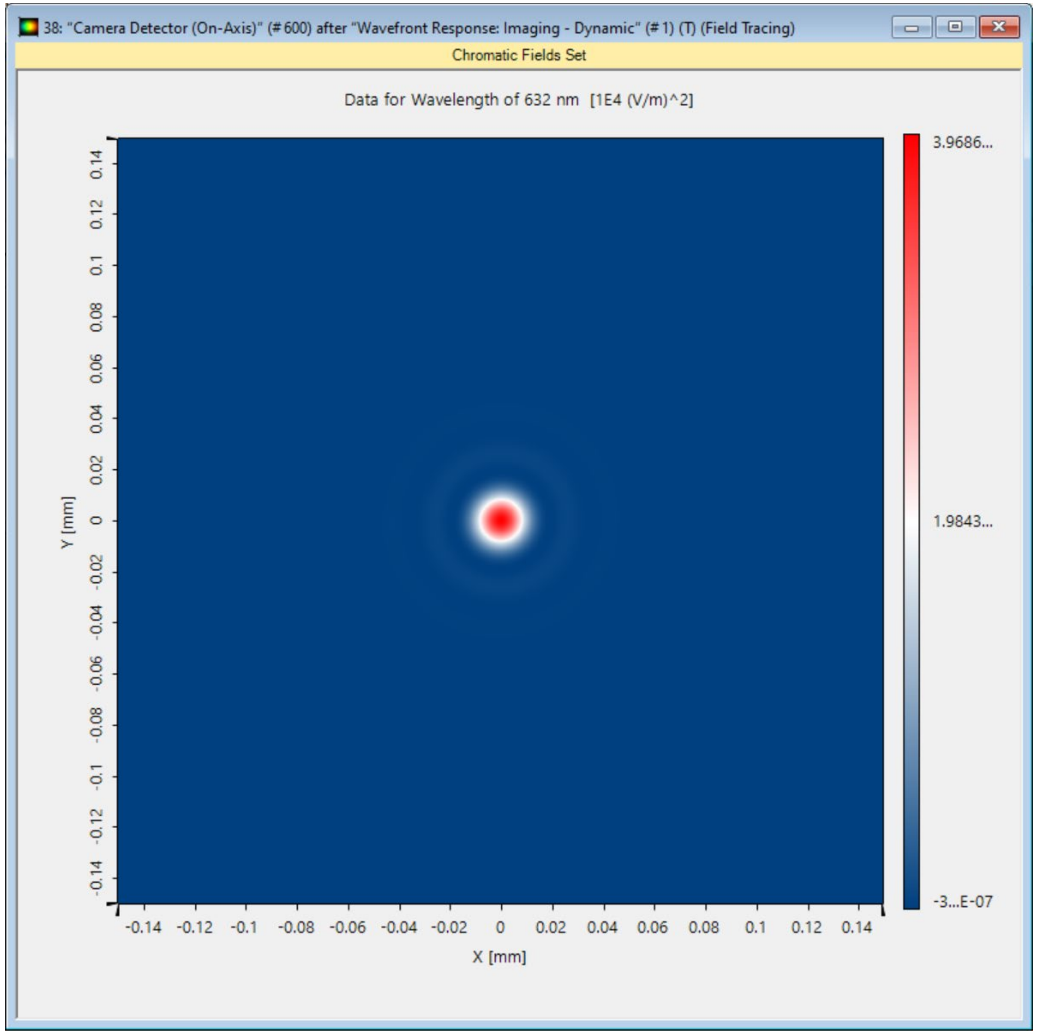
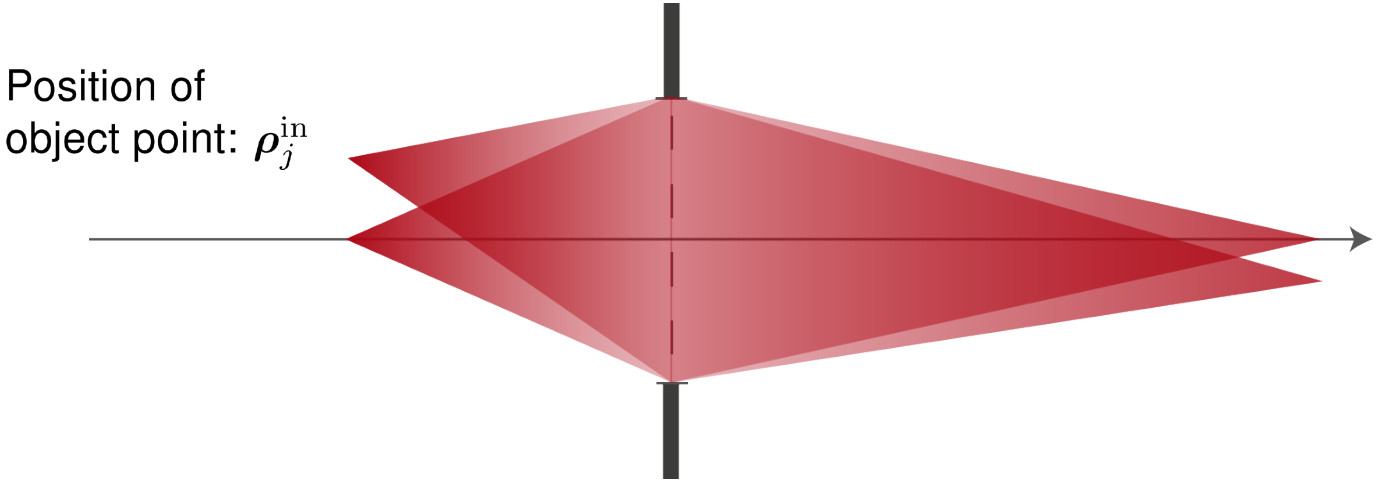




Wavefront Response Component (Multifield): Structural Design

How can the component select the correct wavefront response per field?

Answer: **Angular multiplexing** via the dependency $\Delta\psi(\alpha_j^{\mathrm{in}})$ of the local incident angle α.



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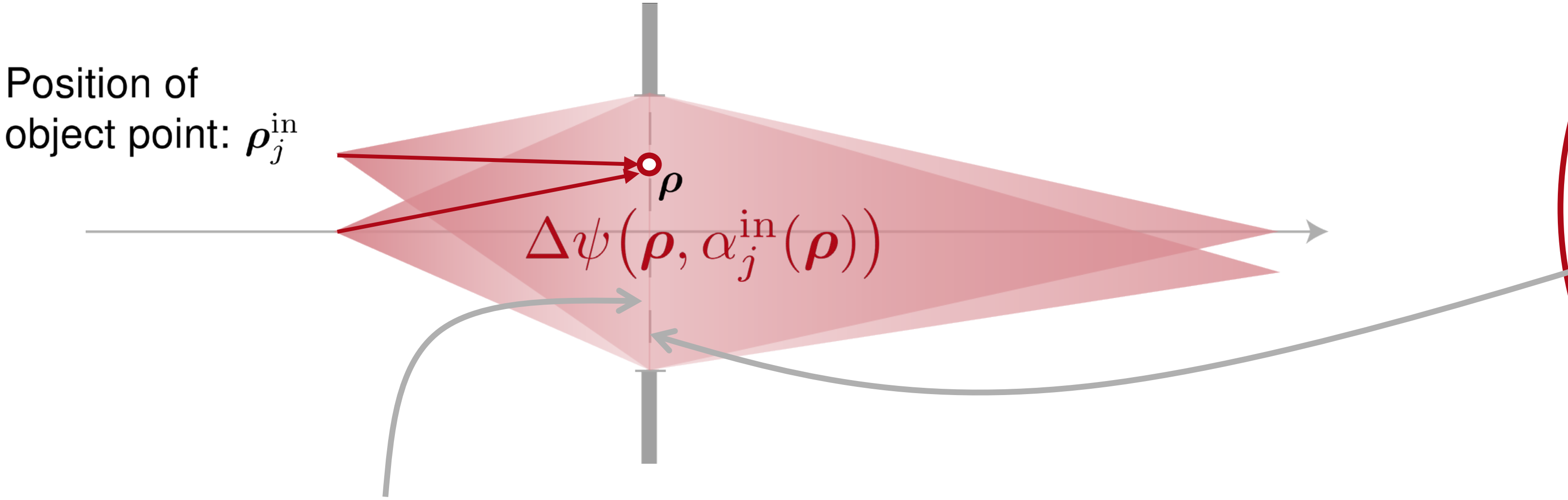
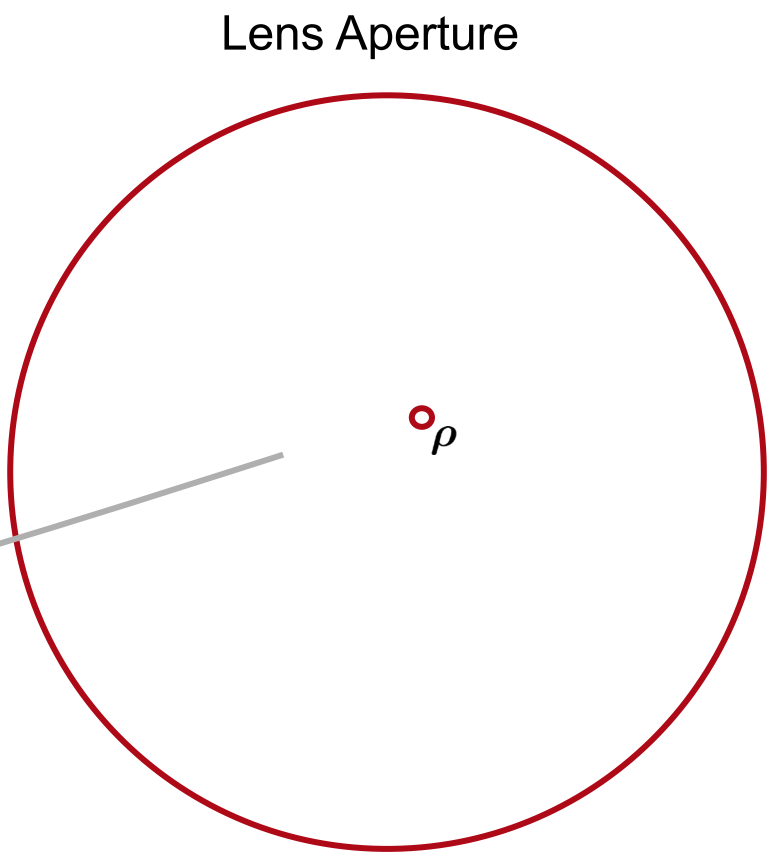
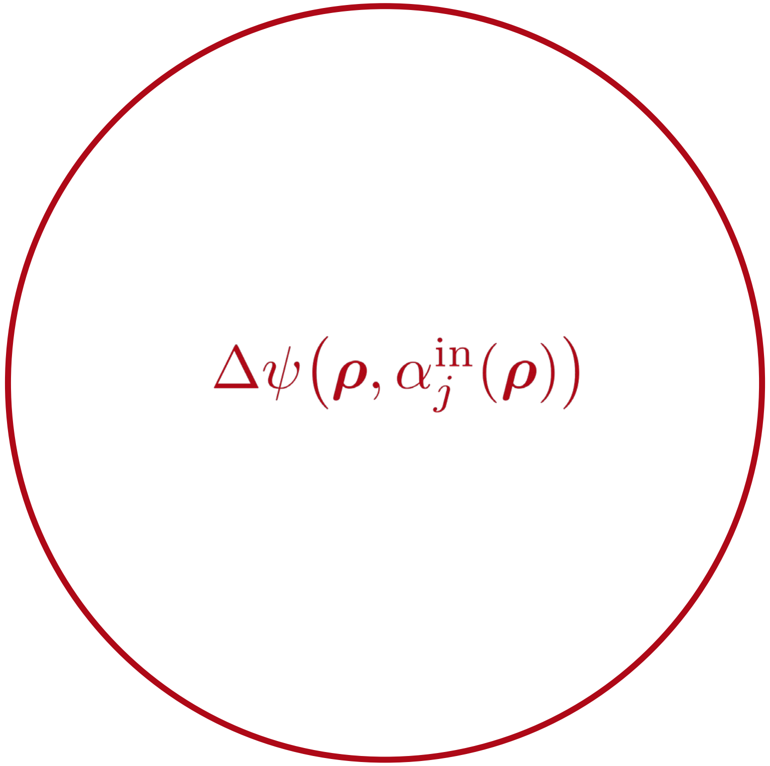




In any position $\boldsymbol{\rho}$ we need to find a structure which has a specific phase response dependency of the local incident angle α: $\Delta\psi(\alpha_j^{\text{in}})$

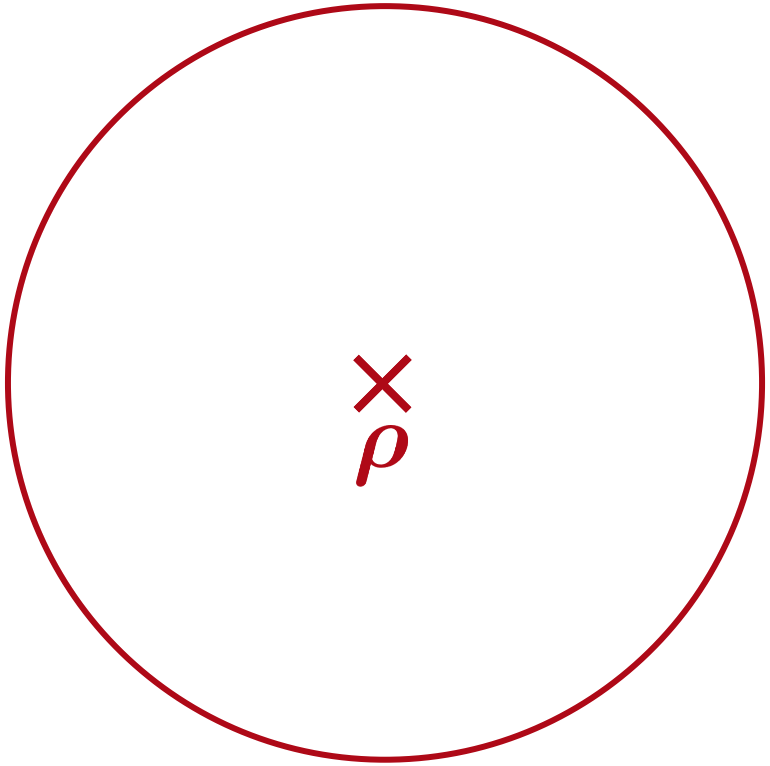
Wavefront Response Component (Multifield): Structural Design

Lens Aperture

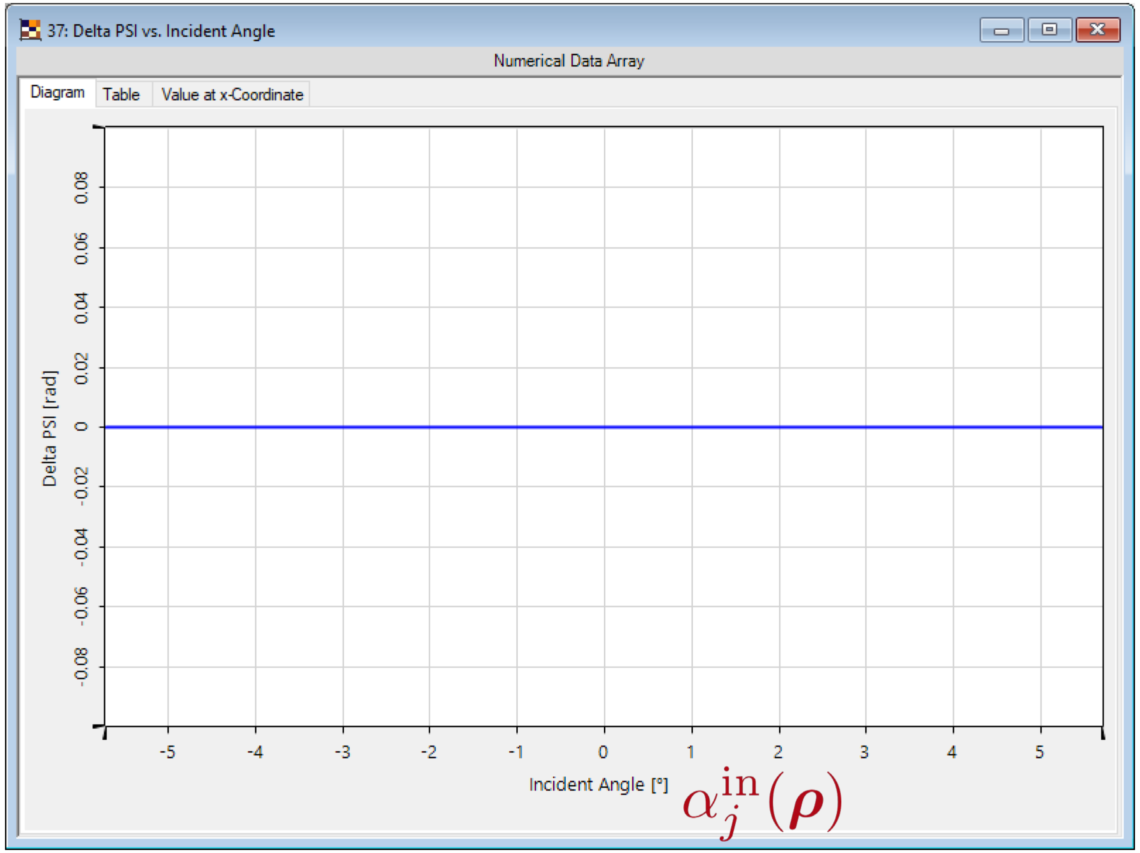


Wavefront Response Component (Multifield): Structural Design

Lens Aperture



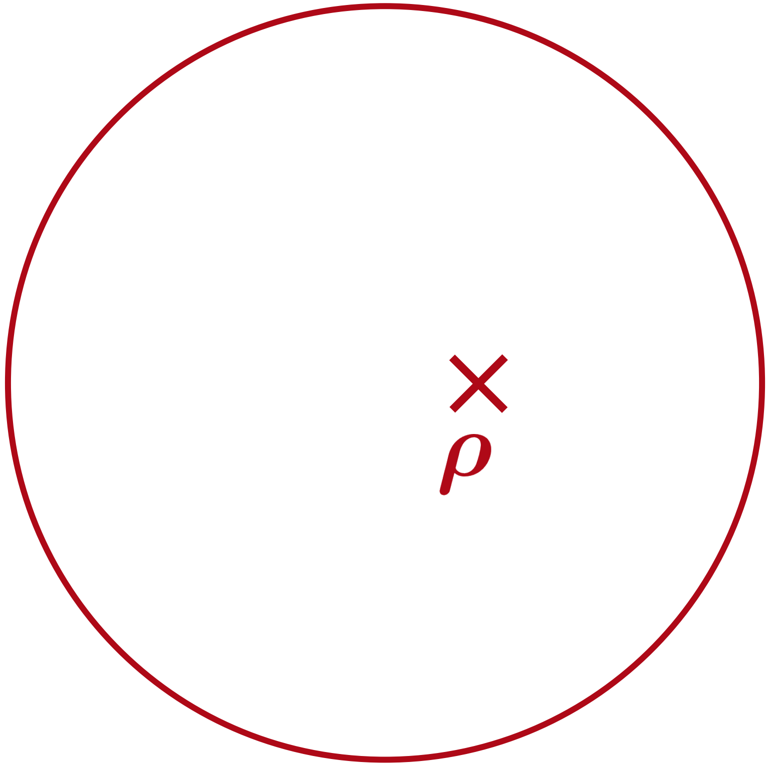
$$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$$



