Photonics West 2019: VirtualLab Fusion Workshop in cooperation with Zemax

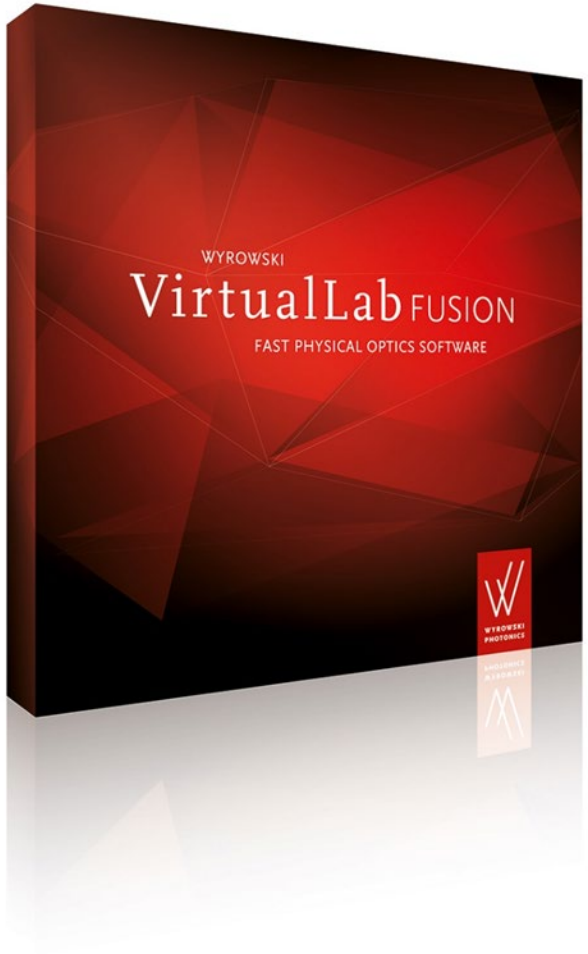
Modeling and Design of Diffractive- and Meta-lenses with VirtualLab Fusion

Frank Wyrowski, Akil Bhagat, Roberto Knoth, Site Zhang

VirtualLab Meta- and Diffractive Surface Solutions

- We prepare a new VirtualLab product for design and modeling of meta- and diffractive surfaces to be released in 2019.
- It will be based on the theory presented in this talk. The examples shown in this talk will be included in the product as special Use Cases together with suitable workflows.

This workshop gives a product preview by presenting its theoretical concepts, the working principles, and application examples.



Structure of Workshop

- Introduction of theory
  - Frank Wyrowski
- Design of binary surfaces in OpticStudio®
  - Akil Bhagat
- Physical-optics analysis of imported systems from OpticStudio: Diffractive lenses
  - Roberto Knoth
- Metalenses theory and modeling
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- Fabrication export
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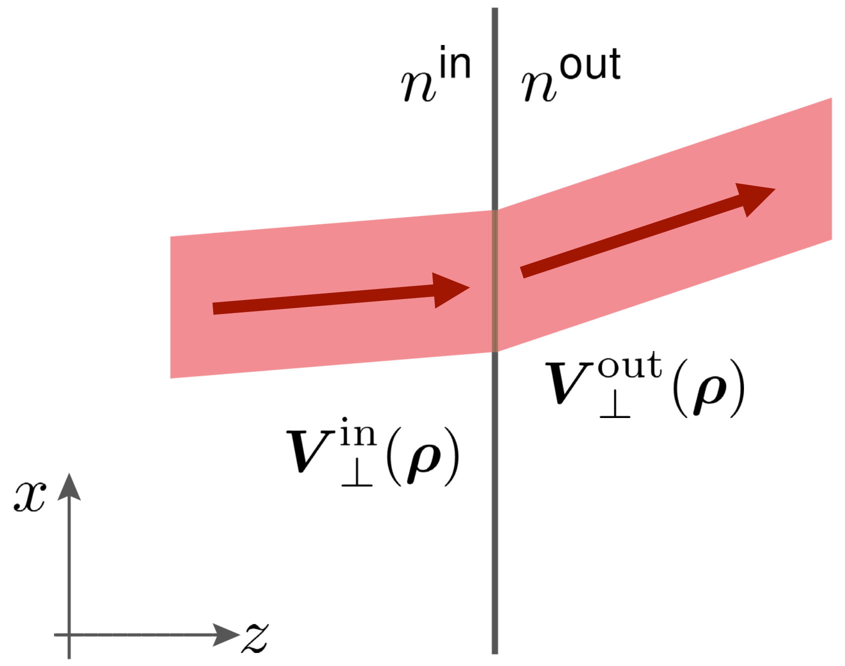
Wavefront Surface Response Function

Unifying approach for dealing with different structure concepts in optical modeling and design

Plane Wave Interaction with Plane Surface



- For a field in a plane we use the notation $\boldsymbol{\rho} = (x, y)$ and $\boldsymbol{V}_\perp(\boldsymbol{\rho}) = (E_x(\boldsymbol{\rho}), E_y(\boldsymbol{\rho}))$.
- A plane input field is given by

$$\boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho}) = \boldsymbol{U}_\perp^{\text{in}} \exp\left(\mathrm{i}\boldsymbol{\kappa}^{\text{in}}\boldsymbol{\rho}\right)$$

with $\boldsymbol{\kappa} = (k_x, k_y)$.

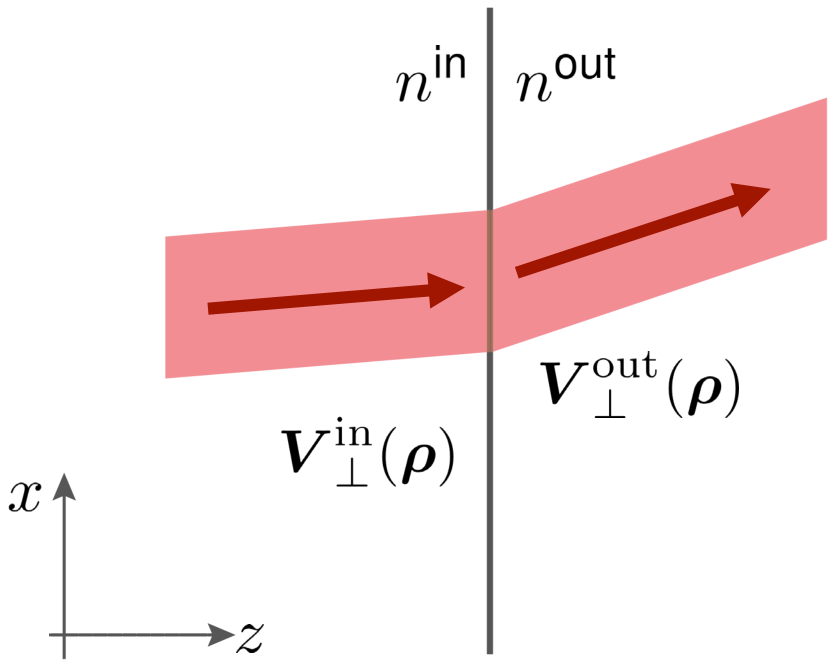
- The transmitted plane output field is given by

$$\boldsymbol{V}_\perp^{\text{out}}(\boldsymbol{\rho}) = \left(\mathbf{B}(\boldsymbol{\kappa}^{\text{in}})\boldsymbol{U}_\perp^{\text{in}}\right) \exp\left(\mathrm{i}\boldsymbol{\kappa}^{\text{out}}\boldsymbol{\rho}\right)$$

with the Fresnel effect at the surface is expressed by the 2×2 matrix $\mathbf{B}(\boldsymbol{\kappa}^{\text{in}})$.

- From the boundary conditions follows: $\boldsymbol{\kappa}^{\text{out}} \overset{!}{=} \boldsymbol{\kappa}^{\text{in}}$

Plane Wave Interaction with Plane Surface

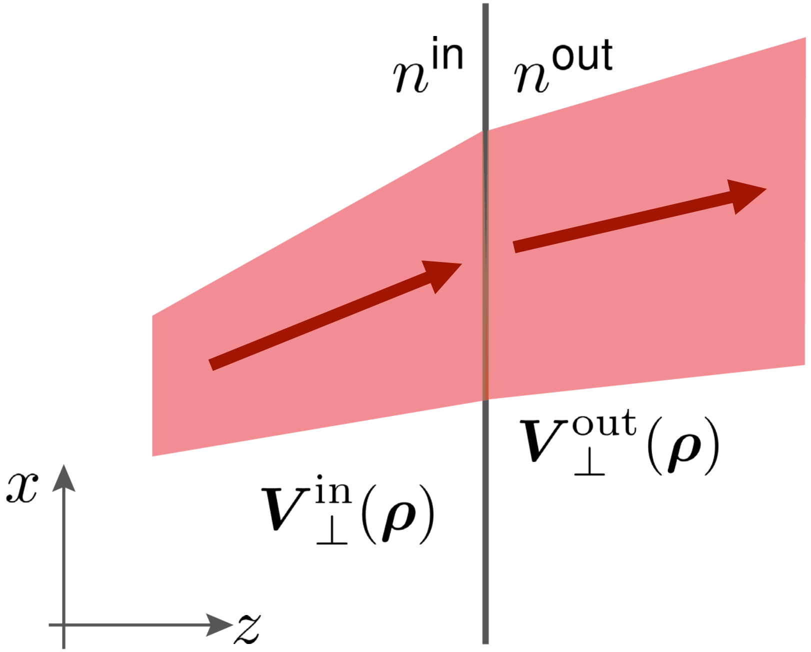


- From the boundary conditions follows: $\boldsymbol{\kappa}^{\text{out}} \stackrel{!}{=} \boldsymbol{\kappa}^{\text{in}}$
- With $\boldsymbol{\kappa} = k_0 n \hat{\boldsymbol{s}}_{\perp} = k_0 n(\sin\theta\cos\phi, \sin\theta\cos\phi)$ and $\phi = 0$ the law of refraction follows: $n^{\text{in}} \sin\theta^{\text{in}} = n^{\text{out}} \sin\theta^{\text{out}}$.
- For plane wave fields the wavefront phase is given by $\psi(\boldsymbol{\rho}) = \boldsymbol{\kappa} \cdot \boldsymbol{\rho}$.
- With $\boldsymbol{\kappa}^{\text{out}} \stackrel{!}{=} \boldsymbol{\kappa}^{\text{in}}$ we conclude $\psi^{\text{out}}(\boldsymbol{\rho}) = \psi^{\text{in}}(\boldsymbol{\rho})$.
- With $\nabla_{\perp} = \left\{ \frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right\}$ we find for plane wave fields:

$$\boldsymbol{\kappa} = \nabla_{\perp}\psi(\boldsymbol{\rho})$$

- Then $\boldsymbol{\kappa}^{\text{out}} \stackrel{!}{=} \boldsymbol{\kappa}^{\text{in}}$, that is the law of refraction, can be expressed by $\nabla_{\perp}\psi^{\text{in}}(\boldsymbol{\rho}) = \nabla_{\perp}\psi^{\text{out}}(\boldsymbol{\rho})$.

General Field Interaction with Plane Surface



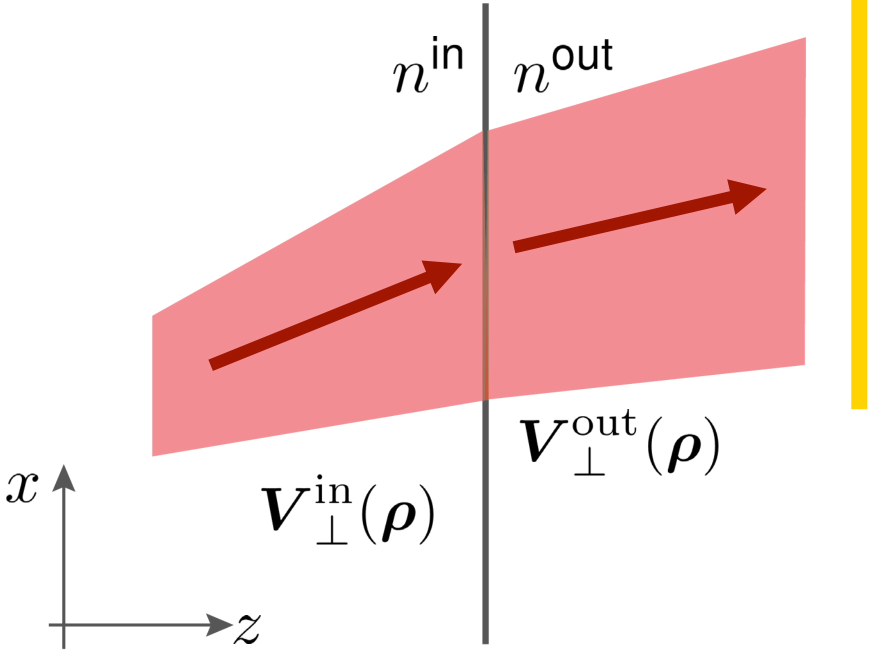
- Consider a general input field $\boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho}) = \boldsymbol{U}_\perp^{\text{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})\right)$.
- In general the effect of the plane surface on the input field can be expressed by the operator equation $\boldsymbol{V}_\perp^{\text{out}}(\boldsymbol{\rho}) = \boldsymbol{\mathcal{B}} \boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho})$.
- Next we assume that we are allowed to apply the plane wave results locally. In physical optics that means the fields are in its homeomorphic field zone (HFZ).
- In the homeomorphic field zone we can express the effect of the plane surface on the input field locally:

$$\boldsymbol{U}_\perp^{\text{out}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho})\right) = \mathbf{B}(\boldsymbol{\rho}) \left\{\boldsymbol{U}_\perp^{\text{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})\right)\right\}$$

- The local use of the law of refraction can be expressed by:

$$\nabla_\perp \psi^{\text{in}}(\boldsymbol{\rho}) = \nabla_\perp \psi^{\text{out}}(\boldsymbol{\rho})$$

General Field Interaction with Plane Surface



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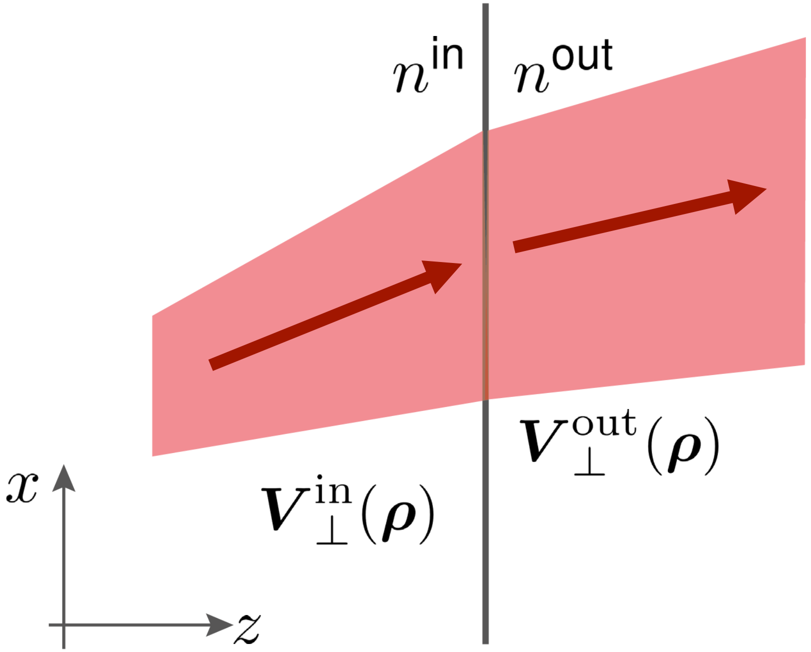
- The local use of the law of refraction is expressed by:

$$\nabla_\perp \psi^{\mathrm{in}}(\boldsymbol{\rho}) = \nabla_\perp \psi^{\mathrm{out}}(\boldsymbol{\rho})$$

- In conclusion the effect on the phase is described by the local Fresnel effects:

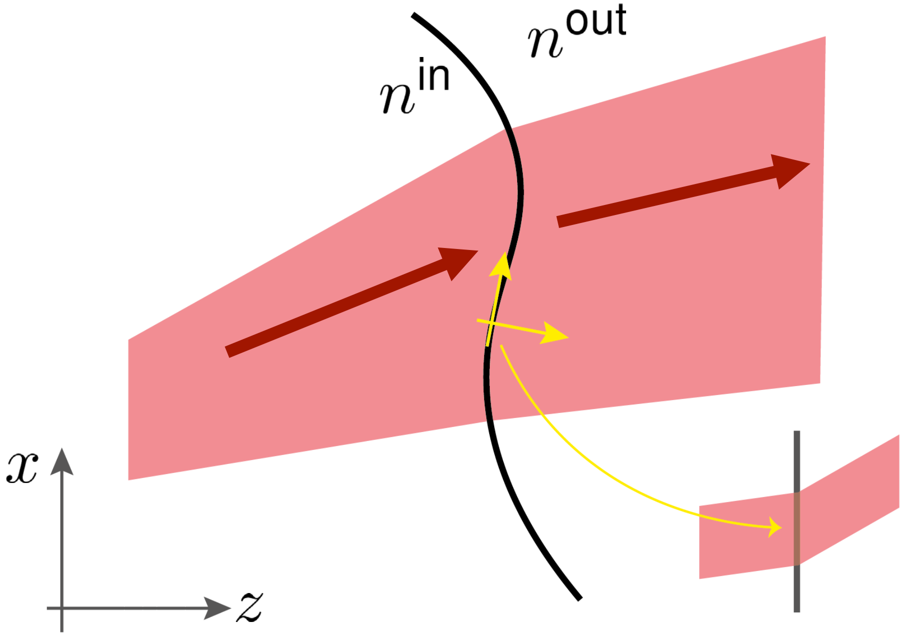
$$\boldsymbol{U}_\perp^{\mathrm{out}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho})\right) = \left\{\mathbf{B}(\boldsymbol{\rho}; \psi^{\mathrm{in}})\boldsymbol{U}_\perp^{\mathrm{in}}(\boldsymbol{\rho})\right\} \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho})\right)$$

General Field Interaction with Plane Surface



- Intermediate result: Plane surfaces do not change the wavefront phase of the incident field.

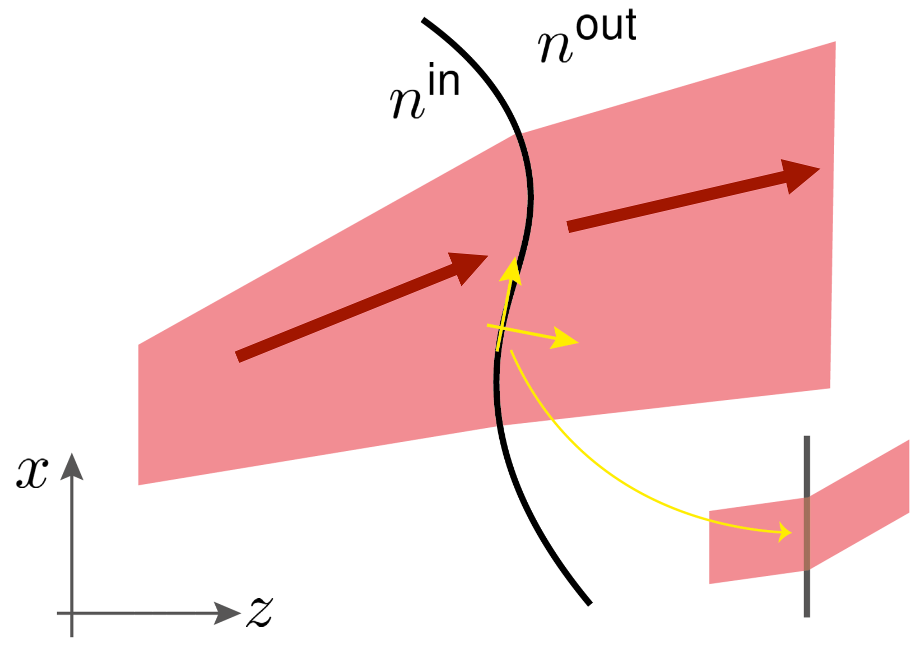
General Field Interaction with Curved Surface



- Intermediate result: Plane surfaces do not change the wavefront phase of the incident field.
- For curved surfaces the modeling can be still applied locally. Then the wavefront phase can be shaped by the shape of the surface:

$$\psi^{\text{out}}(\boldsymbol{\rho}) \neq \psi^{\text{in}}(\boldsymbol{\rho})$$

General Field Interaction with Curved Surface

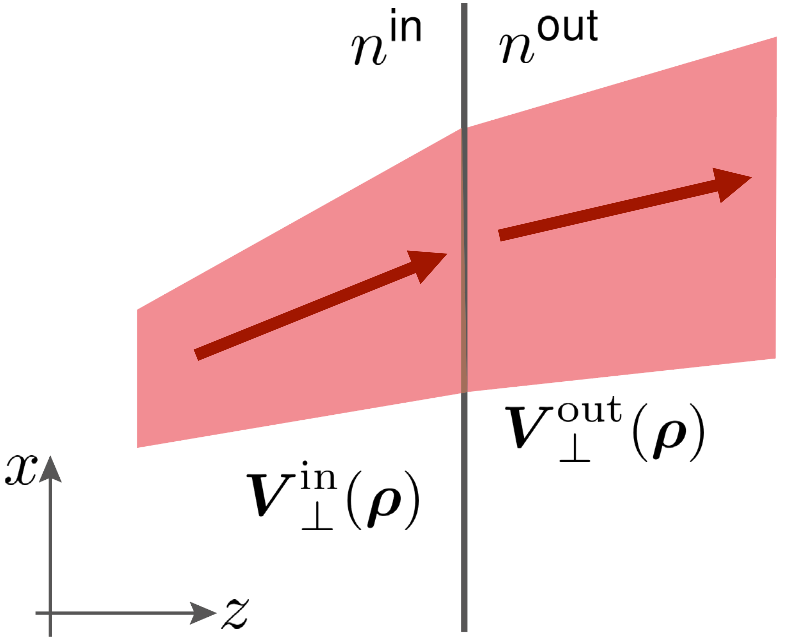


- Intermediate result: Plane surfaces do not change the wavefront phase of the incident field.
- For curved surfaces the modeling can be still applied locally. Then the wavefront phase can be shaped by the shape of the surface:

$$\psi^{\text{out}}(\boldsymbol{\rho}) \neq \psi^{\text{in}}(\boldsymbol{\rho})$$

- In what follows a change of the wavefront phase should be enforced by assuming a Wavefront Response Function $\Delta\psi(\boldsymbol{\rho})$ instead of (in addition to) a curved surface.

Wavefront Surface Response (WSR)



- For plane surfaces we found $\nabla_\perp \psi^{\mathrm{in}}(\boldsymbol{\rho}) = \nabla_\perp \psi^{\mathrm{out}}(\boldsymbol{\rho})$ and in conclusion

$$\boldsymbol{U}_\perp^{\mathrm{out}}(\boldsymbol{\rho}) \exp\big(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho})\big) = \left\{\mathbf{B}(\boldsymbol{\rho};\psi^{\mathrm{in}})\boldsymbol{U}_\perp^{\mathrm{in}}(\boldsymbol{\rho})\right\} \exp\big(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho})\big)\,.$$

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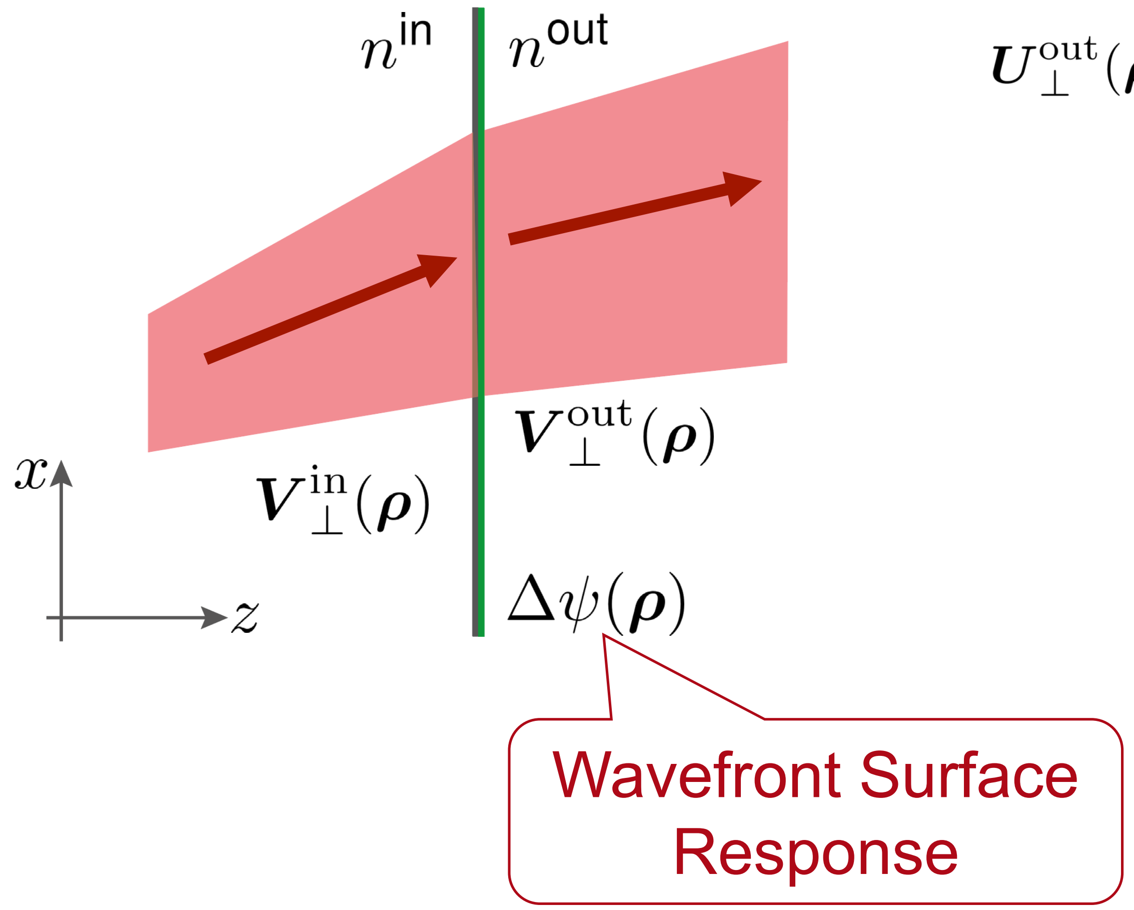

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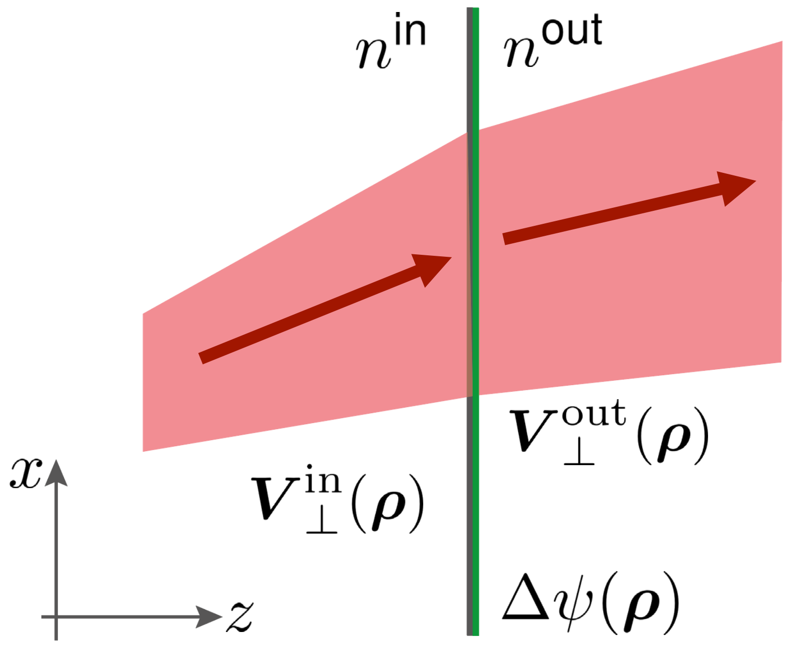

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- By introducing the wavefront surface response we assume an effect at the surface of the form

$$\boldsymbol{U}_{\perp}^{\text{out}}(\boldsymbol{\rho})\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho})\right) = \left\{\mathbf{B}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\text{out}}(\boldsymbol{\rho})\right)$$

with

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

and thus

$$\nabla_{\perp}\psi^{\text{out}}(\boldsymbol{\rho}) = \nabla_{\perp}\psi^{\text{in}}(\boldsymbol{\rho}) + \nabla_{\perp}\left(\Delta\psi(\boldsymbol{\rho})\right).$$

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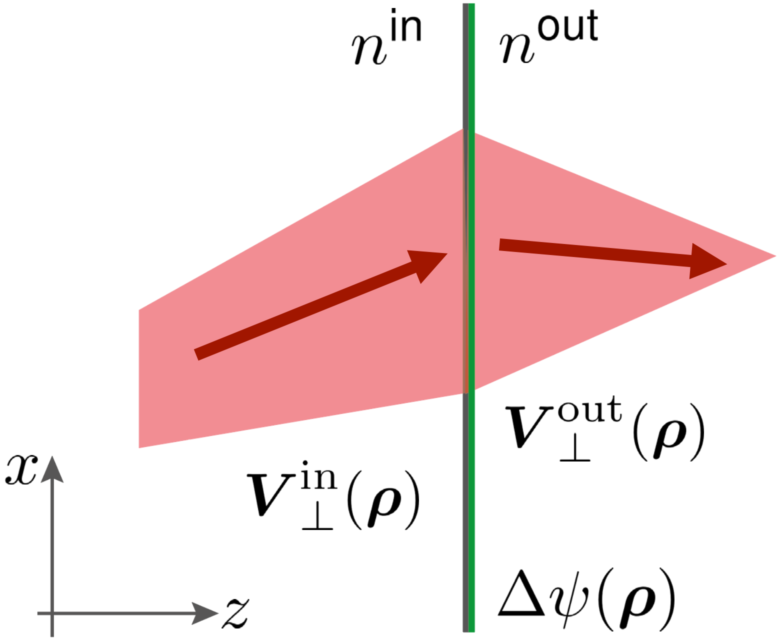

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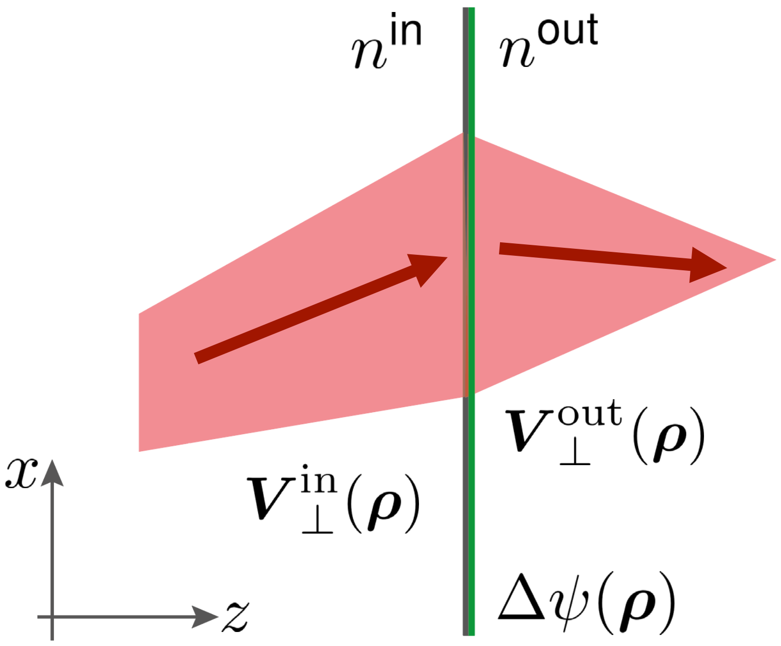


- The equation

$$\nabla_{\perp}\psi^{\text{out}}(\boldsymbol{\rho}) = \nabla_{\perp}\psi^{\text{in}}(\boldsymbol{\rho}) + \nabla_{\perp}\left(\Delta\psi(\boldsymbol{\rho})\right)$$

results because of the local plane wave assumption (homeomorphic zone) into

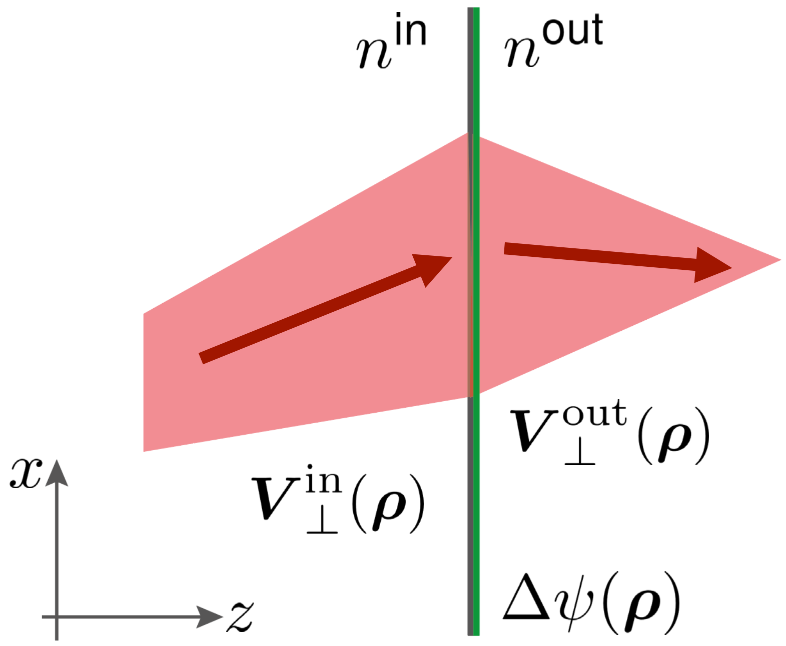
$$\boldsymbol{\kappa}^{\text{out}}(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{in}}(\boldsymbol{\rho}) + \boldsymbol{K}(\boldsymbol{\rho})$$

with $\boldsymbol{K}(\boldsymbol{\rho}) \stackrel{\text{def}}{=} \nabla_{\perp}\left(\Delta\psi(\boldsymbol{\rho})\right)$.

- That gives a direct access to ray tracing with $\boldsymbol{\kappa}(\boldsymbol{\rho}) = k_0 n \hat{\boldsymbol{s}}_{\perp}(\boldsymbol{\rho})$ via

$$n^{\text{out}}\hat{\boldsymbol{s}}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = n^{\text{in}}\hat{\boldsymbol{s}}_{\perp}^{\text{in}}(\boldsymbol{\rho}) + \boldsymbol{K}(\boldsymbol{\rho})/k_0.$$

How to Realize a Desired Wavefront Surface Response (WSR)?



- From a physical-optics point of view the question arises, if there exists any manipulation of the structure of the surface, which provides an effect of the form:

$$\boldsymbol{U}_{\perp}^{\text{out}}(\boldsymbol{\rho})\exp\big(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})+\Delta\psi(\boldsymbol{\rho})\big)=\left\{\mathbf{B}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\big(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})\big)$$

- A detailed answer can only be given for a specific surface structure.
- By introducing microstructured layers onto the surface a wavefront surface response can be implemented:
  - Graded-index layer
  - Volume hologram layer
  - Diffractive layer
  - Metamaterial layer

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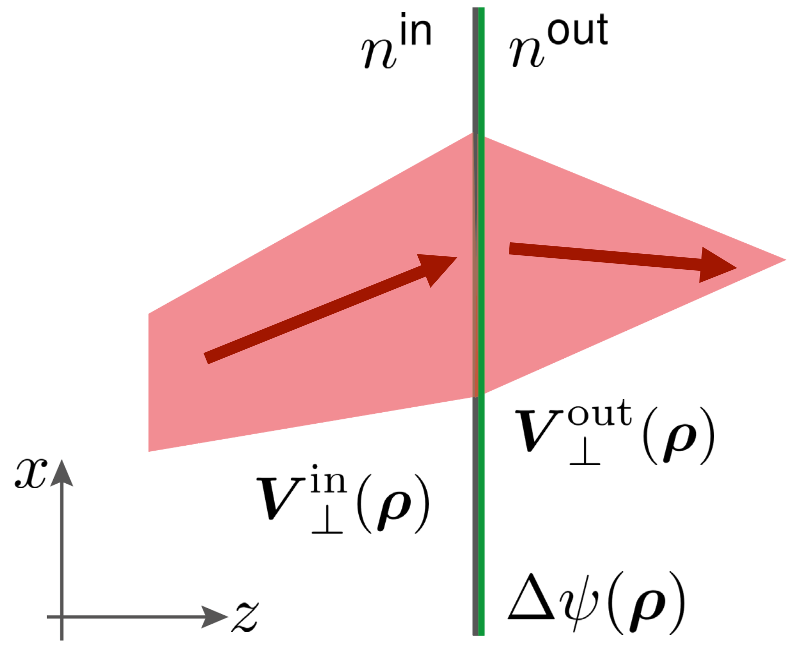

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  - **Diffractive layer**
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Physical Optics Modeling: Metasurface Layer

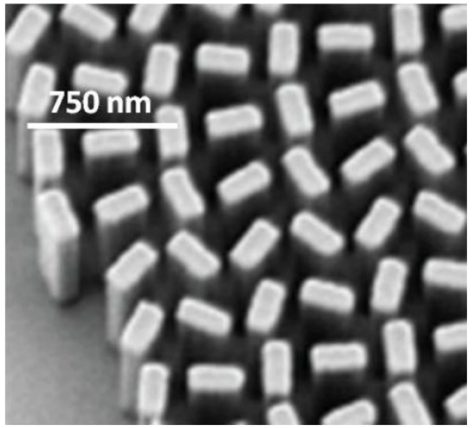
- In general a real surface layer structure does not just realize the desired wavefront response but additional effects and fields:

$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = \left\{\mathbf{B}(\boldsymbol{\rho};\psi^{\mathsf{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\mathsf{in}}(\boldsymbol{\rho})+\Delta\psi(\boldsymbol{\rho})\right)+\boldsymbol{V}_{\perp}^{\mathrm{res}}(\boldsymbol{\rho})$$

- For nanofin-based metalayers the typical result can be written as:

$$\begin{aligned}\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = &\left\{\mathbf{B}^{+}(\boldsymbol{\rho};\psi^{\mathsf{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\mathsf{in}}(\boldsymbol{\rho})+\Delta\psi(\boldsymbol{\rho})\right)\\ &+\left\{\mathbf{B}^{-}(\boldsymbol{\rho};\psi^{\mathsf{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\mathsf{in}}(\boldsymbol{\rho})-\Delta\psi(\boldsymbol{\rho})\right)\end{aligned}$$

- In depth investigation reveals, that $+\Delta\psi$ occurs for R-circularly polarized input fields and the conjugate phase for L-circularly polarized input.