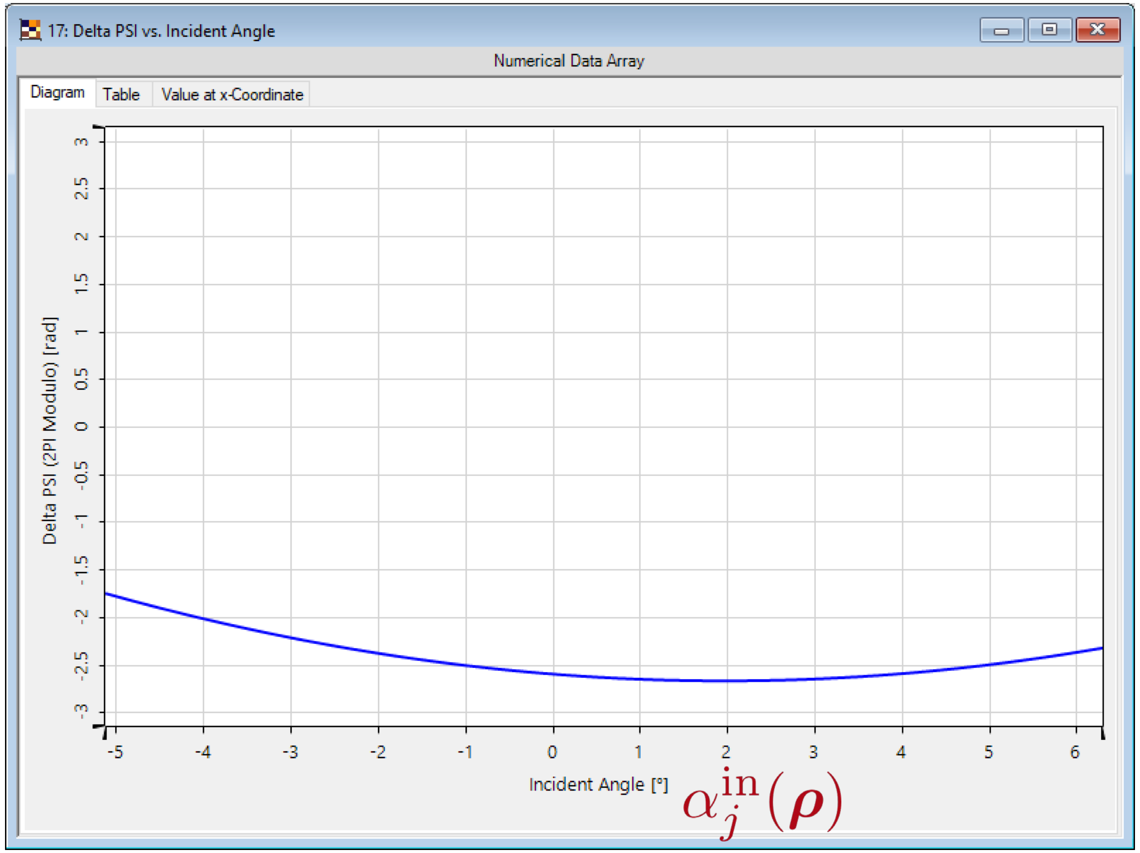
$$\alpha_j^{\text{in}}(\boldsymbol{\rho})$$

Wavefront Response Component (Multifield): Structural Design

Lens Aperture

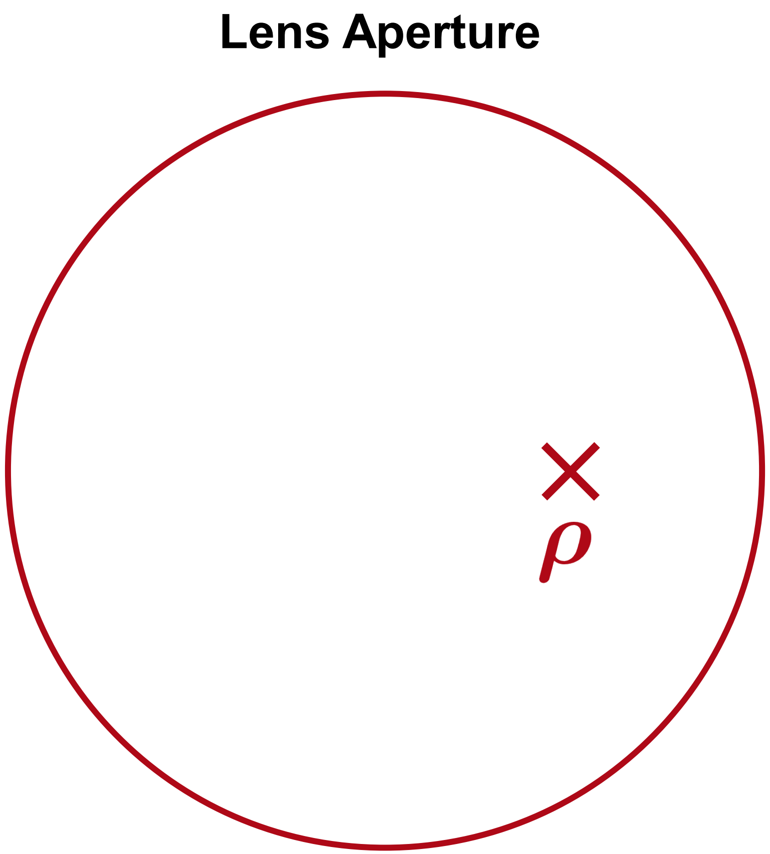


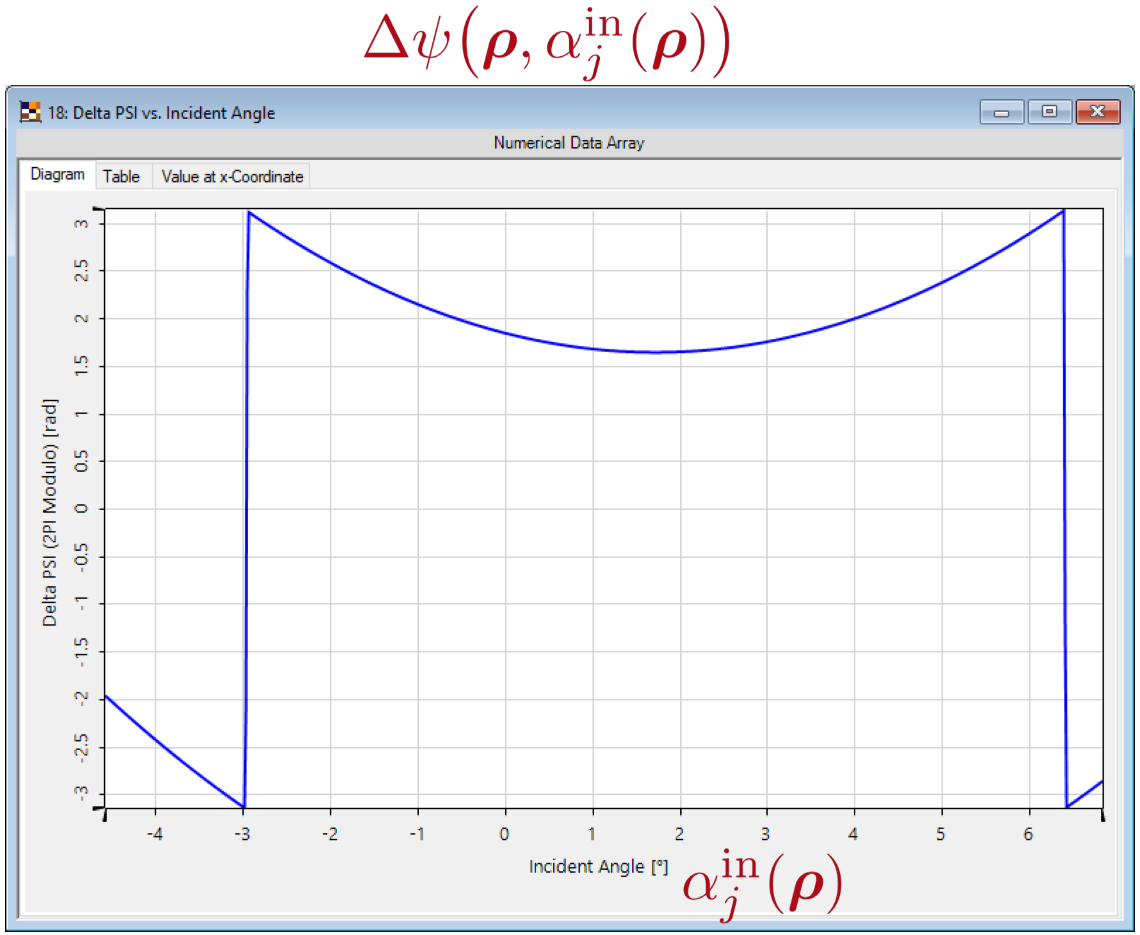
$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



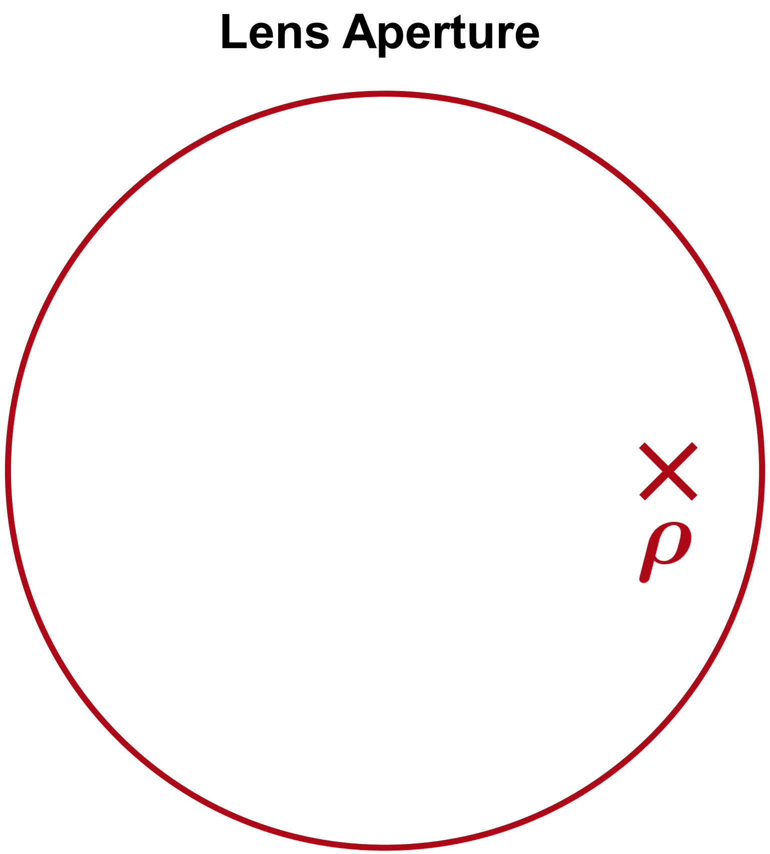
$\alpha_j^{\text{in}}(\boldsymbol{\rho})$

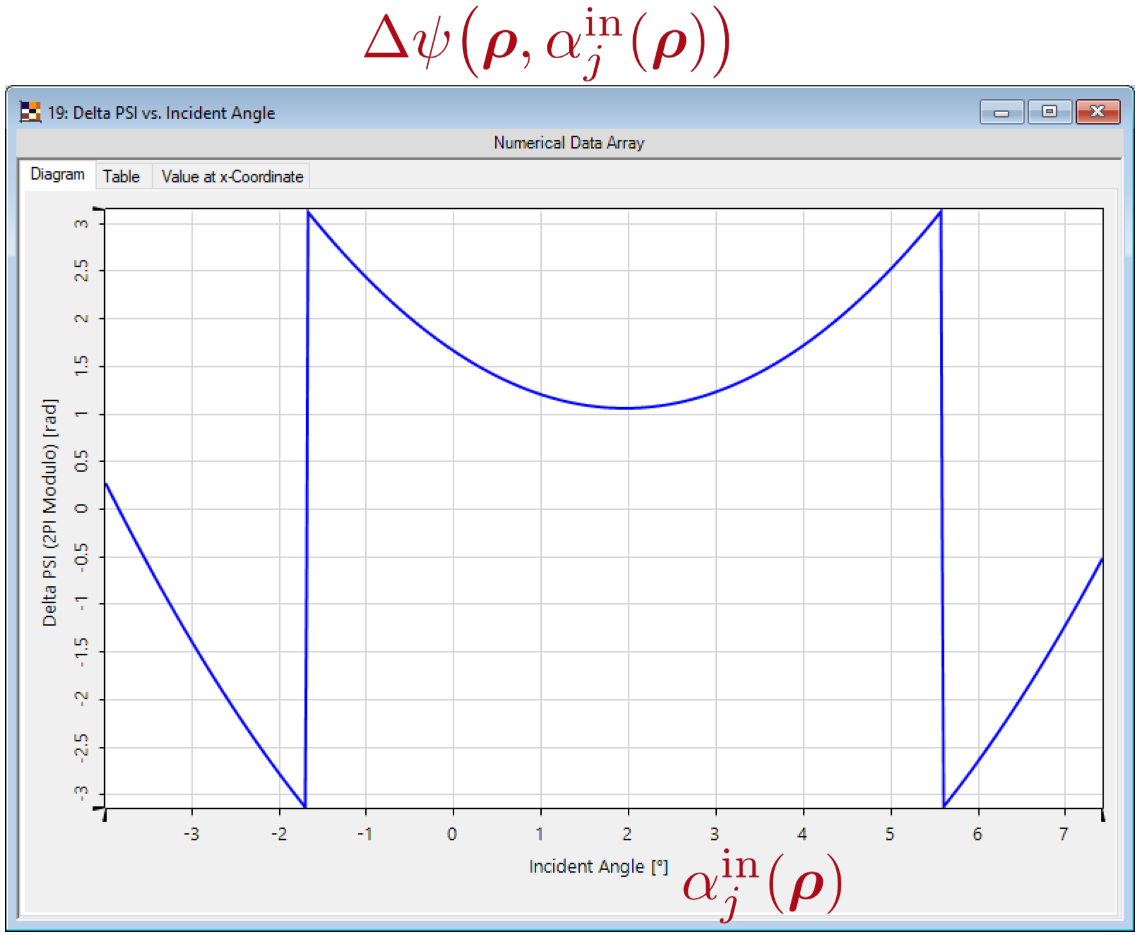
Wavefront Response Component (Multifield): Structural Design





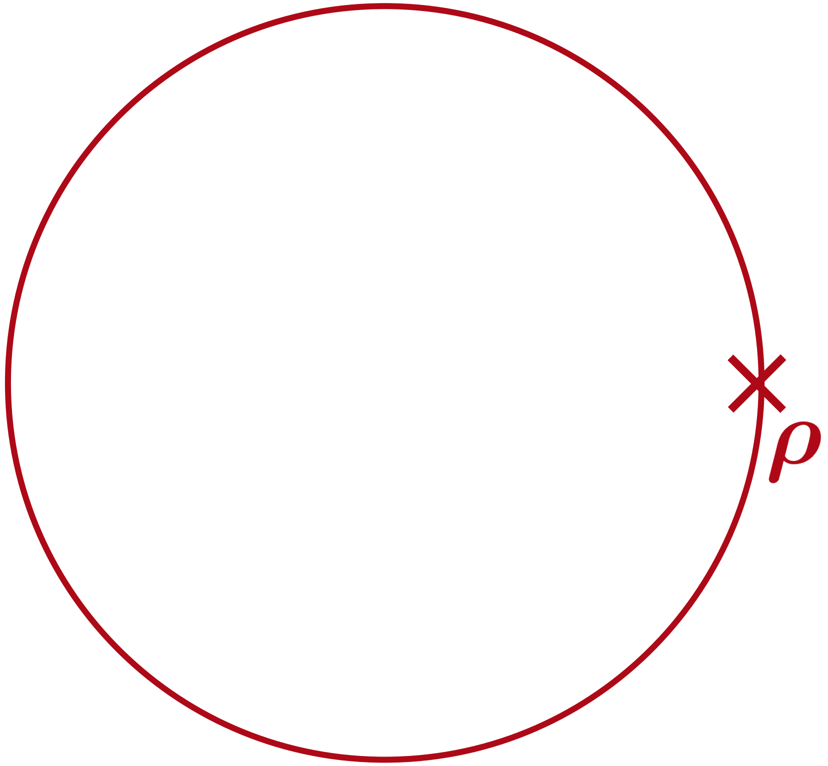
Wavefront Response Component (Multifield): Structural Design



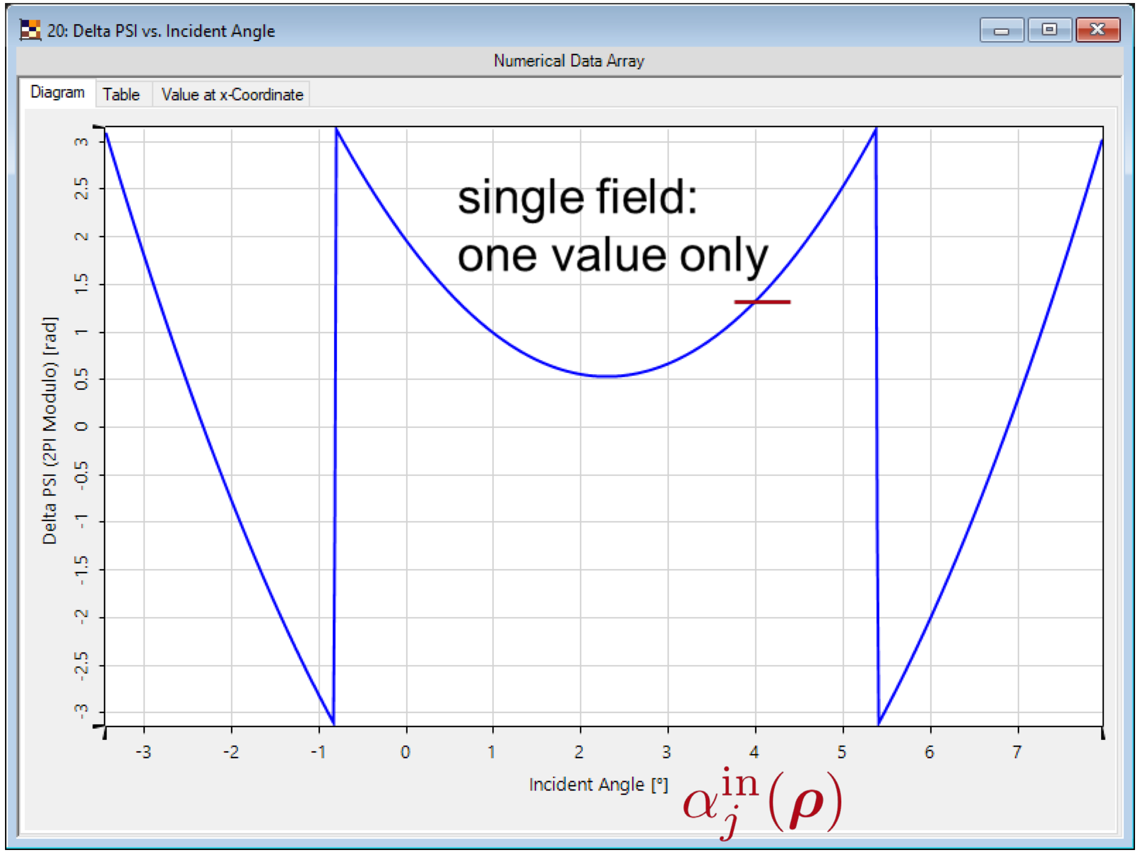


Wavefront Response Component (Multifield): Structural Design

Lens Aperture



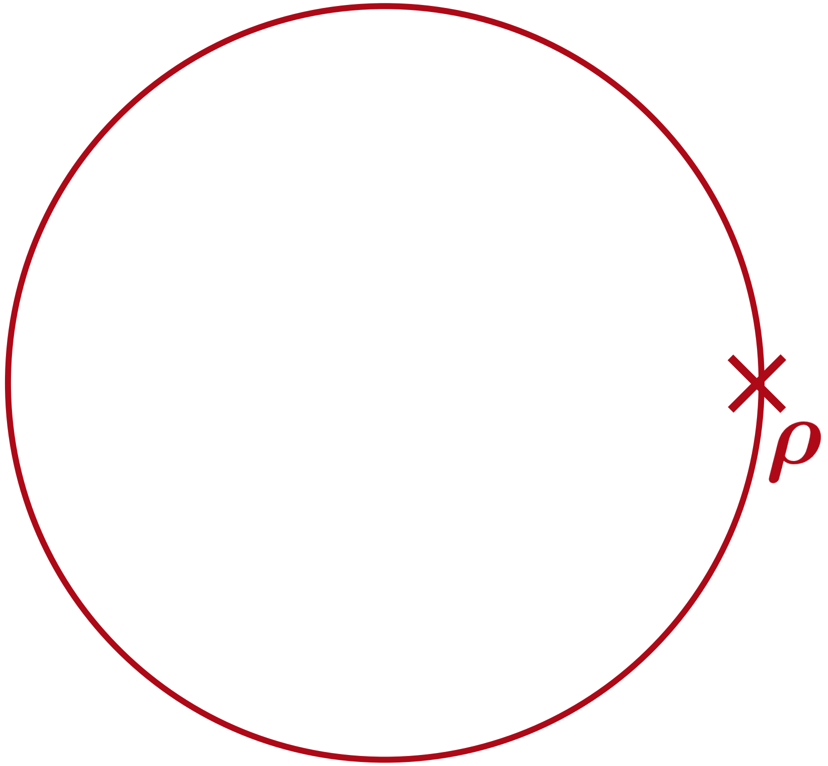
$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



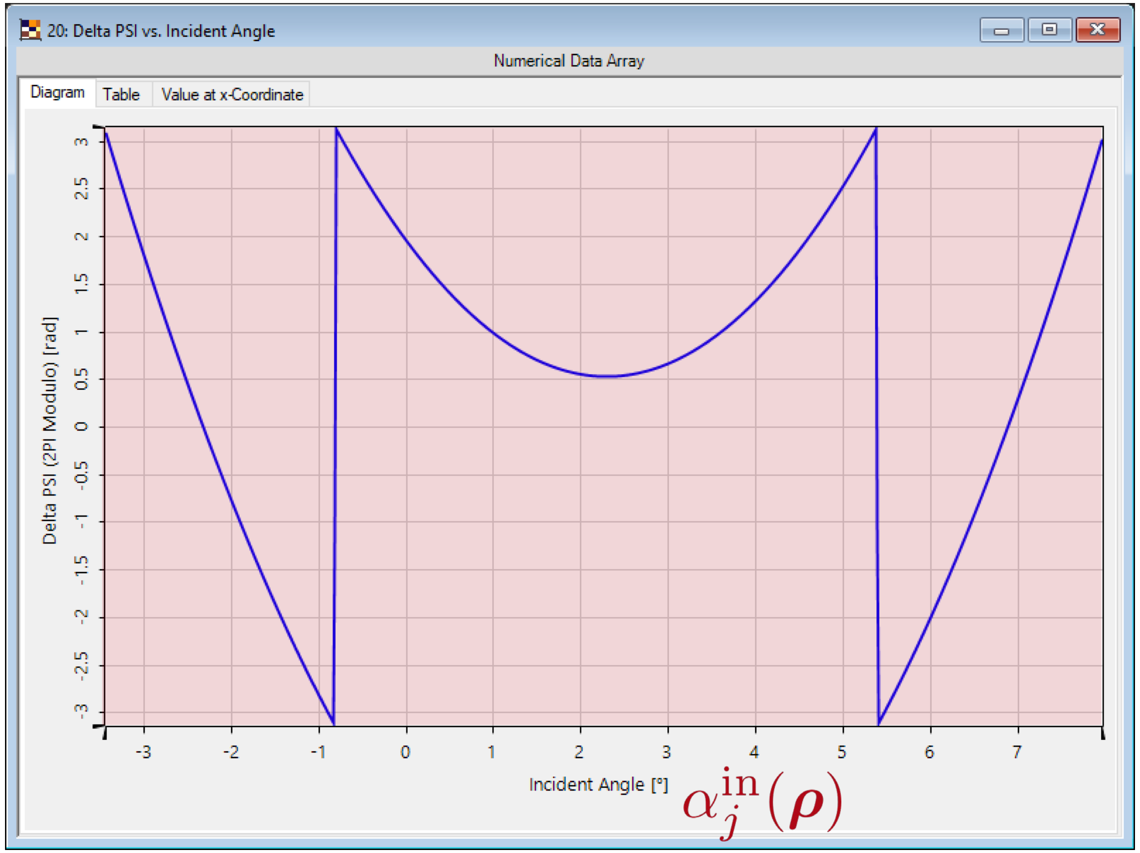
$\alpha_j^{\text{in}}(\boldsymbol{\rho})$

Wavefront Response Component (Multifield): Structural Design

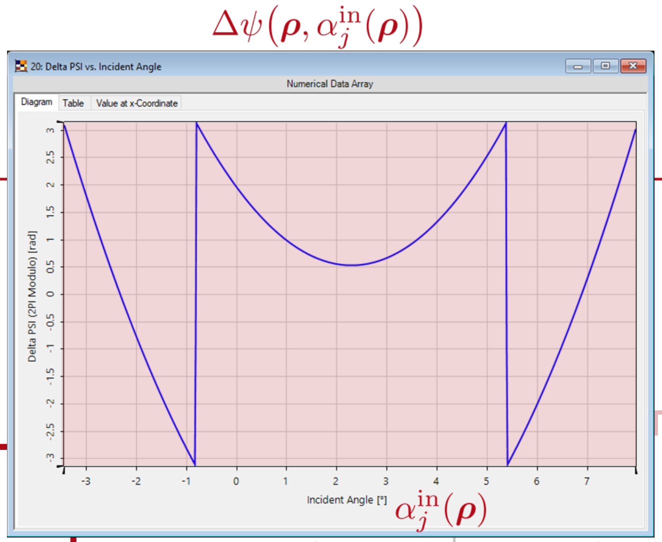
Lens Aperture



$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



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 &

merit functions.

FURTHER

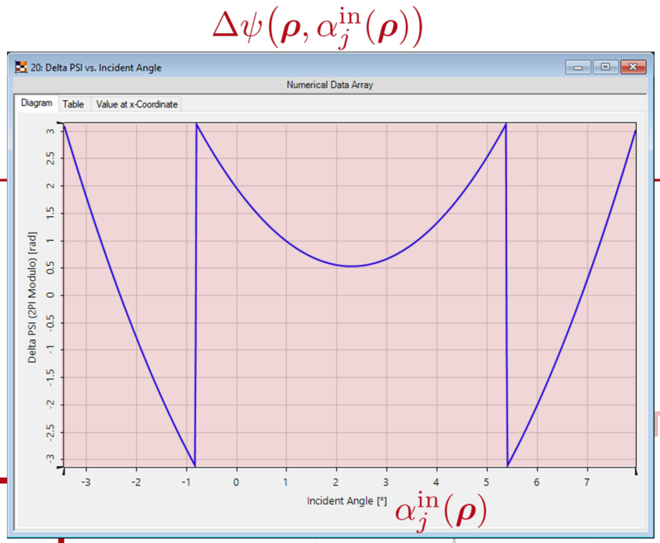
Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

TION

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

With the multifield functional design we can specify the demands on the flat optics!

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.

- Freeform design
- Segmented components
- Fresnel lenses
- HOE
- Metasurfaces

MODELING & EVALUATION

N v a c t b detectors and merit functions.

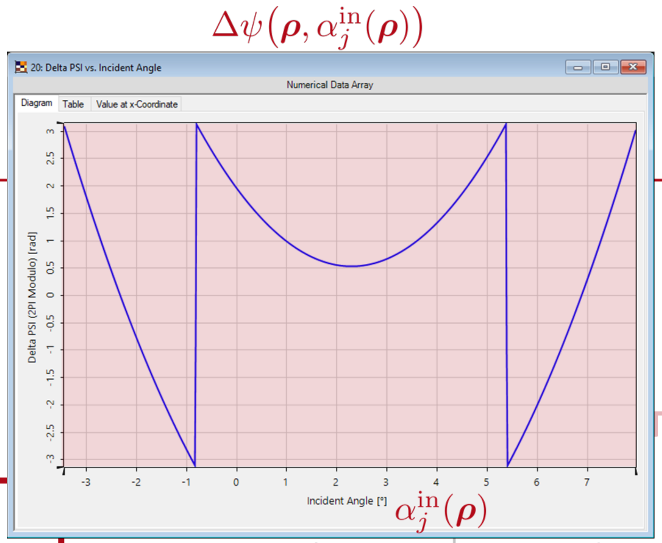
FURTHER OPTIMIZATION

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

TION

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

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

M
v
a
c
t
b
detectors and merit functions.

FURTHER OPTIMIZATION

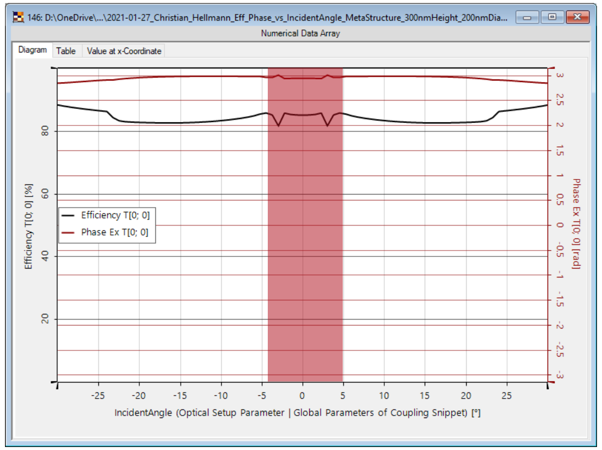
Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.

...TION

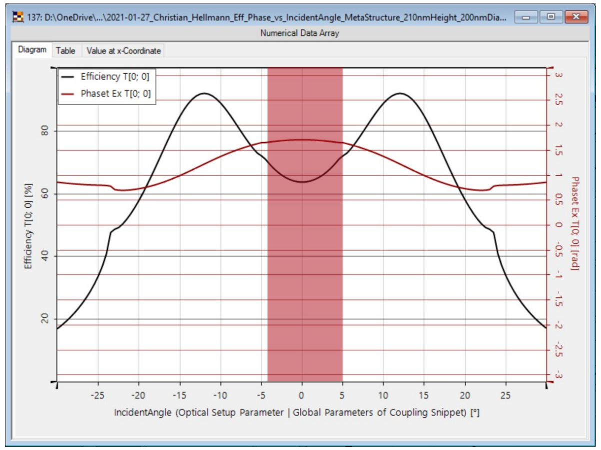
Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

- ~~Freeform design~~
- ~~Segmented components~~
- ~~Fresnel lenses~~
- ~~HOE~~
- Metasurfaces ?