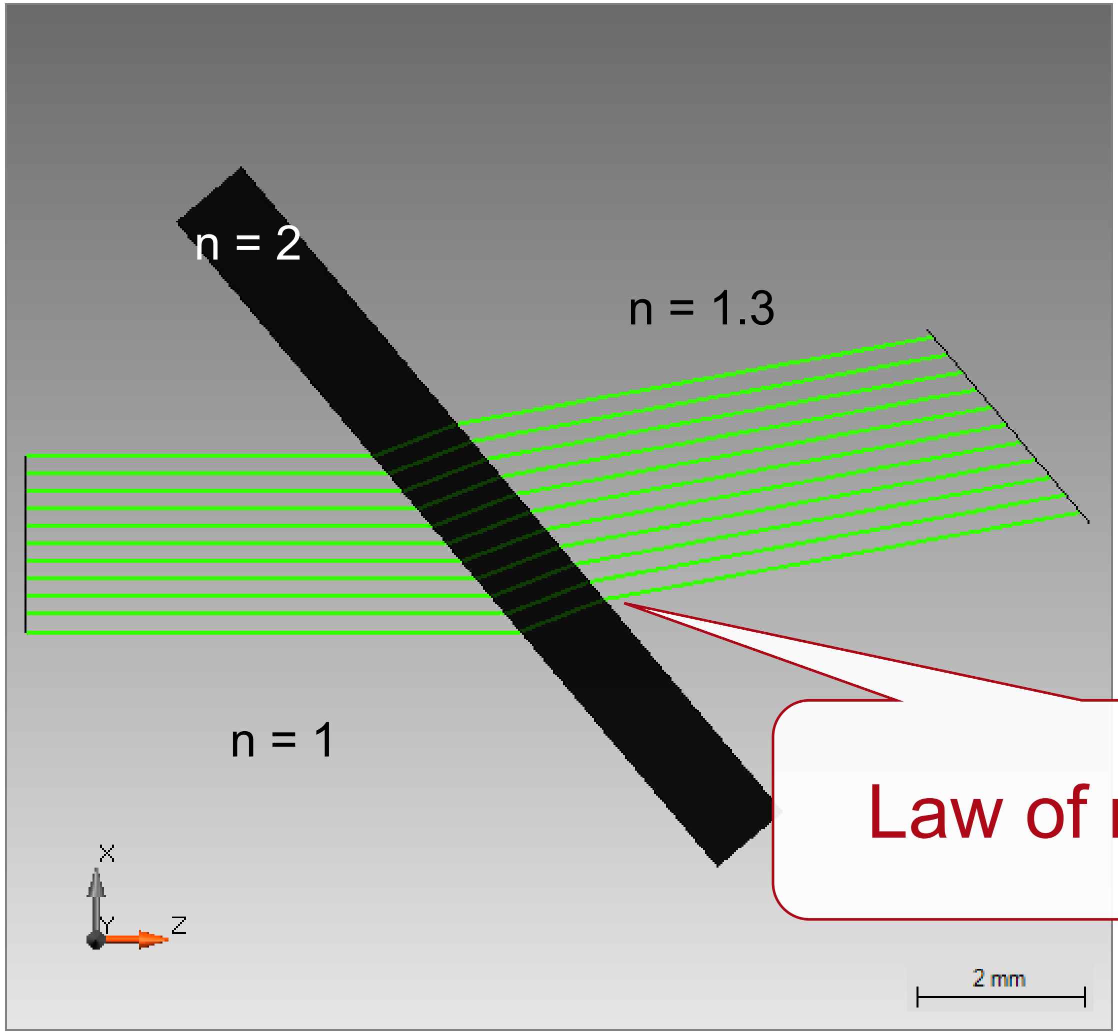


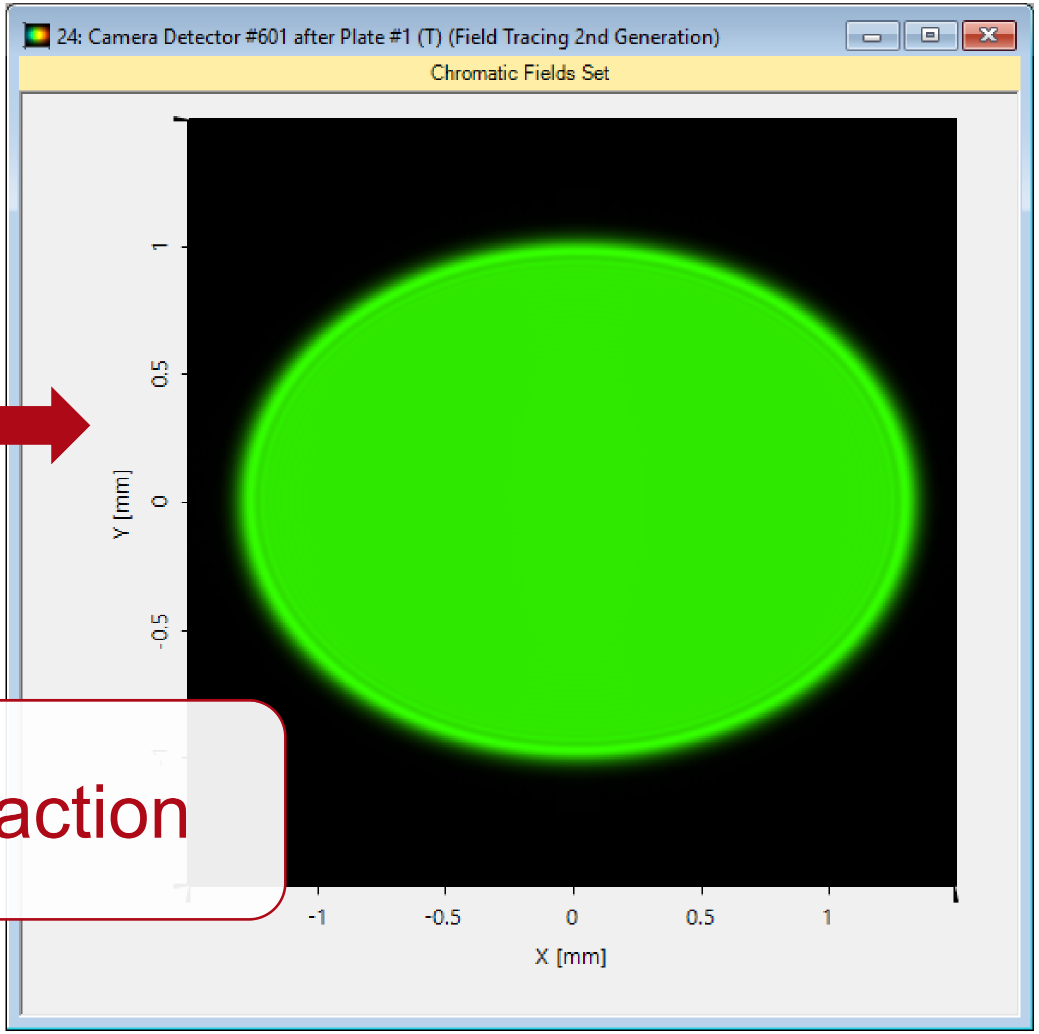
M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

Metasurface layer

Linear Wavefront Response Function

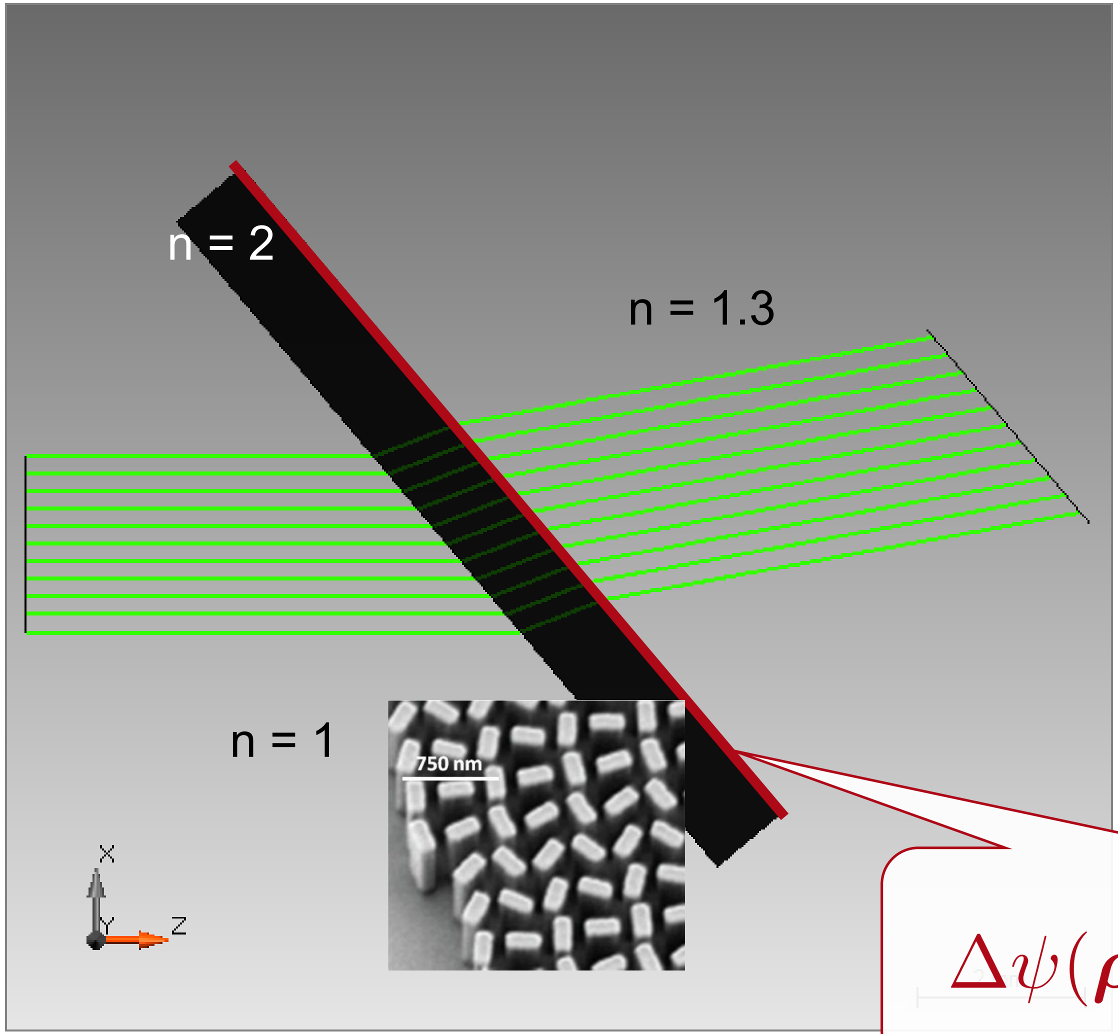
Plane Wave through Plate: Ray and Field Tracing

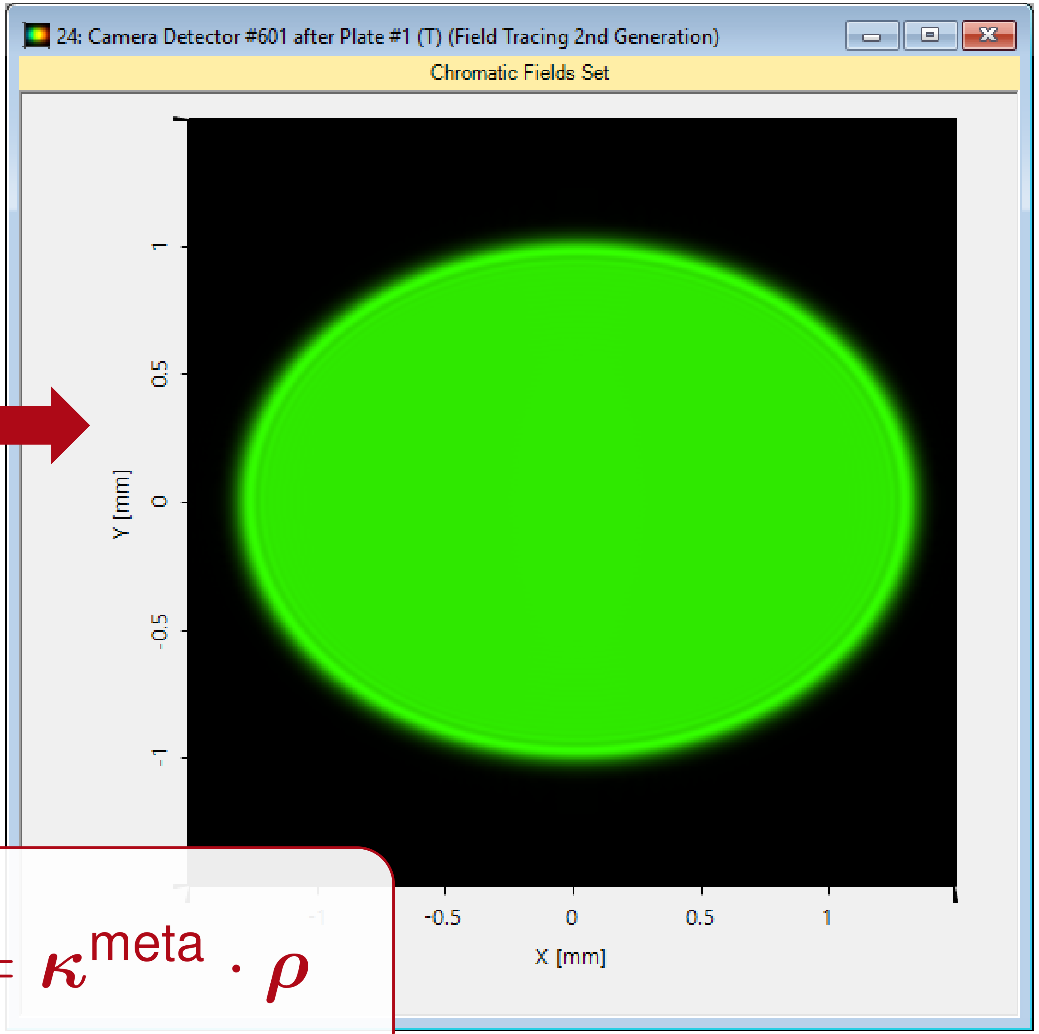




Law of refraction

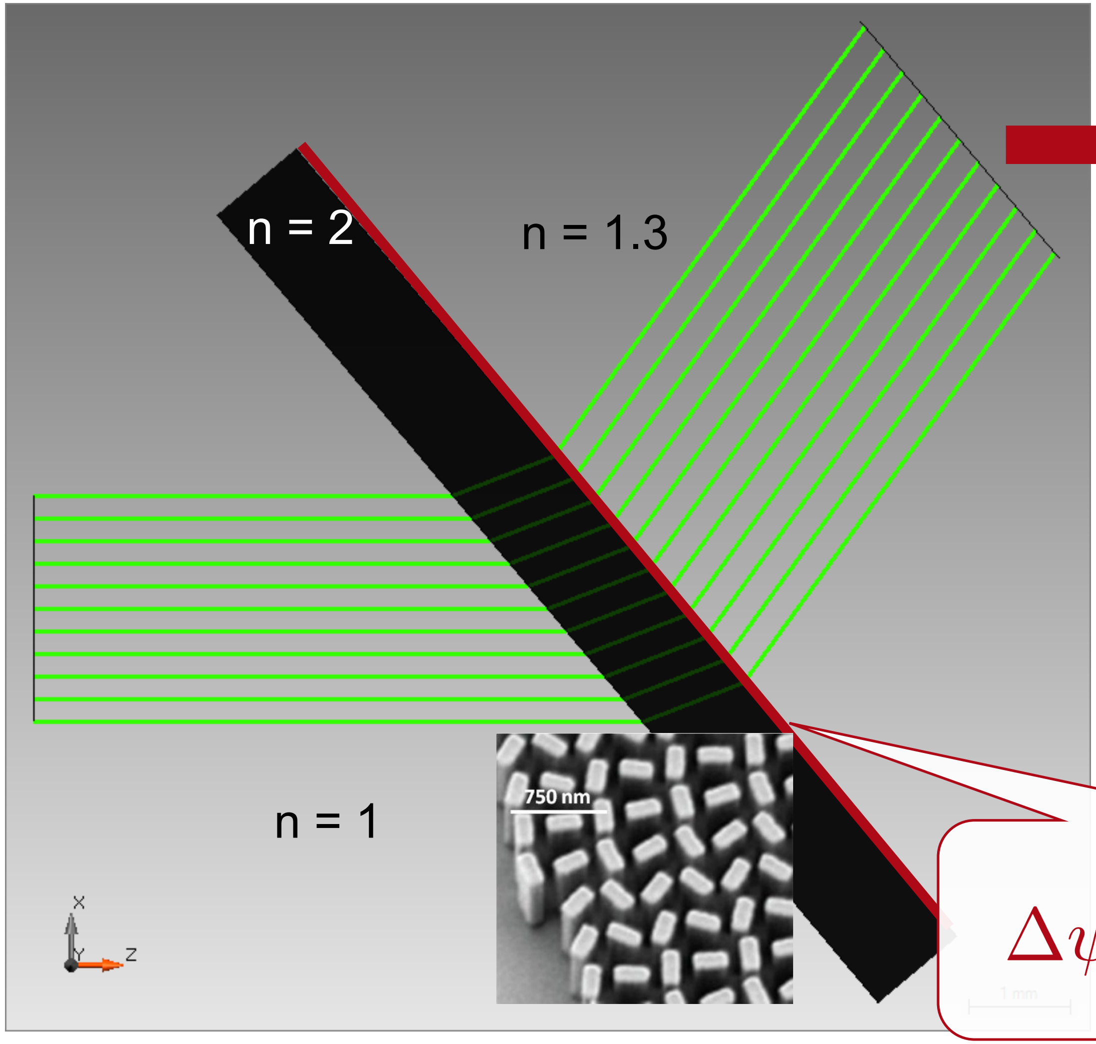
Plane Wave through Plate: Introducing Metasurface

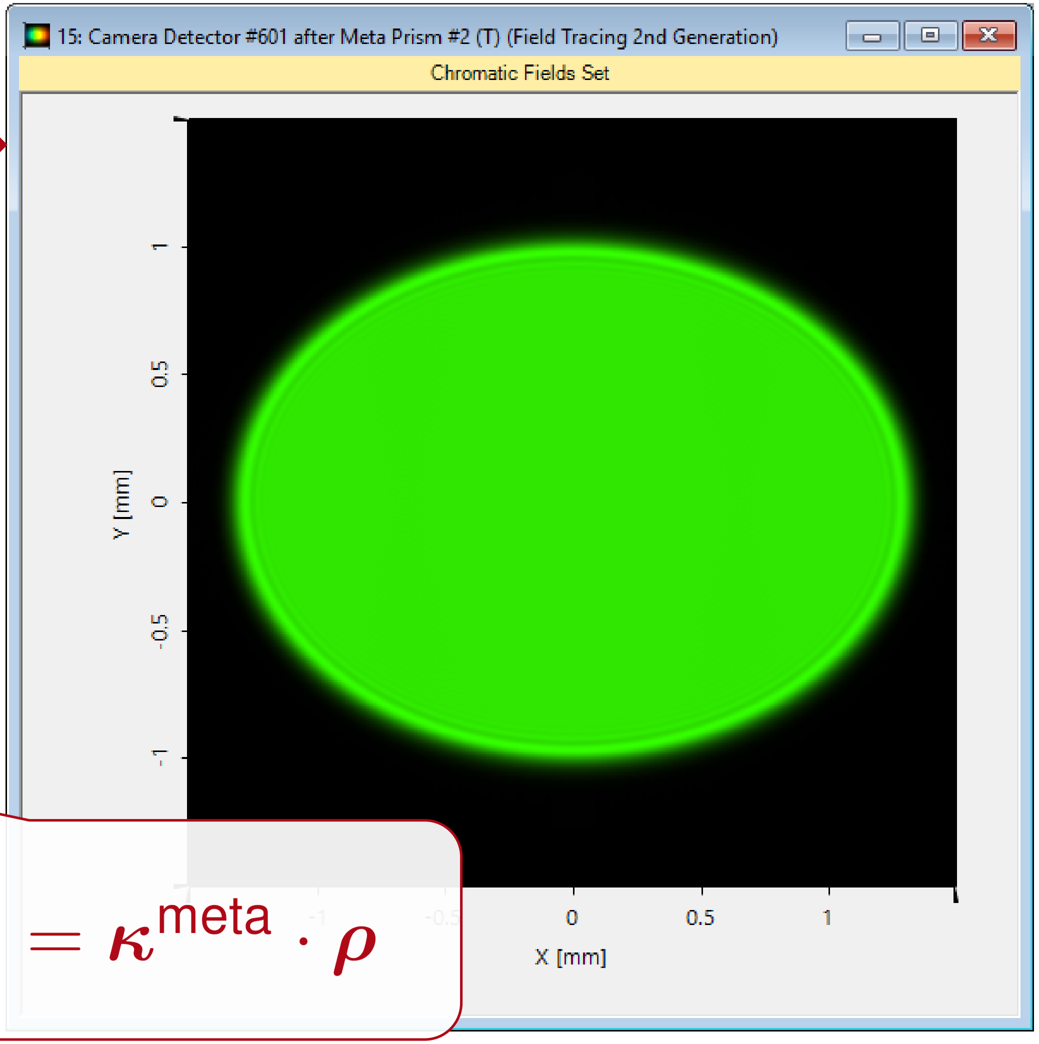




$$\Delta\psi(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{meta}} \cdot \boldsymbol{\rho}$$

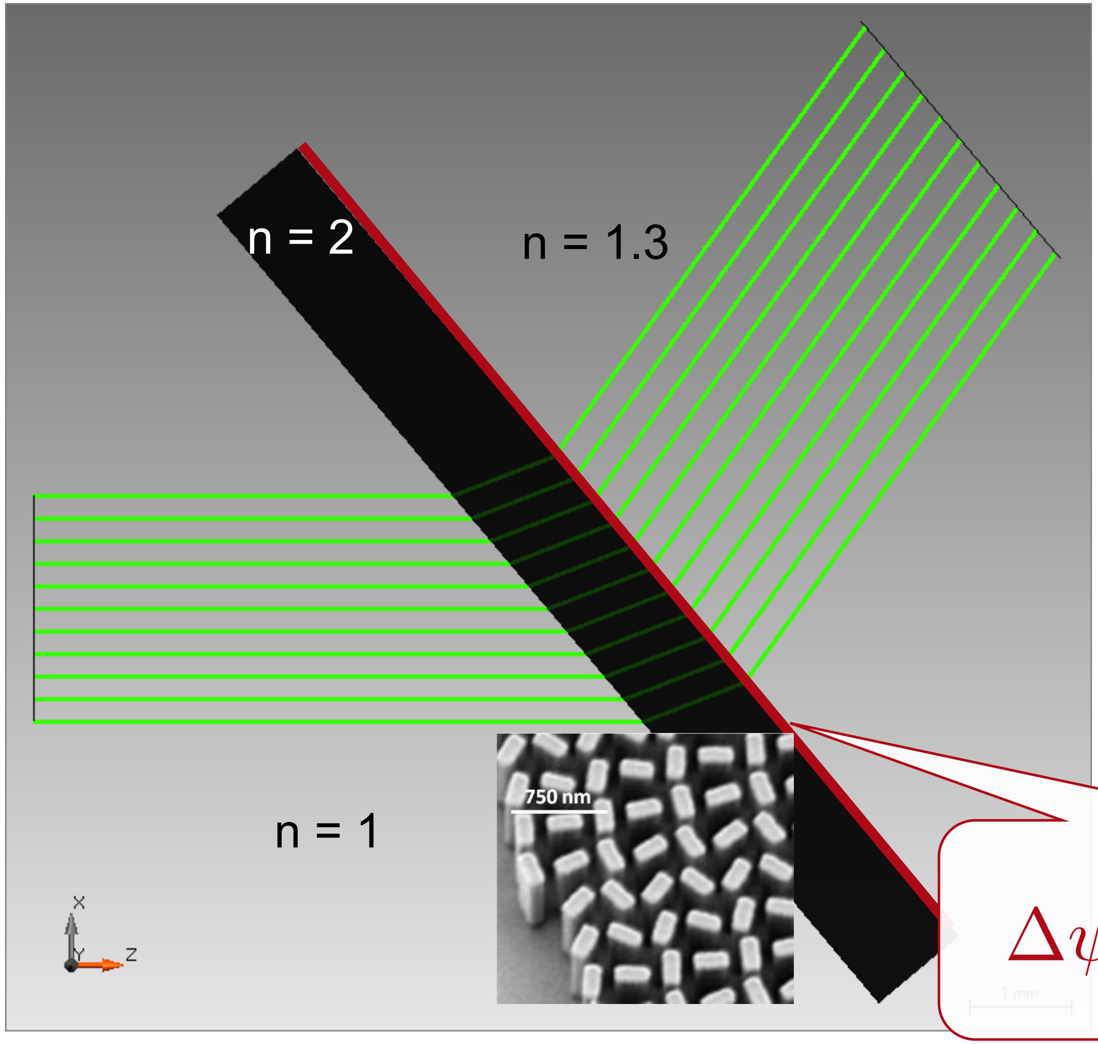
Propagation Plate with Metasurface: Ray and Field Tracing

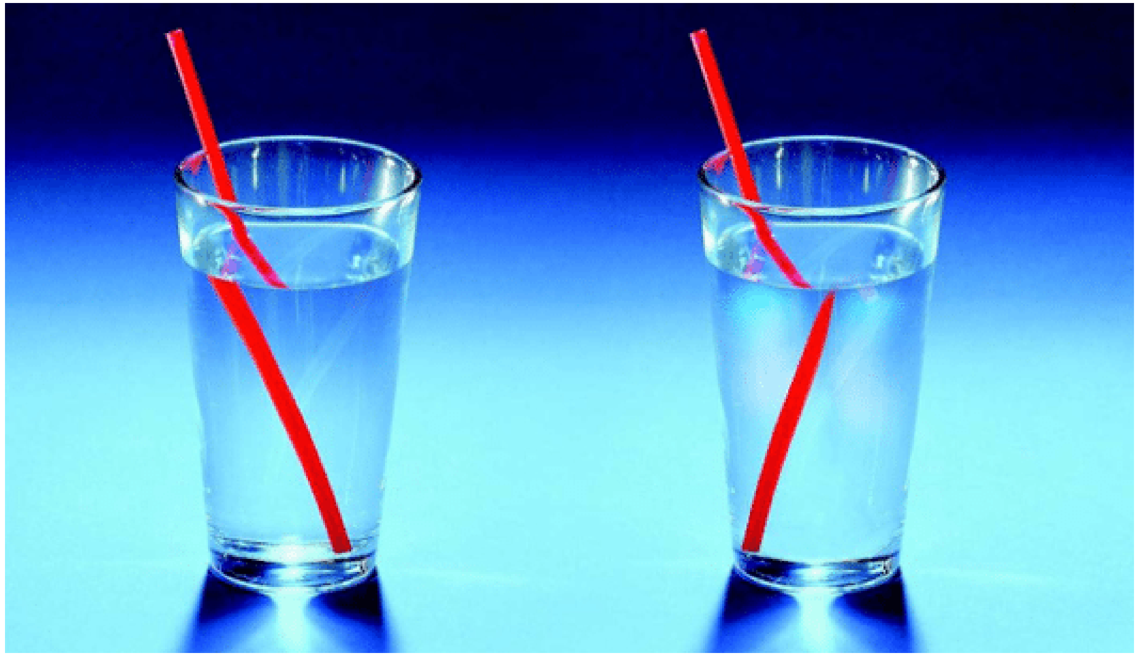




$$\Delta\psi(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{meta}} \cdot \boldsymbol{\rho}$$

Propagation Plate with Metasurface: Ray and Field Tracing





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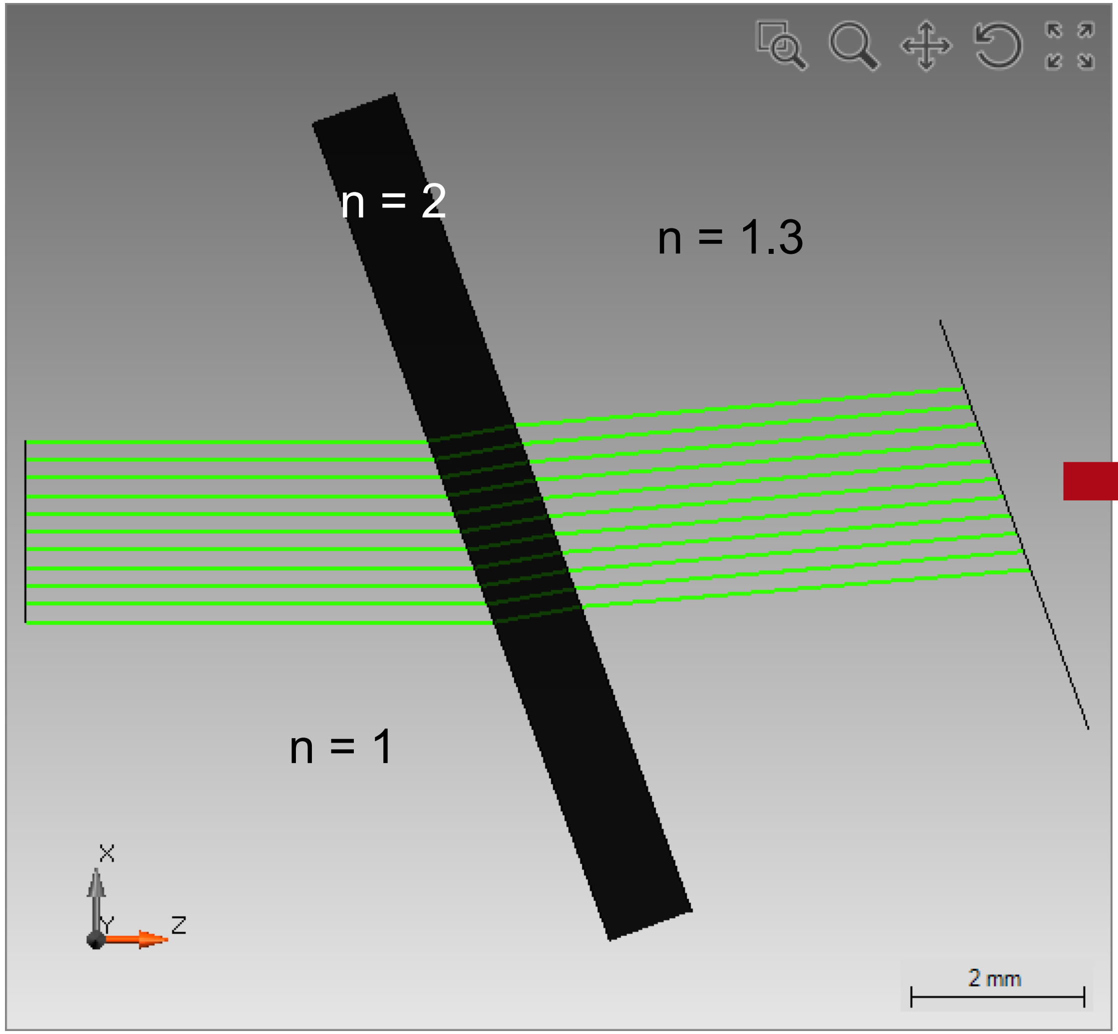
Plane Wave through Plate: Ray and Field Tracing



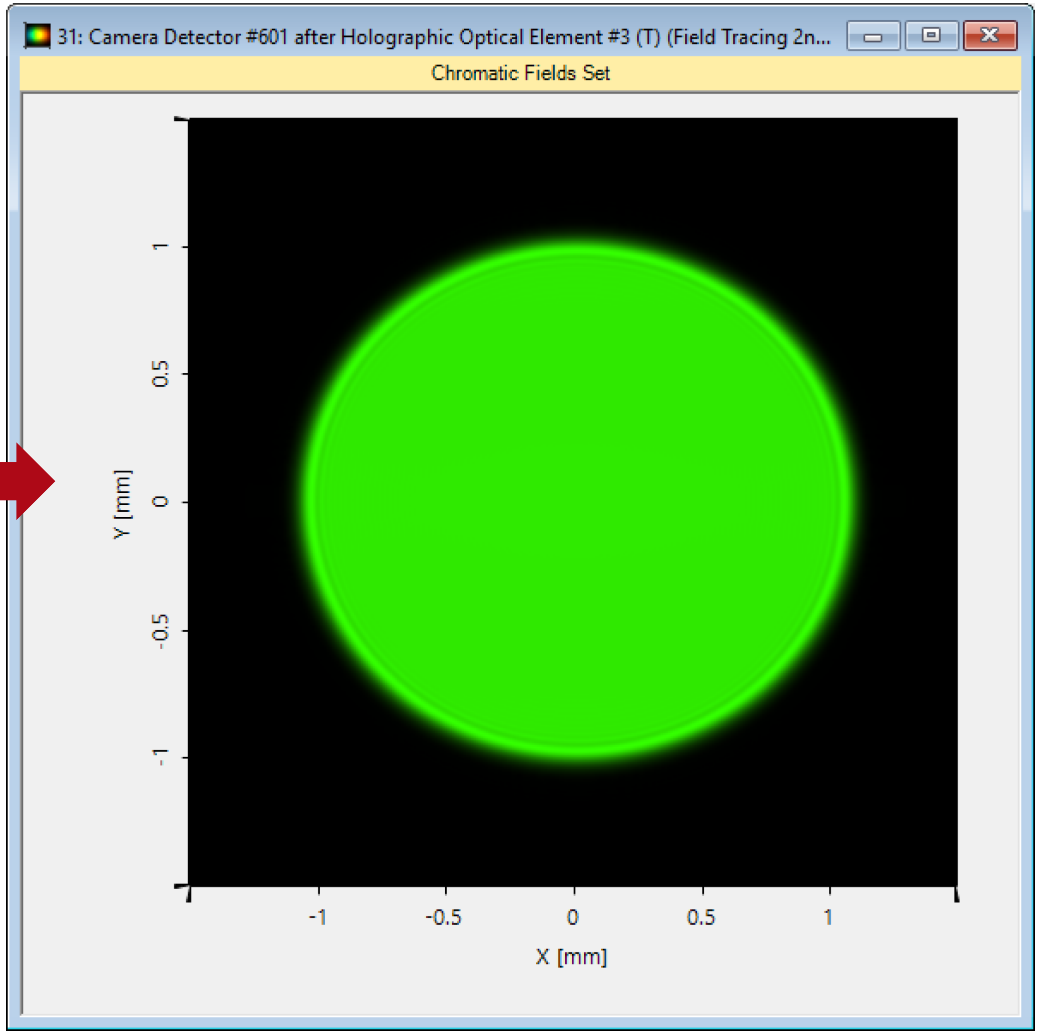
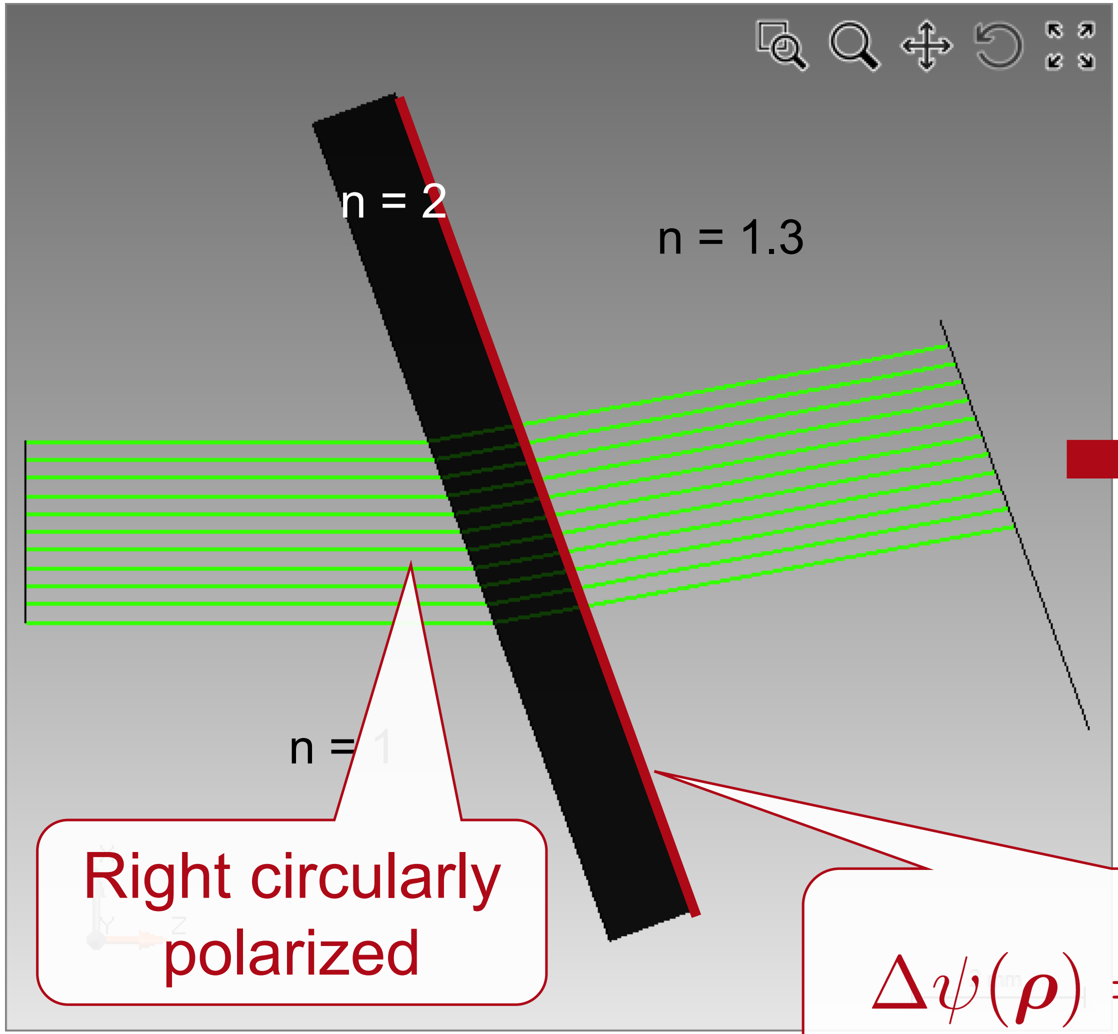
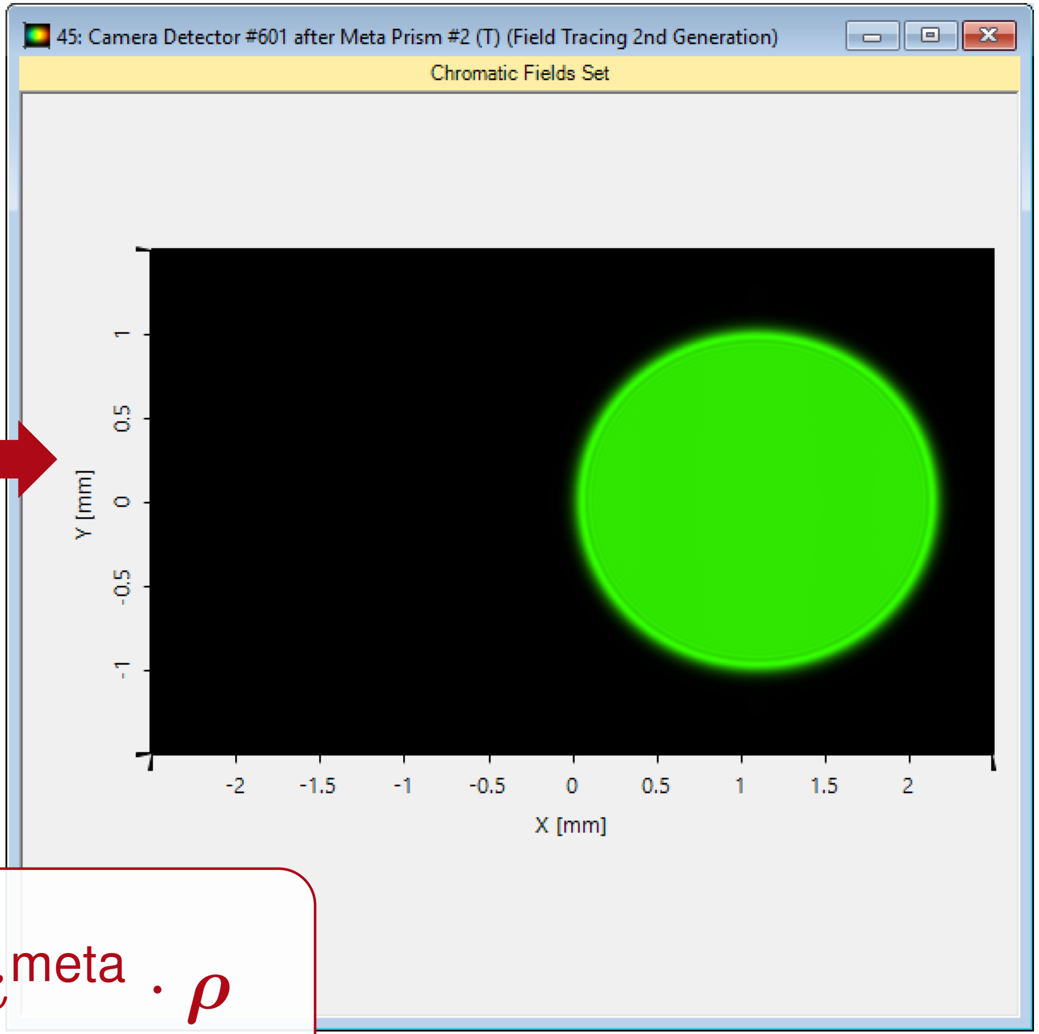