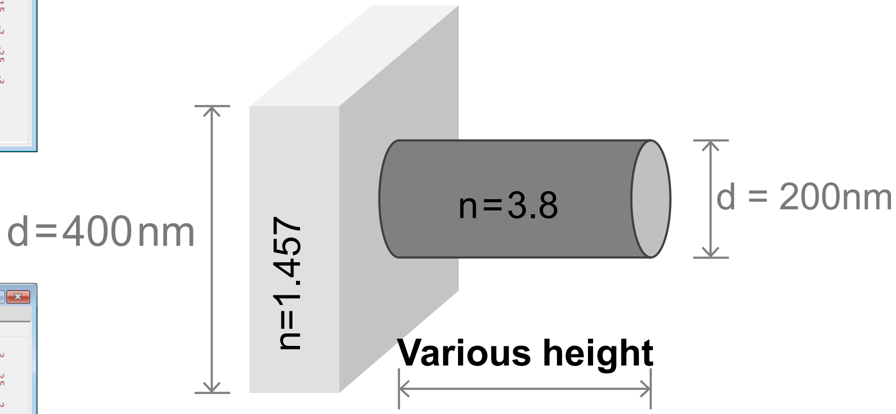
Metastructure: Efficiency & Phase vs Incident Angle (Heights)

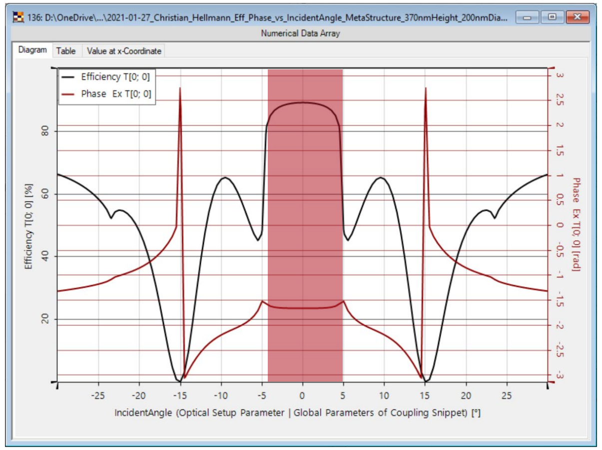


h = 300nm

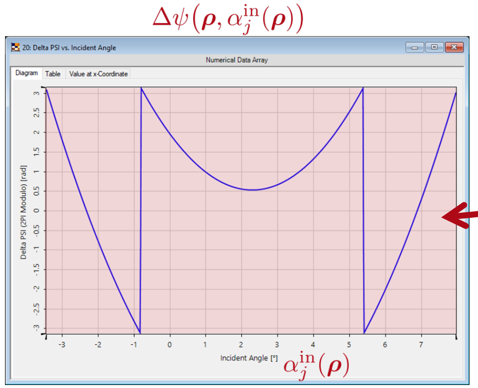


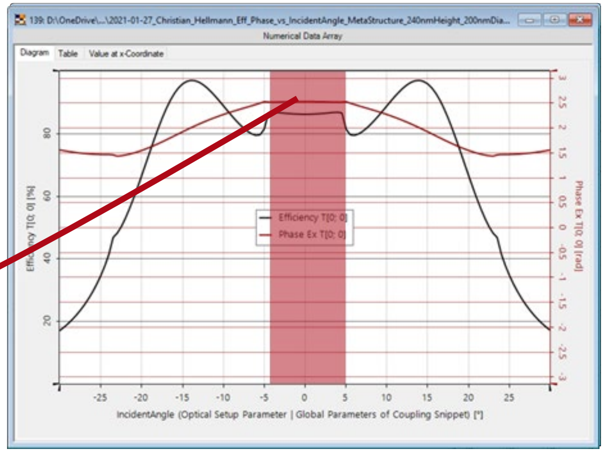
h = 210nm





h = 370nm

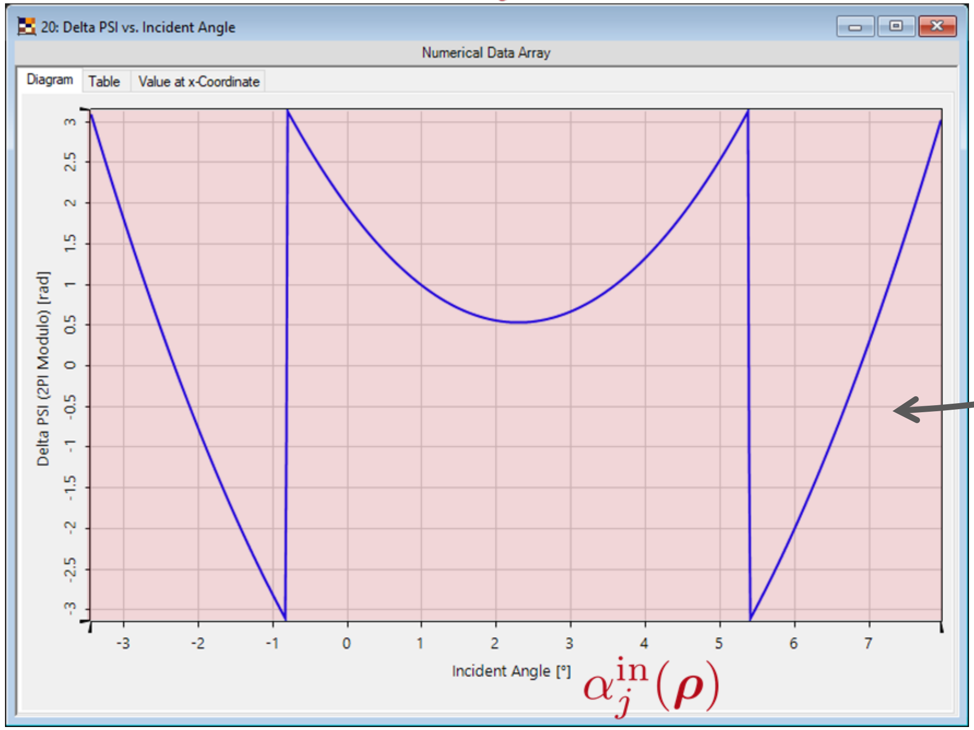




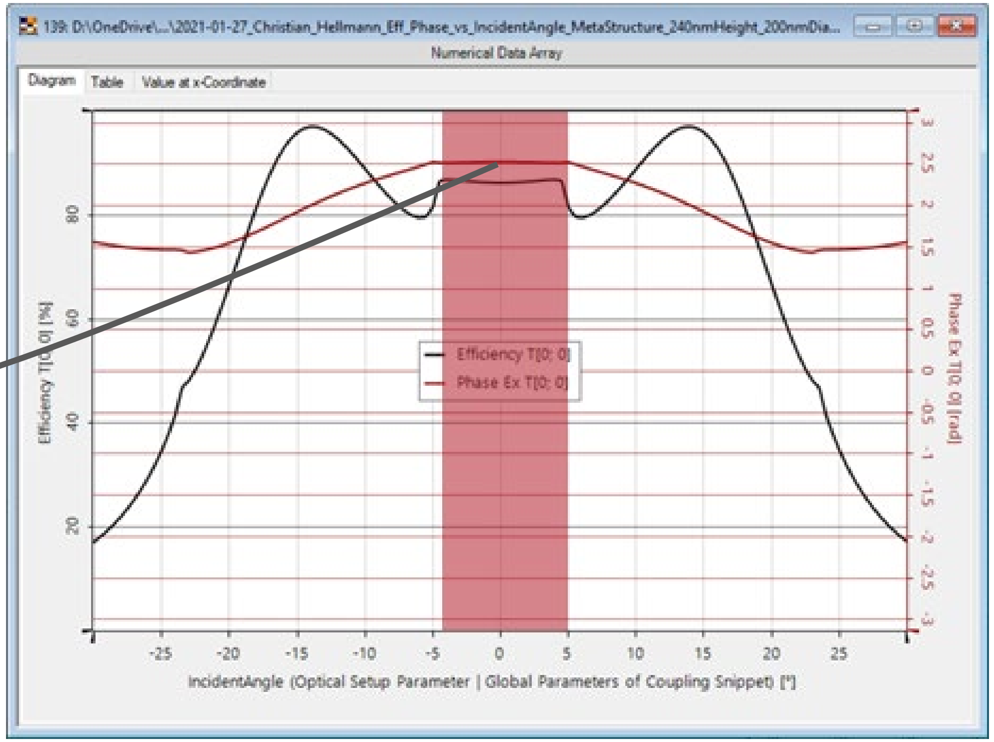
h = 240nm

Metastructure: Efficiency & Phase vs Incident Angle (Heights)

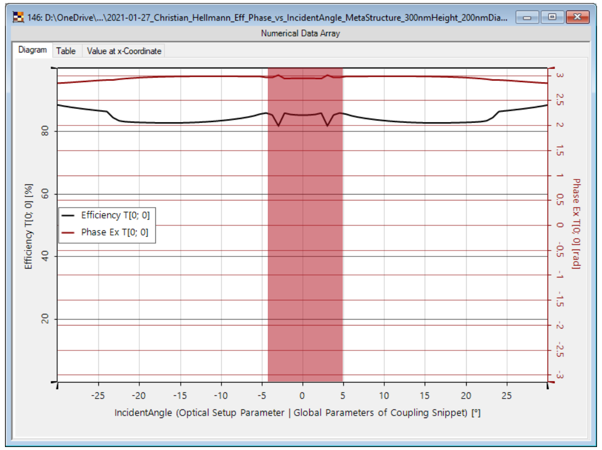
$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



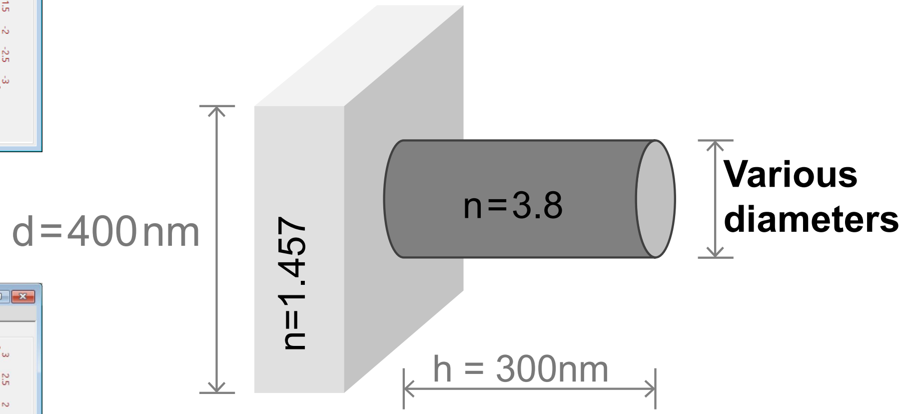
$\alpha_j^{\text{in}}(\boldsymbol{\rho})$

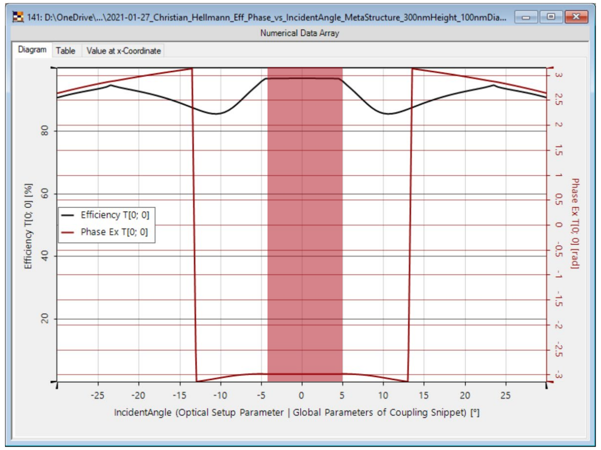


Metastructure: Efficiency & Phase vs Incident Angle (Diameters)

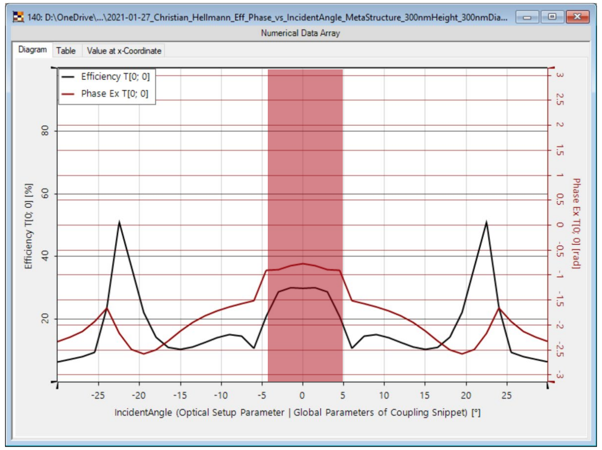


d = 200nm

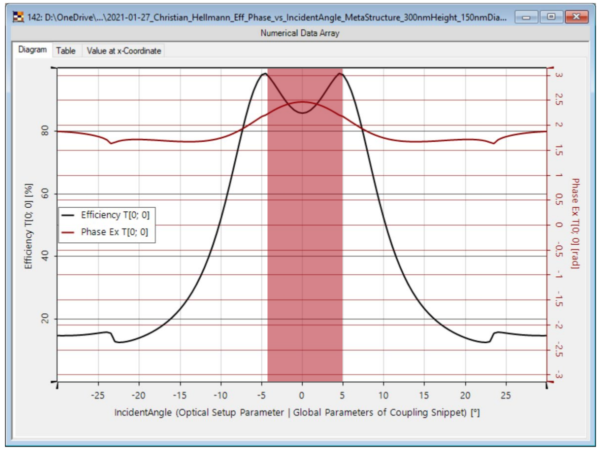




d = 100nm



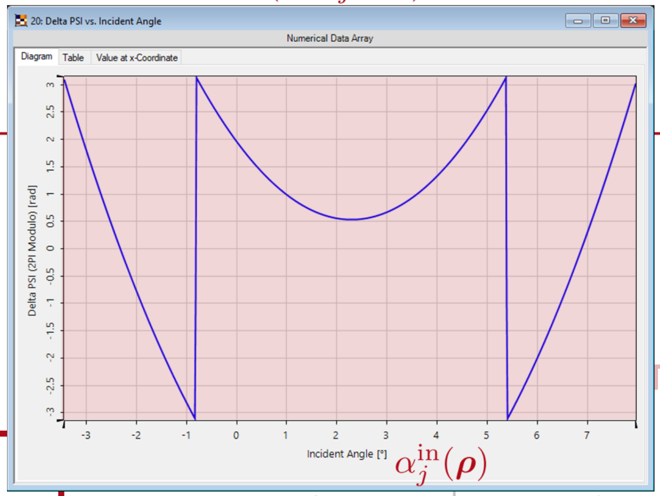
d = 300nm



d = 240nm

Design Workflow in VirtualLab Fusion

$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



$\alpha_j^{\text{in}}(\boldsymbol{\rho})$

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

detectors and merit functions.

FURTHER OPTIMIZATION

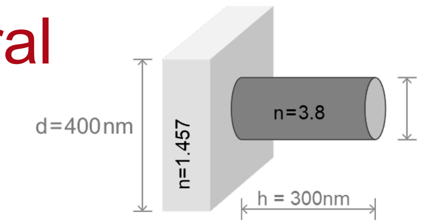
- ~~Freeform design~~
- ~~Segmented components~~
- ~~Fresnel lenses~~
- ~~HOE~~
- Metasurfaces ?

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

TION

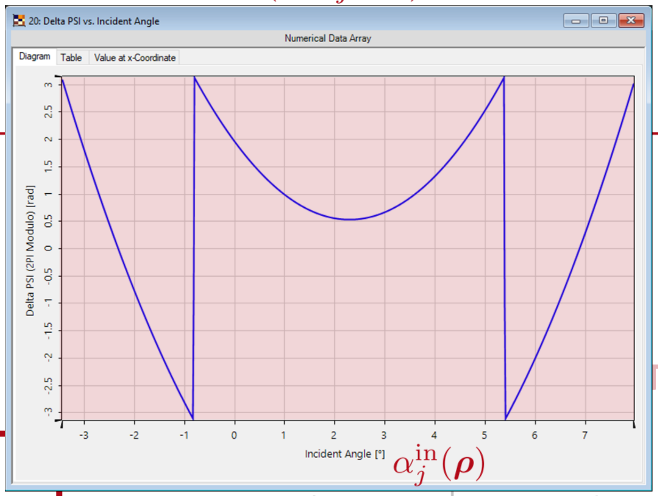
Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

Must be highly nanostructured cells to introduce enough freedoms for structural design!



Design Workflow in VirtualLab Fusion

$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho}))$



$\alpha_j^{\text{in}}(\boldsymbol{\rho})$

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detectors and merit functions.

- ~~Freeform design~~
- ~~Segmented components~~
- ~~Fresnel lenses~~
- ~~HOE~~
- Metasurfaces ?

FURTHER OPTIMIZATION

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

TION

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

VirtualLab Fusion 2021

- Potential for going beyond “conventional surfaces” exists.
- Also restricted control of angle dependency of interest.

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

Calculate and export fabrication data from the surfaces which result from structural design and optimization.

Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN

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

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FABRICATION DATA

Calculate and export fabrication data from the surfaces which result from structural design and optimization.

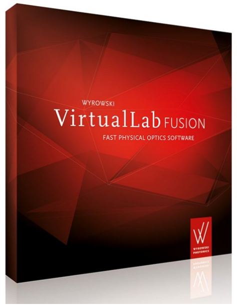
Zemax® enables functional design of a wavefront phase response (binary surfaces) by parametric optimization

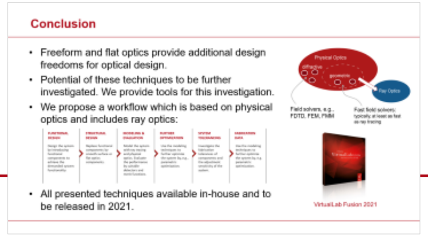
$$\Delta\psi(\boldsymbol{\rho}, \alpha_j^{\text{in}}(\boldsymbol{\rho})) \longrightarrow \Delta\psi(\boldsymbol{\rho})$$

Design Workflow in VirtualLab Fusion

FUNCTIONAL DESIGN	STRUCTURAL DESIGN	MODELING & EVALUATION	FURTHER OPTIMIZATION	SYSTEM TOLERANCING	FABRICATION DATA
Design the system by introducing functional components to achieve the demanded system functionality.	Replace functional components by smooth surface or flat optics components.	Model the system with ray tracing and physical optics. Evaluate the performance by suitable detectors and merit functions.	Use the modeling techniques to further optimize the system by, e.g., parametric optimization.	Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.	Calculate and export fabrication data from the surfaces which result from structural design and optimization.

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

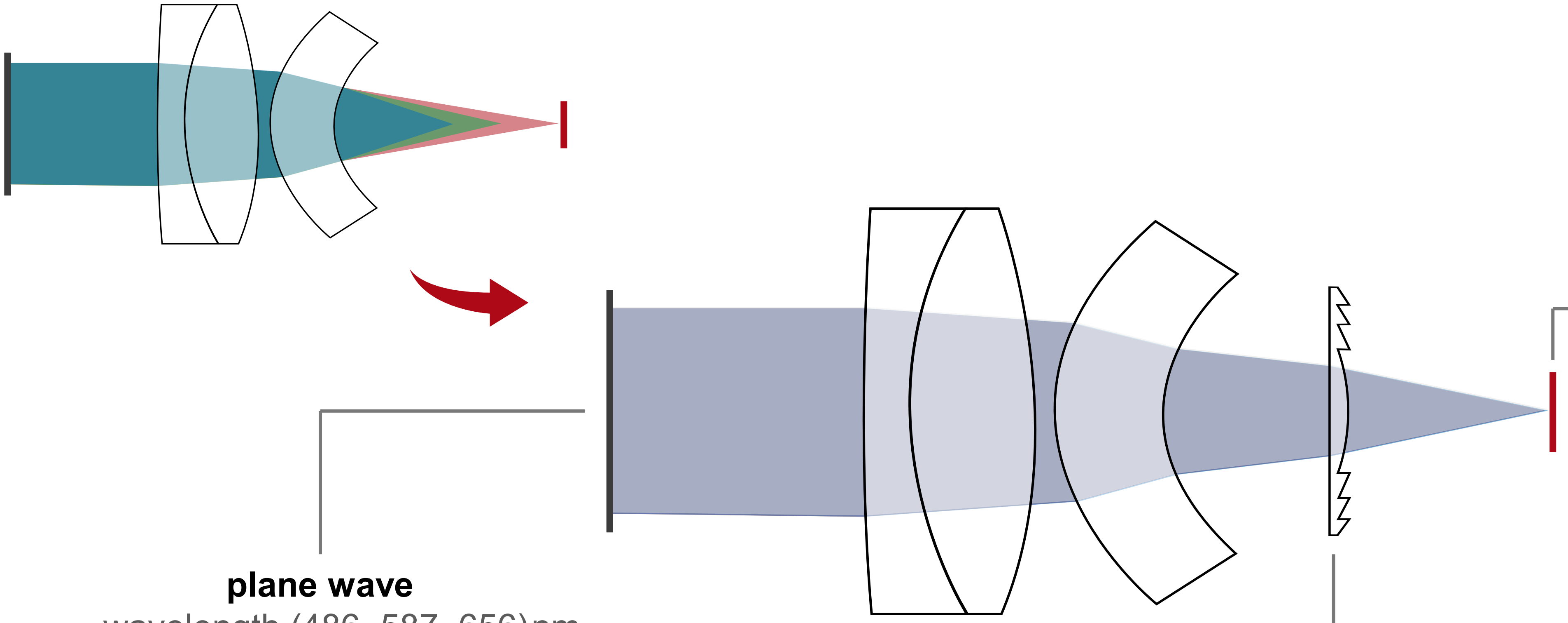




Design and Analysis of a Hybrid Eyepiece for Correction of Chromatic Aberration

Functional design in Zemax® OpticStudio®

Modeling and Design Scenario



plane wave

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

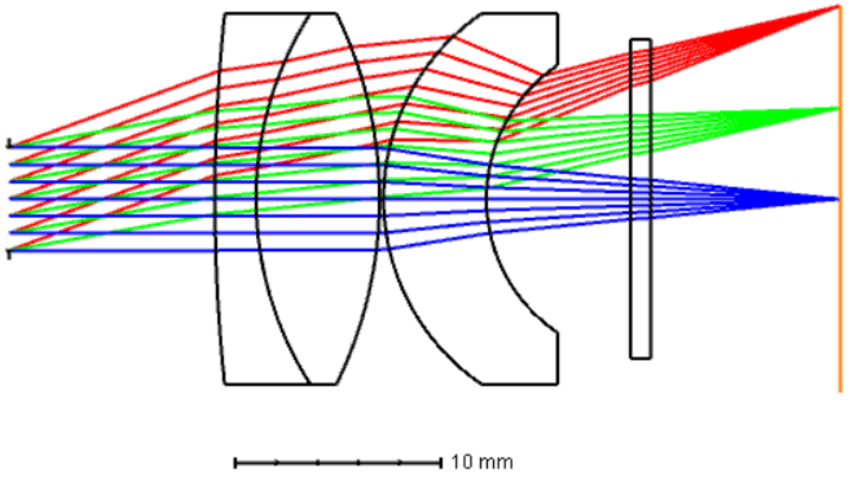
detectors

- point spread function
- modulation transfer function (MTF)

lens solution

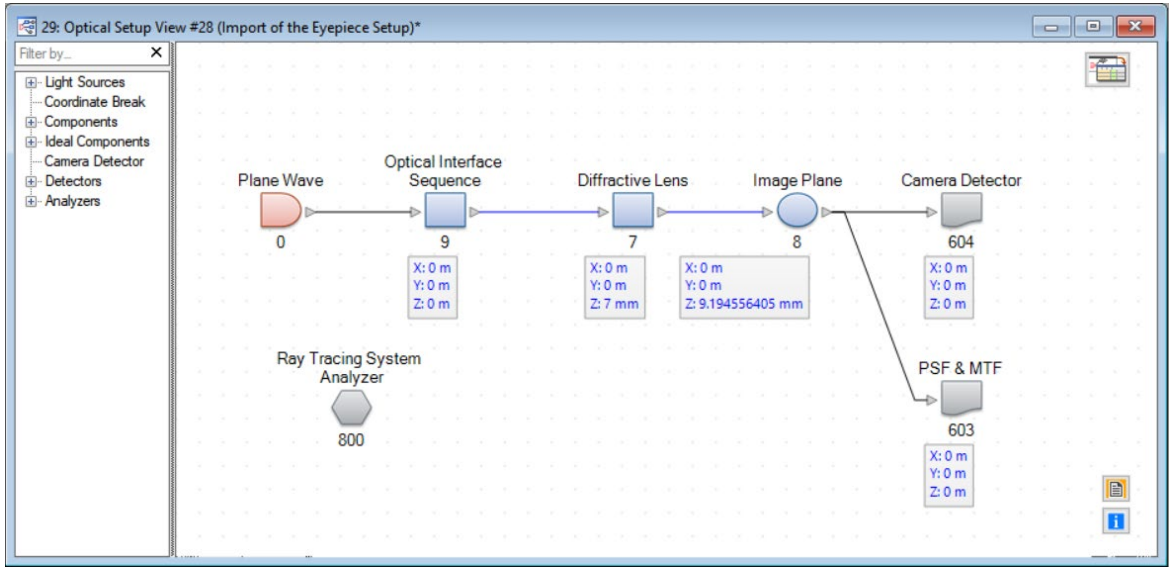
- wavefront response function
- diffractive lens
- meta lens

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



Design Workflow in VirtualLab Fusion

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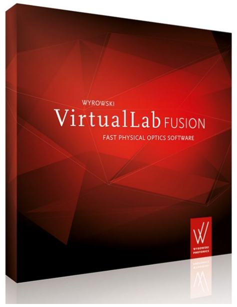
SYSTEM TOLERANCING

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

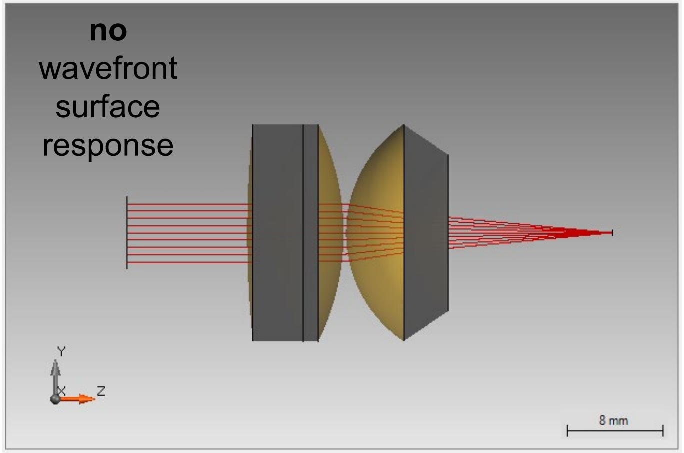
FABRICATION DATA

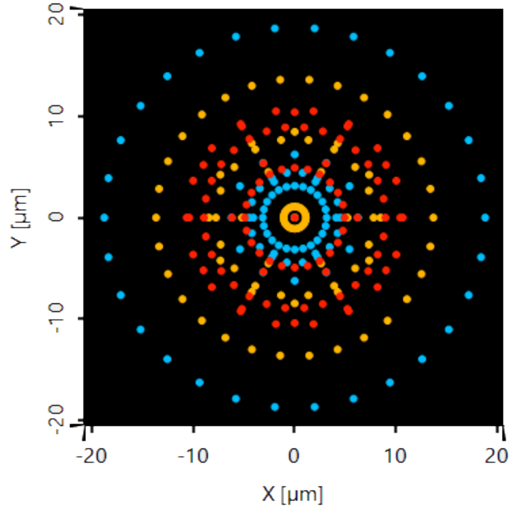
Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

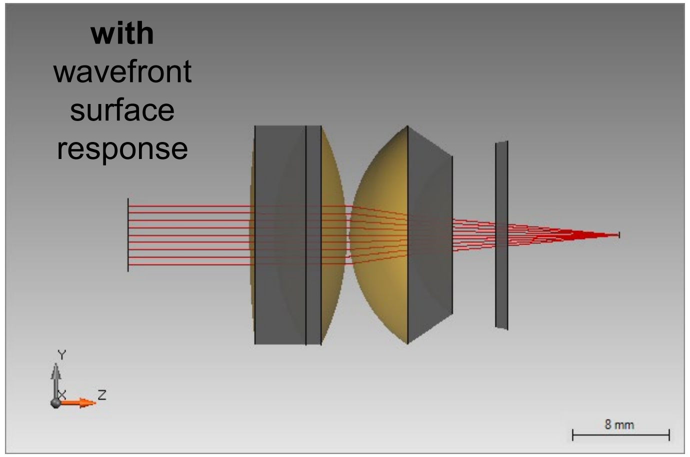
Import of Zemax file into VirtualLab Fusion and further processing of workflow.