Plate with Metasurface: Ray and Field Tracing





Right circularly polarized

$$\Delta\psi(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\mathrm{meta}} \cdot \boldsymbol{\rho}$$

Plate with Metasurface: Ray and Field Tracing

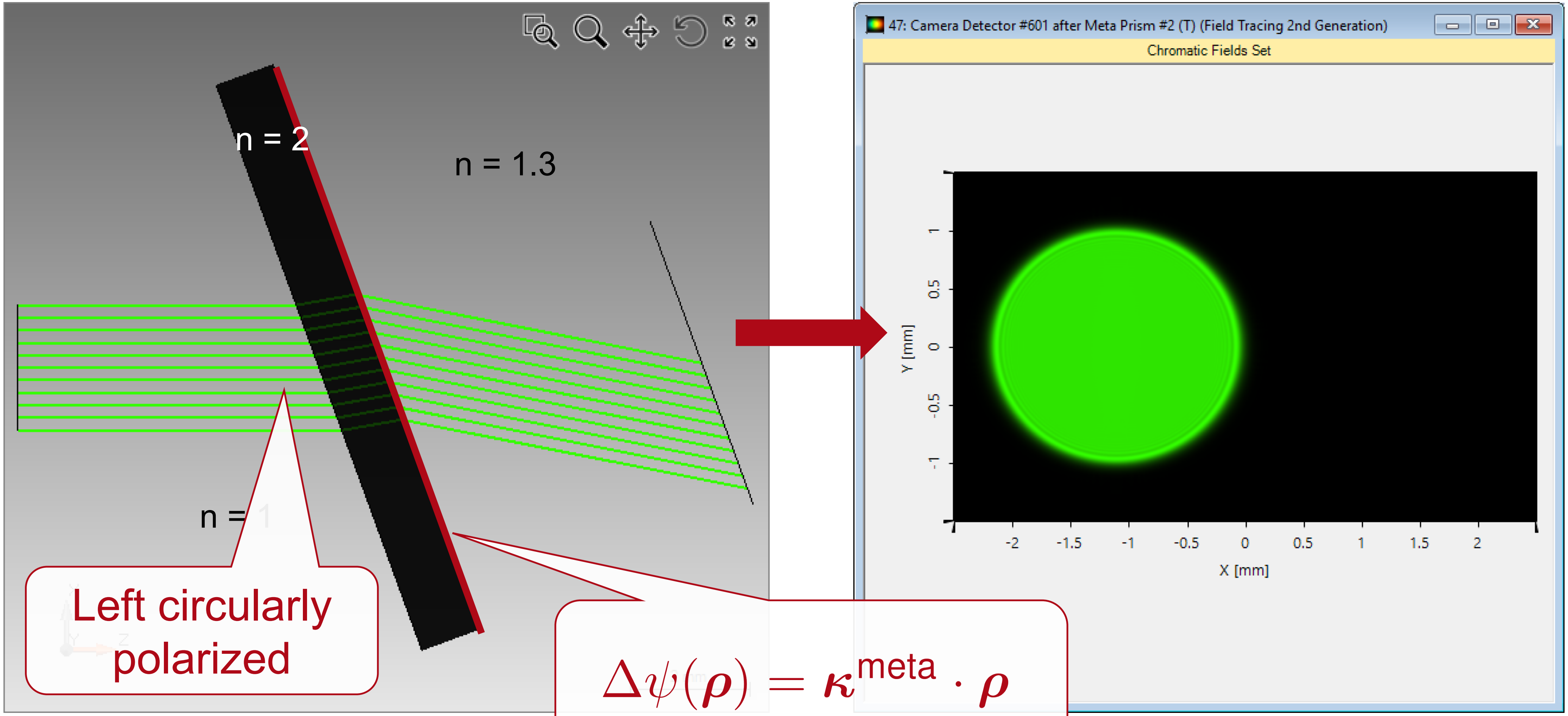


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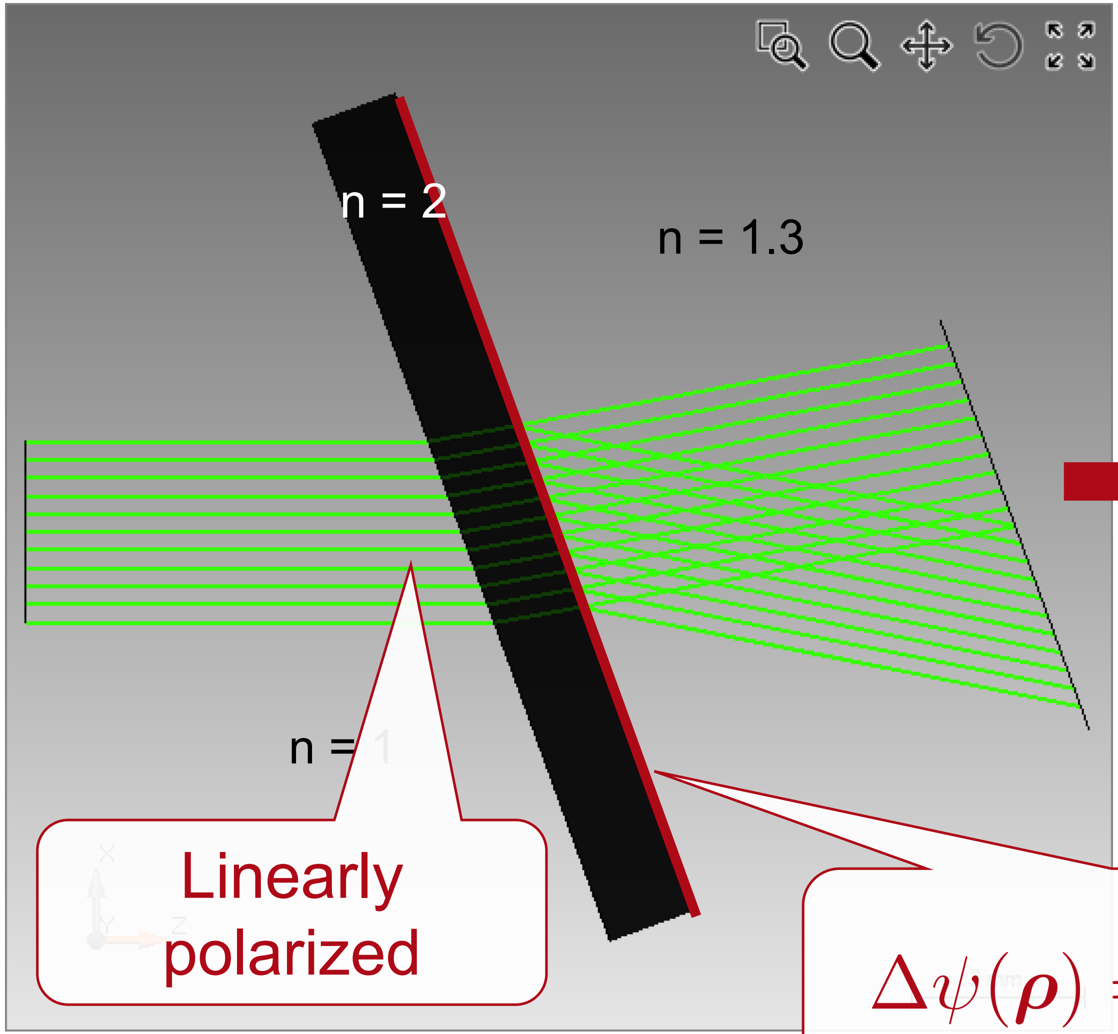
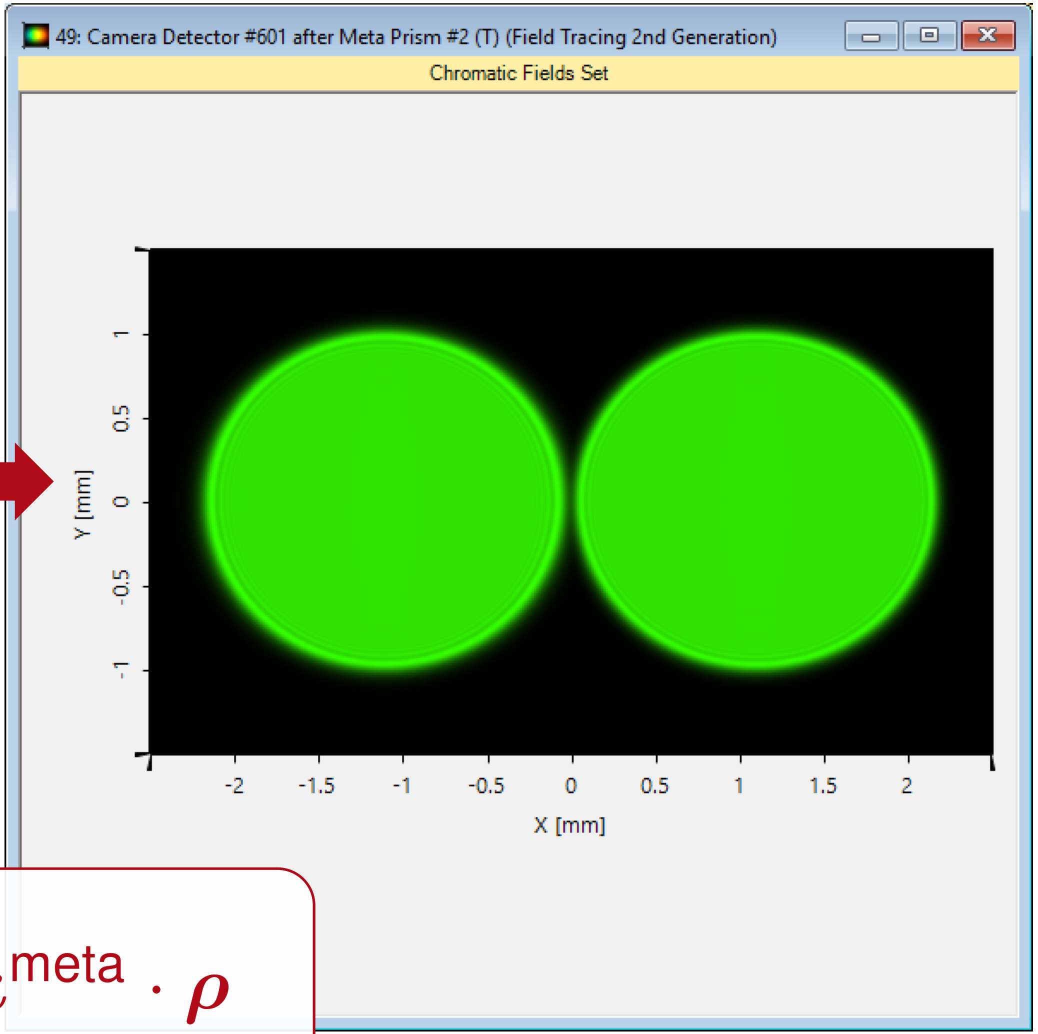
Plate with Metasurface: Ray and Field Tracing

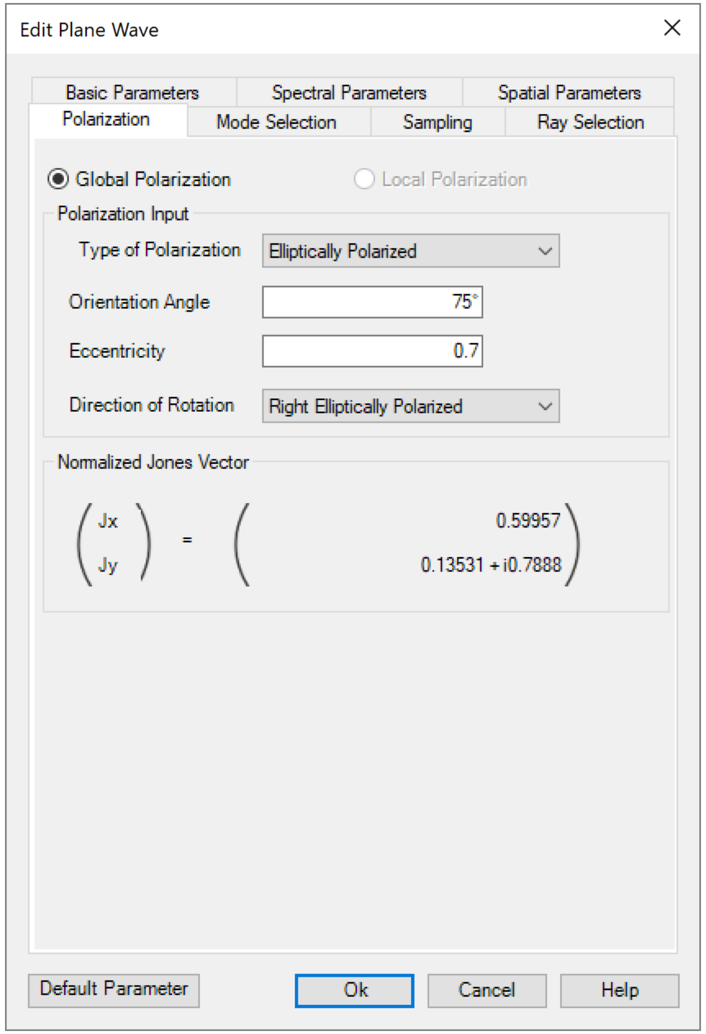


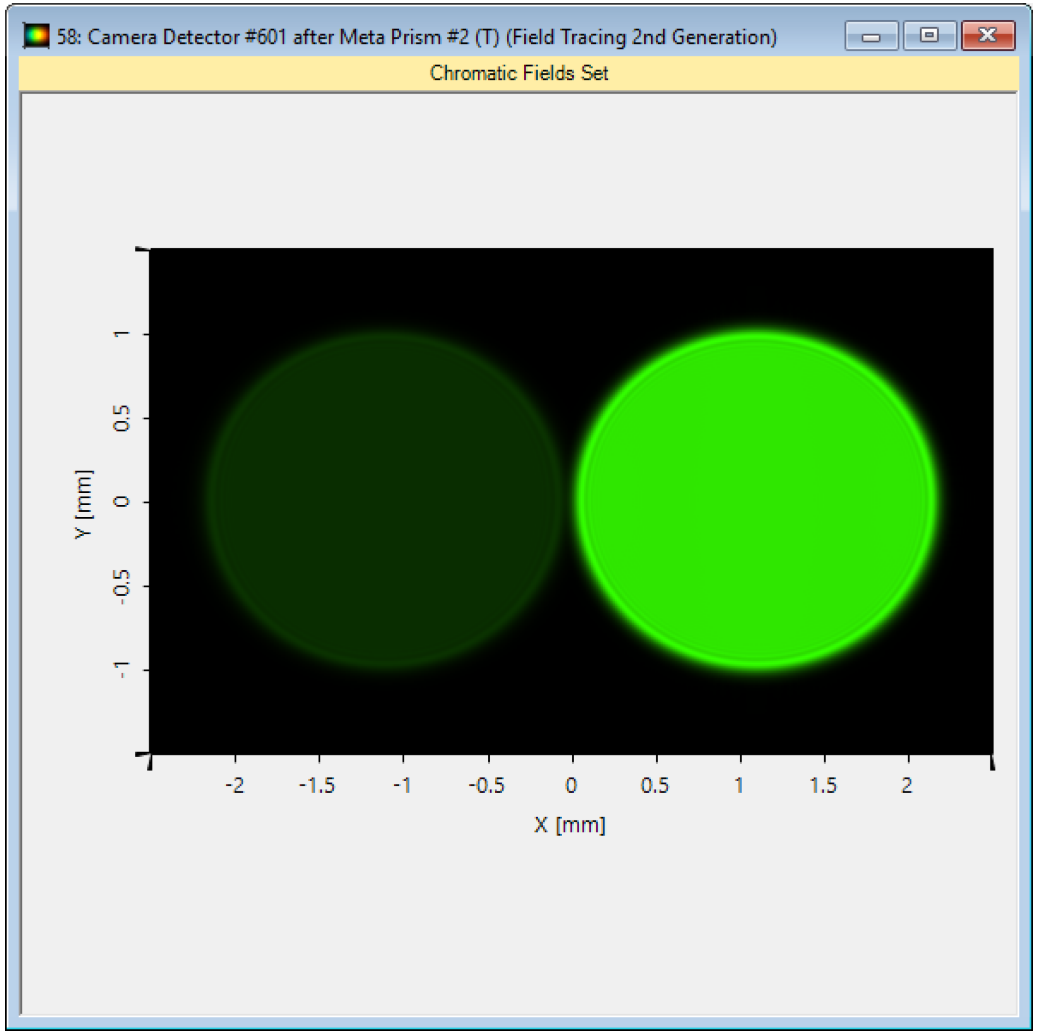


$$\Delta\psi(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{meta}} \cdot \boldsymbol{\rho}$$

Polarization Dependent Fuction of Nanofin Metalayer

Elliptical Polarization:





Diffractive layer

… with application to lenses

Physical Optics Modeling: Diffractive Layer

- In general a wavefront surface response $\Delta\psi(\boldsymbol{\rho})$ leads to the equation $\nabla_\perp\psi^{\text{out}}(\boldsymbol{\rho}) = \nabla_\perp\psi^{\text{in}}(\boldsymbol{\rho}) + \nabla_\perp\left(\Delta\psi(\boldsymbol{\rho})\right)$ and because of the local plane wave assumption (homeomorphic zone) into

$$\boldsymbol{\kappa}^{\text{out}}(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{in}}(\boldsymbol{\rho}) + \boldsymbol{K}(\boldsymbol{\rho})$$

  with $\boldsymbol{K}(\boldsymbol{\rho}) \stackrel{\text{def}}{=} \nabla_\perp\left(\Delta\psi(\boldsymbol{\rho})\right)$.

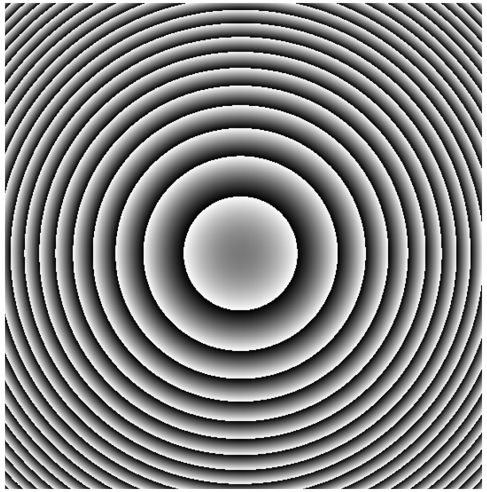
- This equation is directly related to a locally formulated grating equation

$$\boldsymbol{\kappa}^{\text{out}}(\boldsymbol{\rho}) = \boldsymbol{\kappa}^{\text{in}}(\boldsymbol{\rho}) + m\left(2\pi/d_x(\boldsymbol{\rho}), 2\pi/d_y(\boldsymbol{\rho})\right)$$

  with the local grating period $\boldsymbol{d}(\boldsymbol{\rho}) = \left(d_x(\boldsymbol{\rho}), d_y(\boldsymbol{\rho})\right)$.

- That leads to the basic principle of a diffractive layer via:

$$\boldsymbol{d}(\boldsymbol{\rho}) = 2\pi\left(\left(\partial\psi(\boldsymbol{\rho})/\partial x\right)^{-1}, \left(\partial\psi(\boldsymbol{\rho})/\partial y\right)^{-1}\right)$$



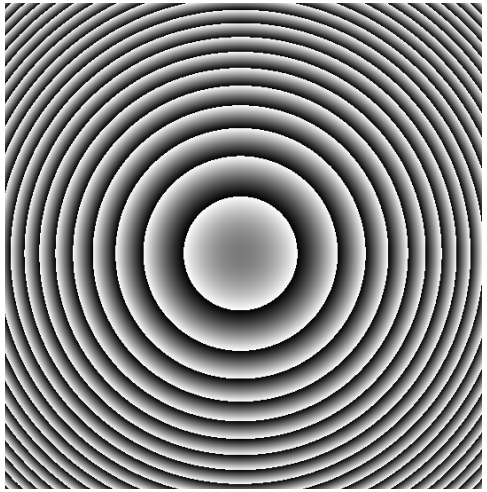
Physical Optics Modeling: Diffractive Layer

- This design and modeling understanding results in the decomposition of the output field into a series of local grating orders:

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \left\{\mathbf{B}^{(1)}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\big(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})+\Delta\psi(\boldsymbol{\rho})\big)$$
$$+\sum_{m=-\infty,m\neq 1}^{\infty}\left\{\mathbf{B}^{(m)}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\big(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})+m\Delta\psi(\boldsymbol{\rho})\big)$$

- The 2×2 matrix $\mathbf{B}^{(m)}(\boldsymbol{\rho};\psi^{\text{in}})$ expresses the Rayleigh-matrix of grating theory and is rigorously calculated per direction and period by the Fourier Modal Method (FMM). Design should minimize Rayleigh coefficients for all undesired orders.

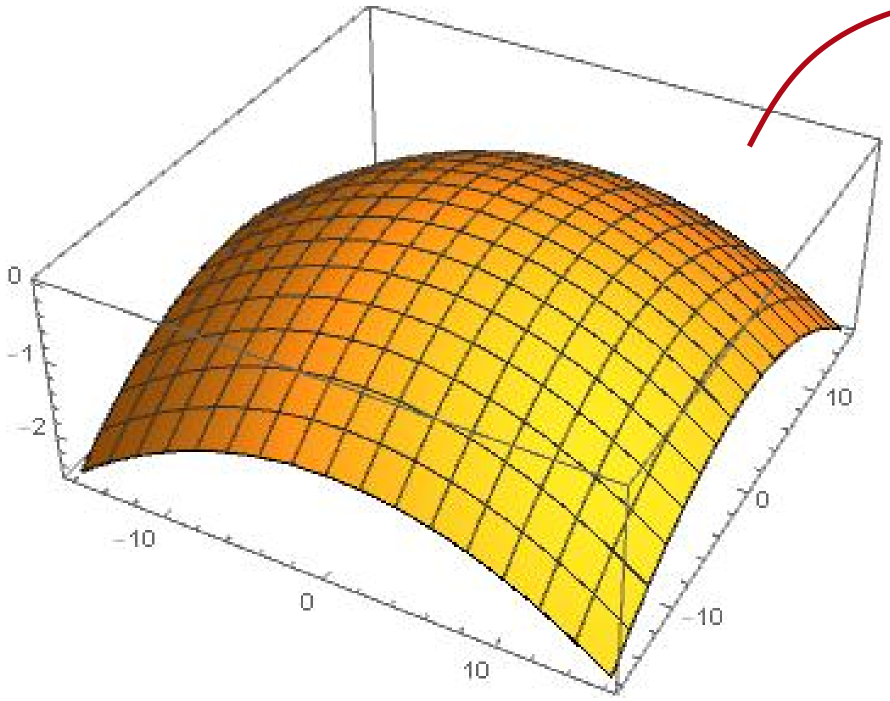
- Complications: Period drastically varies over surface, which results in a laterally varying number of propagating subfields. Full treatment available in **VirtualLab Lens Solutions**.

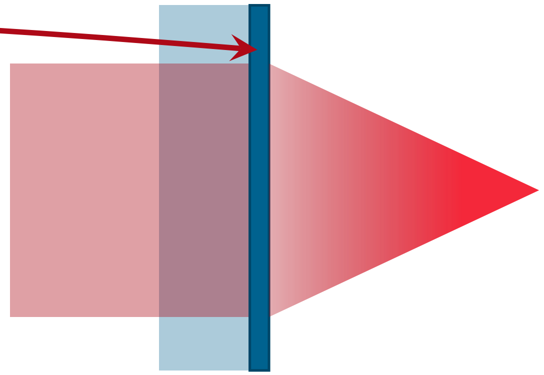


Wavefront Surface Response of Focusing Lens

- In order to transform a plane incident field into a spherical convergent one the wavefront surface response should be:

$$\Delta\psi(\boldsymbol{\rho}) = k_0 n \left(f - \sqrt{\|\boldsymbol{\rho}\|^2 + f^2} \right)$$

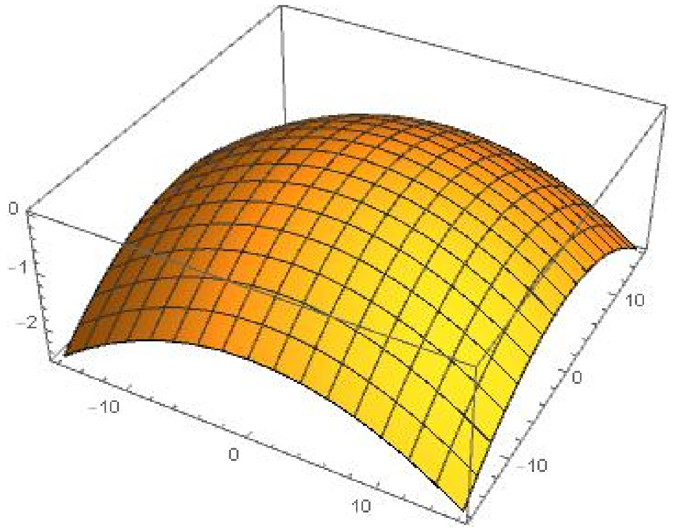


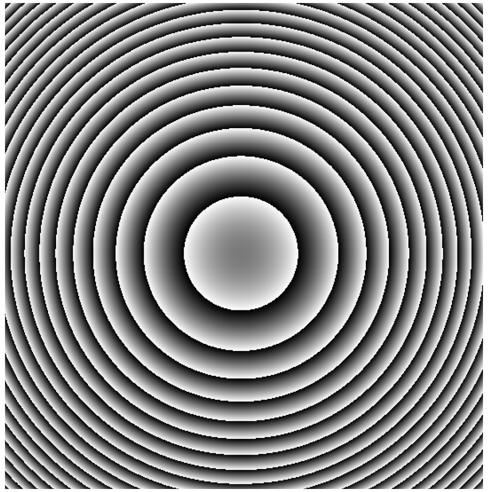


Structure Design

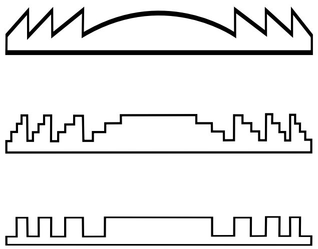
- Wrap the WSR: $(\Delta\psi(\boldsymbol{\rho}))^{\text{DOE}} = \mod_{p2\pi}\left\{k_0 n\left(f - \sqrt{\|\boldsymbol{\rho}\|^2 + f^2}\right)\right\}$ with $p \in \mathbb{N}$.
- For $p = 1$ local radial period follows with $d(\rho) = 2\pi/\Delta\psi'(\rho)$.
- Structure design by inverse Thin Element Approximation (TEA): The height profile h^{DOE} is given by:

$$h^{\text{DOE}}(\rho) = \frac{\lambda}{2\pi\Delta n}\Delta\psi(\rho)^{\text{DOE}}$$

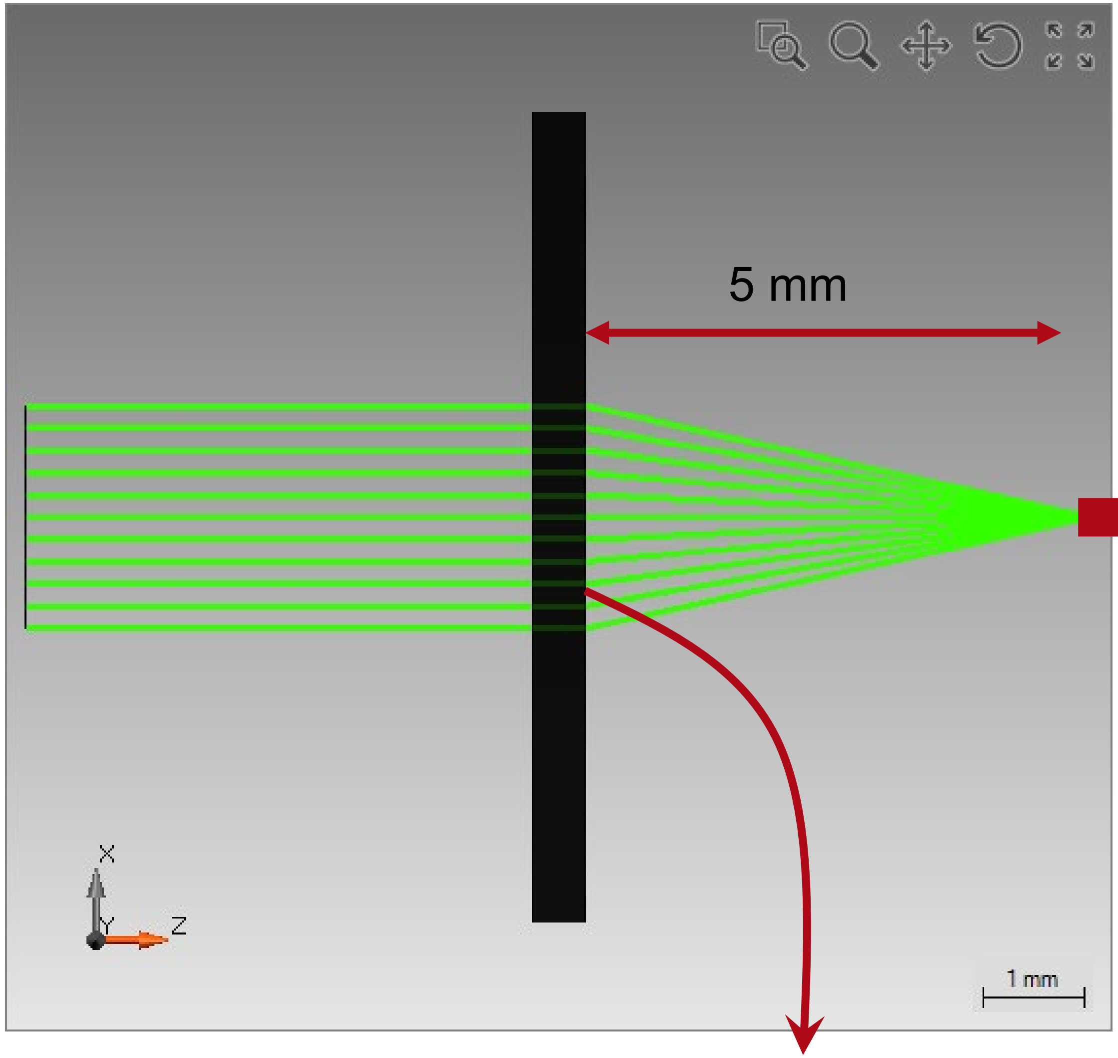


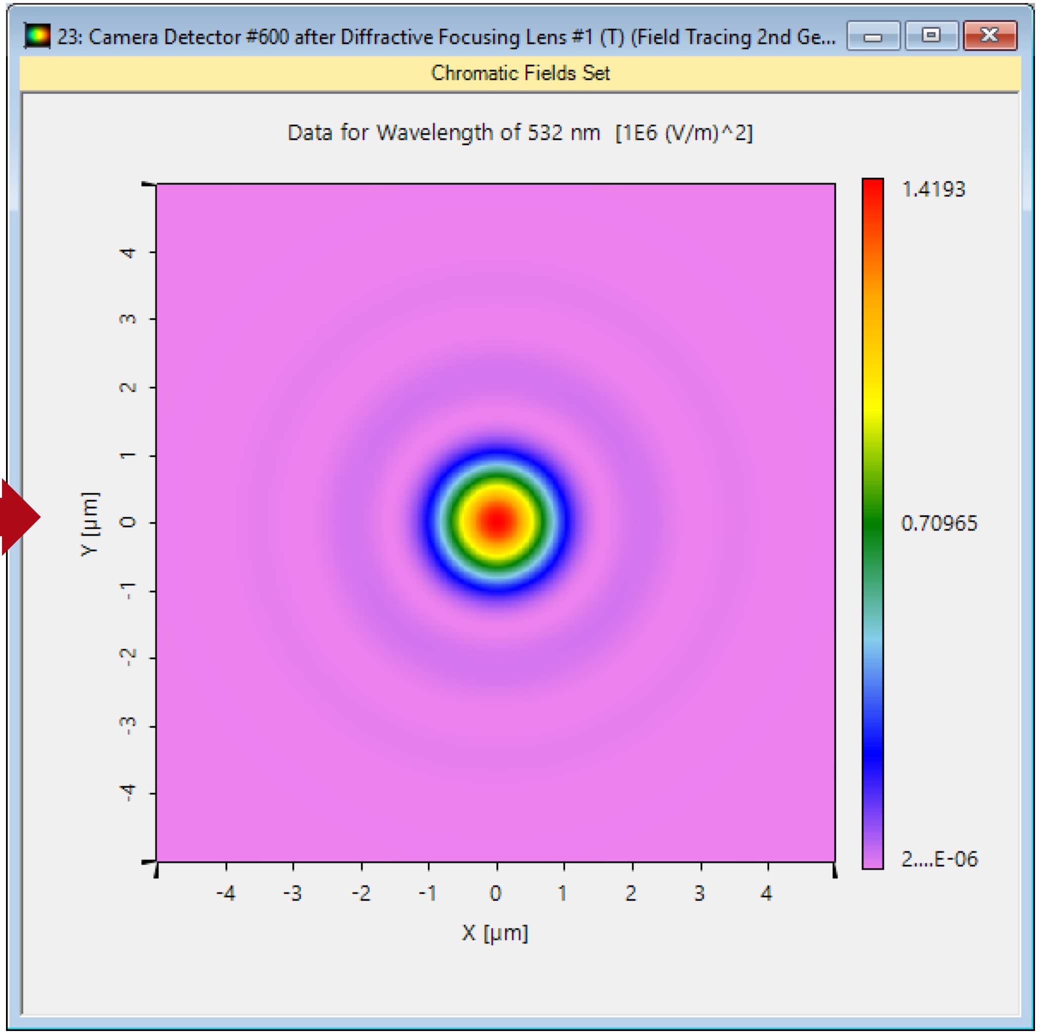


Profile quantization



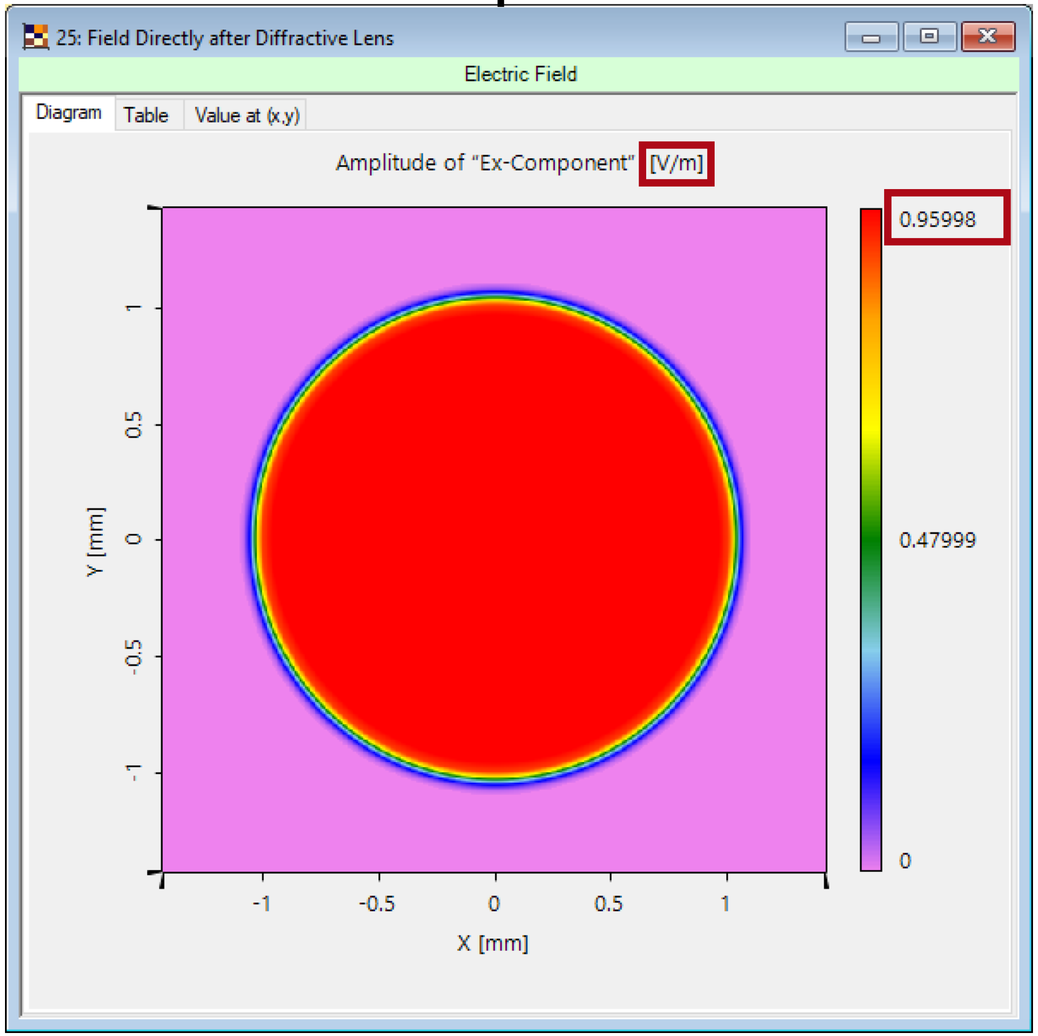
Focusing Diffractive Lens with NA=0.2: Ray and Field Tracing





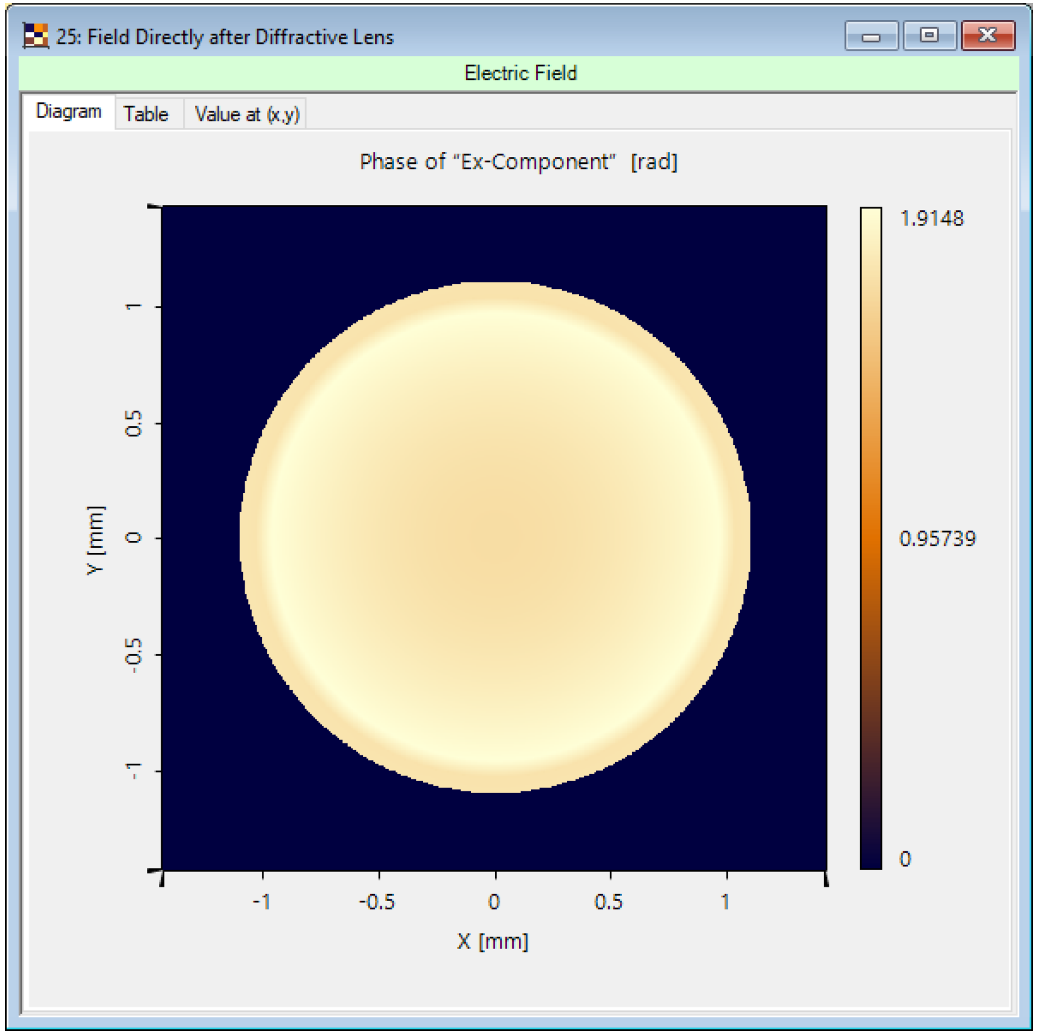
Focusing Diffractive Lens with NA=0.2: Ray and Field Tracing

Amplitude



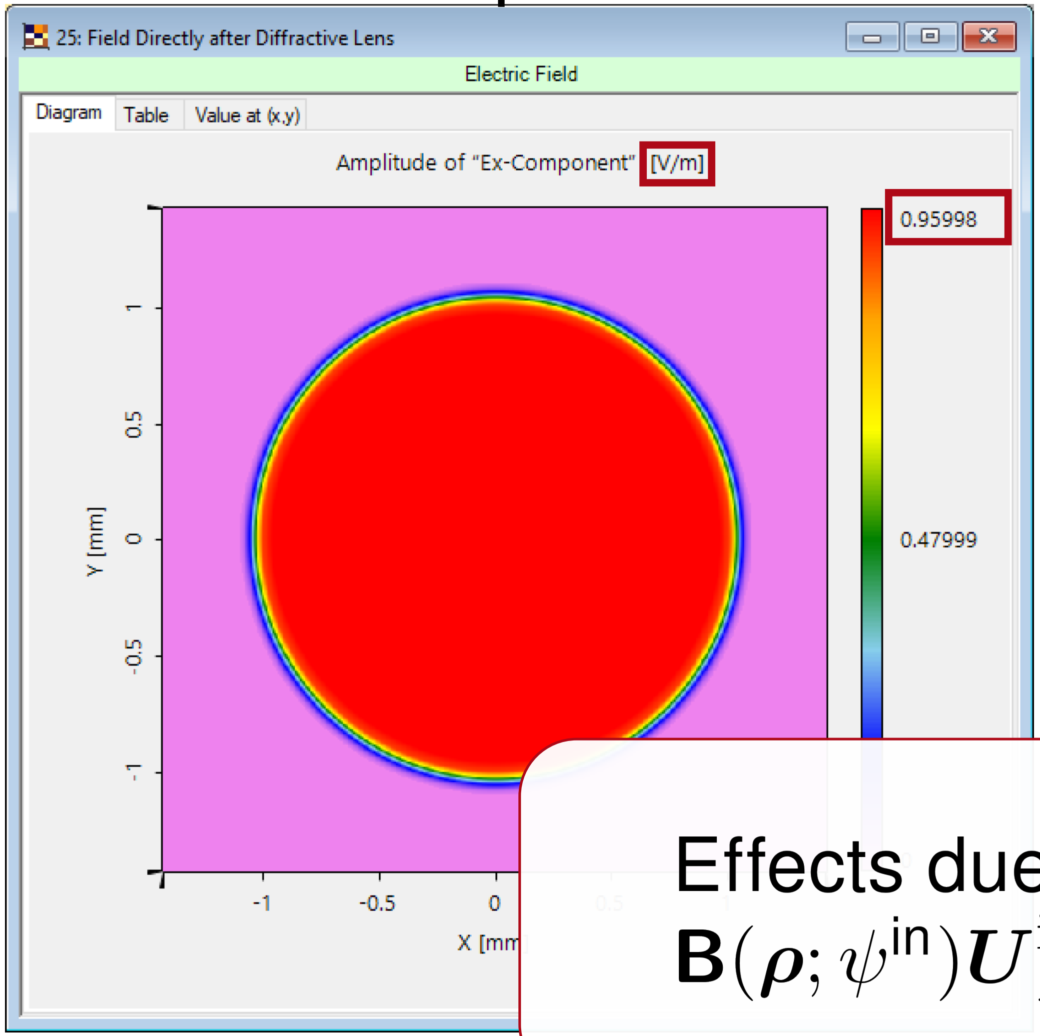
Ex

Phase



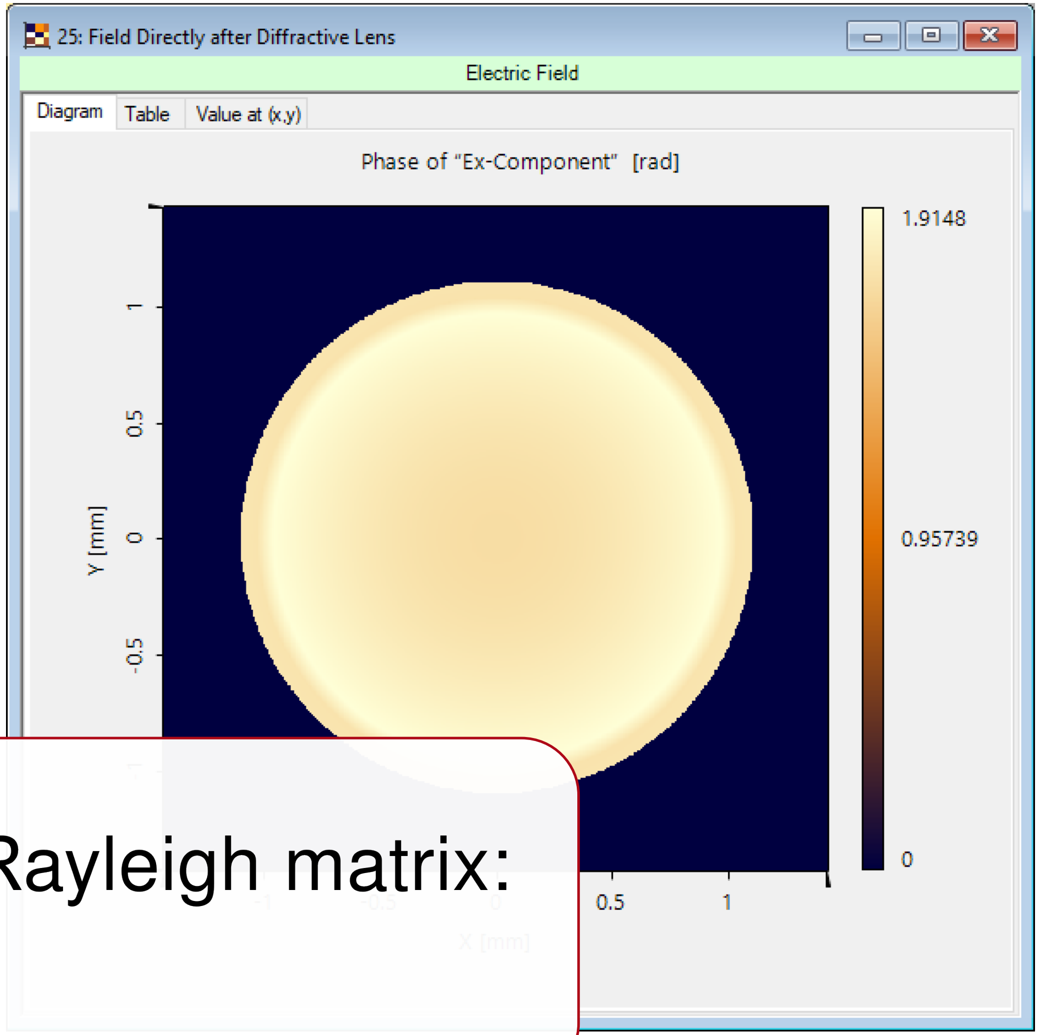
Focusing Diffractive Lens with NA=0.2: Ray and Field Tracing

Amplitude



Ex

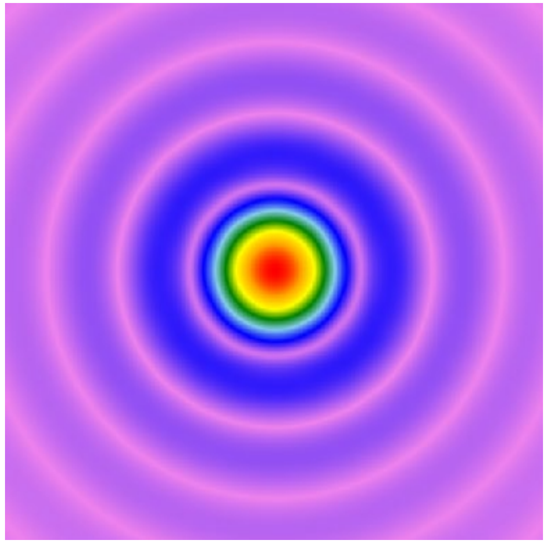
Phase



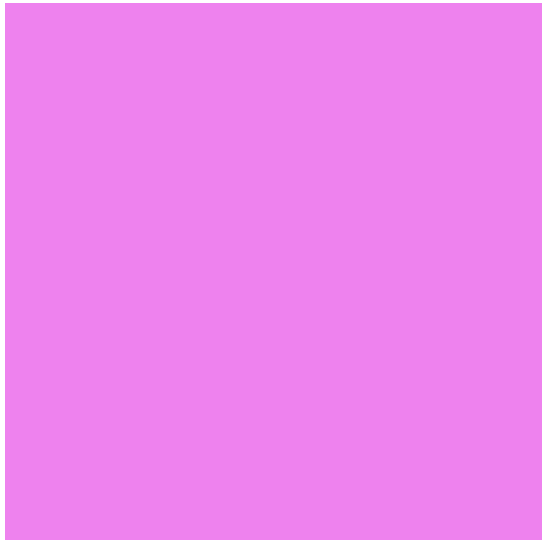
Effects due to Rayleigh matrix:

$$\mathbf{B}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})$$

Focusing Diffractive Lens with NA=0.2: Ray and Field Tracing



Amplitude Ex

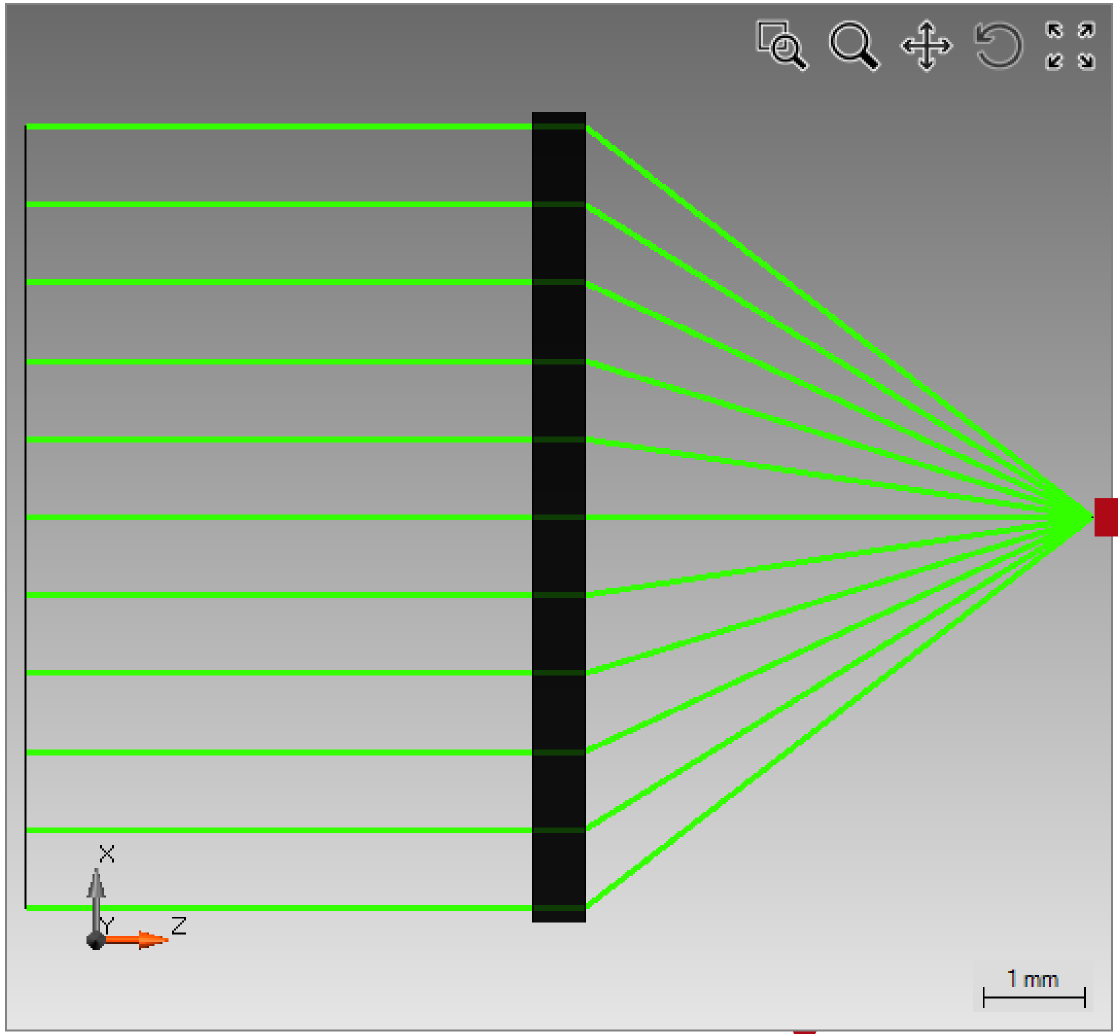


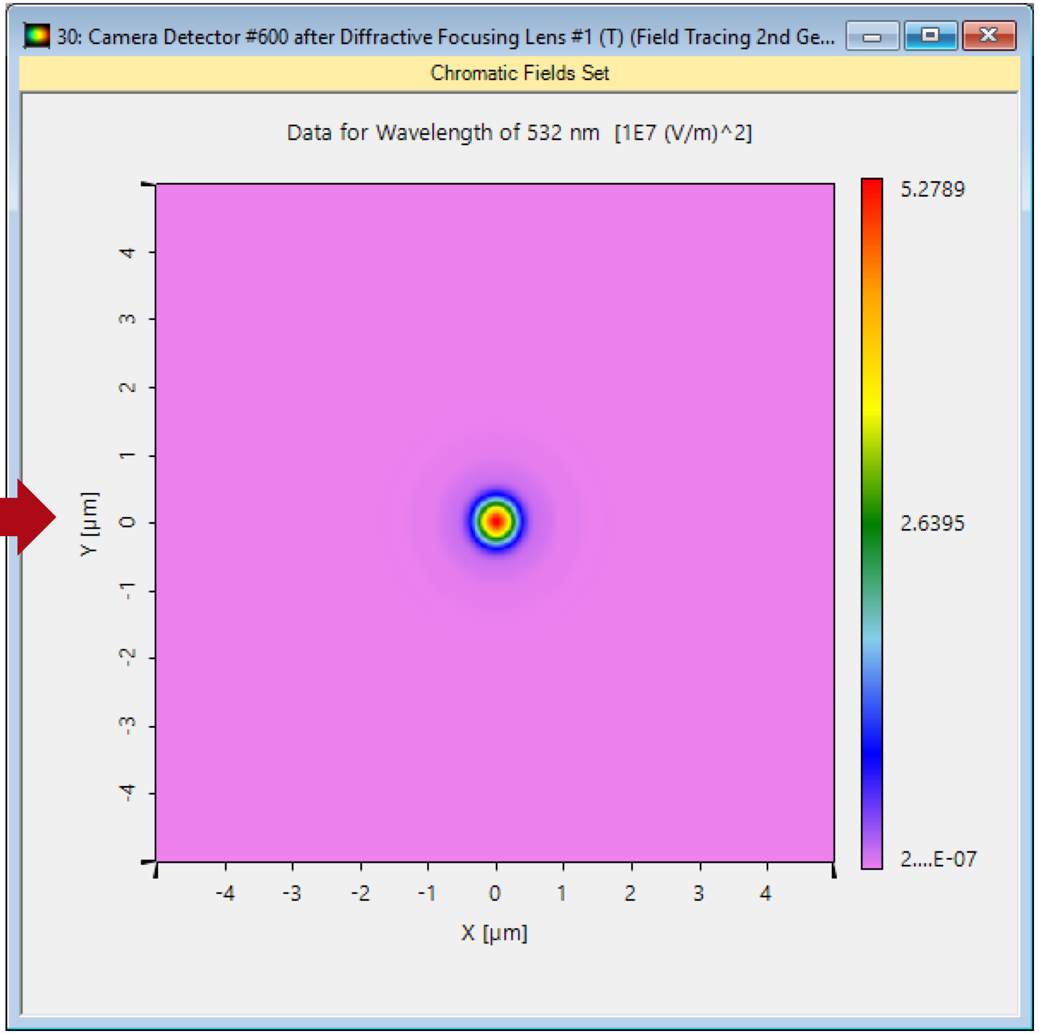
Amplitude Ey

Amplitude Ez

- Amplitudes in Focus (Same scaling!)

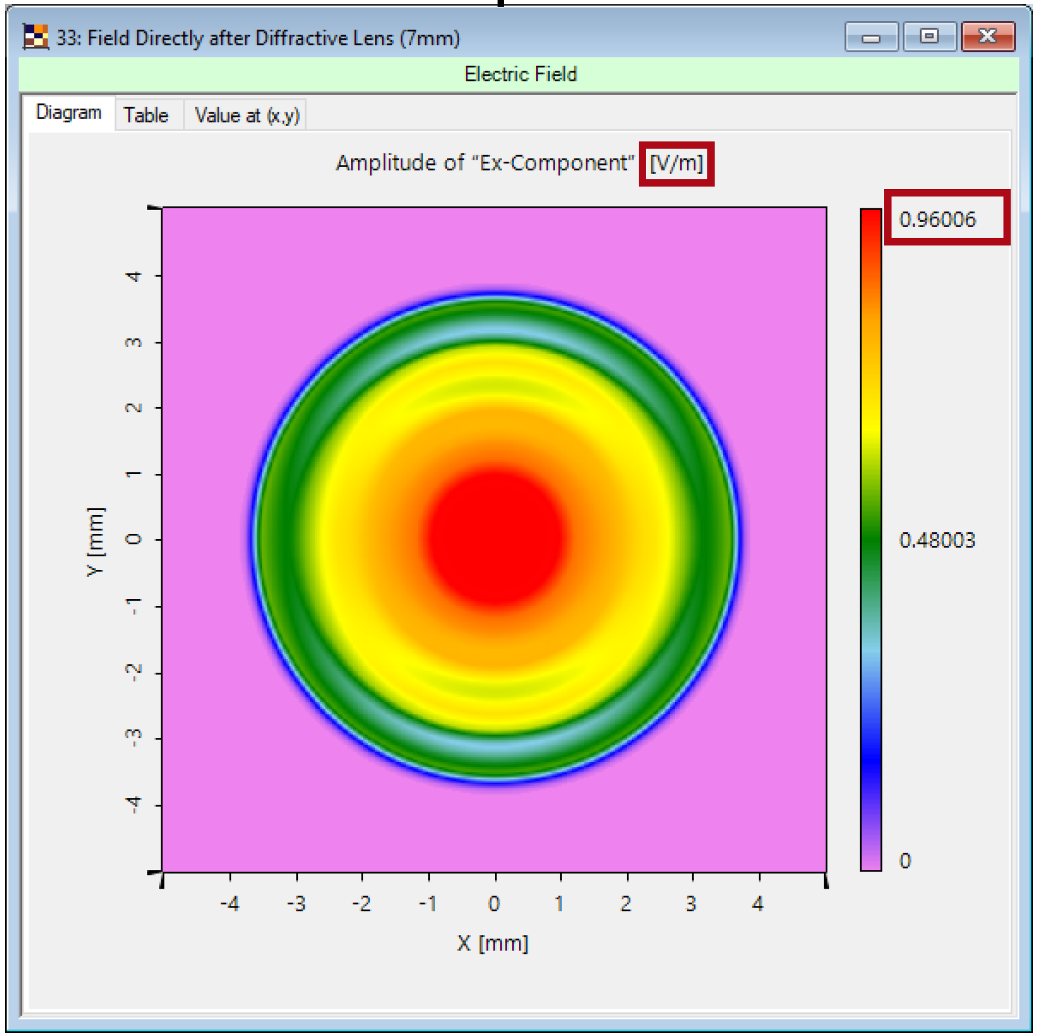
Focusing Diffractive Lens with NA=0.57: Ray and Field Tracing





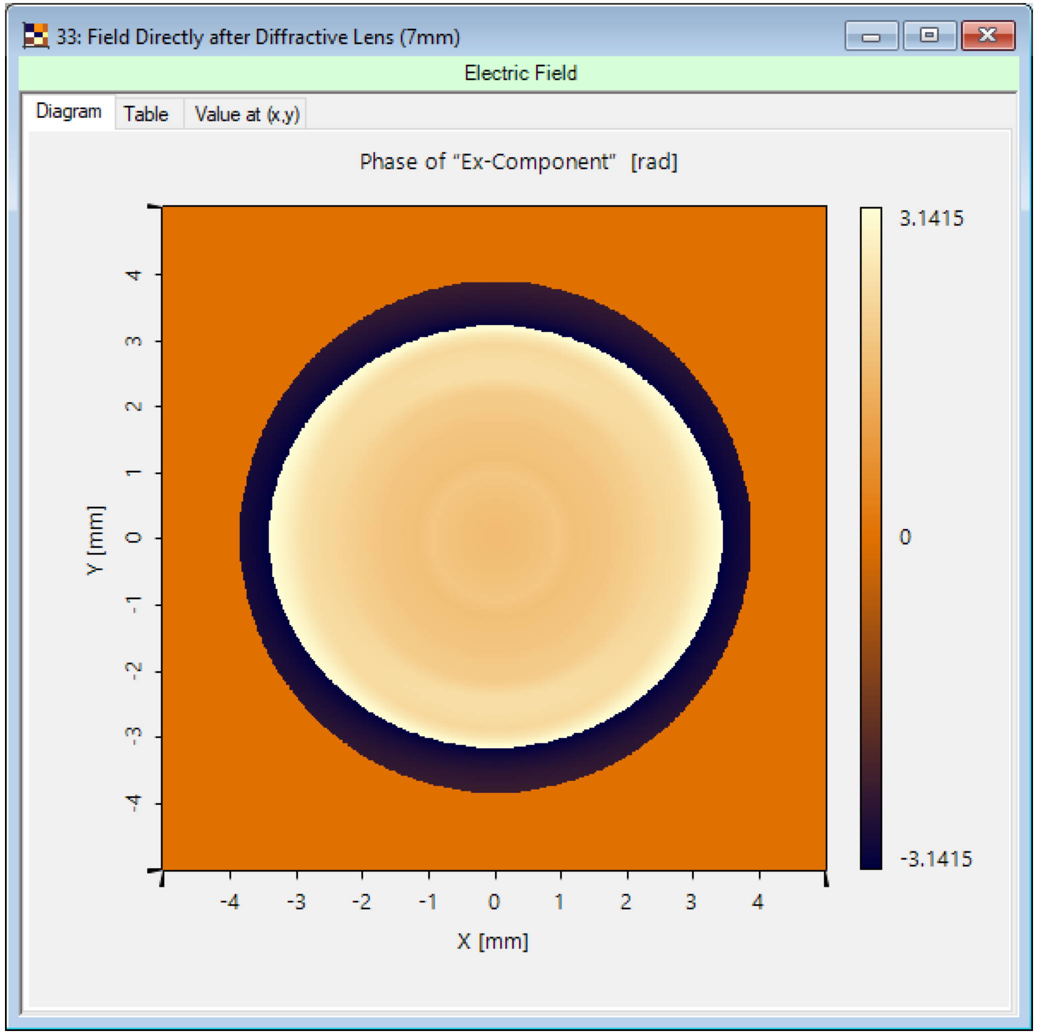
Focusing Diffractive Lens with NA=0.57: Ray and Field Tracing

Amplitude

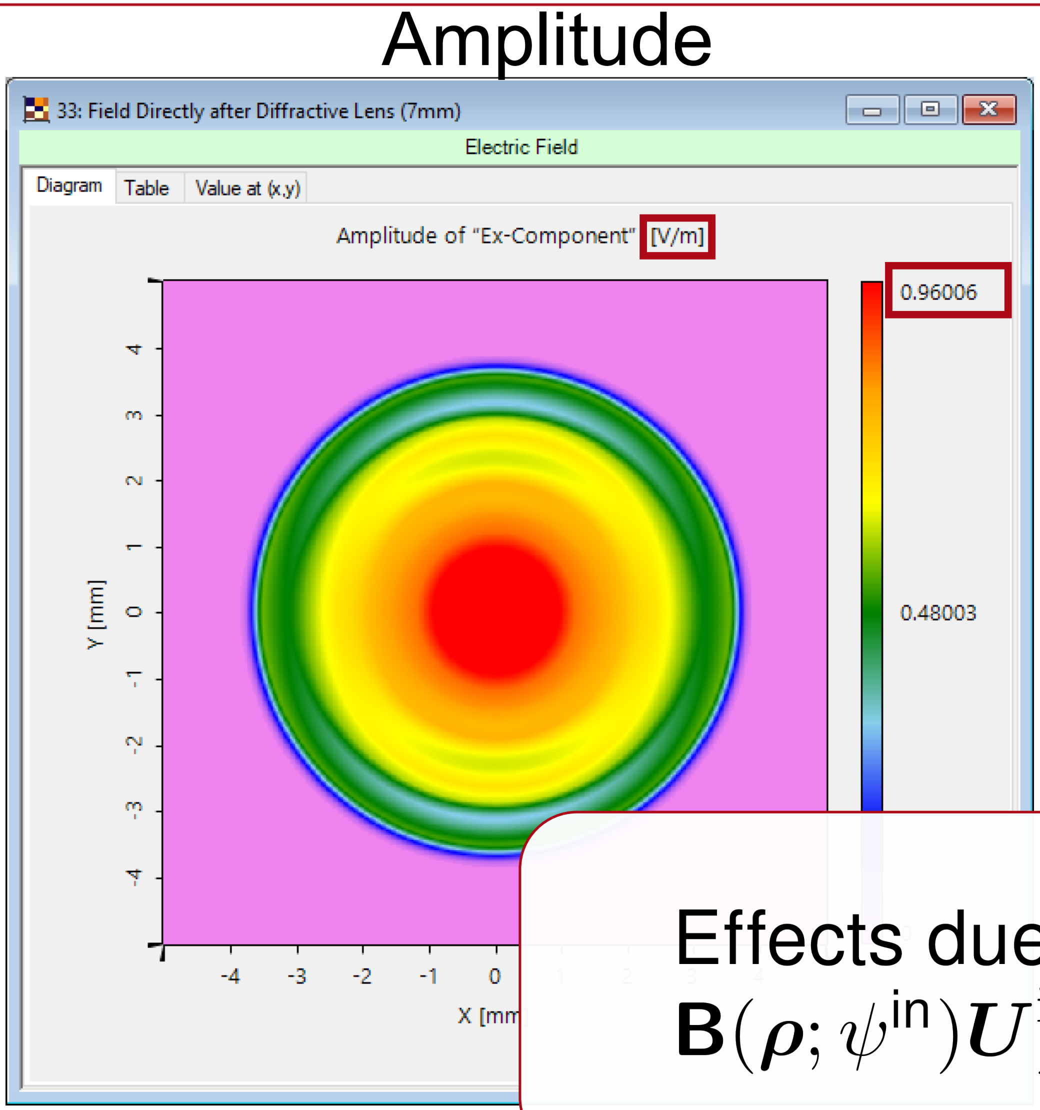


Ex

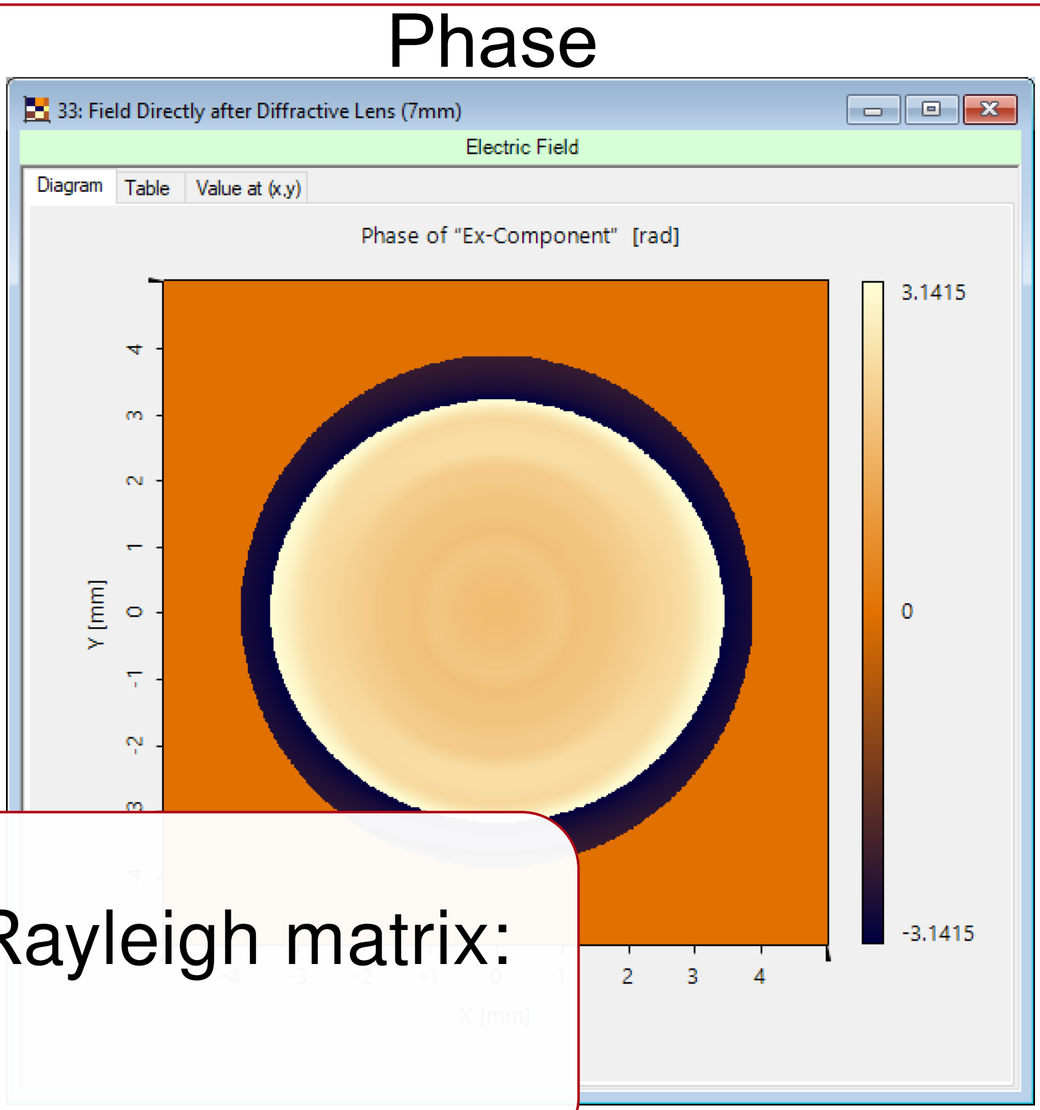
Phase



Focusing Diffractive Lens with NA=0.57: Ray and Field Tracing

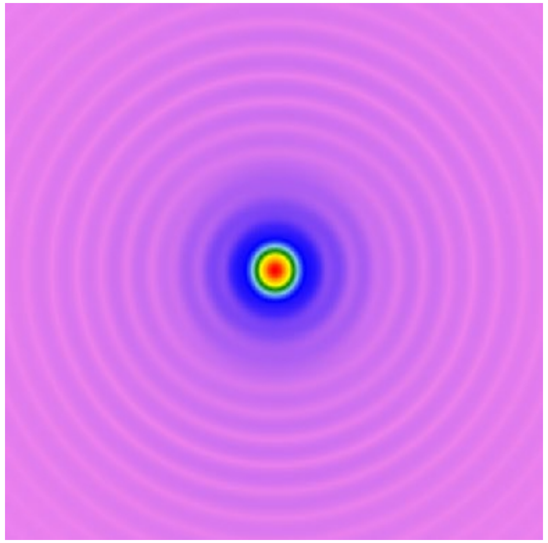


Ex



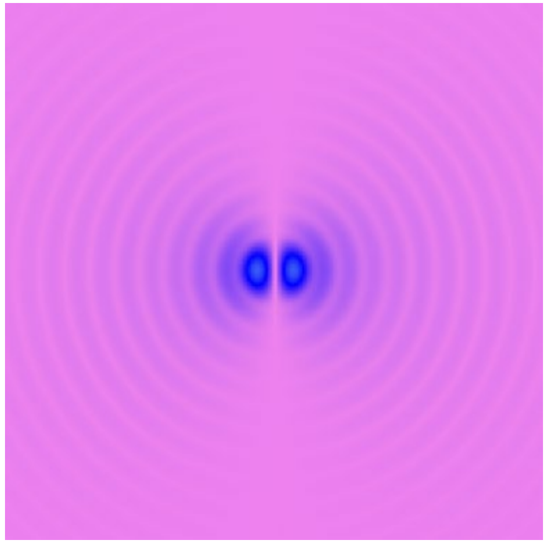
Effects due to Rayleigh matrix:
$\mathbf{B}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})$

Focusing Diffractive Lens with NA=0.57: Ray and Field Tracing



Amplitude Ex

Amplitude Ey



Amplitude Ez

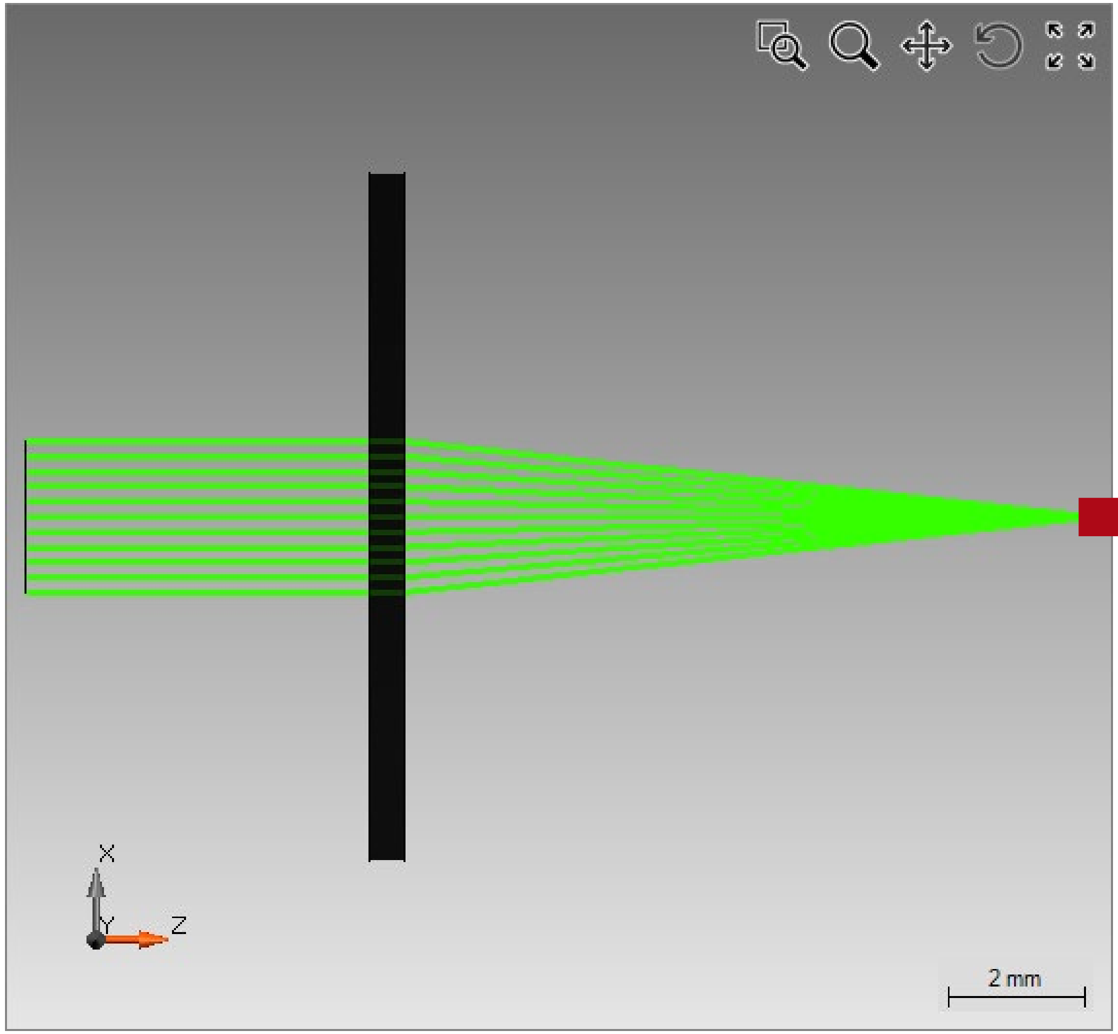
- Amplitudes in Focus (Same scaling!)