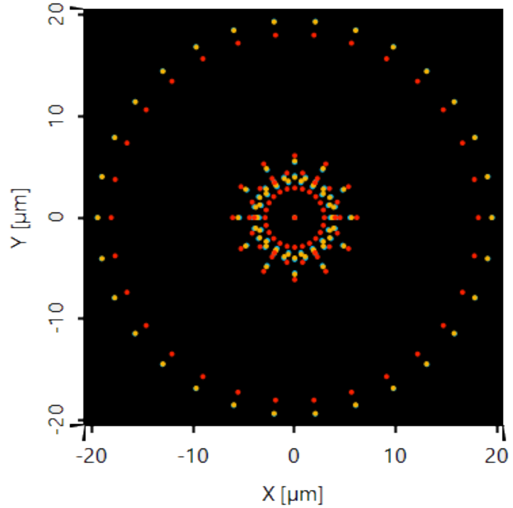


On-Axis Analysis: Comparison of Spot Diagram





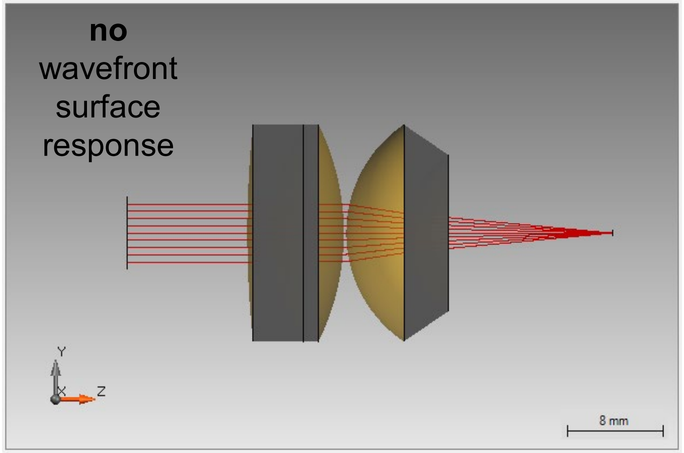


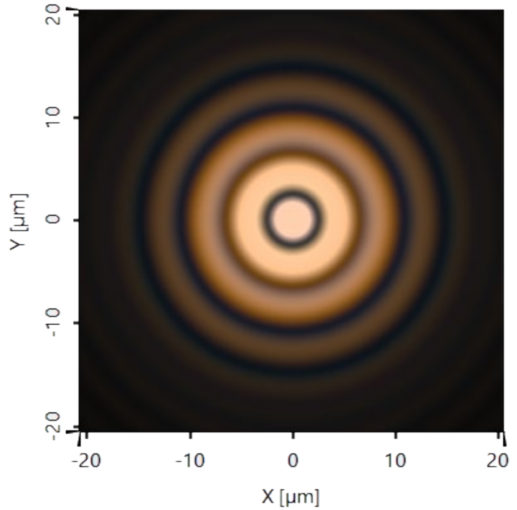


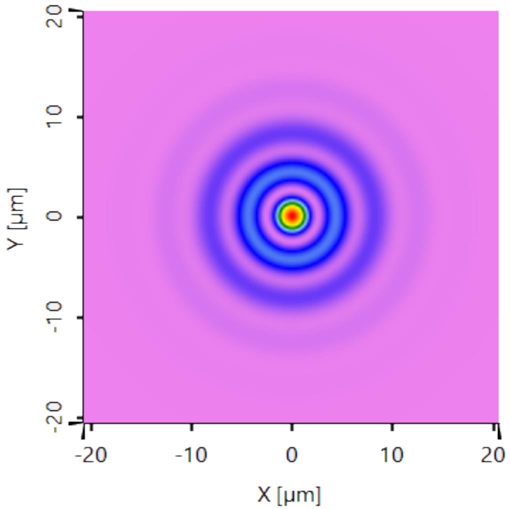
On-Axis Analysis: Comparison of PSF

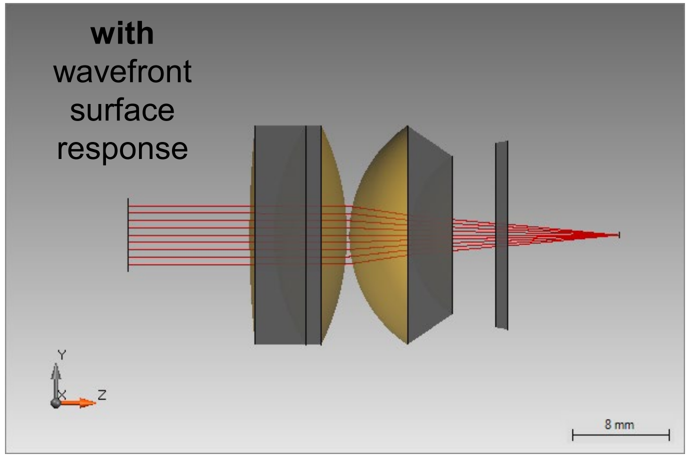
Real Color View

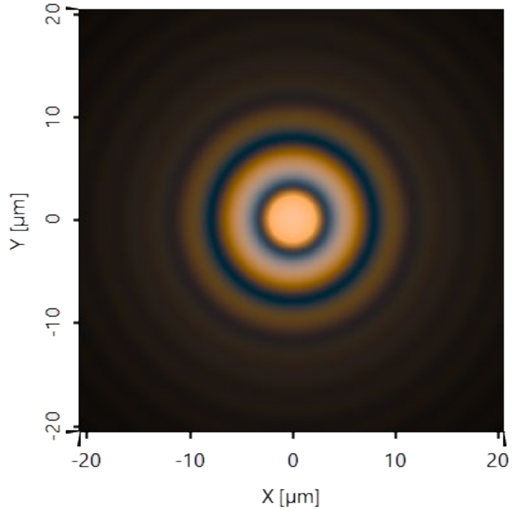
False Color View

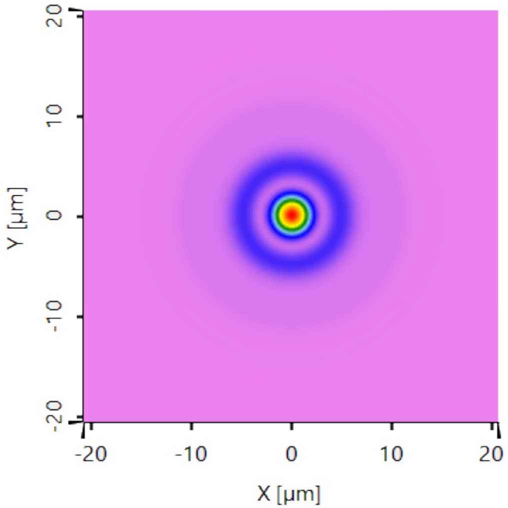




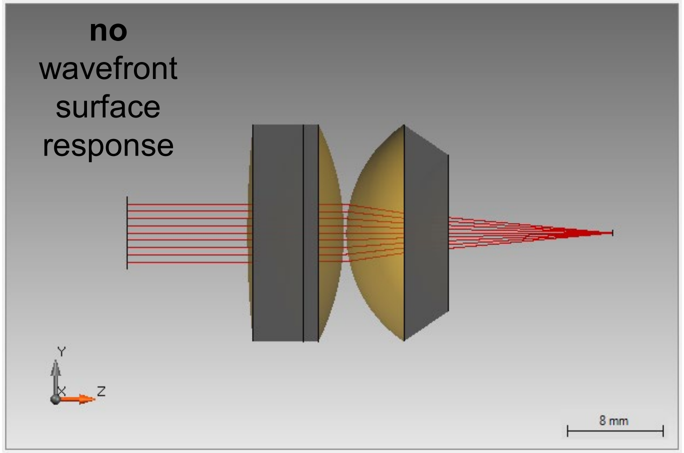


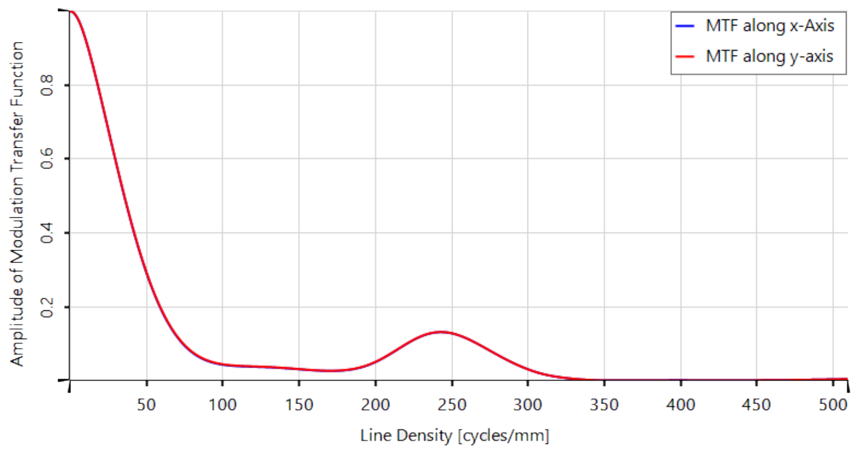


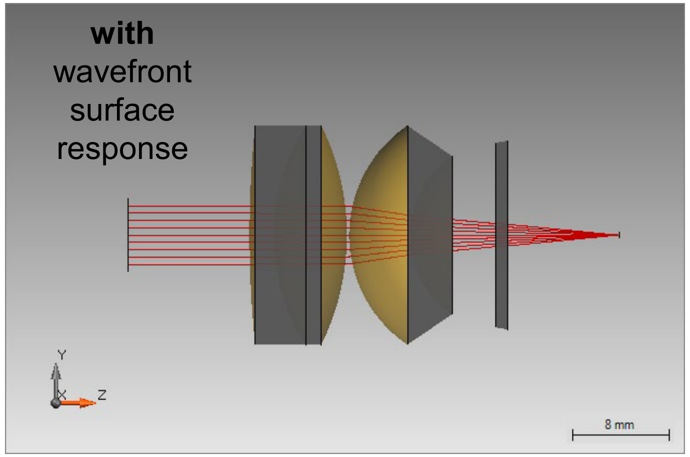


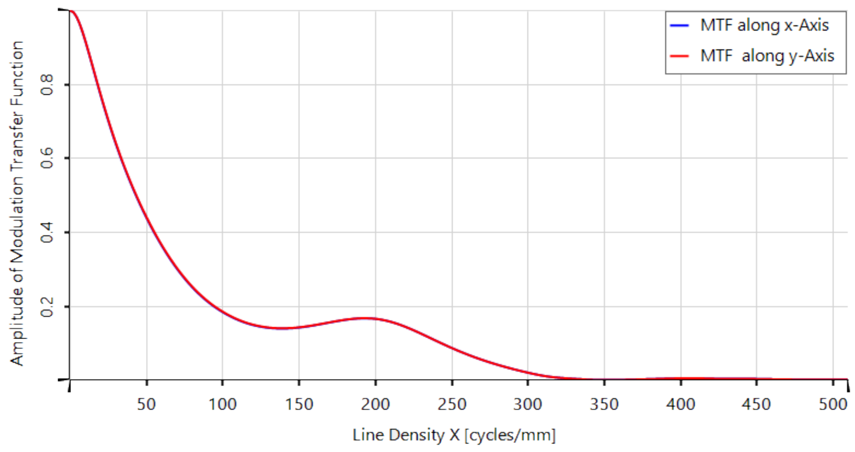


On-Axis Analysis: Comparison of MTF

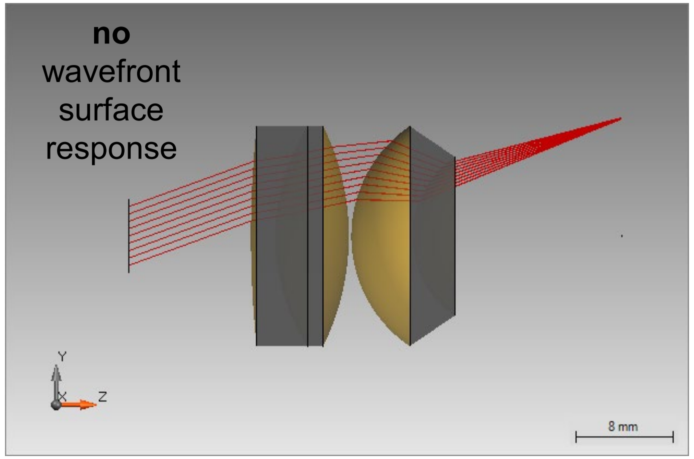


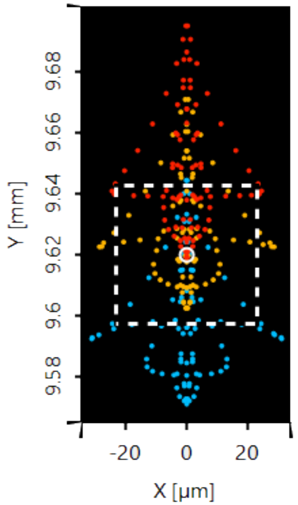


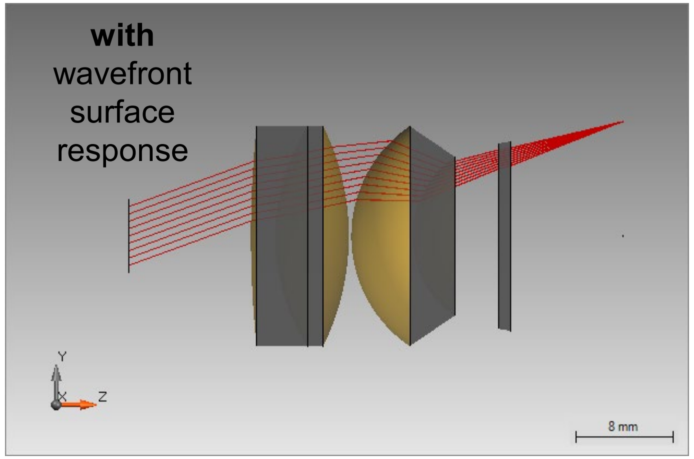


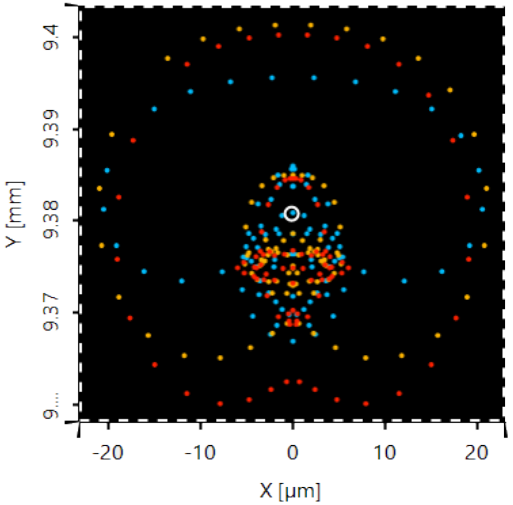


Off-Axis Analysis: Comparison of Spot Diagram

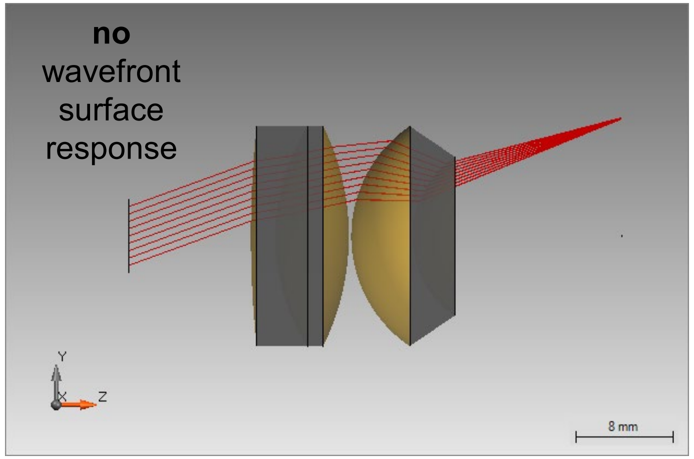


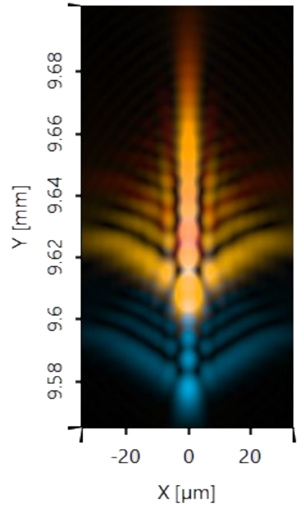


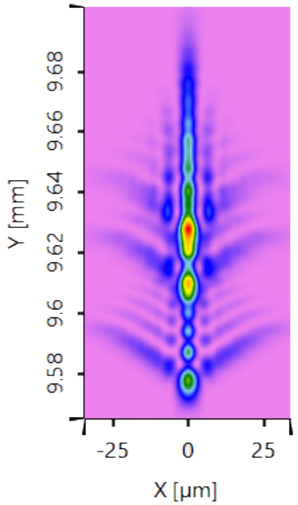


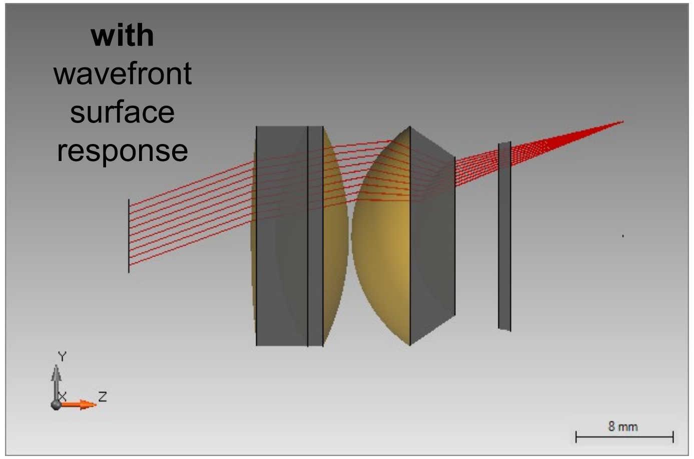


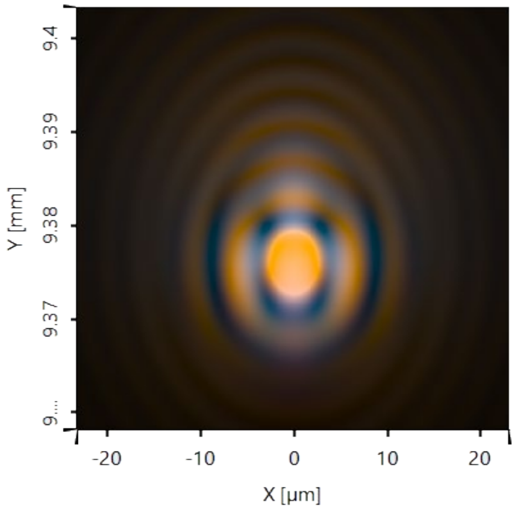
Off-Axis Analysis: Comparison of PSF

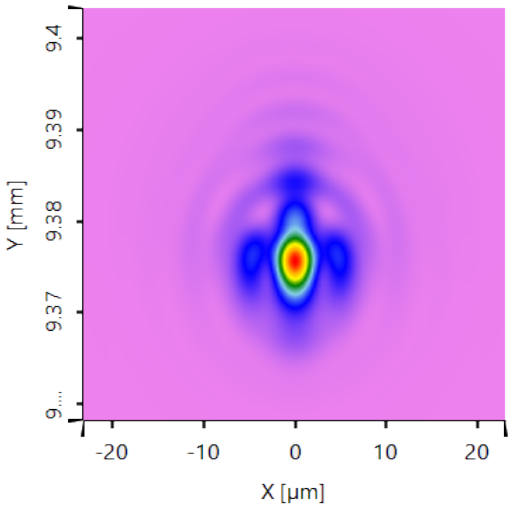




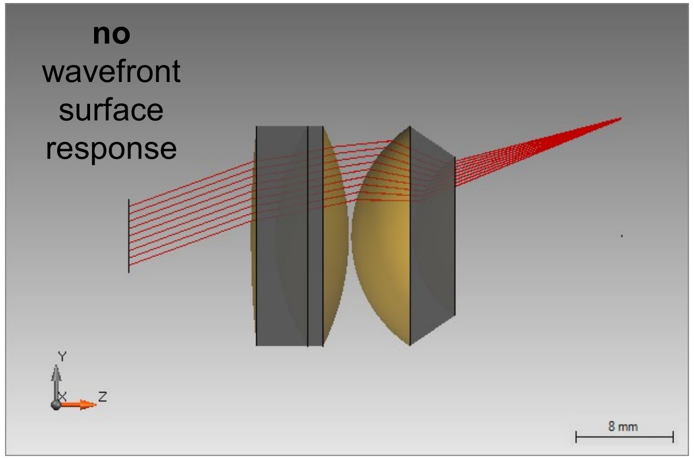


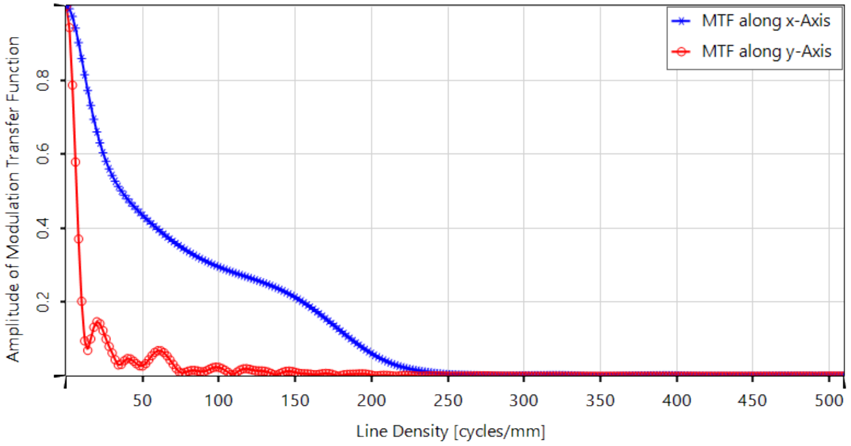


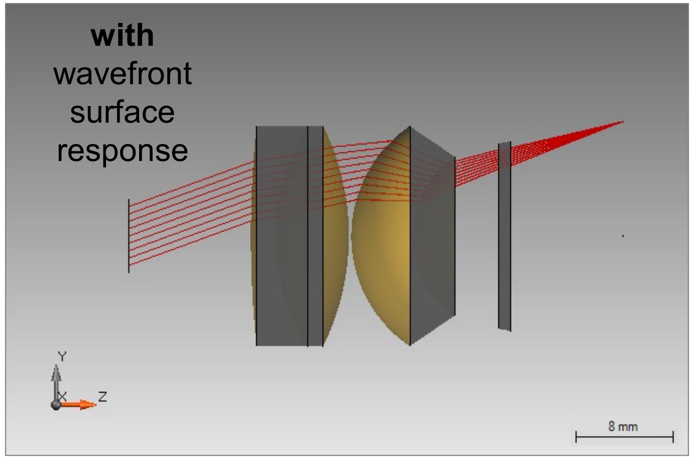


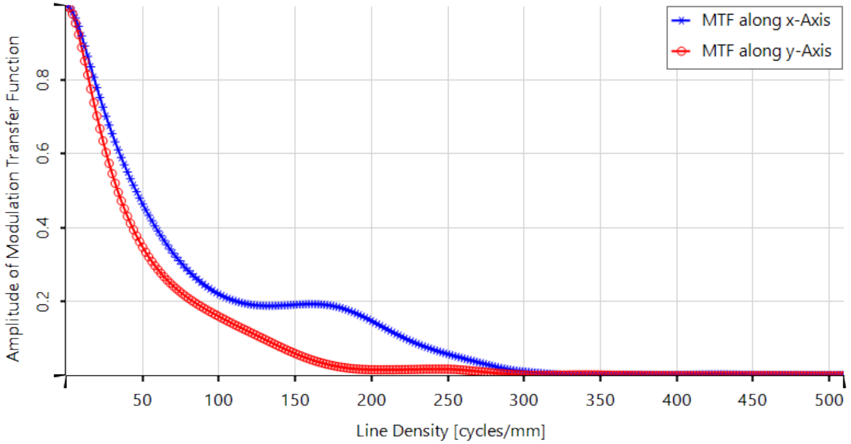


Off-Axis Analysis: Comparison of MTF









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.