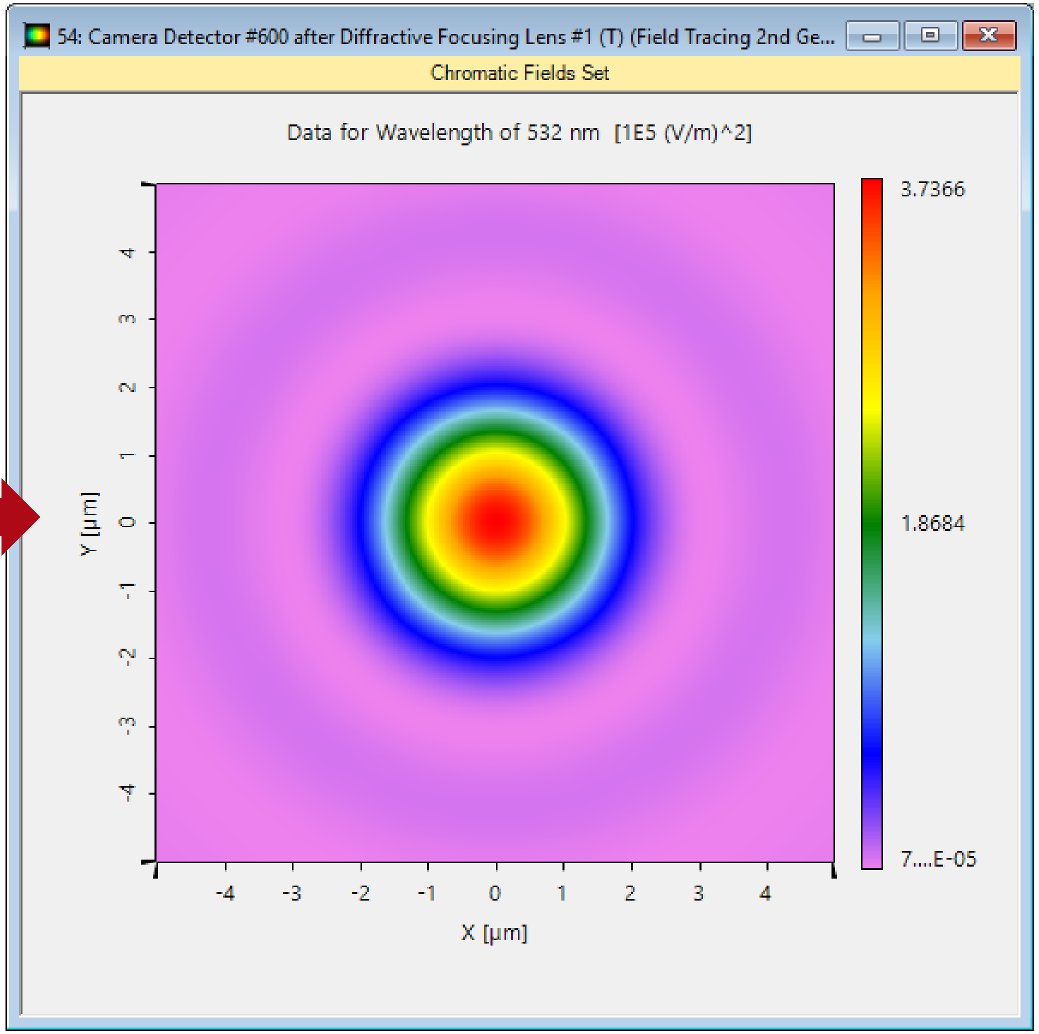
Focusing Diffractive Lens with NA=0.57: Ray and Field Tracing

Amplitude Ex | Amplitude Ey | Amplitude Ez

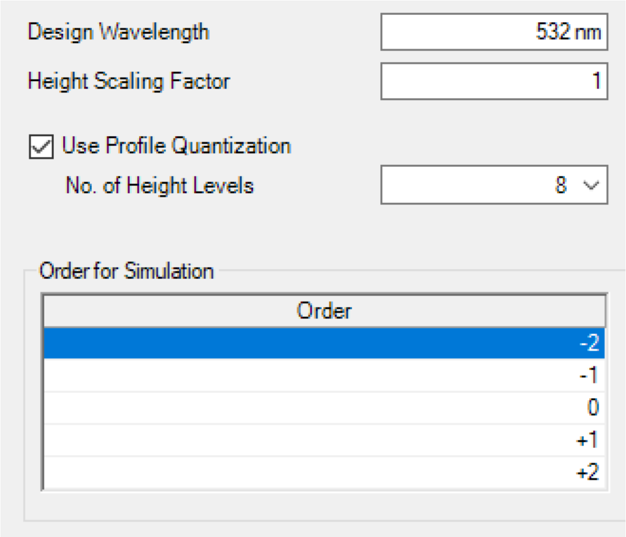
- Amplitudes in Focus (Same scaling!)

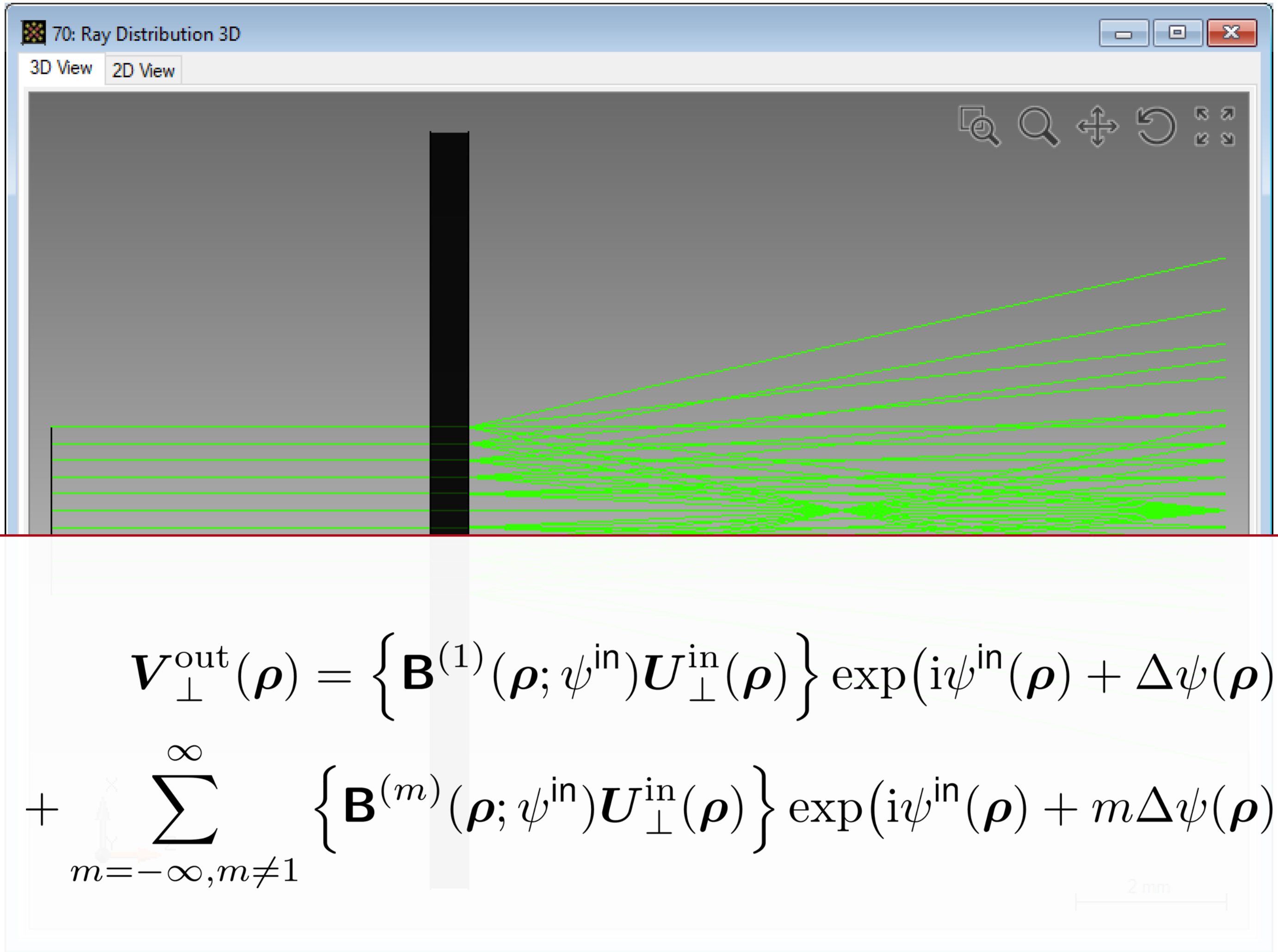
Lens with NA=0.1 and 8 Height Values: Ray and Field Tracing





Inclusion of Higher Orders

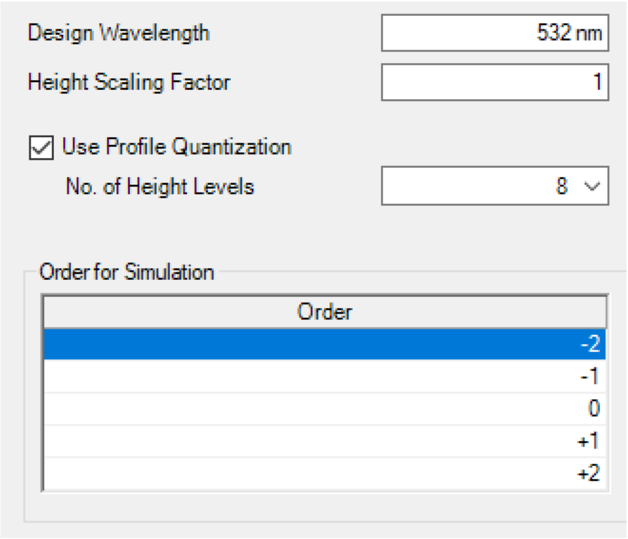


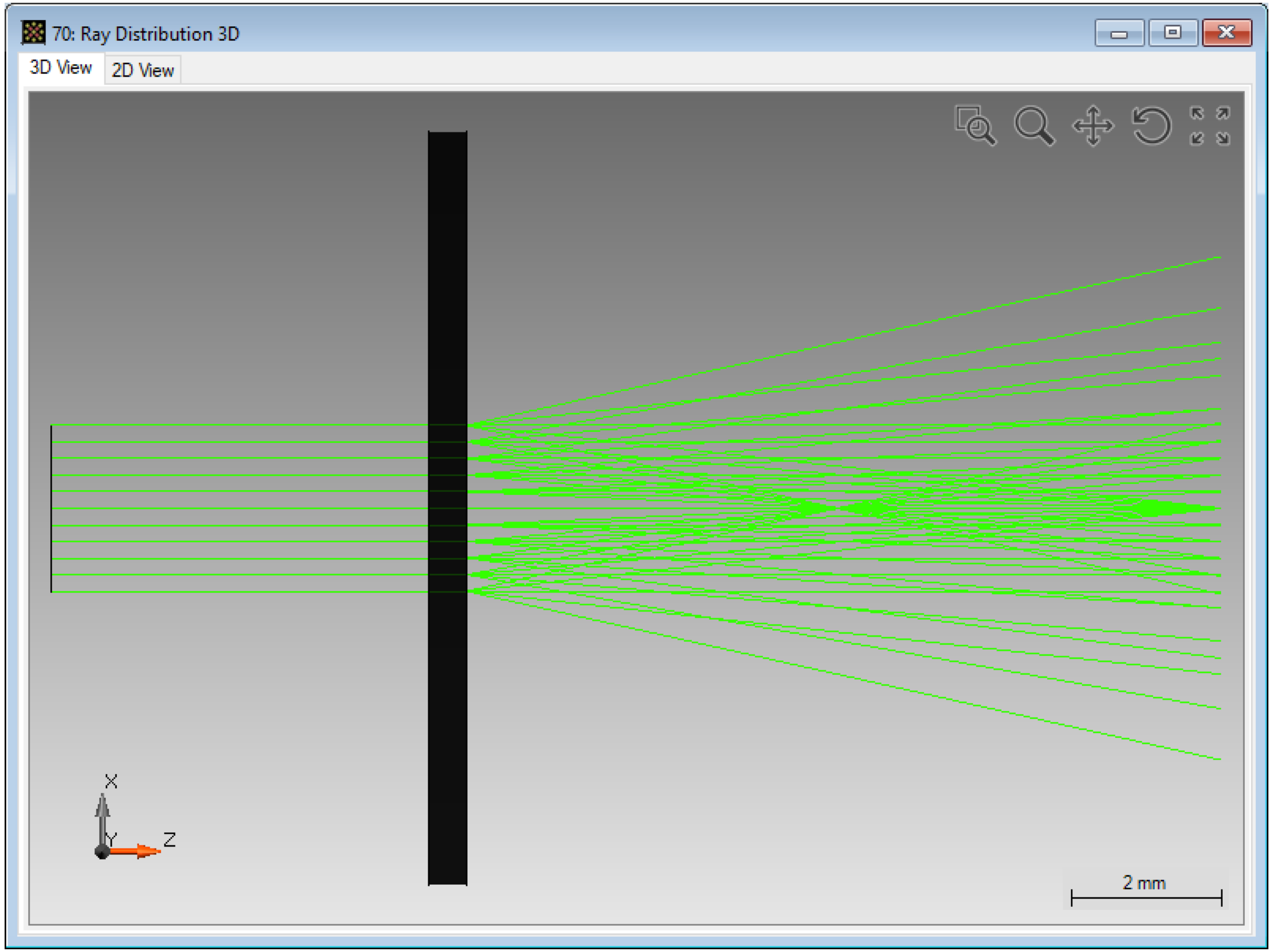


$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = \left\{ \mathbf{B}^{(1)}(\boldsymbol{\rho};\psi^{\mathrm{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \right\} \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho})\right)$$

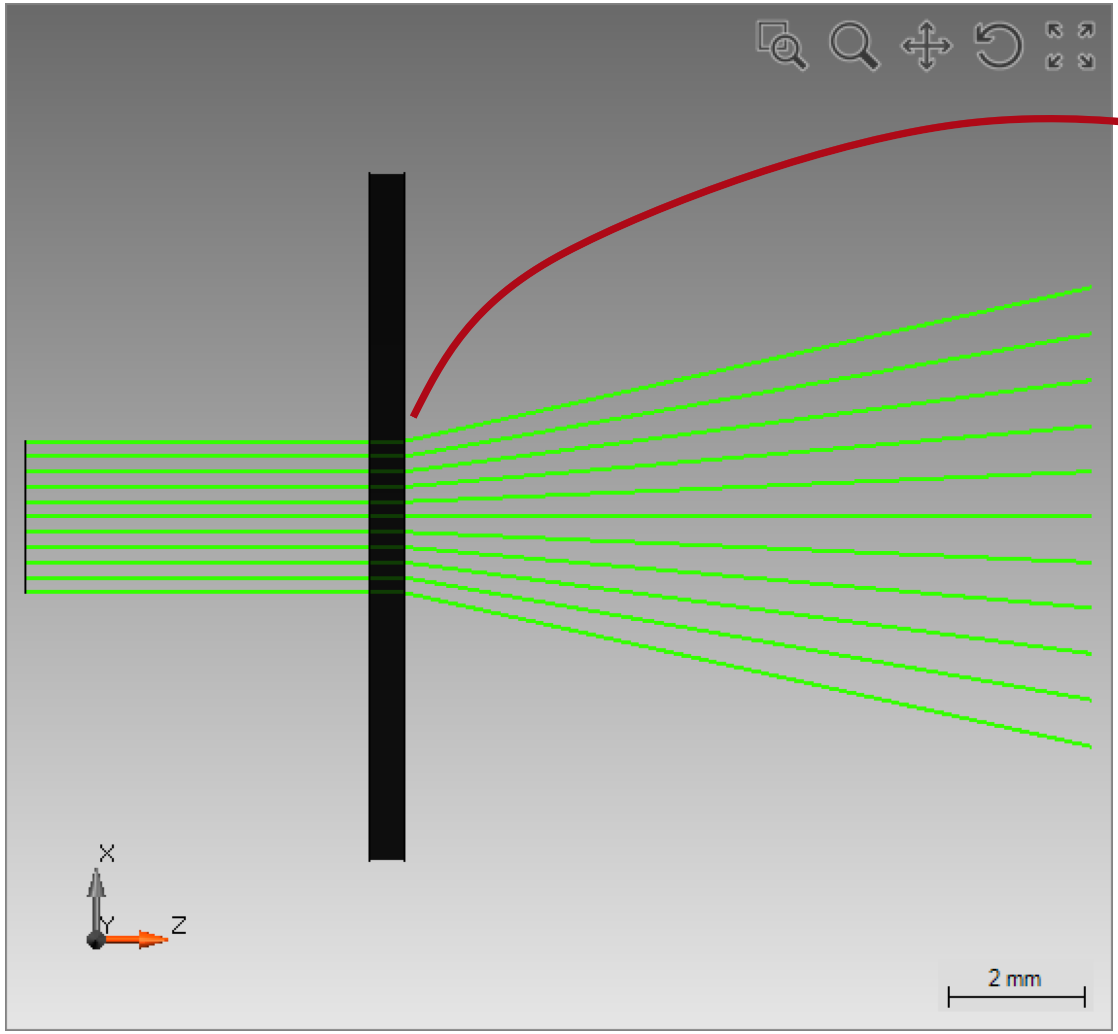
$$+ \sum_{m=-\infty, m\neq 1}^{\infty} \left\{ \mathbf{B}^{(m)}(\boldsymbol{\rho};\psi^{\mathrm{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \right\} \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho}) + m\Delta\psi(\boldsymbol{\rho})\right)$$

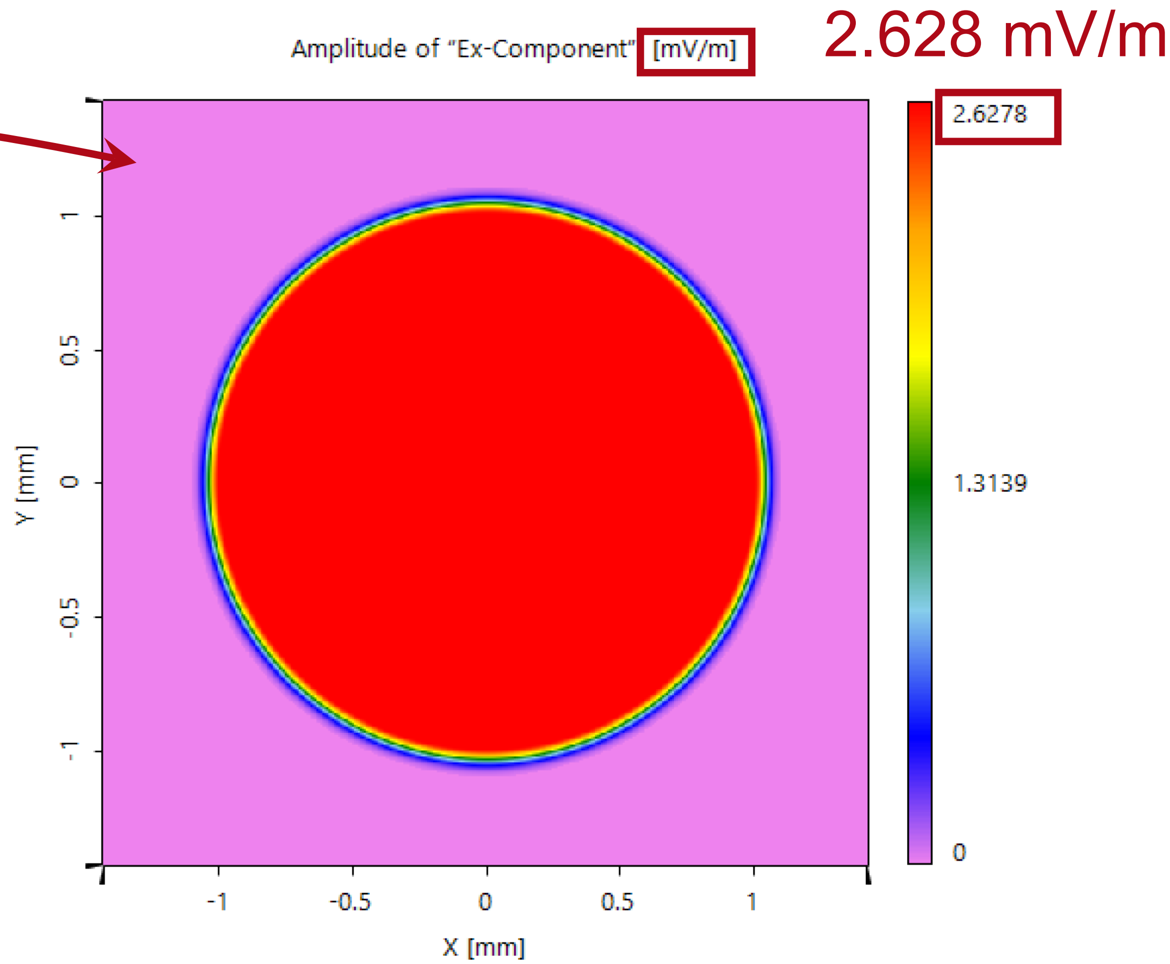
Inclusion of Higher Orders



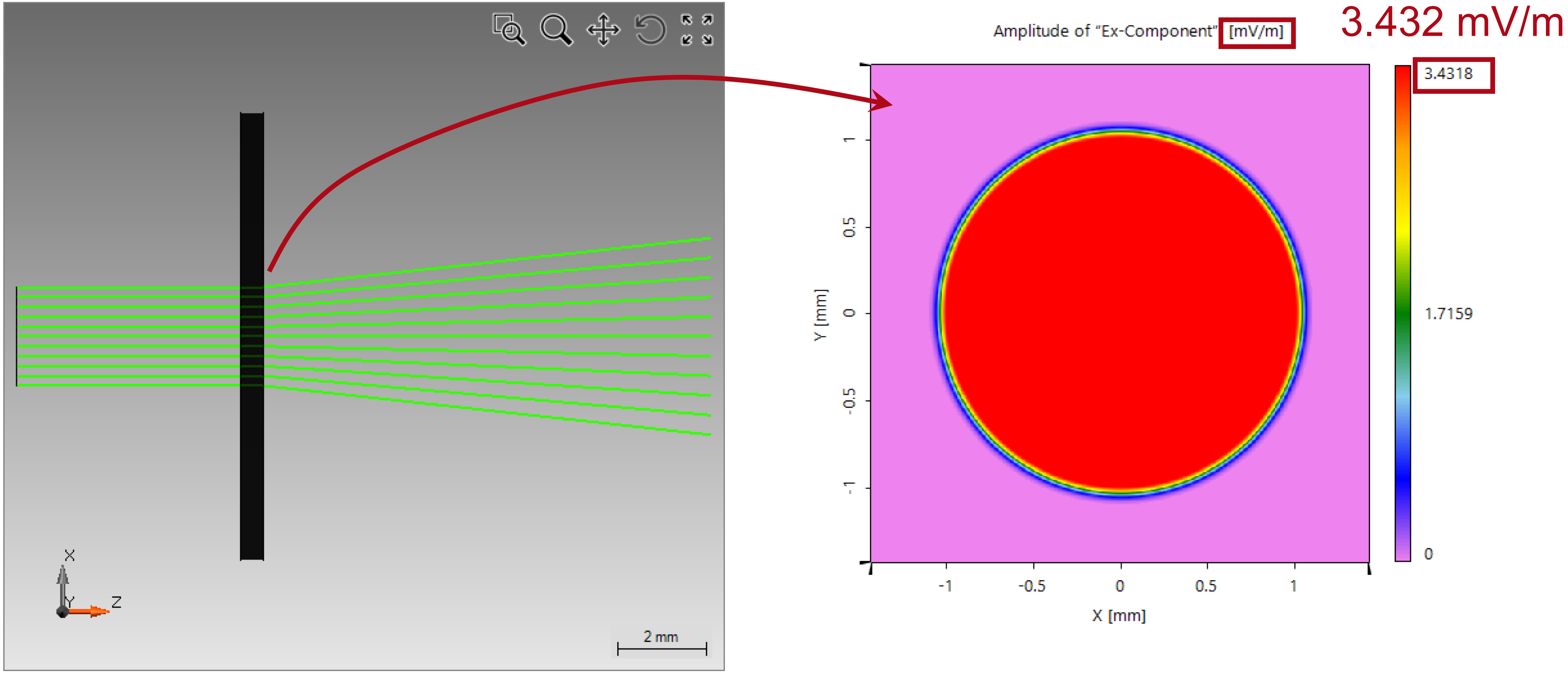


Higher Orders (8 Level): -2nd Order

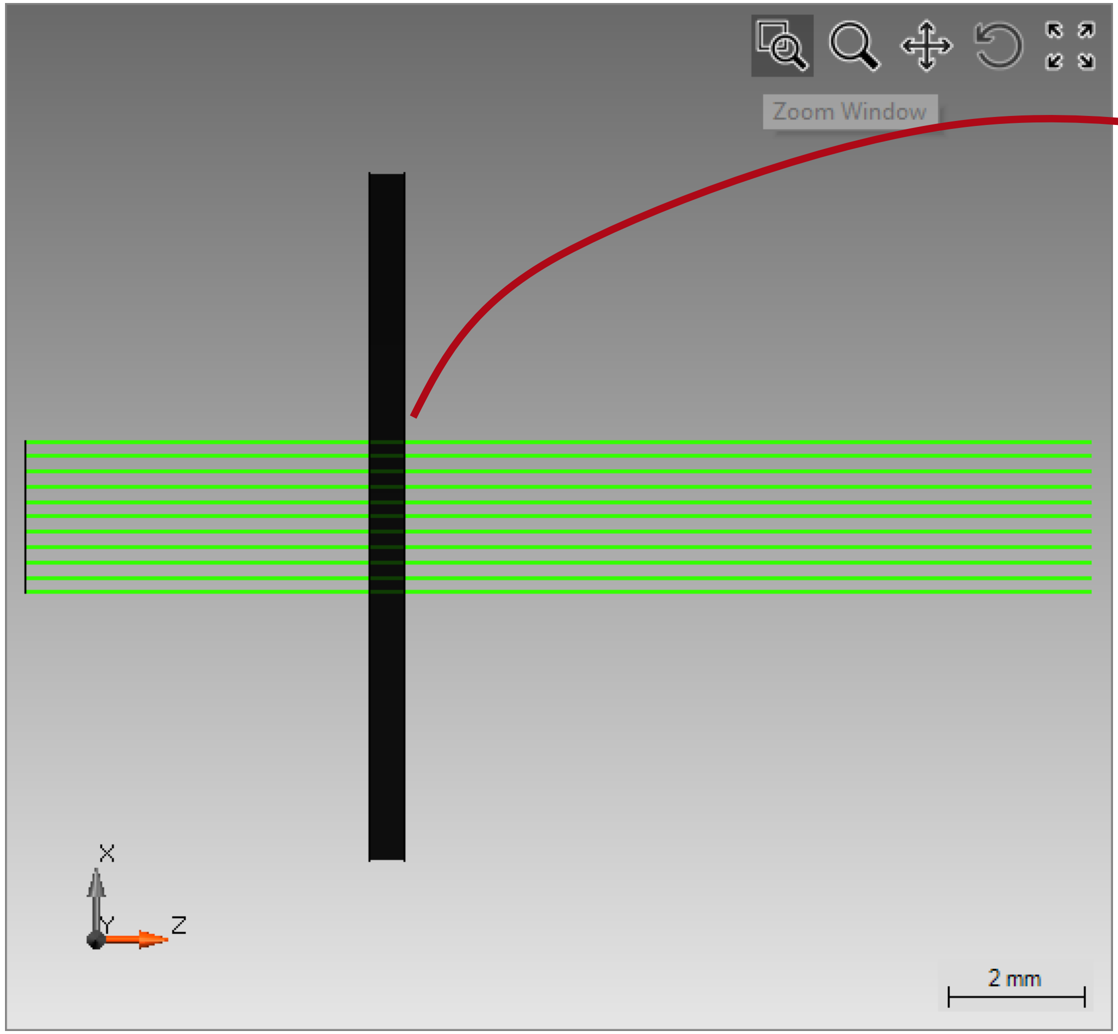


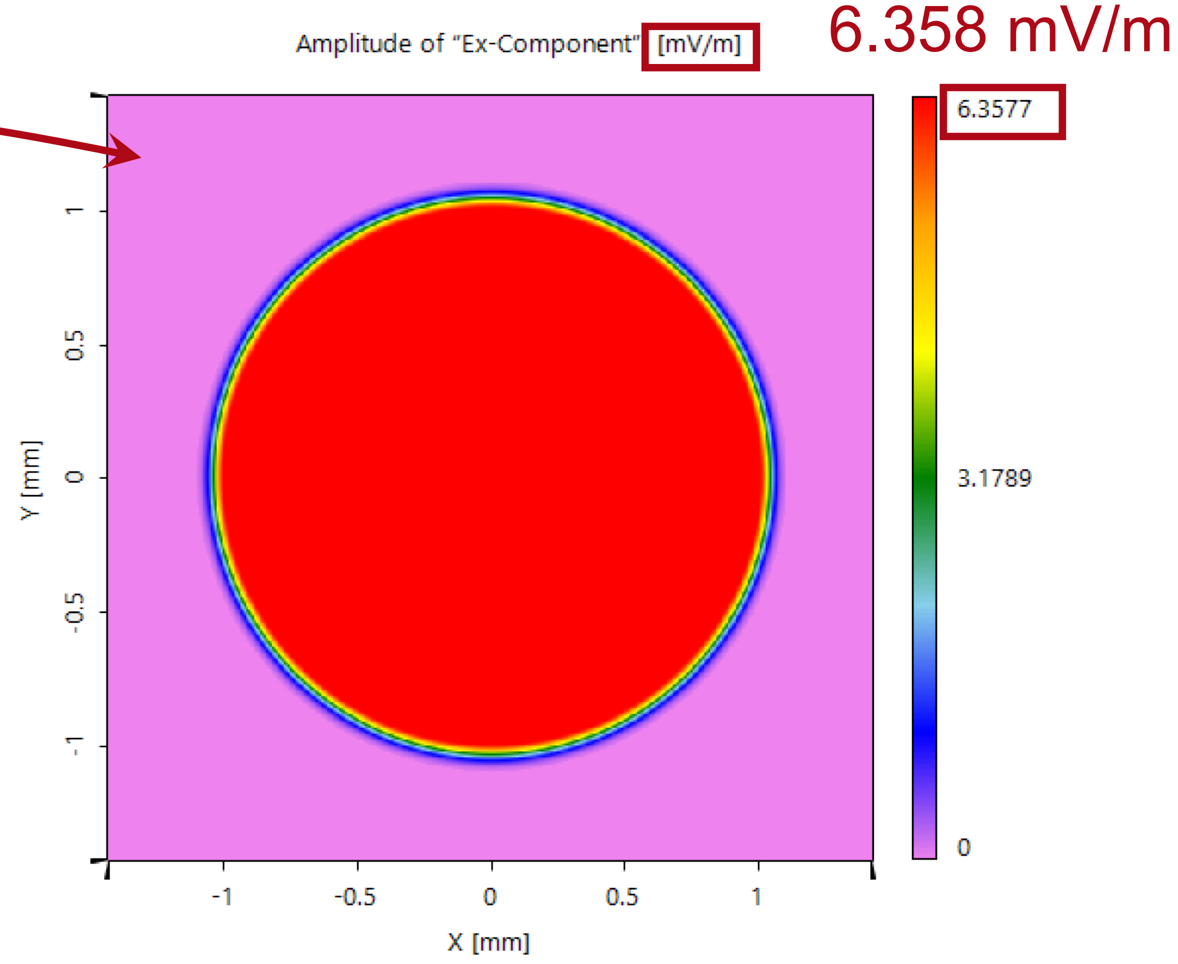


Higher Orders (8 Level): -1st Order

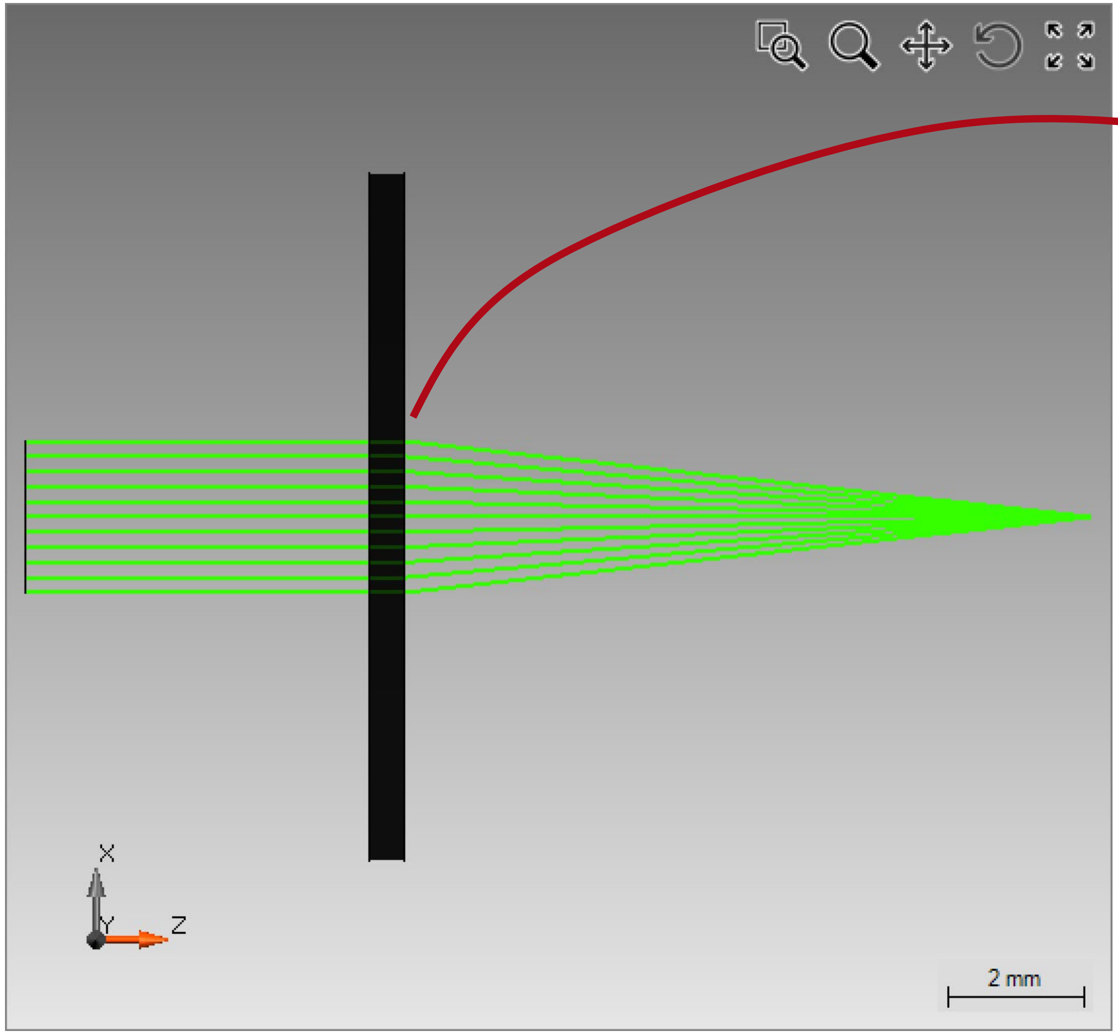


Higher Orders (8 Level): 0^{th} Order

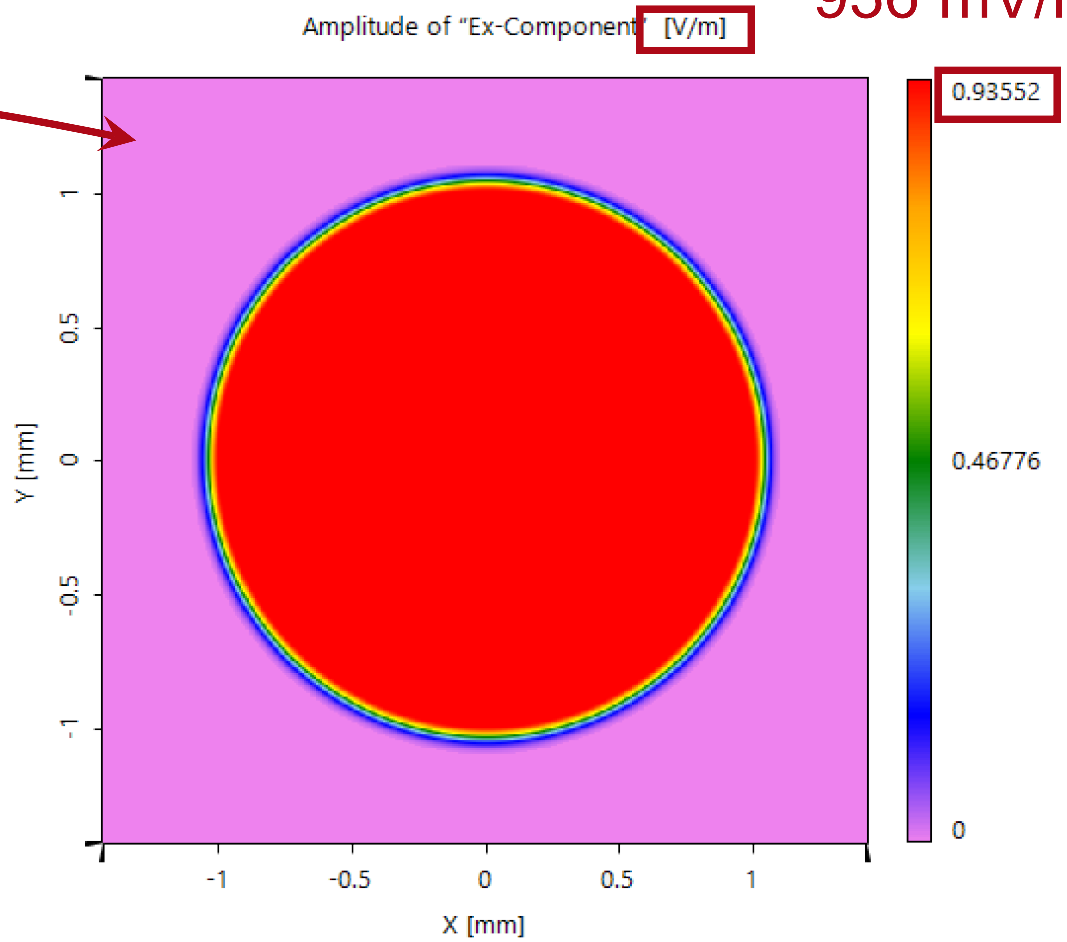




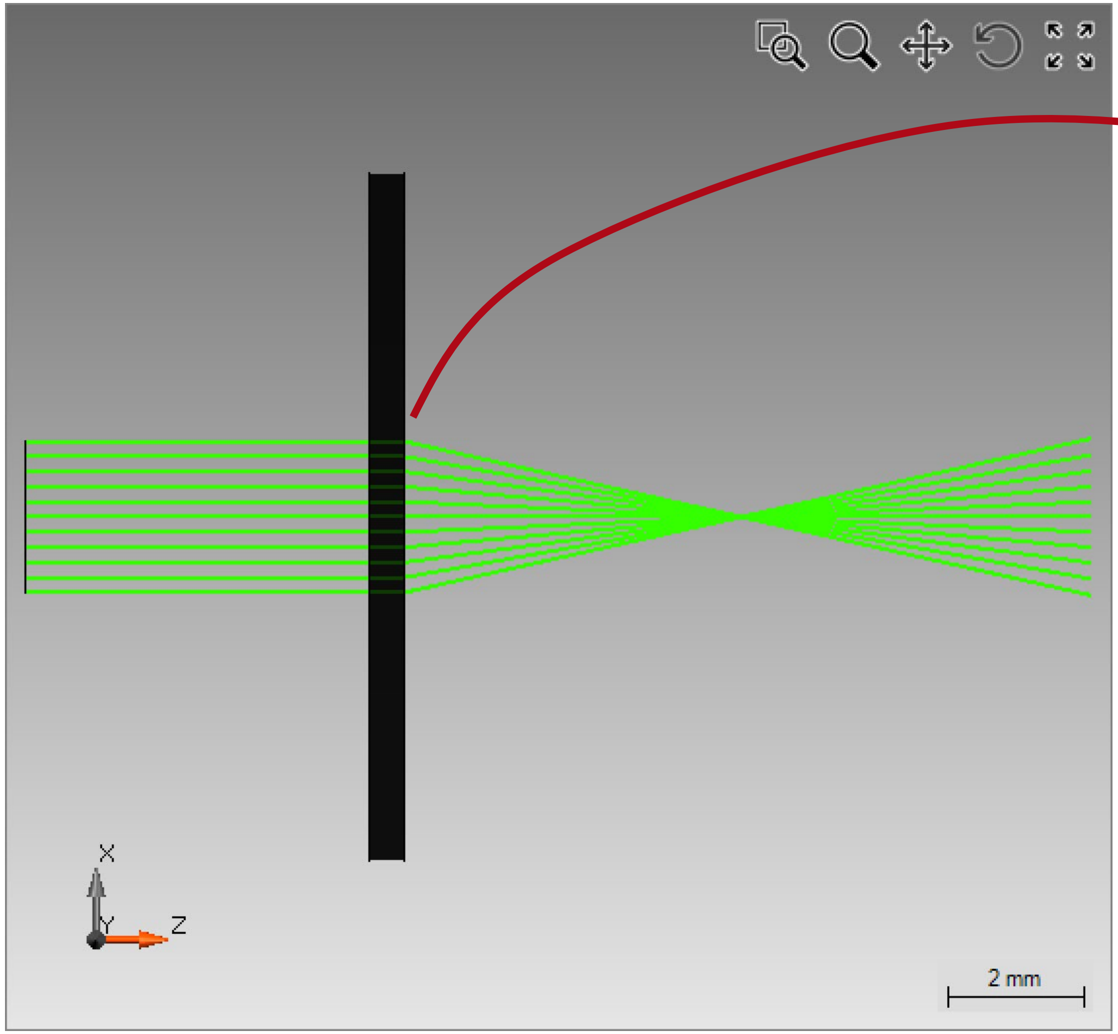
Higher Orders (8 Level): 1st Order (Working Order)

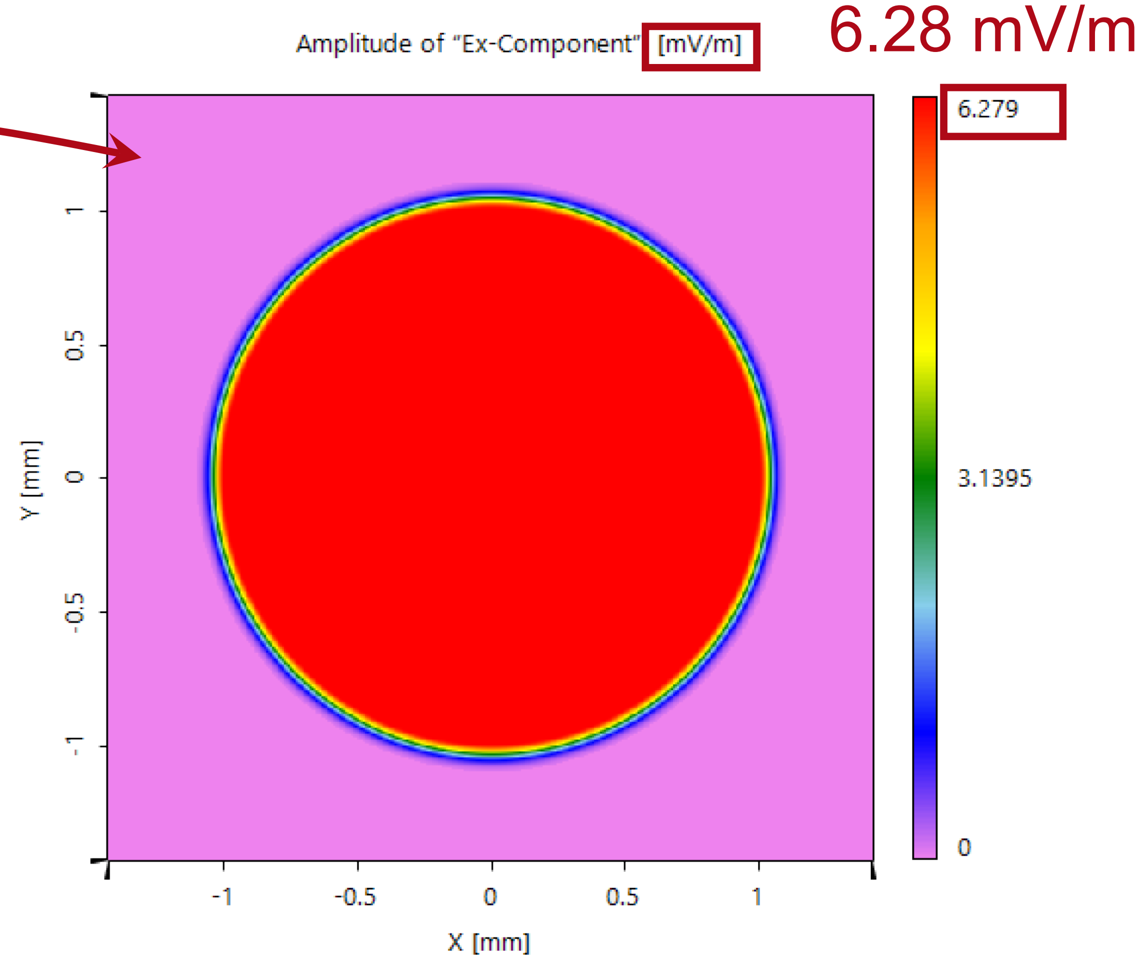


936 mV/m !!!

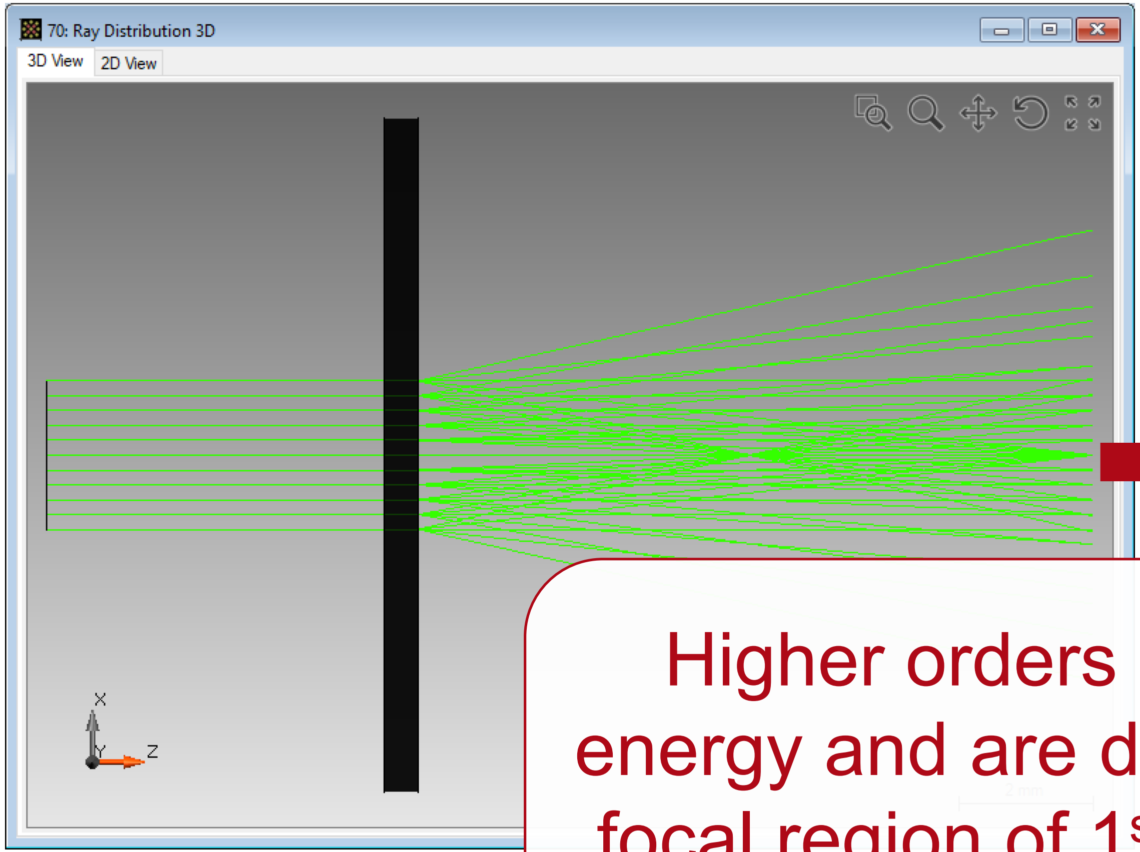


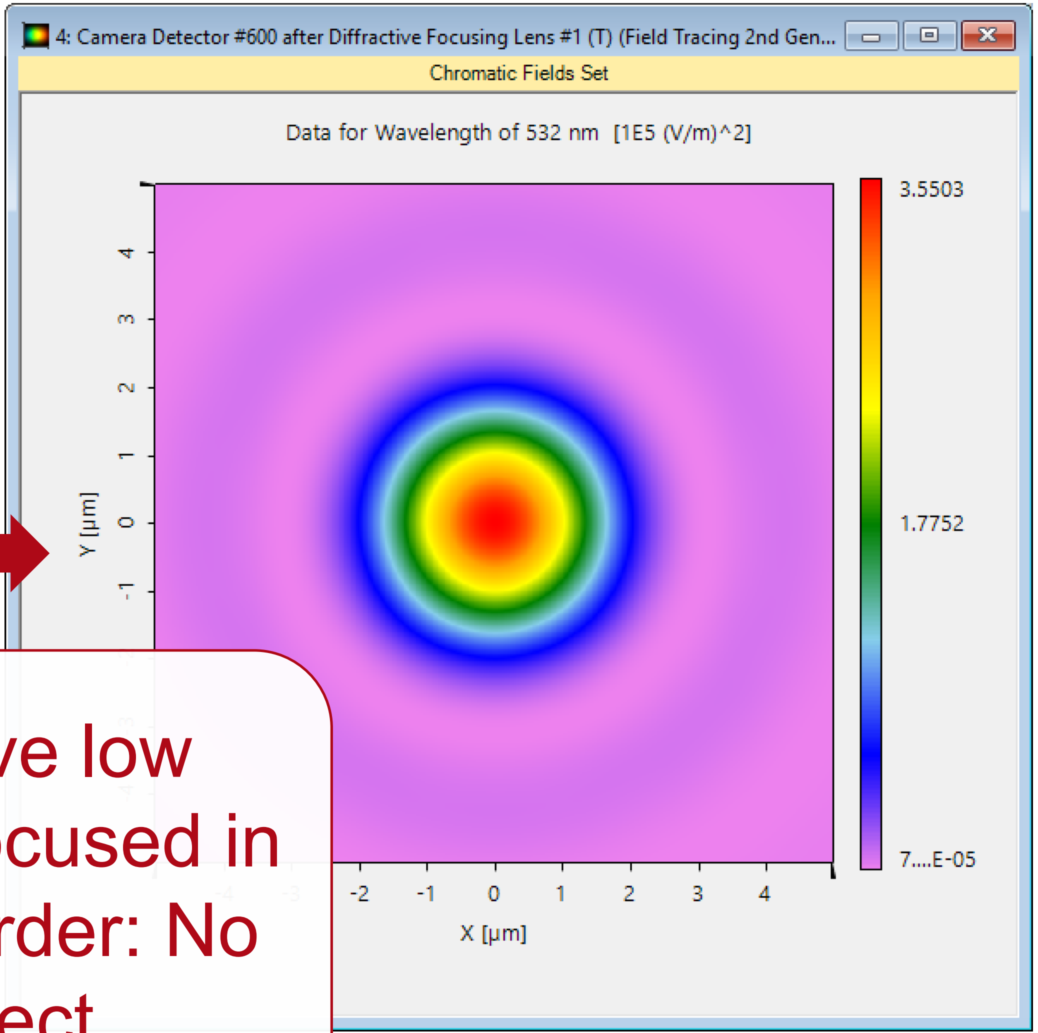
Higher Orders (8 Level): +2nd Order





Lens with NA=0.1 and 8 Height Values: Ray and Field Tracing

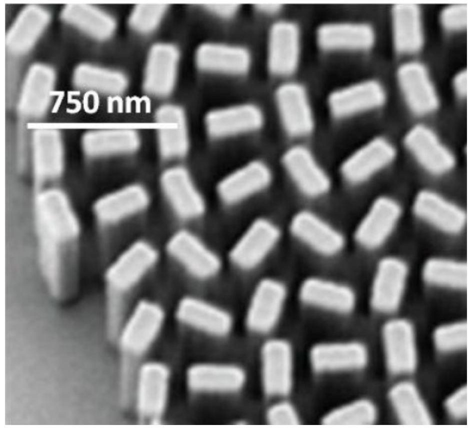




Higher orders have low energy and are defocused in focal region of 1st order: No detrimental effect

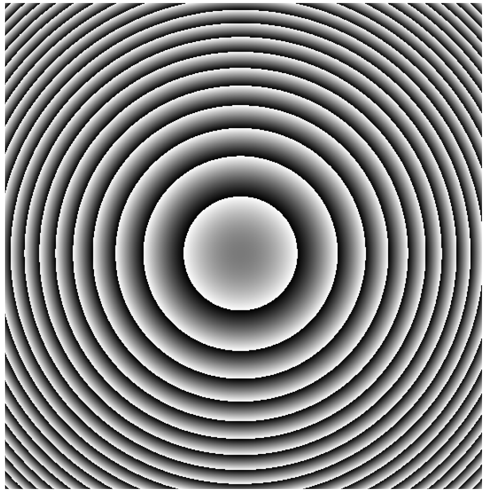
Standard Workflow

- Design of system with optional inclusion of ideal Wavefront Surface Response (WSR) function.
- Decision about most suitable flat optics layer to realize WSR.
- Design of layer structure.
- Analysis of the performance and detrimental additional subfields.



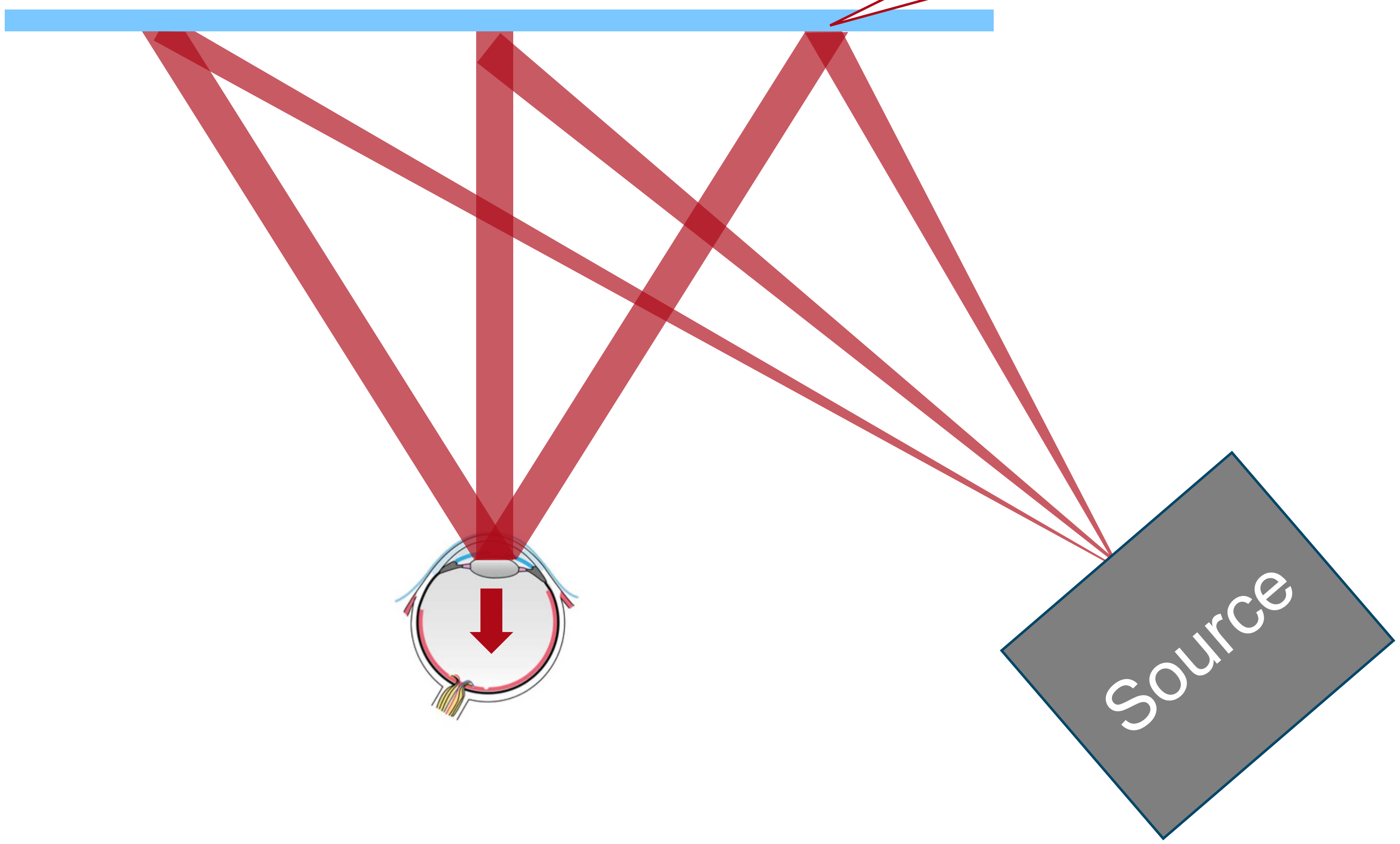
M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

Example VR/AR projection approach

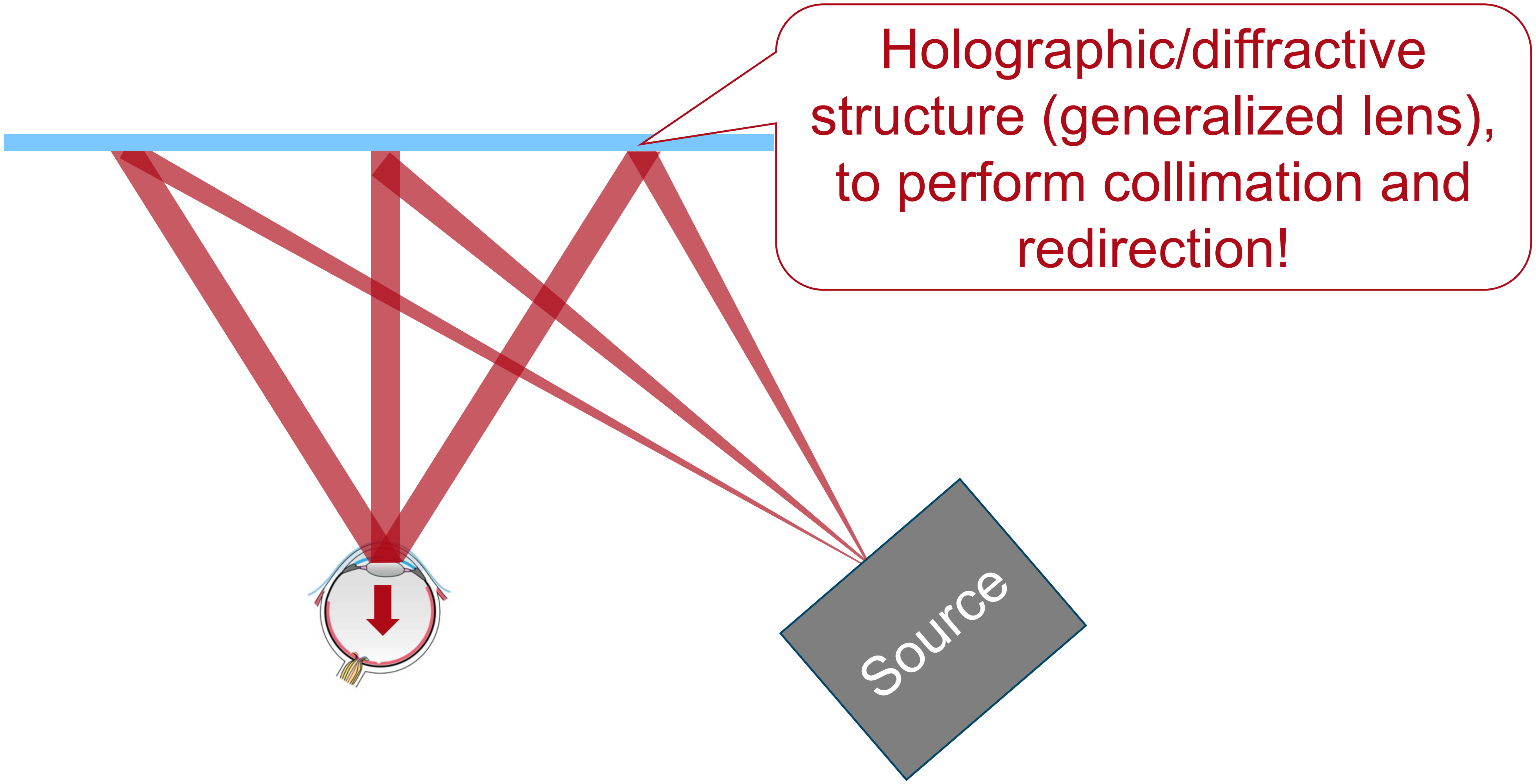


Projection Approach in AR/VR

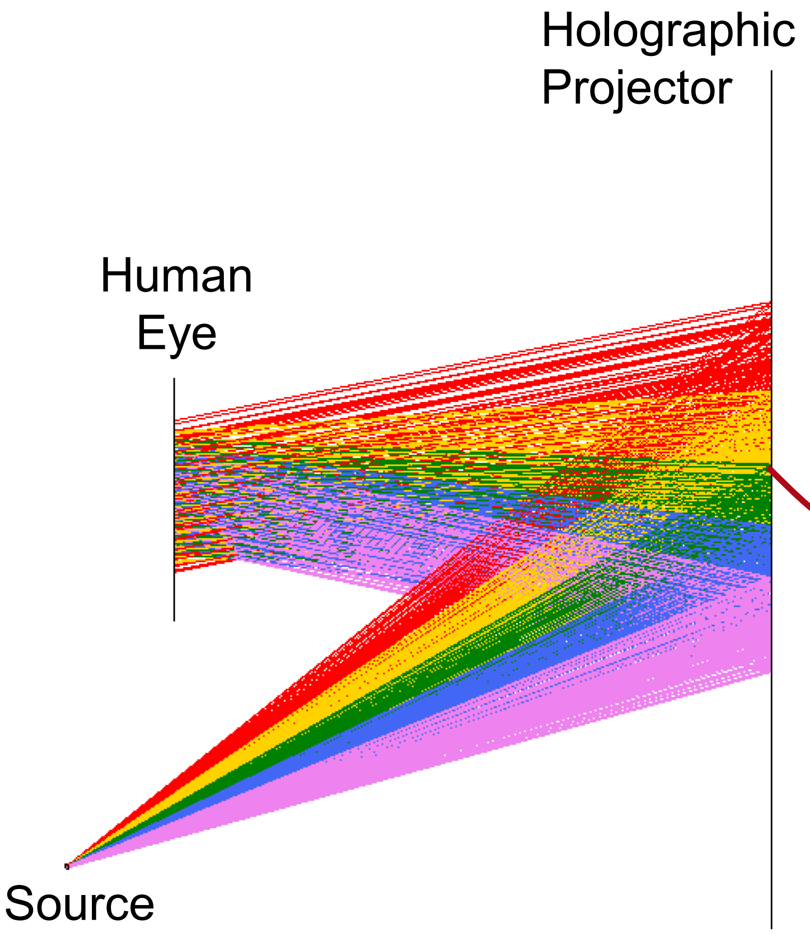
Local optical fuction:
Collimation and
redirection of input beam.



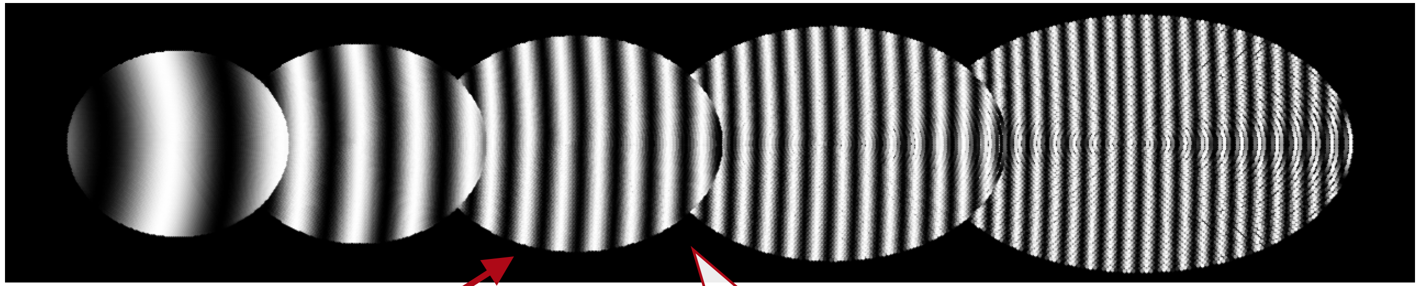
Projection: Holographic/Diffractive Lens Approach



Design and Simulation for Different FOV Angles

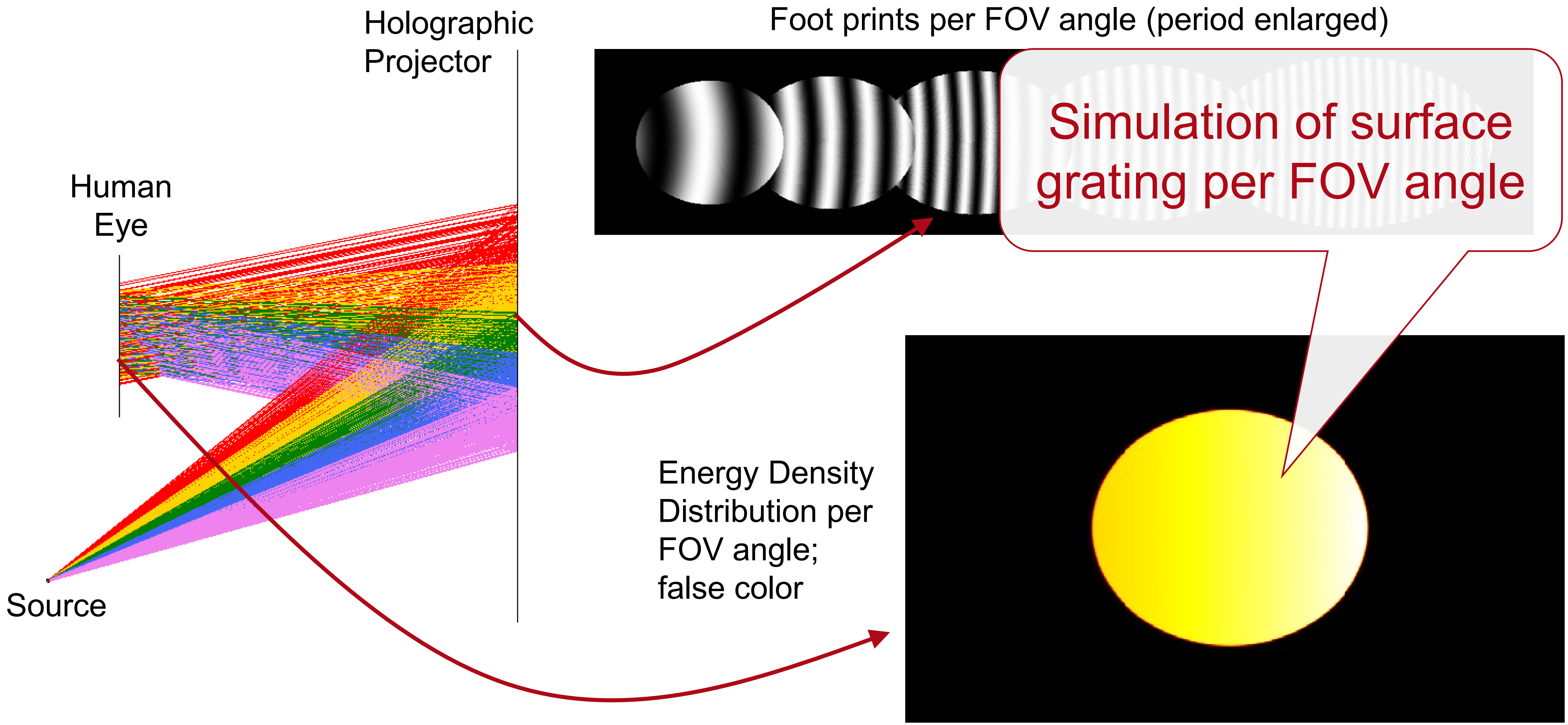


Foot prints per FOV angle (period enlarged)



$$\Re\left\{\Delta\psi(\boldsymbol{\rho})\right\}$$

Design and Simulation for Different FOV Angles



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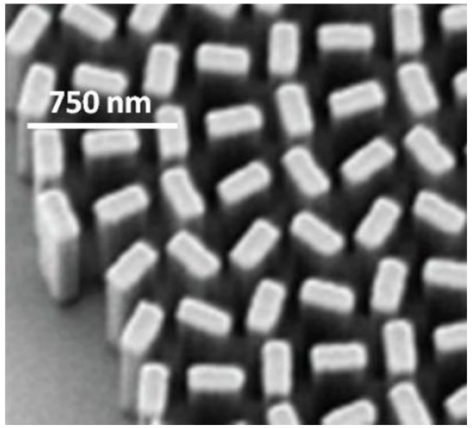
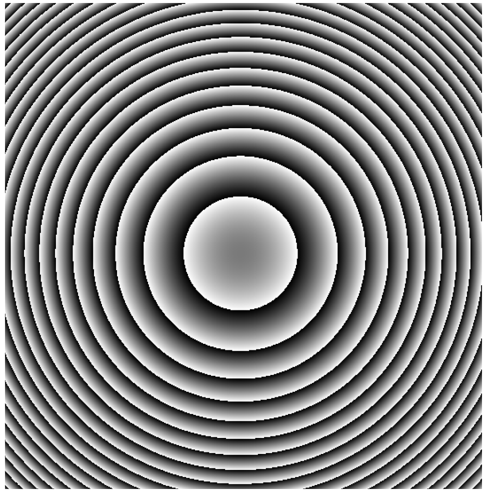
- Tolerancing.
- Export of fabrication data.



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



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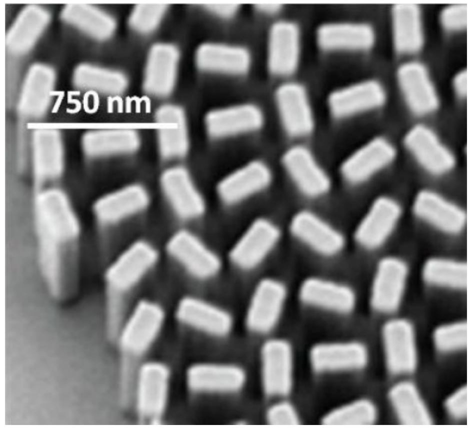
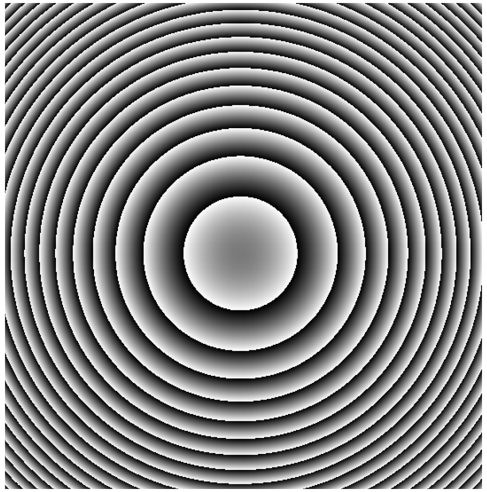
Combination with OpticStudio® via Binary Surfaces, which represent a special form of a WSR.