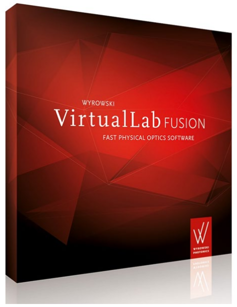
SYSTEM TOLERANCING

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

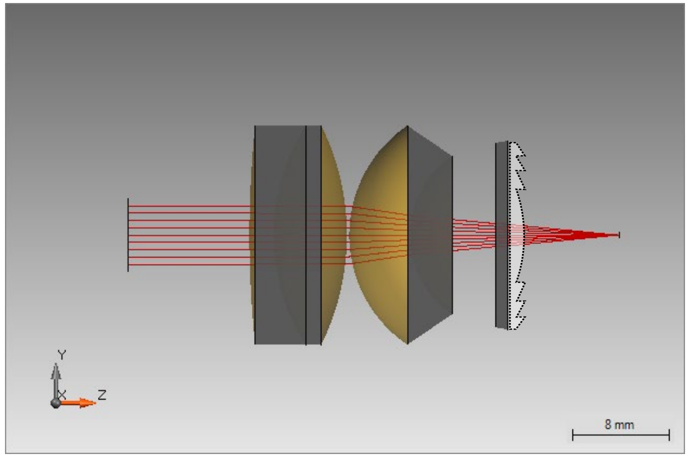
FABRICATION DATA

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

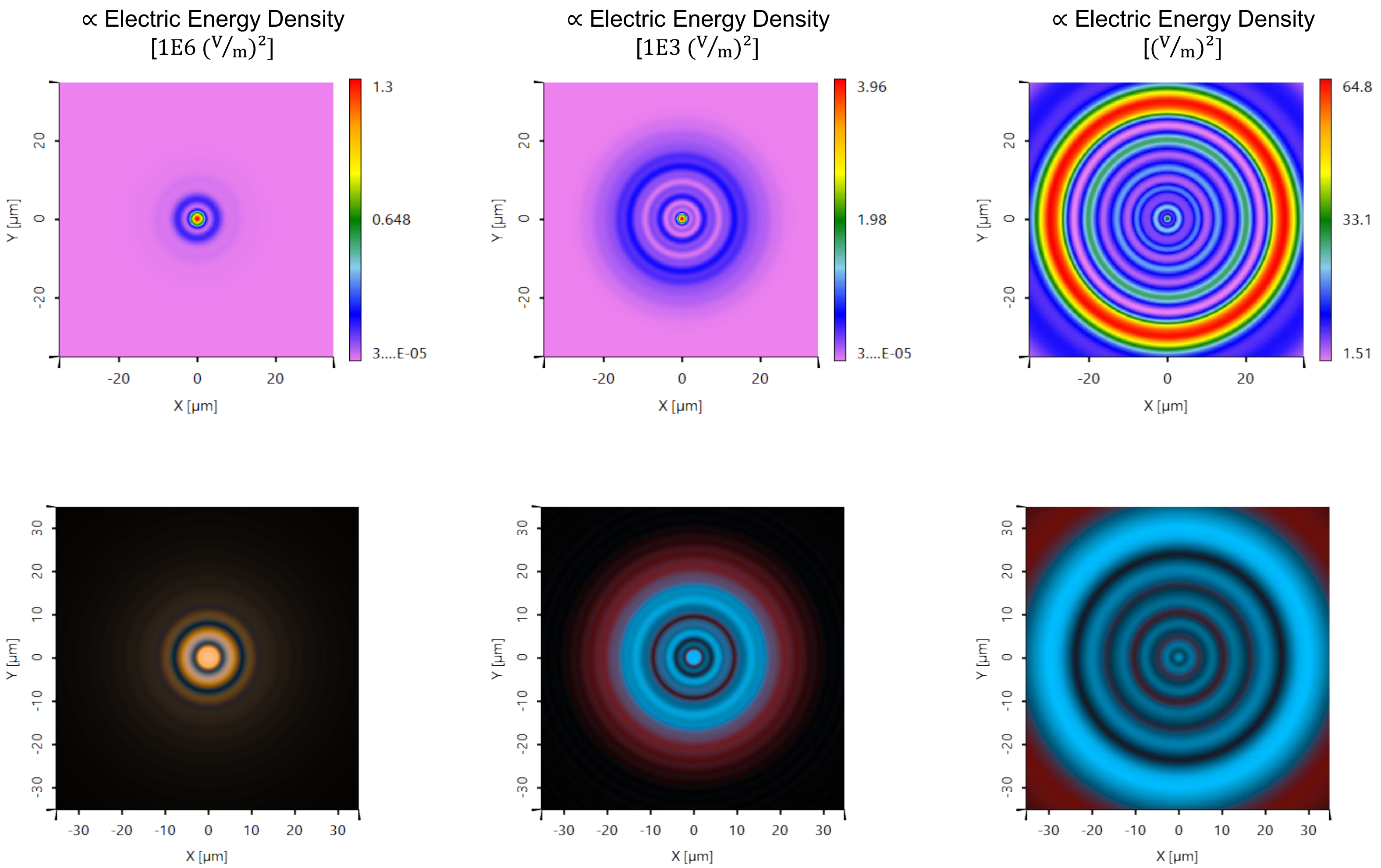
Import of Zemax file into VirtualLab Fusion and further processing of workflow.



On-Axis Analysis: Inclusion of Higher Orders



simulation time per order ~seconds



+1st diffraction order

0th diffraction order

-1st diffraction order

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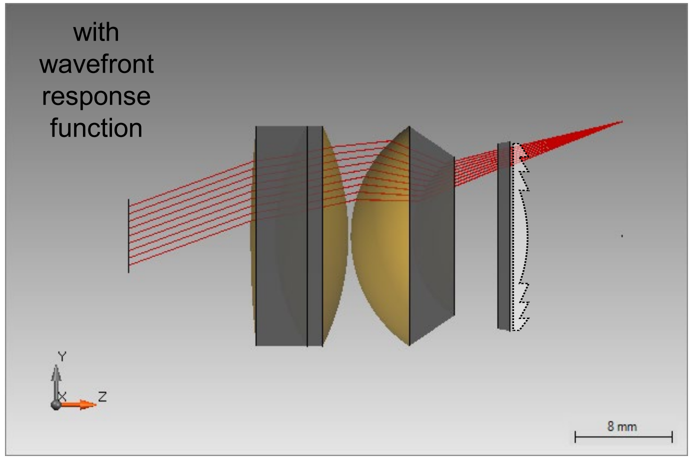
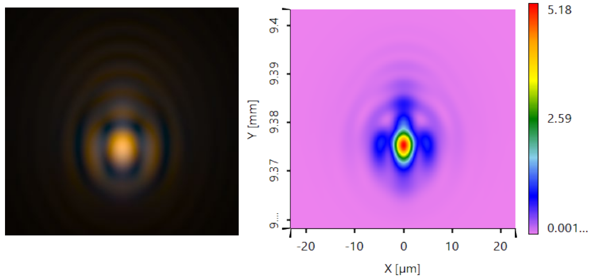
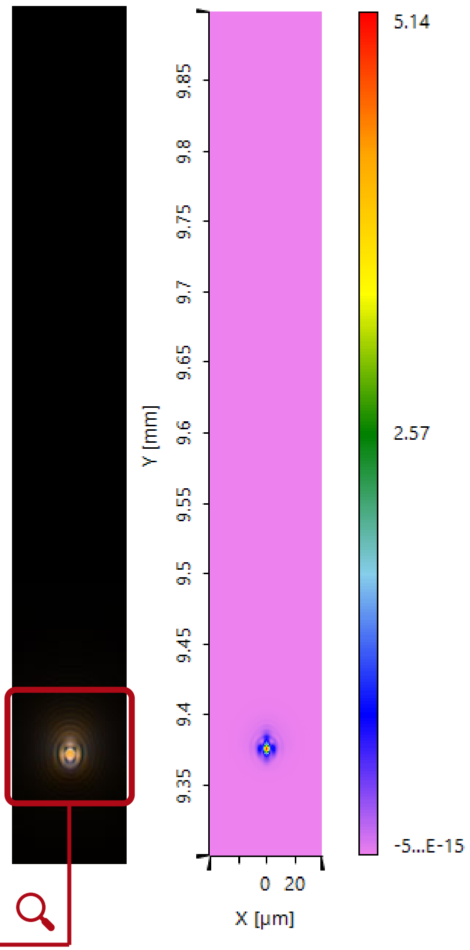


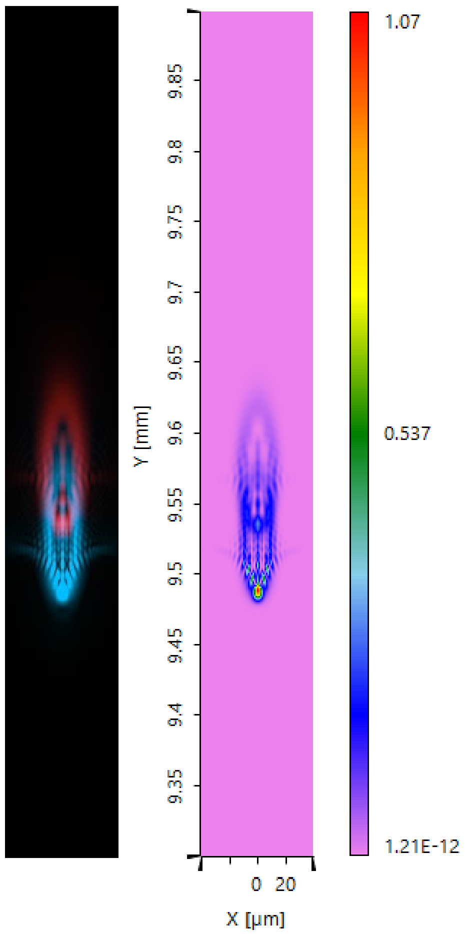


∝ Electric Energy Density
$[1E5\ (V/m)^2]$



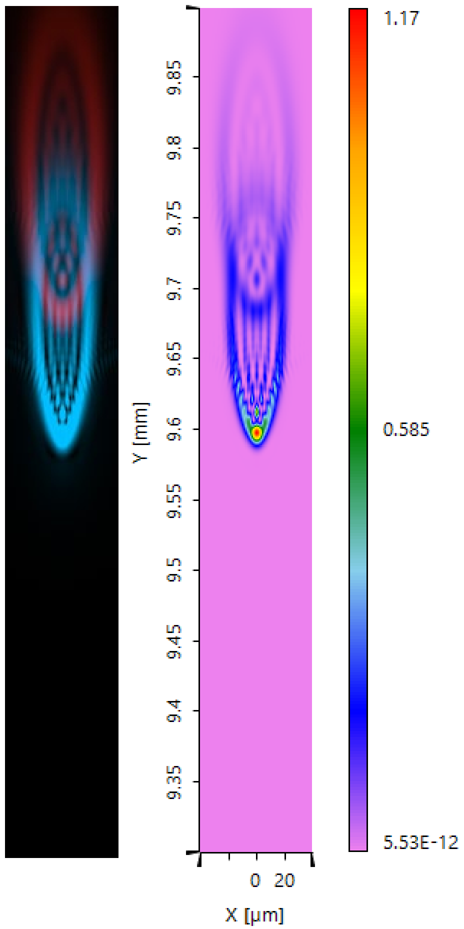
$+1^{st}$ diffraction order

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



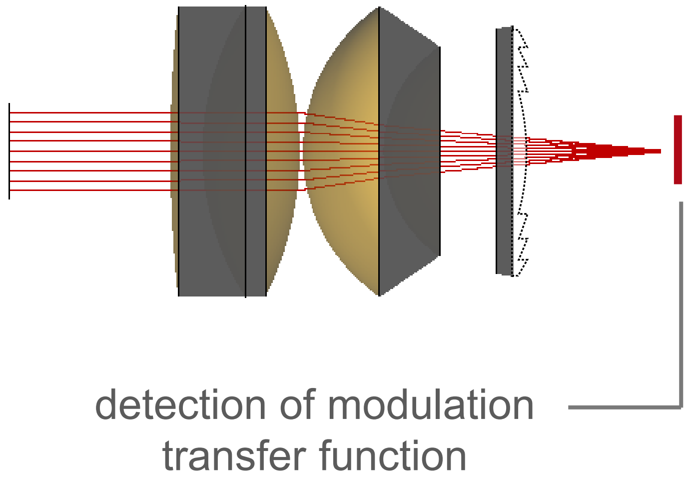
0^{th} diffraction order

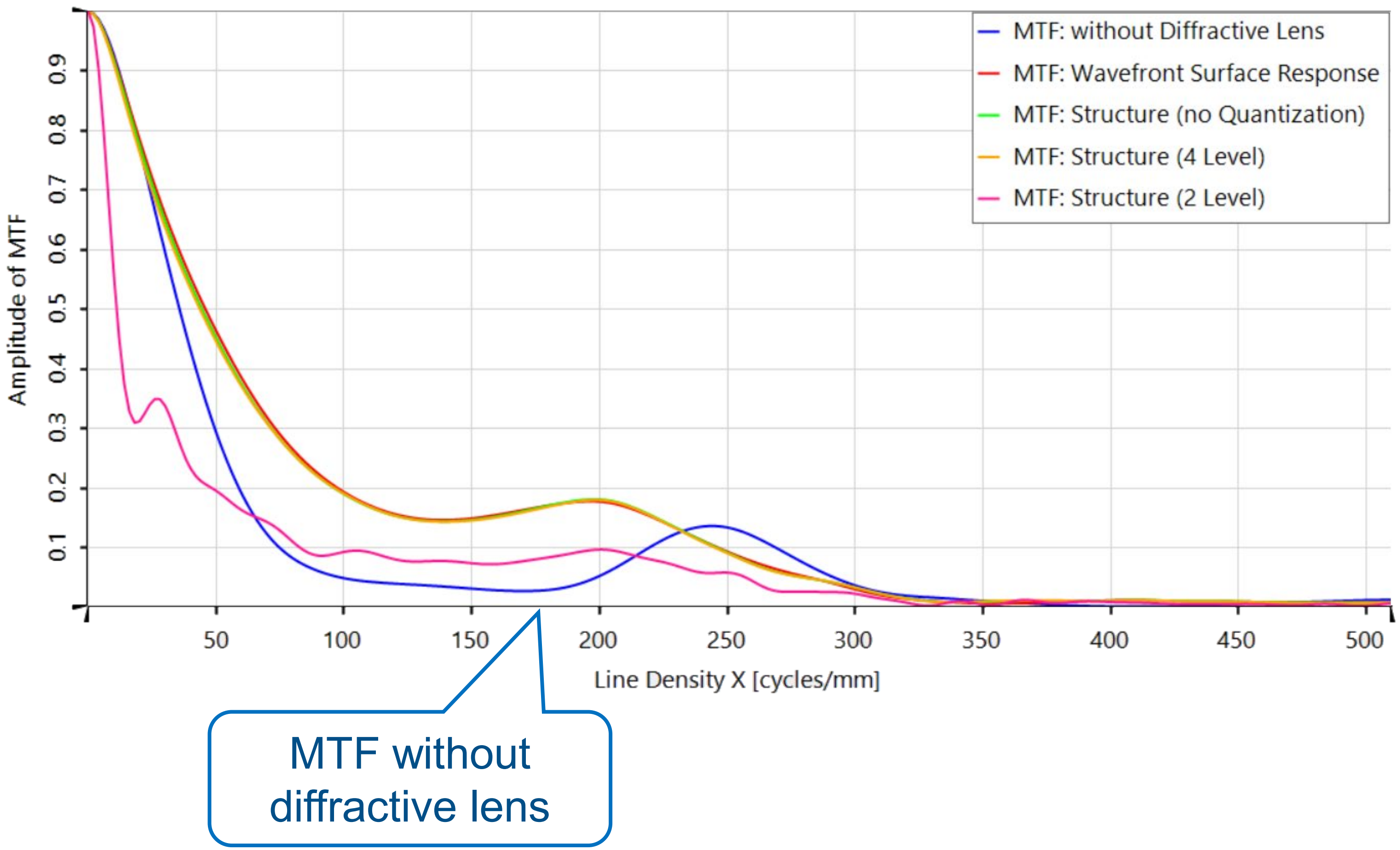
∝ Electric Energy Density
$[1E2\ (V/m)^2]$