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



Structure of Workshop

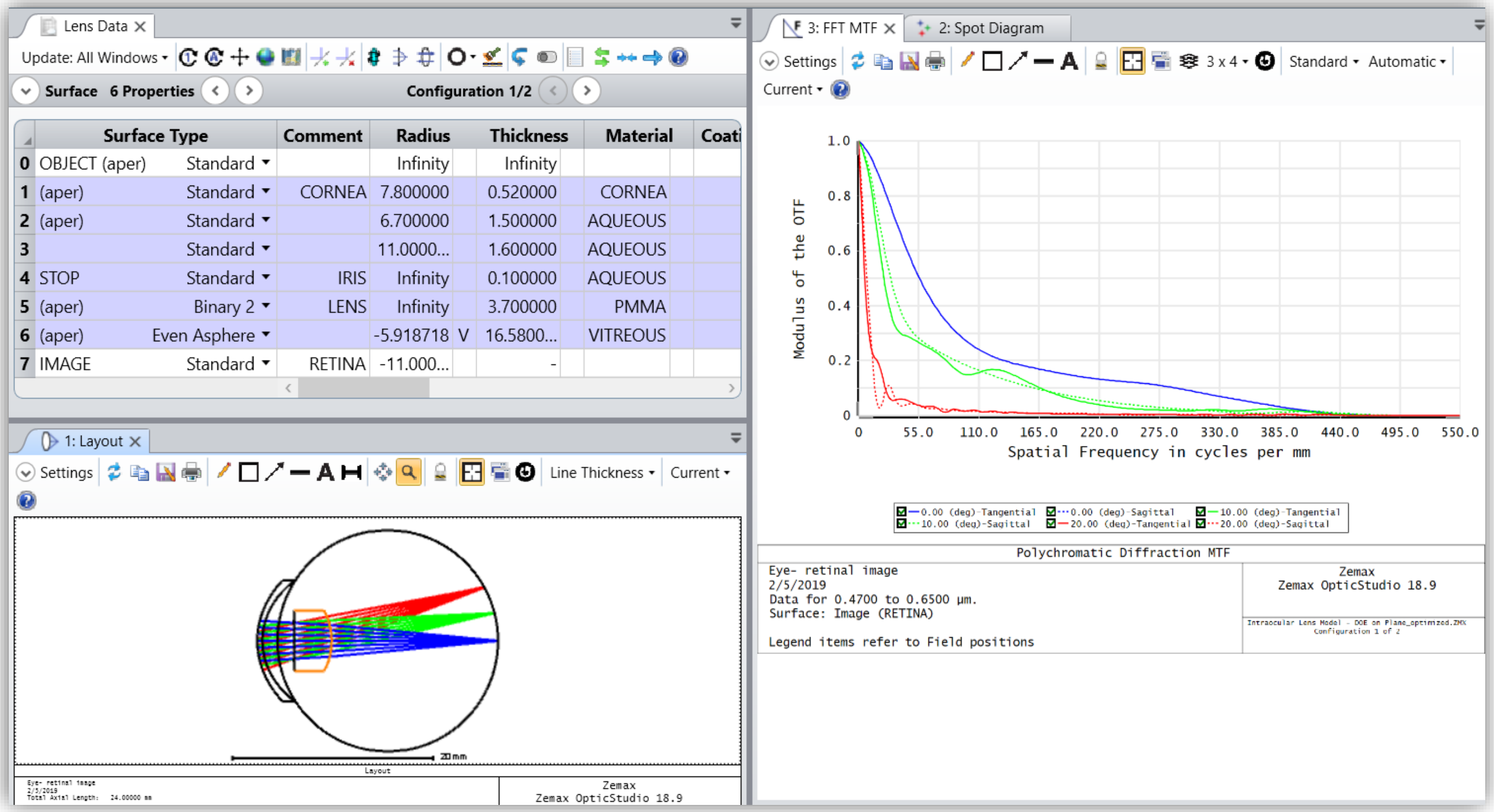
- Introduction of theory
  - Frank Wyrowski
- **Design of binary surfaces in OpticStudio®**
  - **Akil Bhagat**
- Physical-optics analysis of imported systems from OpticStudio: Diffractive lenses
  - Roberto Knoth
- Metalenses theory and modeling
  - Site Zhang
- Fabrication export
  - Roberto Knoth

Binary Surfaces in OpticStudio®

Wavefront Surface Response in OpticStudio®

Intraocular Lens Model using OpticStudio

- Using the Binary 2 surface to model the lens
- Setup and design
- Analysis
- Next Steps



	Surface Type		Comment	Radius	Thickness	Material	Coati
0	OBJECT (aper)	Standard		Infinity	Infinity		
1	(aper)	Standard	CORNEA	7.800000	0.520000	CORNEA	
2	(aper)	Standard		6.700000	1.500000	AQUEOUS	
3		Standard		11.0000...	1.600000	AQUEOUS	
4	STOP	Standard	IRIS	Infinity	0.100000	AQUEOUS	
5	(aper)	Binary 2	LENS	Infinity	3.700000	PMMA	
6	(aper)	Even Asphere		-5.918718 V	16.5800...	VITREOUS	
7	IMAGE	Standard	RETINA	-11.000...	-		

OpticStudio®

Binary 2 Surface

- In this system, the diffractive intraocular lens is modelled using a Binary 2 surface
- The Binary 2 surface has an even asphere base shape, with a grating period defined by a rotationally symmetric polynomial
  - Even Asphere sag:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

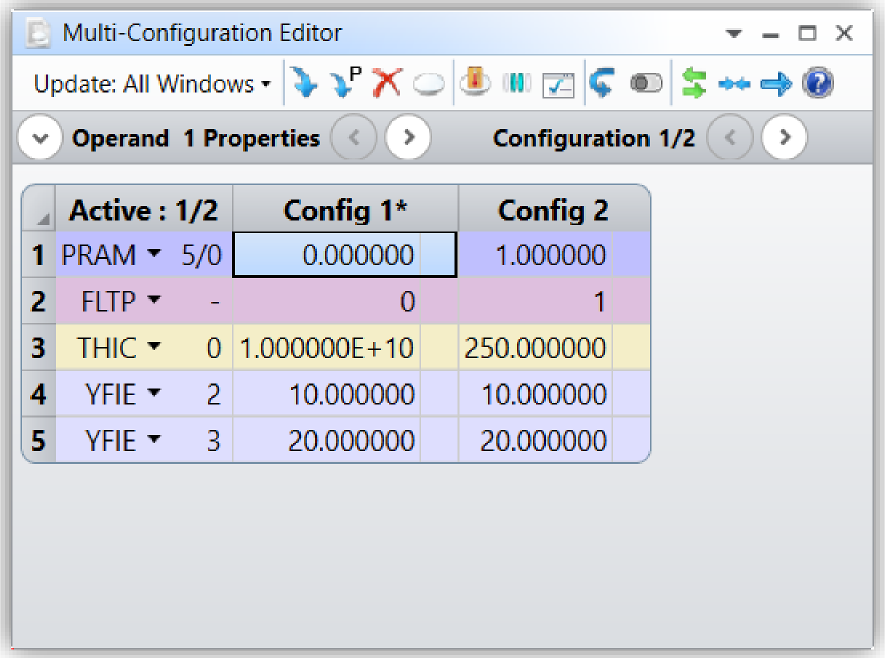
  - Additional Phase added by the grating:

$$\Phi = M \sum_{i=1}^{N} A_i \rho^{2i}$$

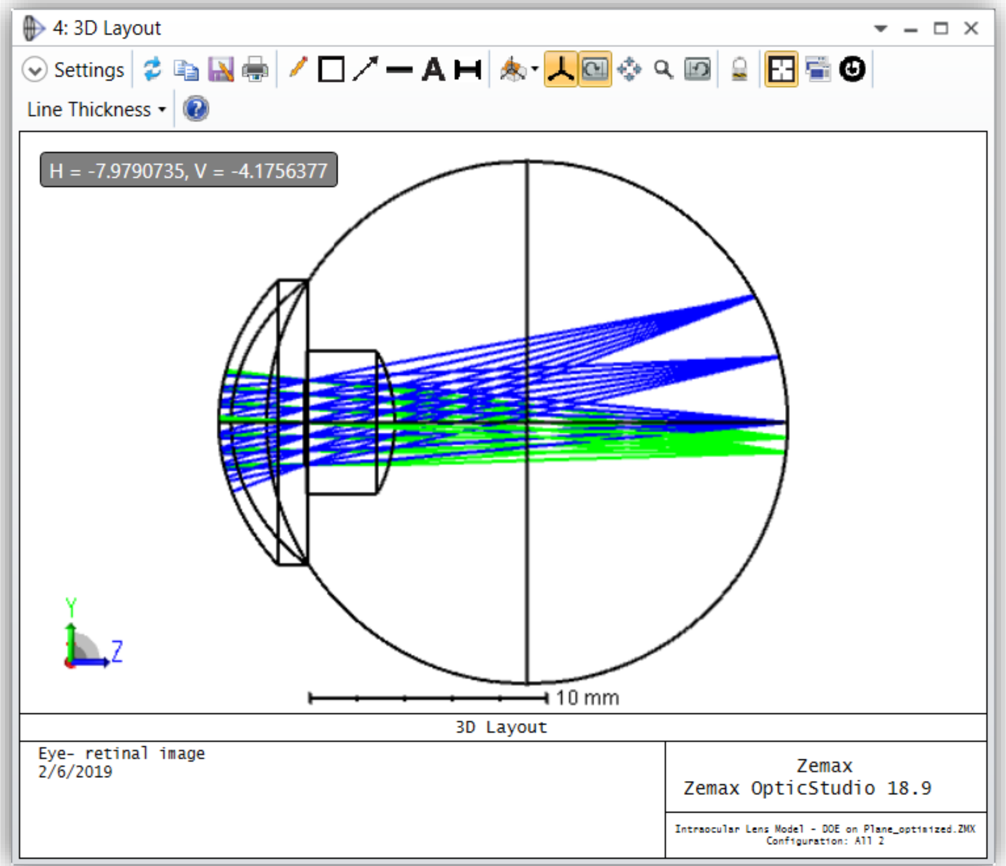
  - For a complete definition of these terms, please see the Binary 2 OpticStudio help file or the article below:
    - https://customers.zemax.com/os/resources/learn/knowledgebase/how-diffractive-surfaces-are-modeled-in-zemax

Setup and Design

- OpticStudio models only 1 diffractive order at a time, which means we will utilize multiple configurations in this file to model 2 orders

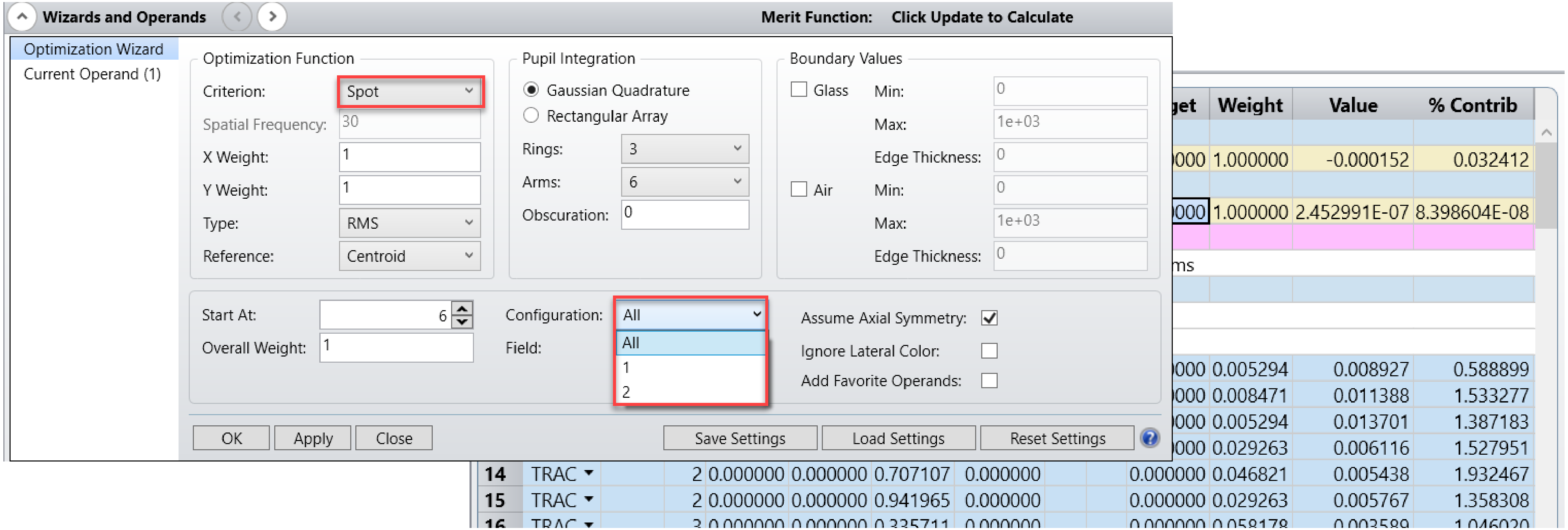


	Active : 1/2		Config 1*	Config 2
1	PRAM	5/0	0.000000	1.000000
2	FLTP	-	0	1
3	THIC	0	1.000000E+10	250.000000
4	YFIE	2	10.000000	10.000000
5	YFIE	3	20.000000	20.000000



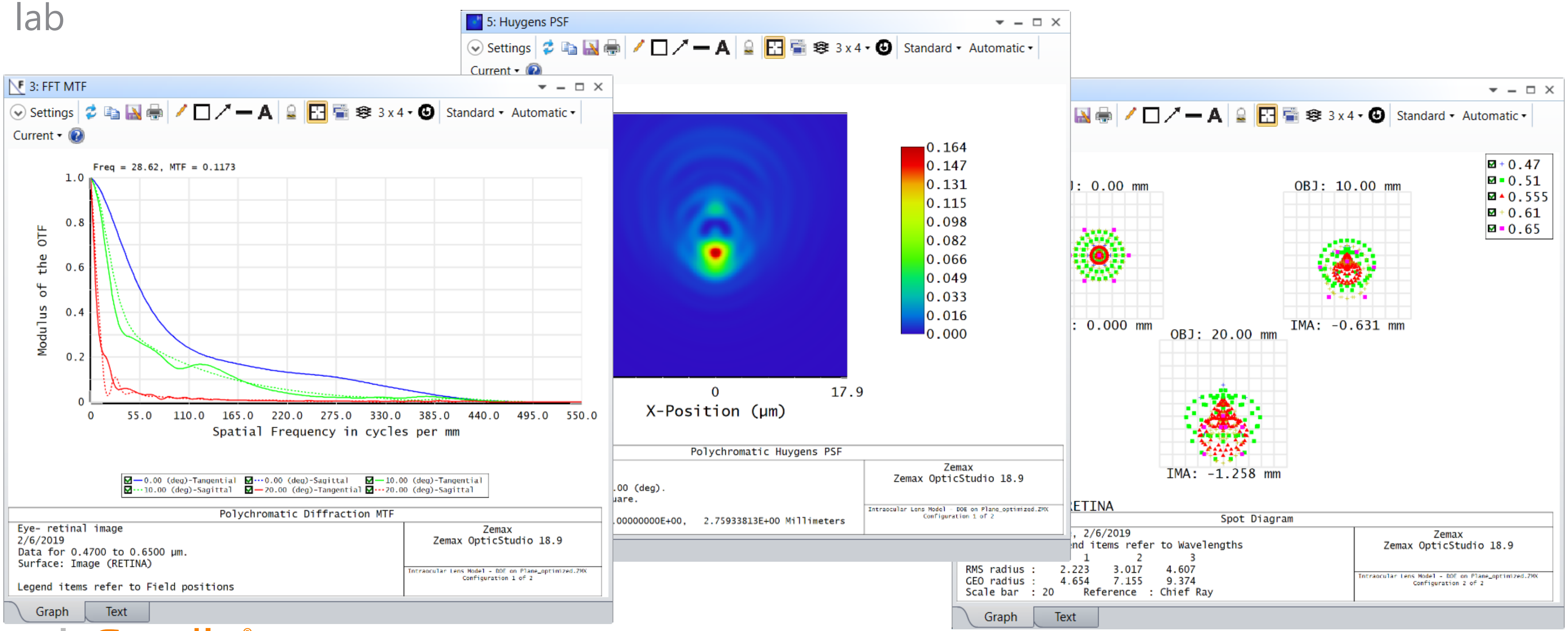
Setup and Design

- Once the initial system is setup, OpticStudio can be used to optimize the system to achieve the best performance for both configurations
- This system was optimized for minimum RMS spot size along both configurations using the built in Optimization Wizard



Analysis

- There are many analysis tools in OpticStudio
- In general, we recommend using a tool that mimics the measurements you will make in the lab



OpticStudio®

Next Steps

- Our system is designed, and the analyses indicate it meets specifications, however our Binary 2 surface is still just an equation and has no real geometry.
- At this point our friends at VirtualLab can take the Binary 2 surface designed in OpticStudio, and create an actual optic out of it which will have the same properties we modelled.

Structure of Workshop

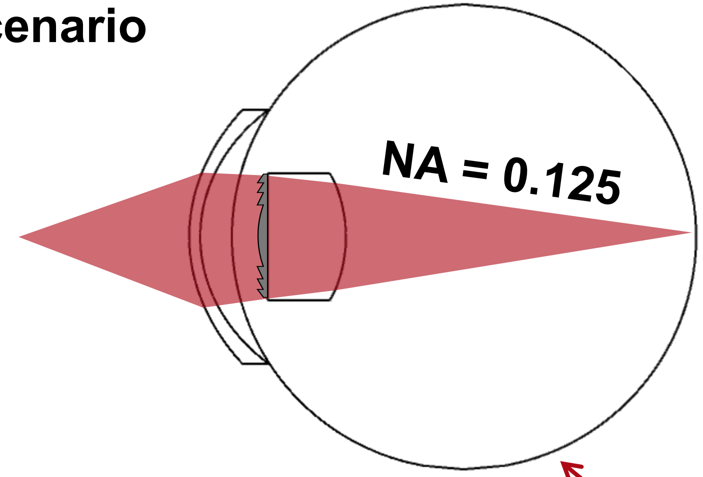
- Introduction of theory
  - Frank Wyrowski
- Design of binary surfaces in OpticStudio
  - Akil Bhagat
- **Physical-optics analysis of imported systems from OpticStudio: Diffractive lenses**
  - **Roberto Knoth**
- Metalenses theory and modeling
  - Site Zhang
- Fabrication export
  - Roberto Knoth

An Example of Diffractive Layer Design

Design and Analysis of Intraocular Diffractive Lens

Design Task for a Diffractive Layer

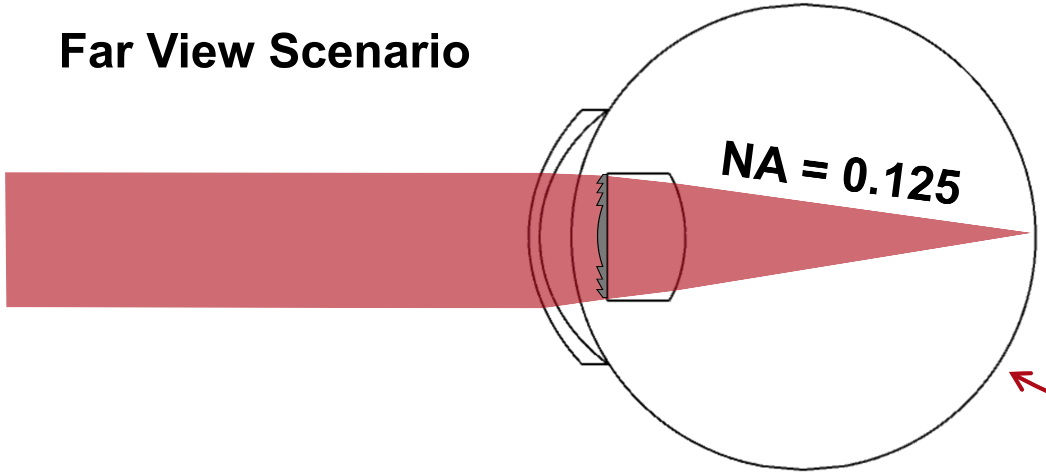
Near View Scenario



Both configuration of the setups require two wavefront surface response functions.

From this reason a diffractive layer design is a good choice to achieve different wavefront effects for the two configurations.

Far View Scenario

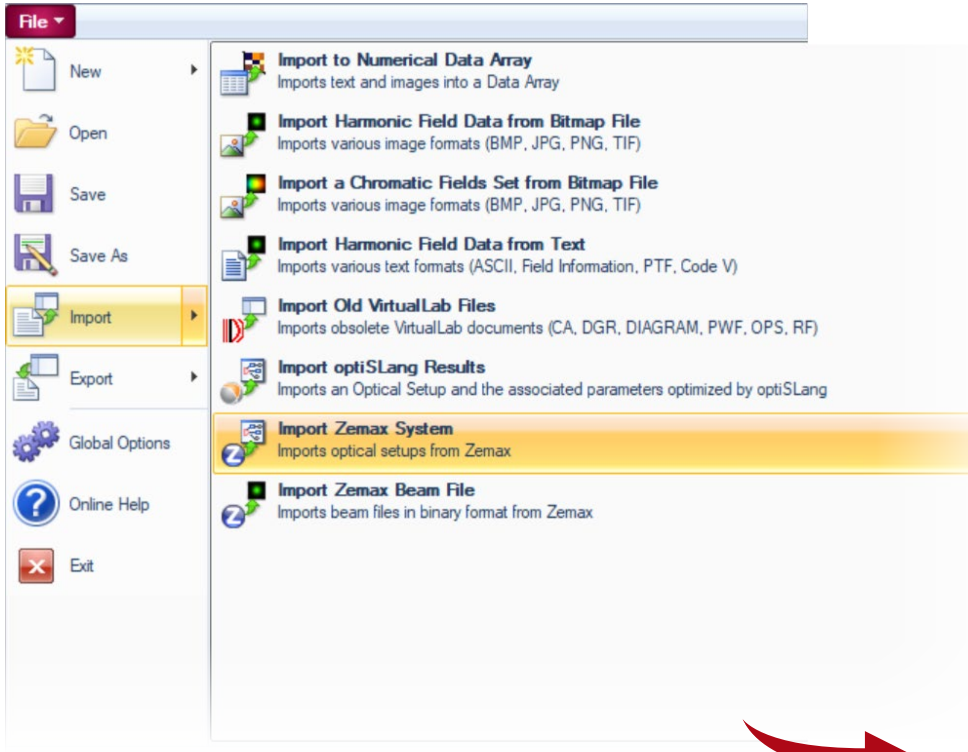


$m = 1$

$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = \left\{ \mathbf{B}^{(1)}(\boldsymbol{\rho}; \psi^{\mathrm{in}}) \boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \right\} \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \boxed{\Delta\psi(\boldsymbol{\rho})}\right) + \sum_{m=-\infty, m\neq 1}^{\infty} \left\{ \mathbf{B}^{(m)}(\boldsymbol{\rho}; \psi^{\mathrm{in}}) \boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \right\} \exp\left(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \boxed{m\Delta\psi(\boldsymbol{\rho})}\right)$$

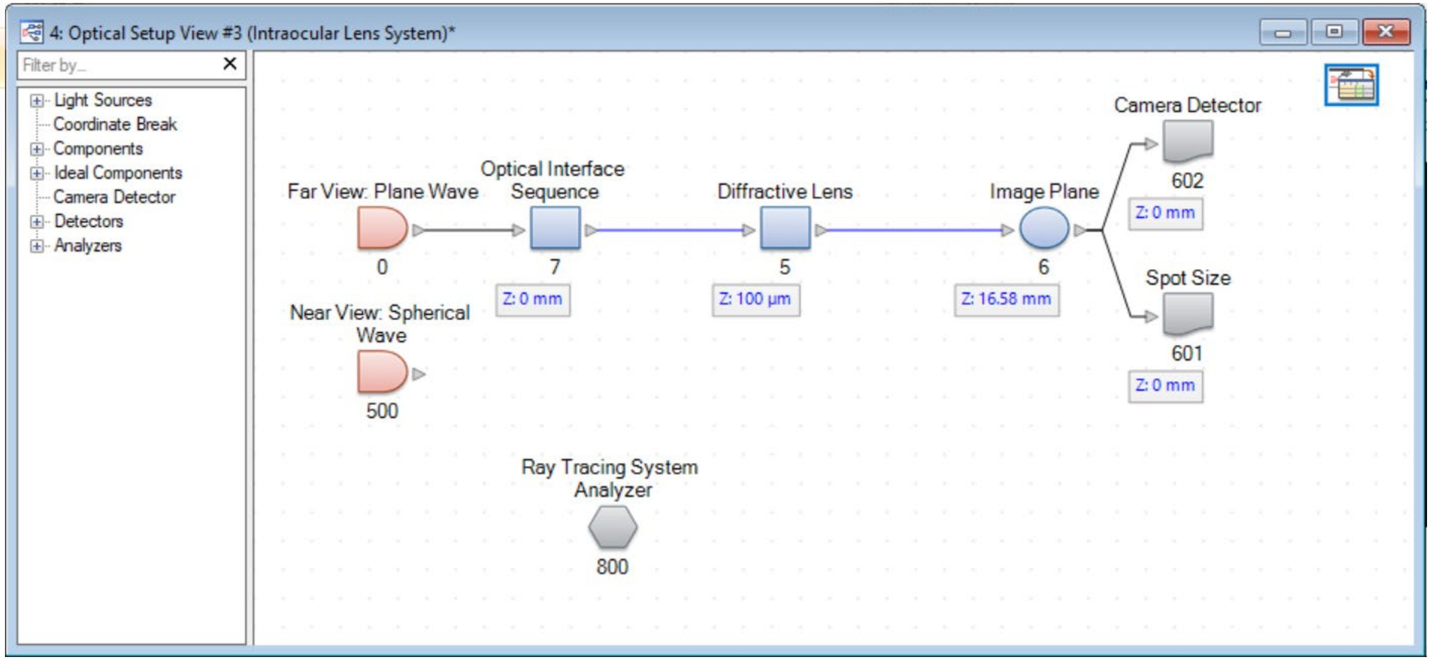
$m = 0$

Import of Optical System from OpticStudio



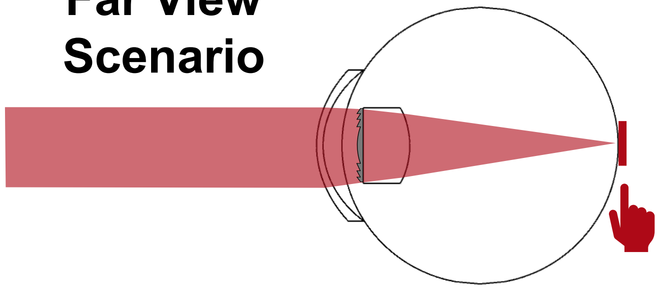
The configuration of the optical setup as well as the design of the wavefront surface response by a Binary-2 surface was generated in OpticSudio.

VirtualLab Fusion provides the capability to import the optical setups and to merge them in a single optical setup configuration.

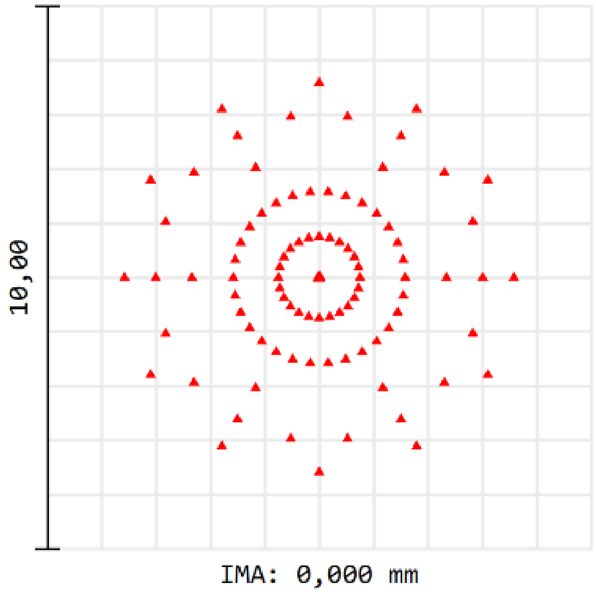


Far View: Conformity of OpticStudio Import

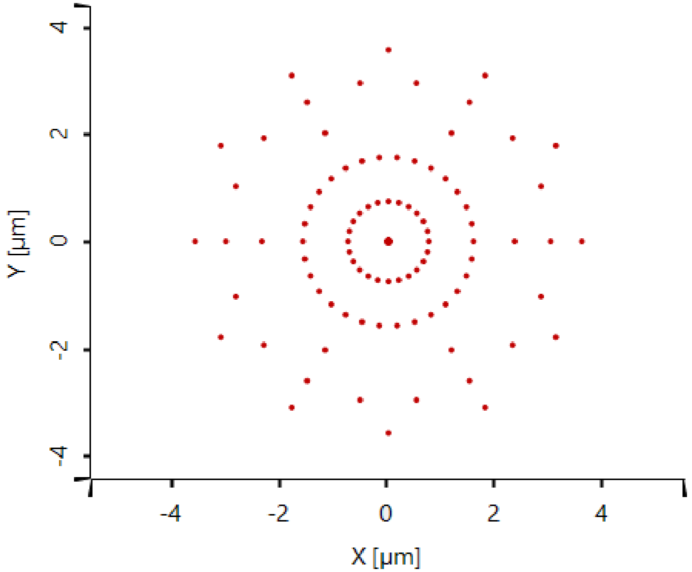
Far View Scenario



spot diagram calculated by **OpticStudio**
– central wavelength of 555 nm
– on-axis mode

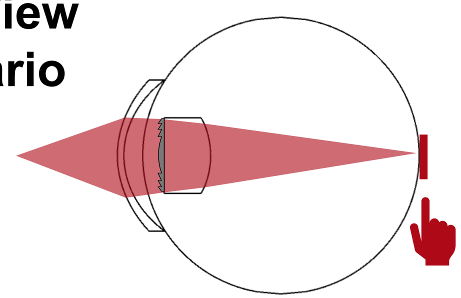


spot diagram calculated by **VirtualLab Fusion**
– central wavelength of 555 nm
– on-axis mode

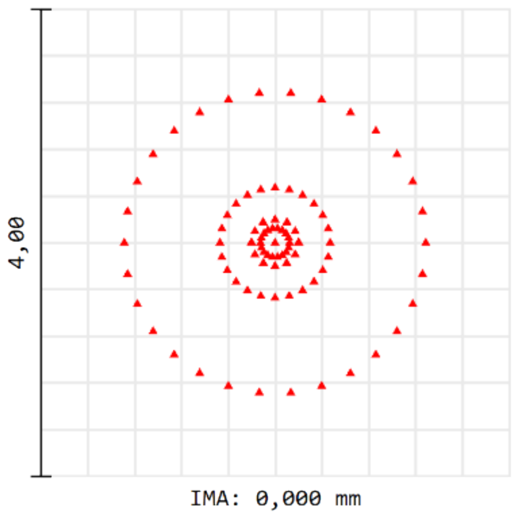


Near View: Conformity of OpticStudio Import

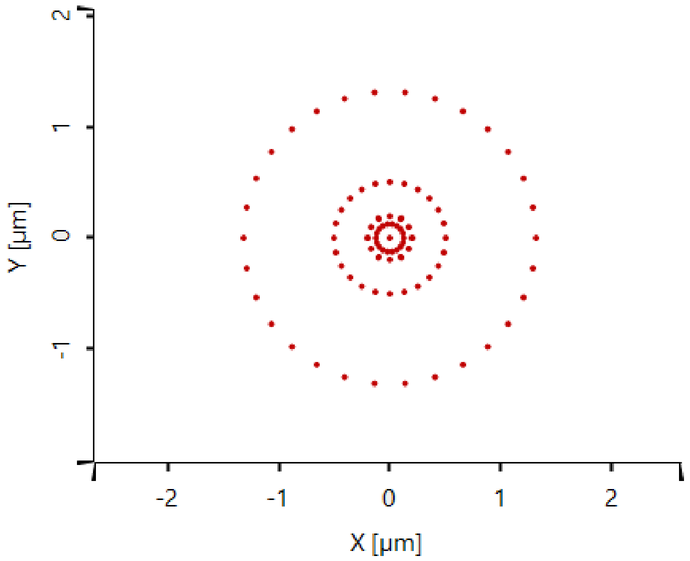
Near View Scenario



spot diagram calculated by **OpticStudio**
– central wavelength of 555 nm
– on-axis mode



spot diagram calculated by **VirtualLab Fusion**
– central wavelength of 555 nm
– on-axis mode



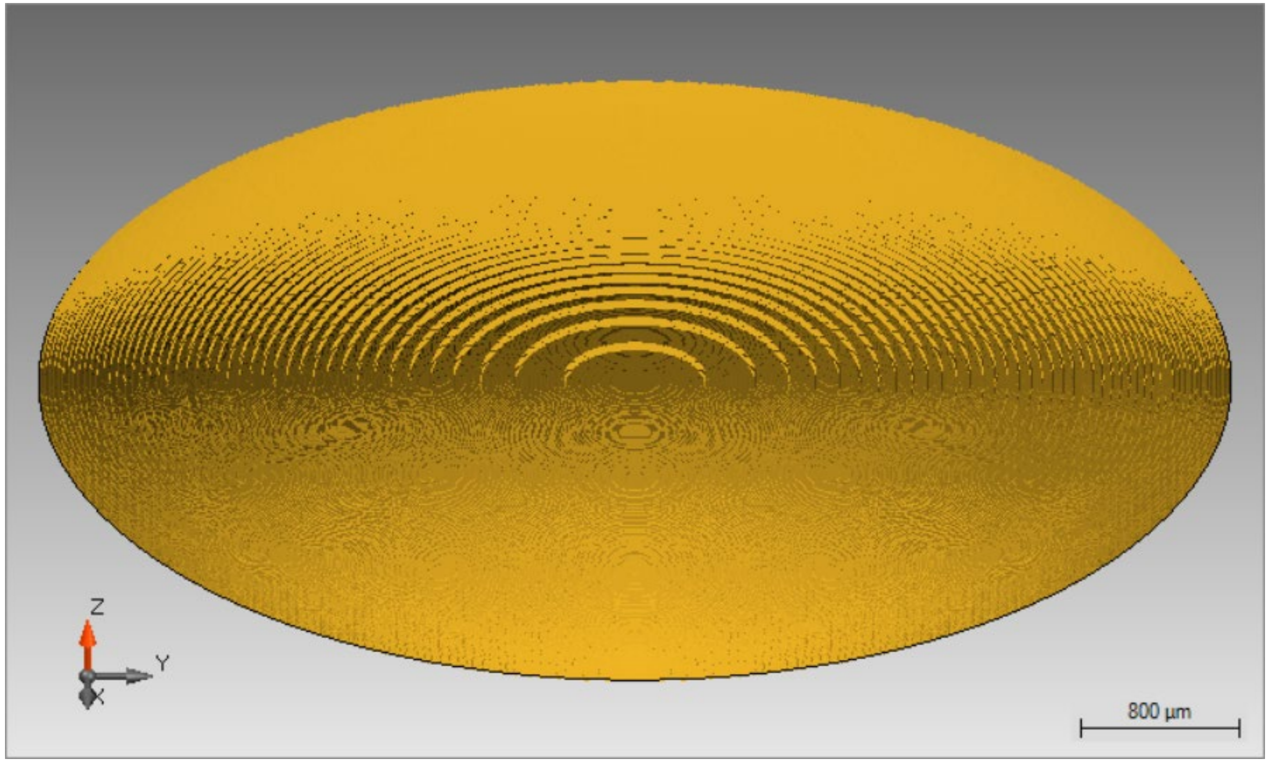
Structure Design: Diffractive Layer Profile Height

- The structure profile of the diffractive layer is calculated by TEA according to the wavefront surface response:

$$h^{DOE}(\rho) = \frac{\lambda}{2\pi\Delta n}\Delta\psi(\rho)^{DOE}$$

TEA provides directly a very high efficiency for the 1st order

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \left\{\mathbf{B}^{(1)}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})+\Delta\psi(\boldsymbol{\rho})\right)$$
$$+\sum_{m=-\infty,m\neq 1}^{\infty}\left\{\mathbf{B}^{(m)}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})+m\Delta\psi(\boldsymbol{\rho})\right)$$

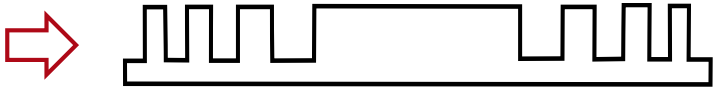


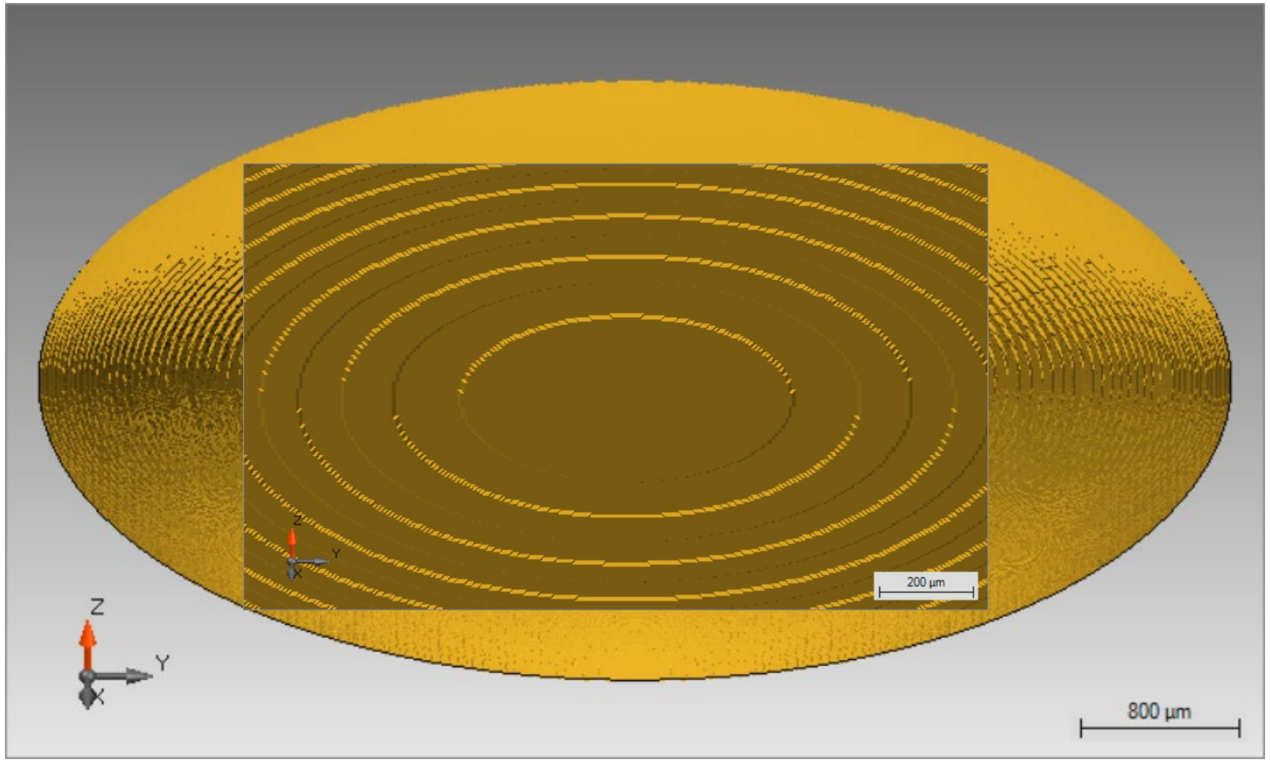
Structure Design: Diffractive Layer Profile Height