-1^{st} diffraction order

MTF for Various Diffractive Lens Structures





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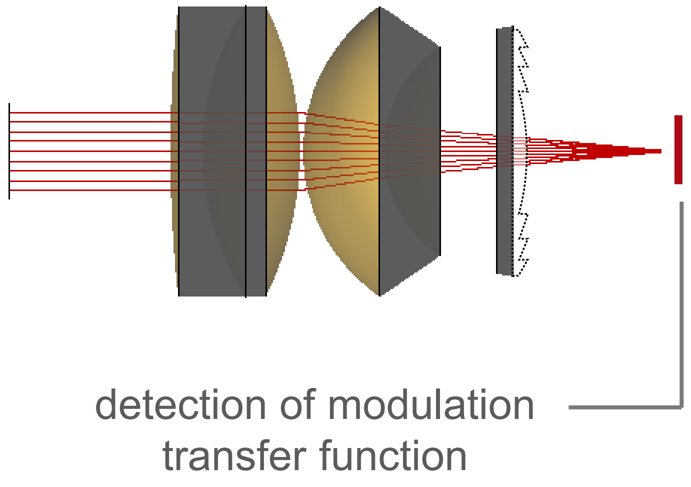

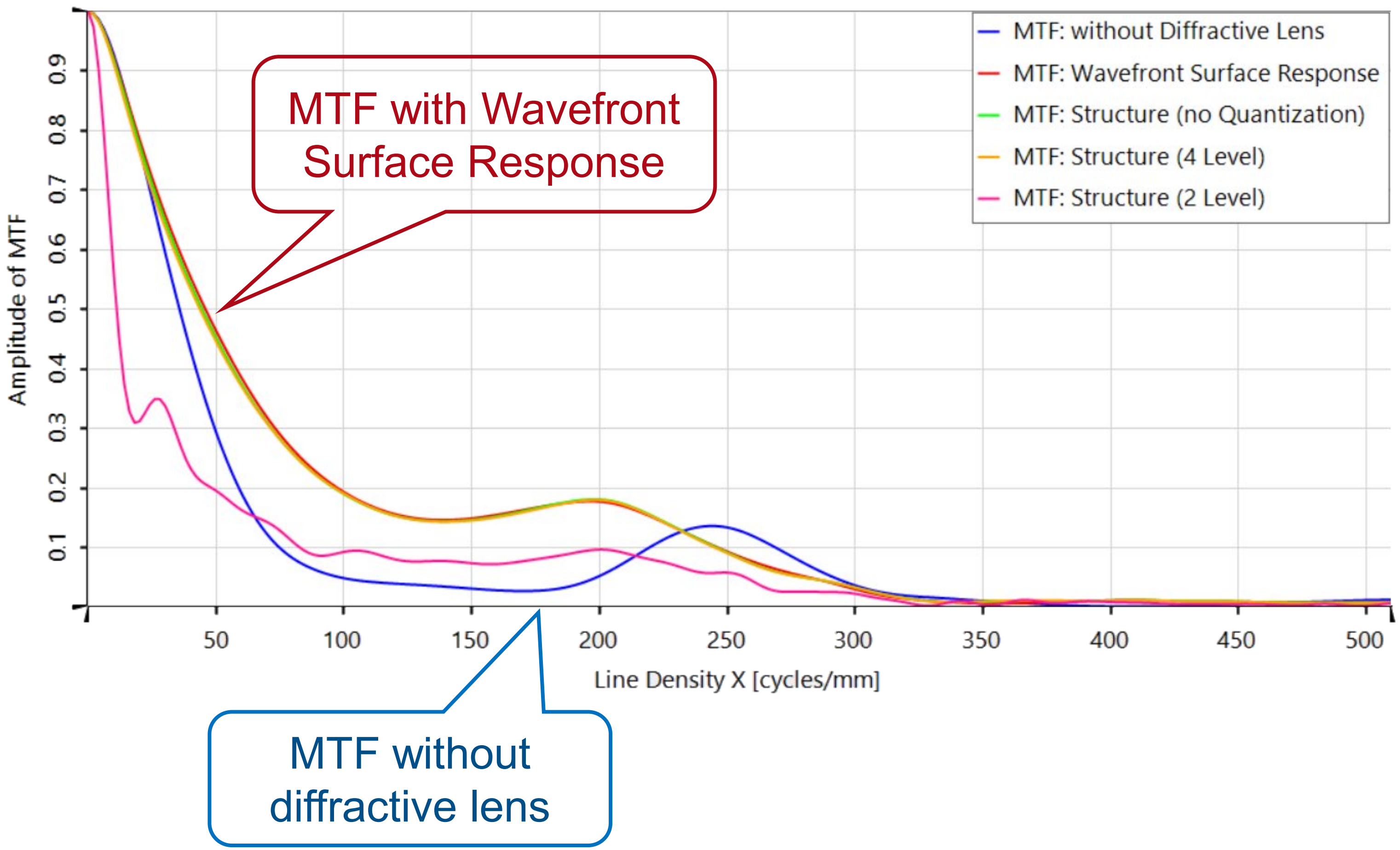

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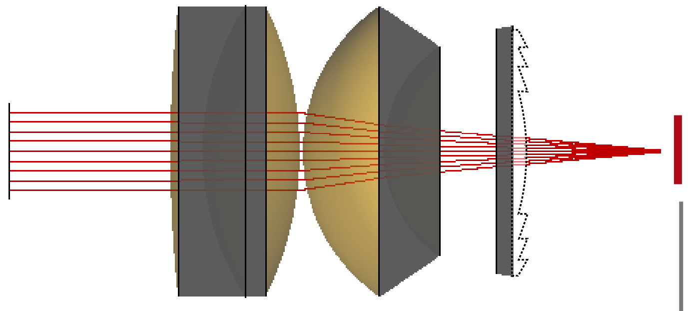
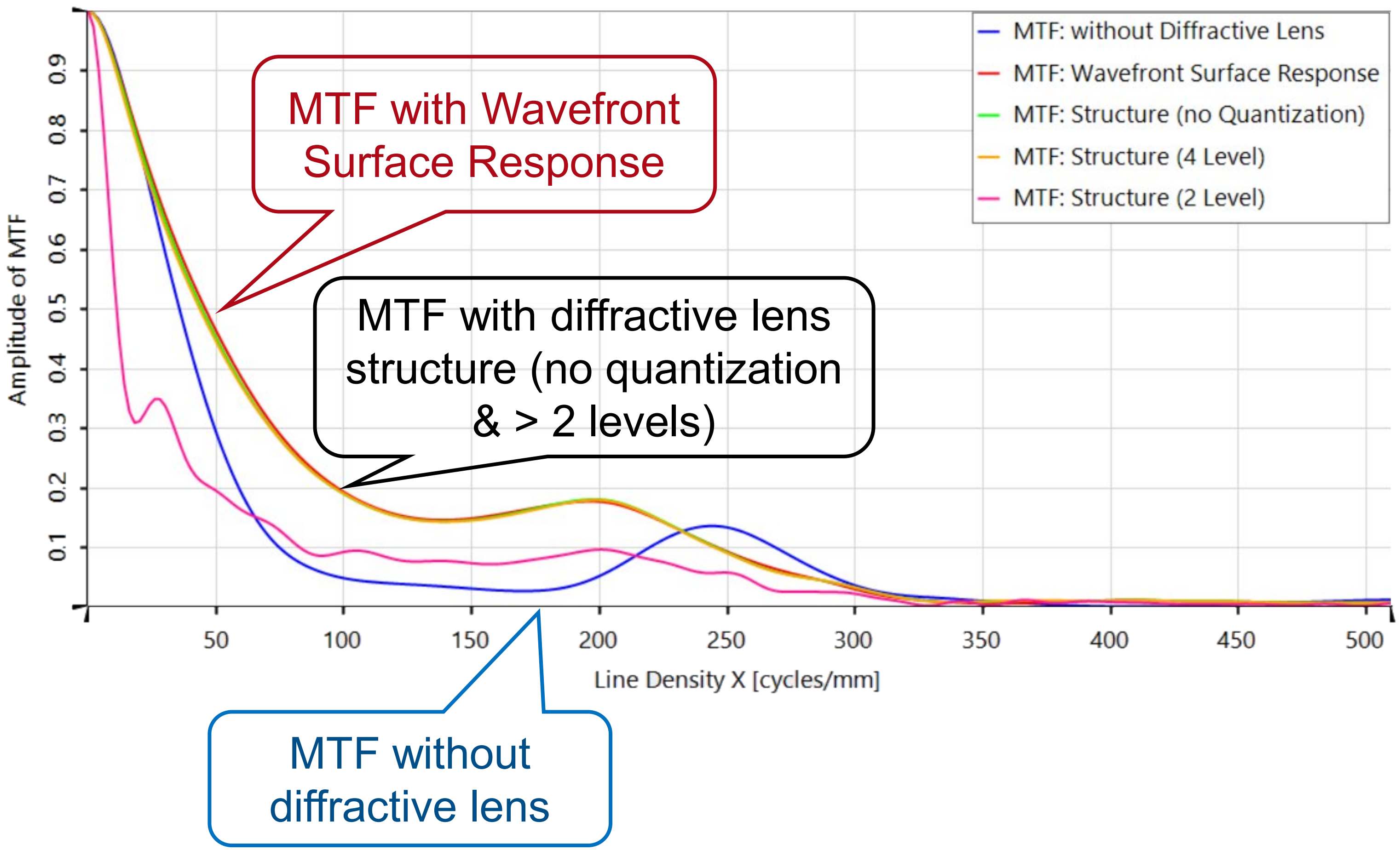
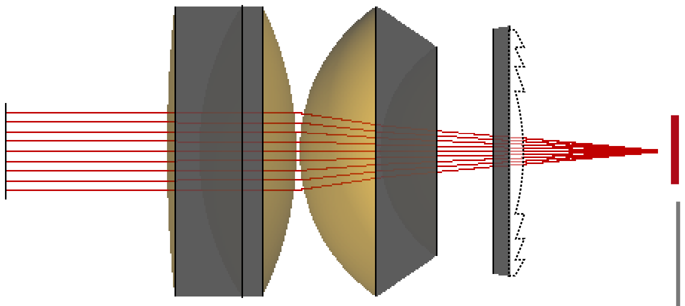
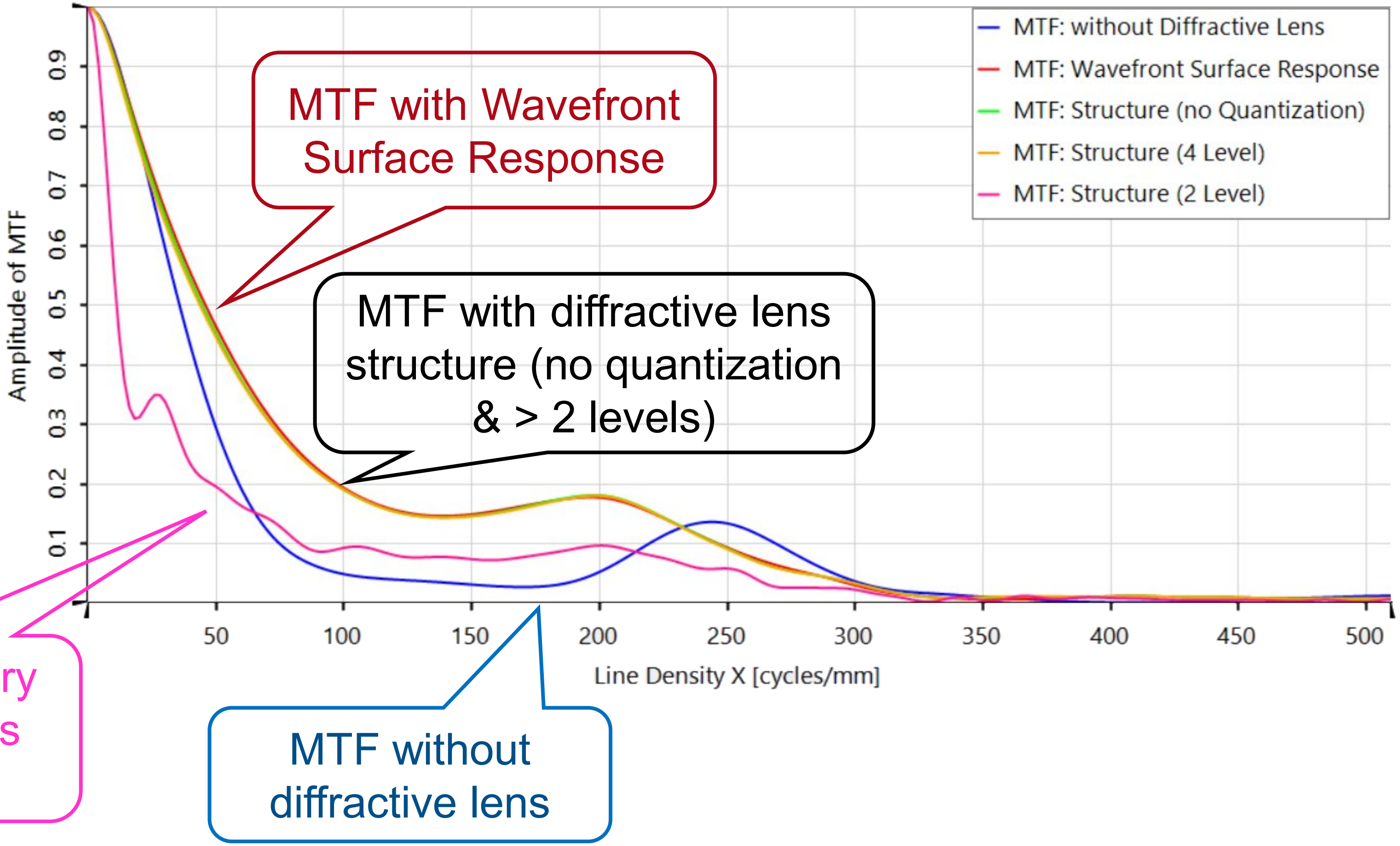


detection of modulation transfer function



MTF for Various Diffractive Lens Structures





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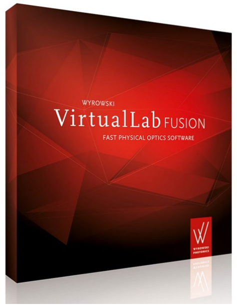
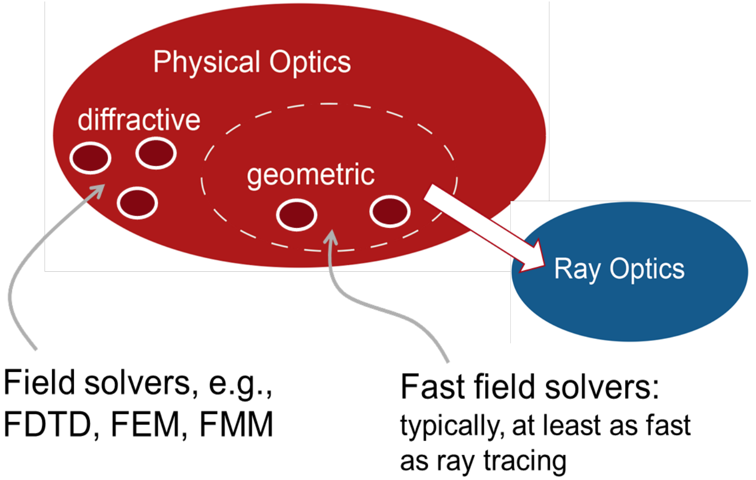


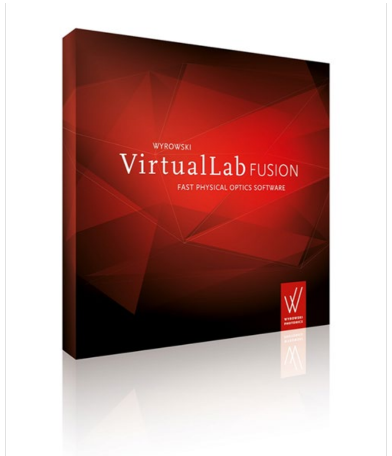
Conclusion

- Freeform and flat optics provide additional design freedoms for optical design.
- Potential of these techniques to be further investigated. We provide tools for this investigation.
- We propose a workflow which is based on physical optics and includes ray optics:

FUNCTIONAL DESIGN	STRUCTURAL DESIGN	MODELING & EVALUATION	FURTHER OPTIMIZATION	SYSTEM TOLERANCING	FABRICATION DATA
Design the system by introducing functional components to achieve the demanded system functionality.	Replace functional components by smooth surface or flat optics components.	Model the system with ray tracing and physical optics. Evaluate the performance by suitable detectors and merit functions.	Use the modeling techniques to further optimize the system by, e.g., parametric optimization.	Investigate the fabrication tolerances of components and the adjustment sensitivity of the system.	Use the modeling techniques to further optimize the system by, e.g. parametric optimization.

- All presented techniques available in-house and to be released in 2021.





VirtualLab Fusion 2021