- With the introduction of a scaling factor in the TEA formula, the resulting structure height is modulated to control the efficiencies of the diffraction orders:

$$h^{DOE}(\rho) = \beta \frac{\lambda}{2\pi \Delta n} \Delta\psi(\rho)^{DOE}$$

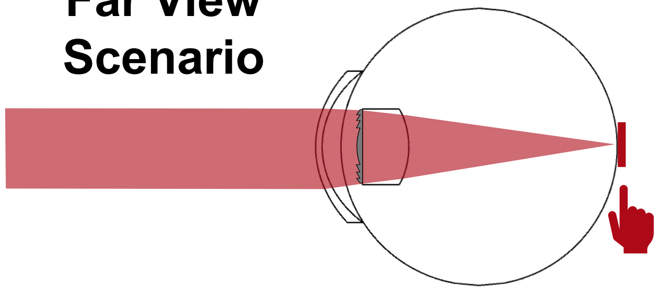
- A quantization of the structure with 2 height levels is chosen because binary diffractive lenses
  - are beneficial for manufacturing (cost, easier to fabricate)
  - give a better control of the efficiencies especially for the 0^{th} and 1^{st} order using the height modulation approach

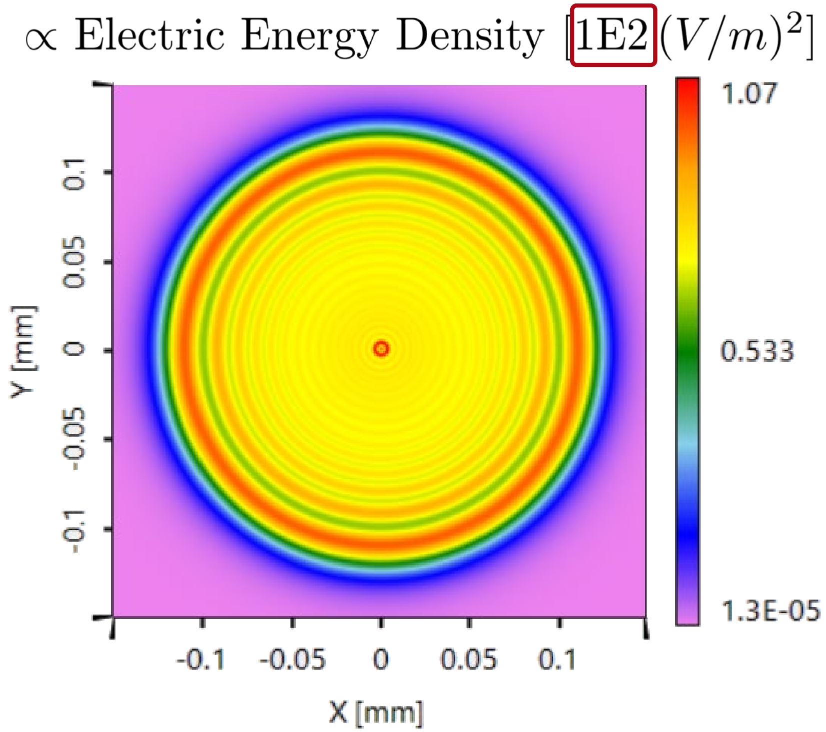


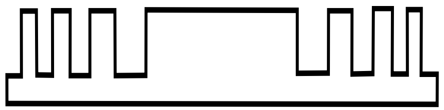


Structure Design: Height Modulation of 1.00

Far View Scenario

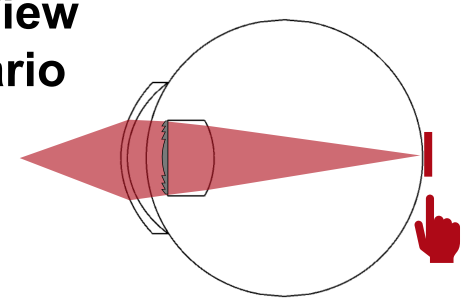


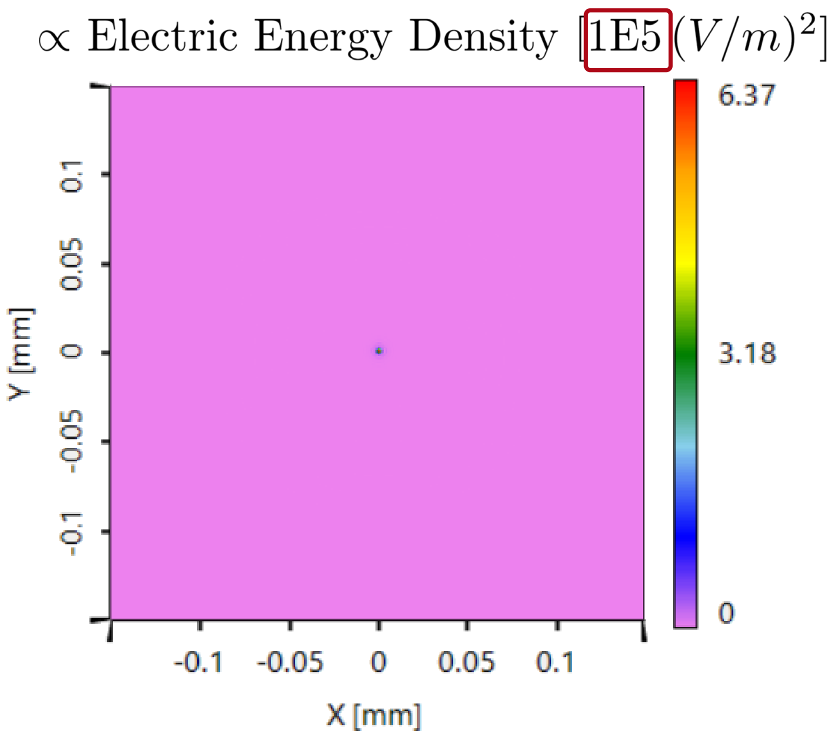




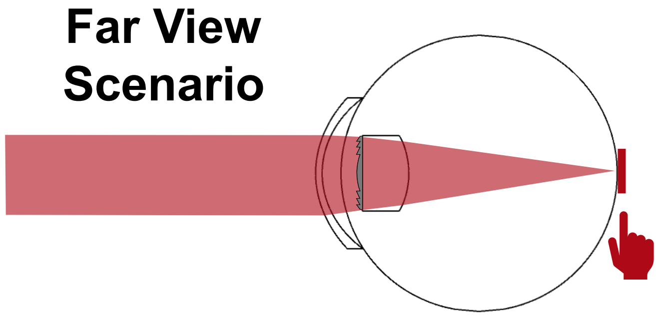
scaling of modulation height by
$\boldsymbol{\beta = 1.00}$

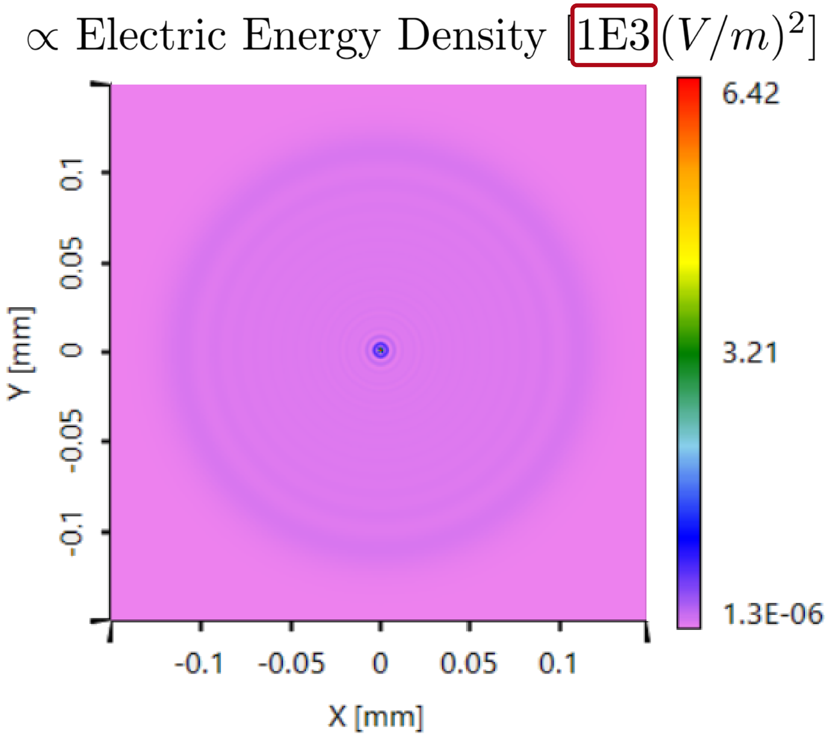
Near View Scenario

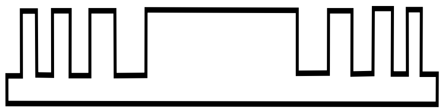




Structure Design: Height Modulation of 0.95

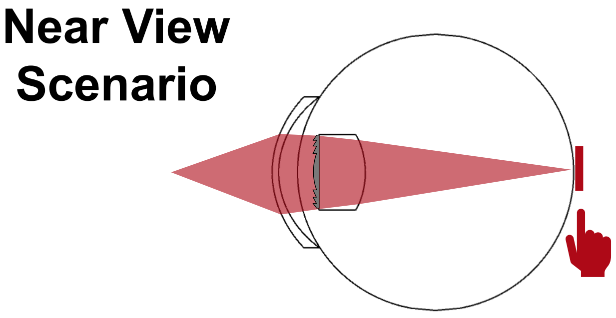


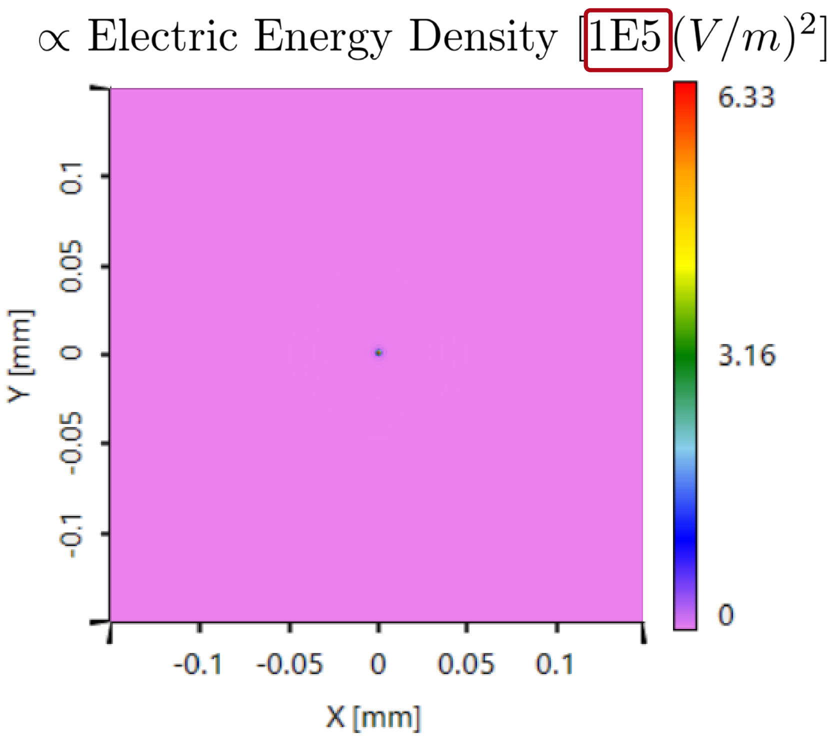




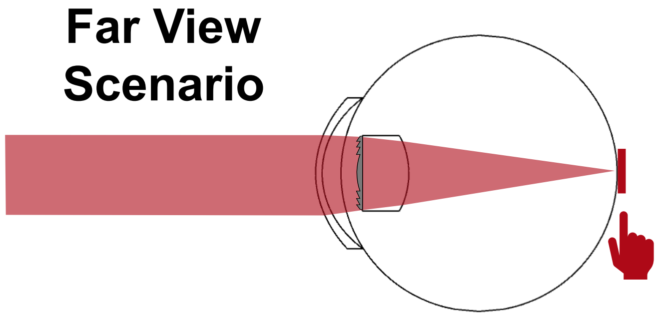
scaling of modulation height by

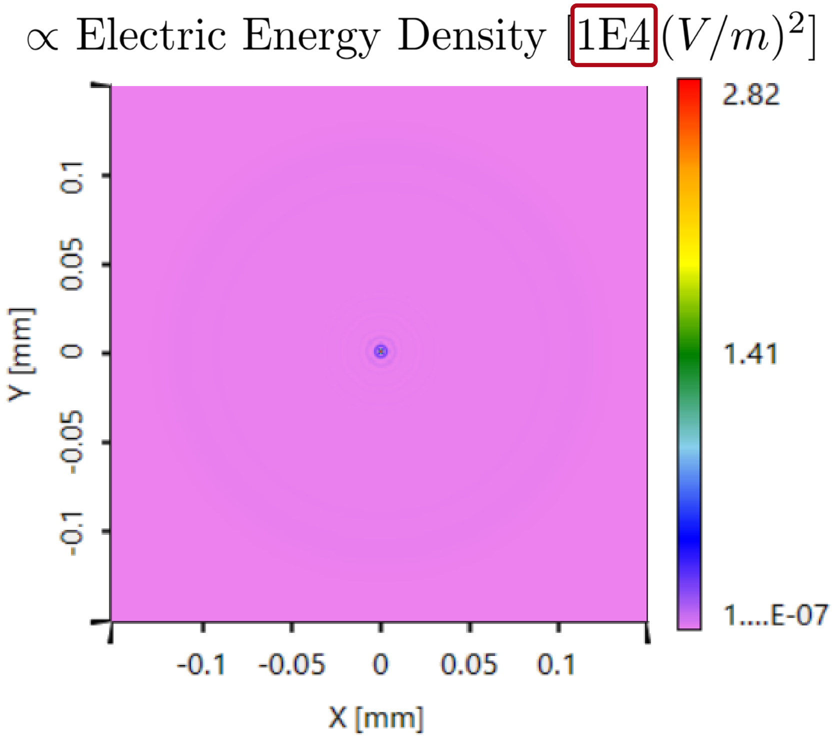
$\boldsymbol{\beta = 0.95}$

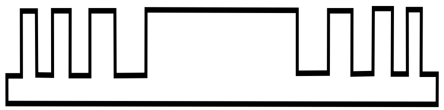




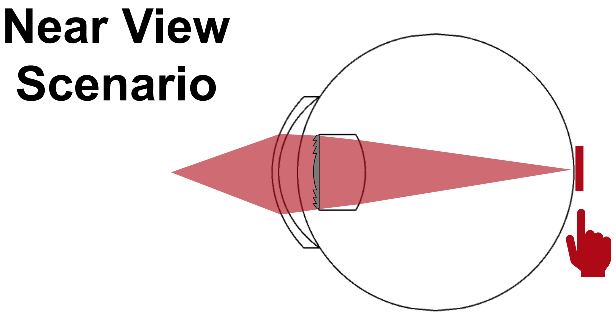
Structure Design: Height Modulation of 0.90

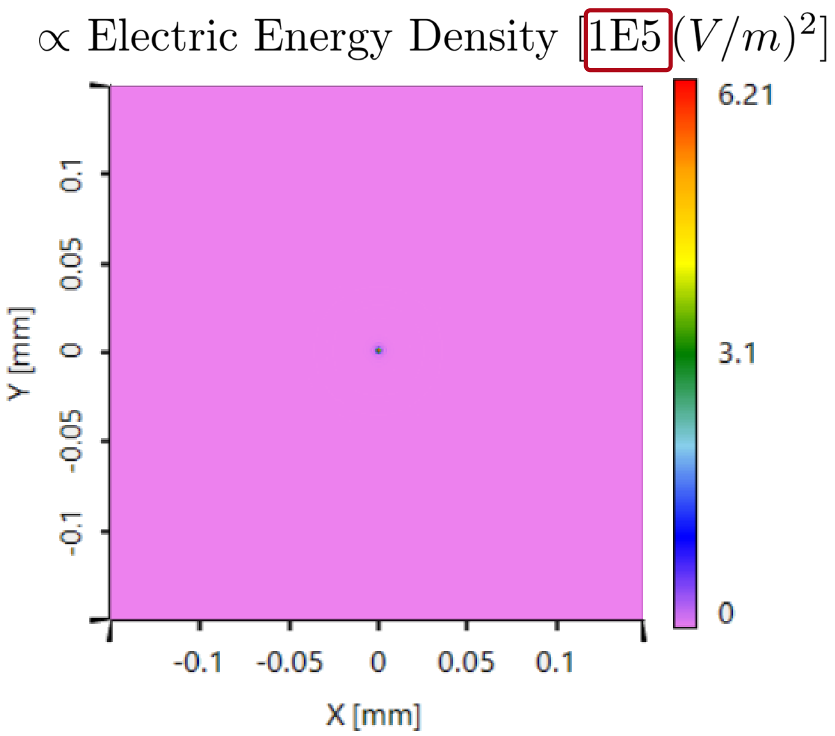






scaling of modulation height by
$\beta = 0.90$

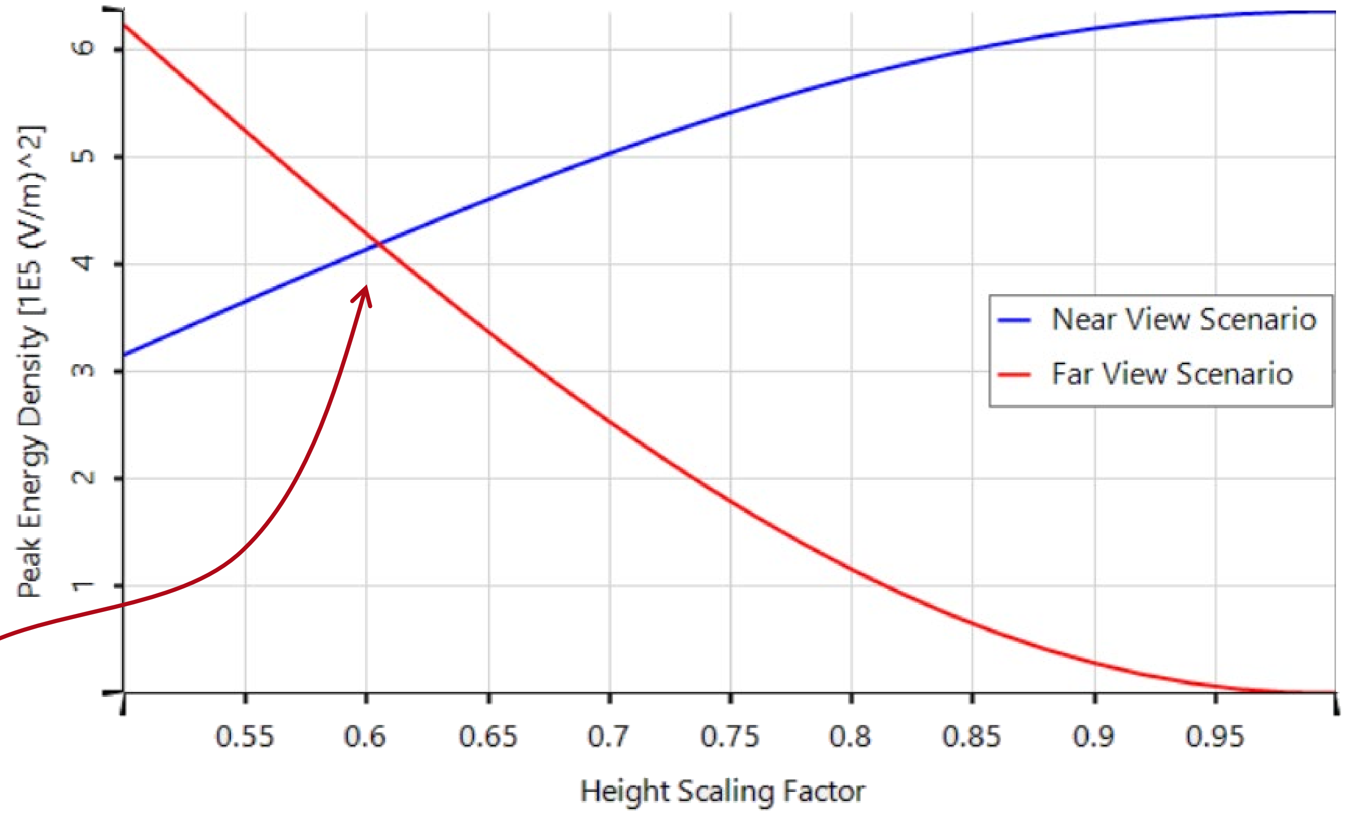




Structure Design: Find the Optimum Scaling Factor

- As a goal the peak energy density of the both foci shall be the same.

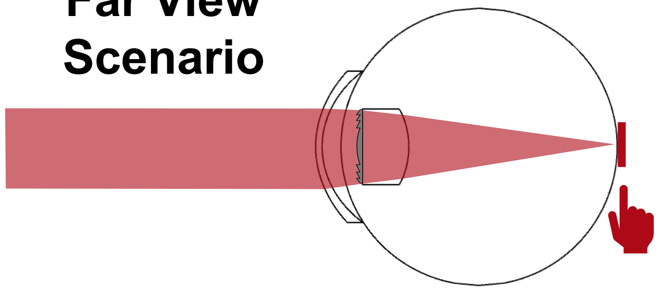
- Therefore, the peak energy density is calculated according to the scaling factor for both scenarios.



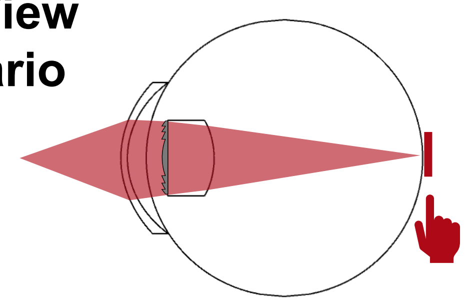
Optimum of the scaling factor for equivalent peak energy density for both foci (near and far view)

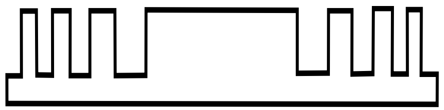
Structure Design: Optimum Height Modulation of 0.605

Far View Scenario



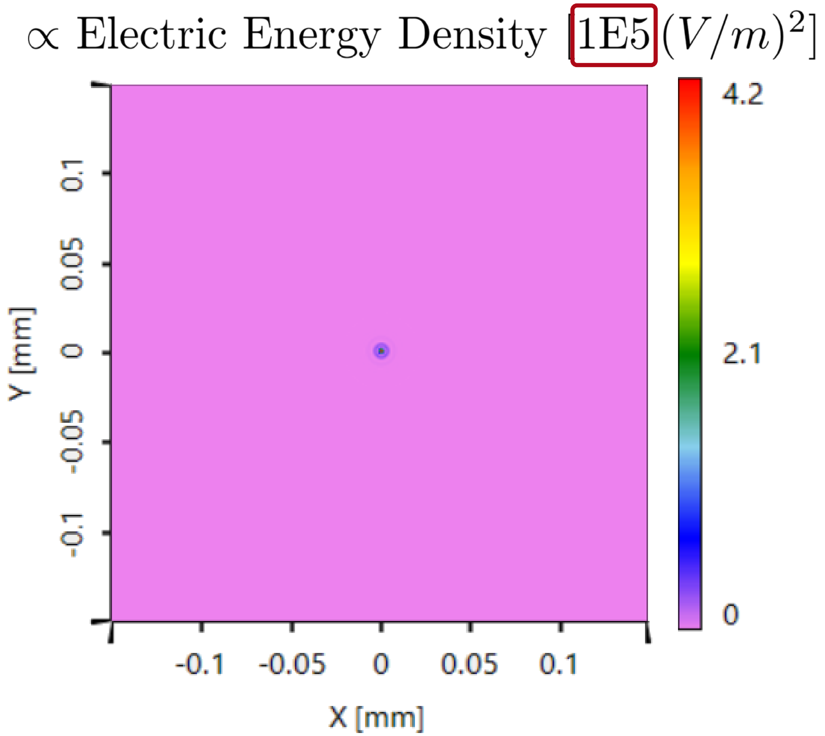
Near View Scenario



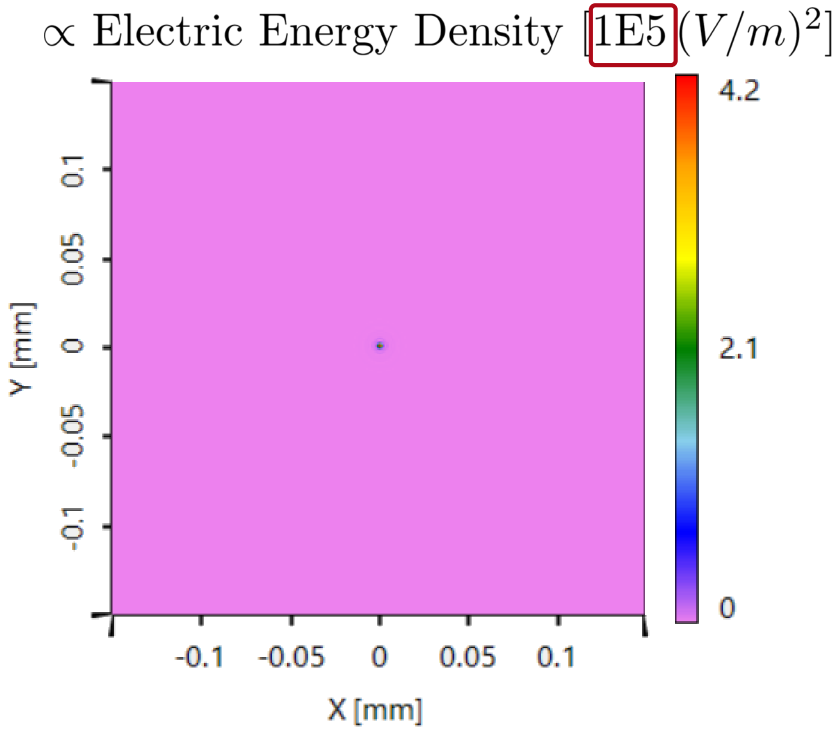


scaling of modulation height by

$\boldsymbol{\beta = 0.605}$

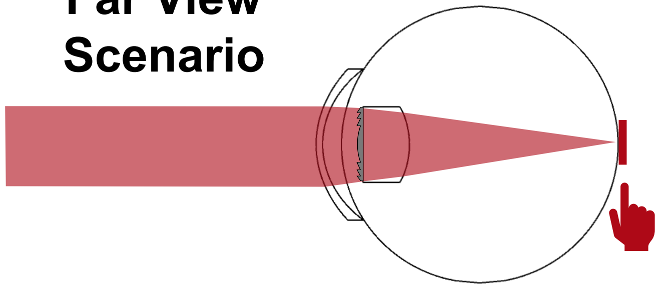


Goal of equivalent maximum energy density for both foci achieved!

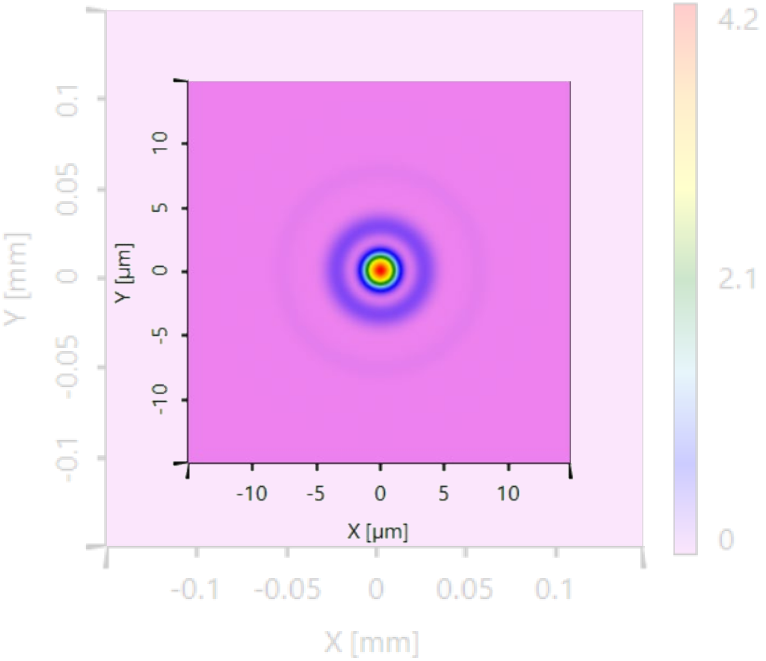


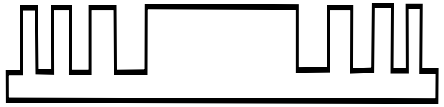
Analysis: PSF of Foci for Optimum Structure Design

Far View Scenario



$\propto$ Electric Energy Density $[1\text{E}5\,(V/m)^2]$

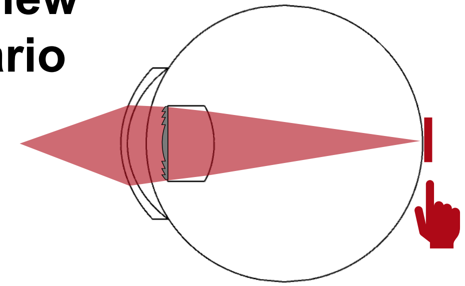




scaling of modulation height by

$\boldsymbol{\beta = 0.605}$

Near View Scenario



$\propto$ Electric Energy Density $[1\text{E}5\,(V/m)^2]$

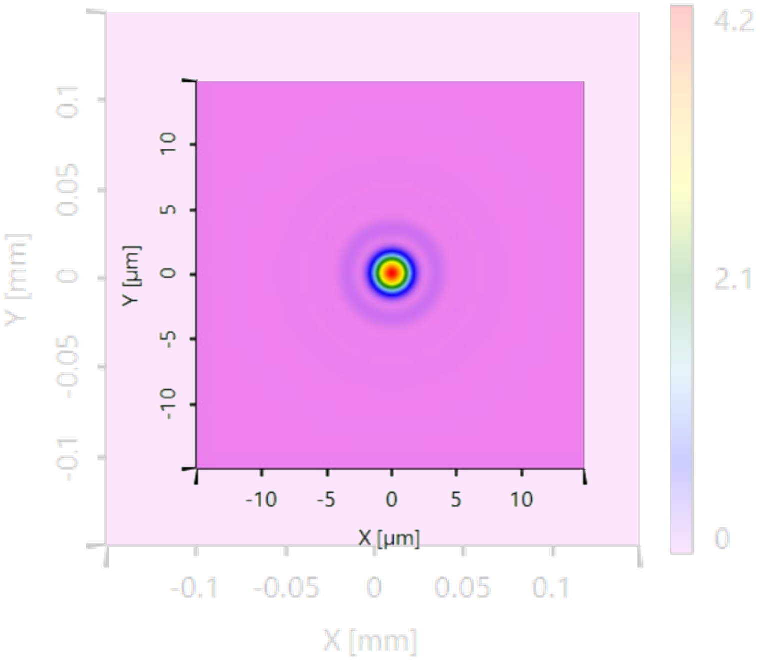
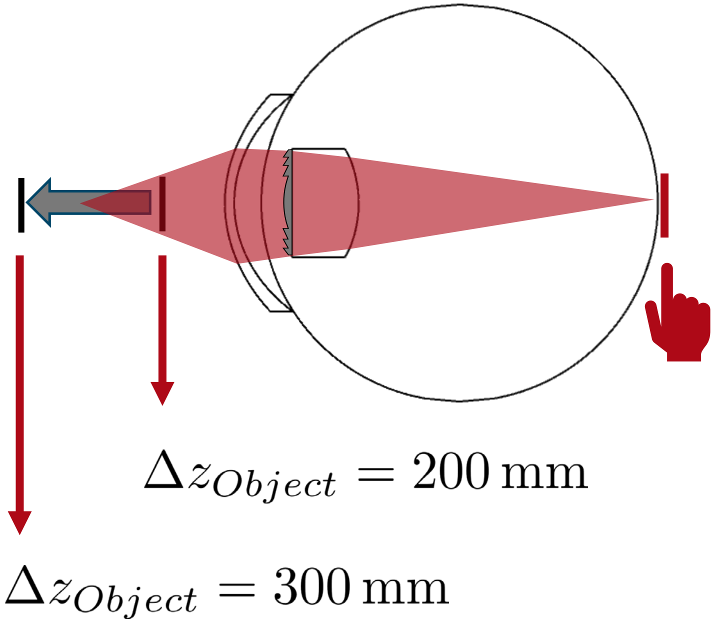


Illustration of Focus Development in Near View Region

Near View Scenario



step size 10 mm
→ 101 simulations
simulation time ~13 min

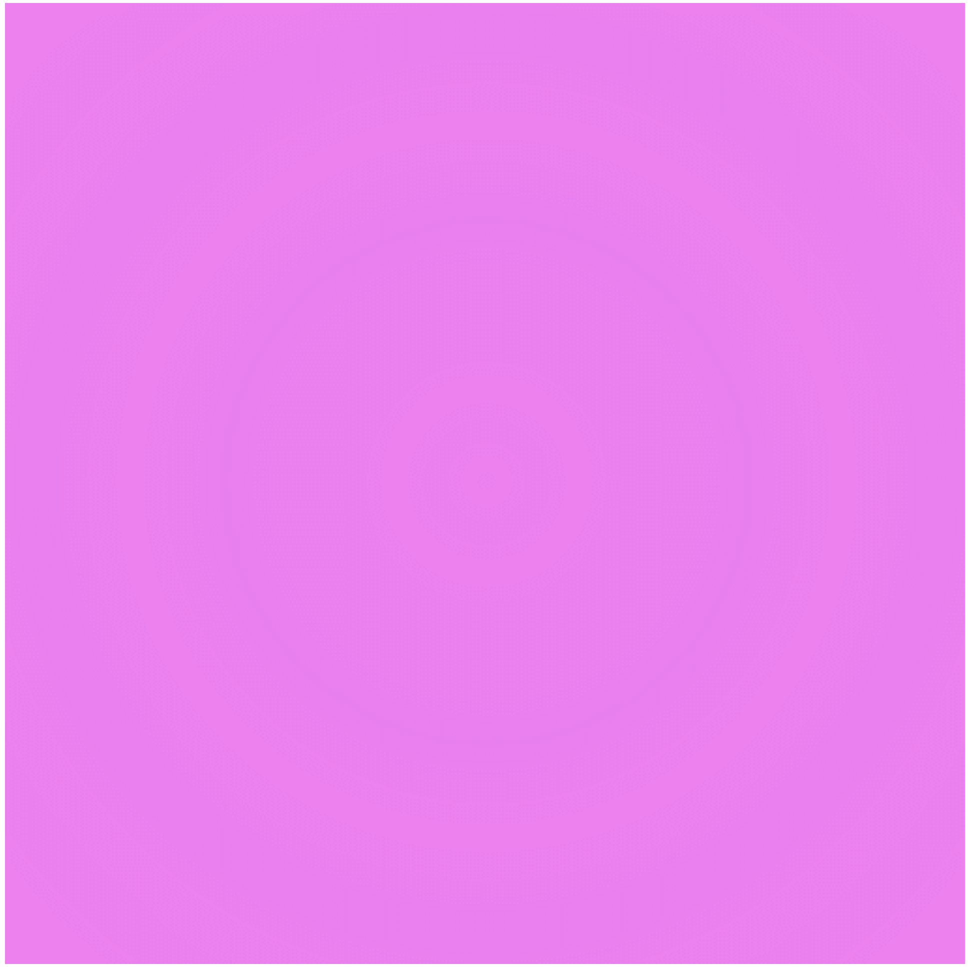
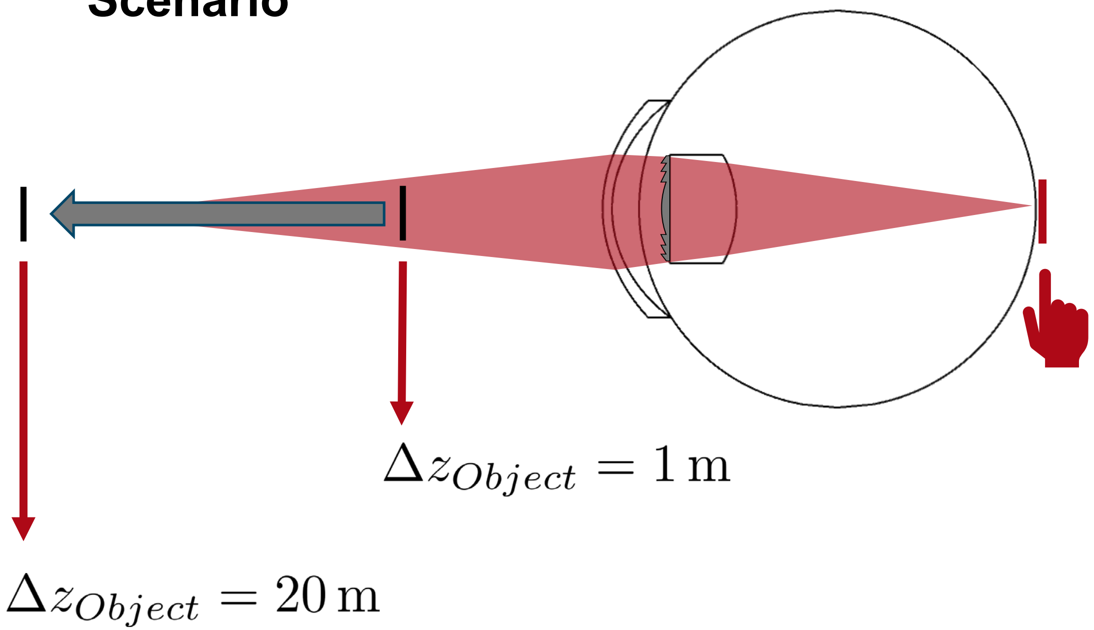


Illustration of Focus Development in Far View Region

Far View Scenario



step size 250 mm
→ 77 simulations
simulation time ~10 min

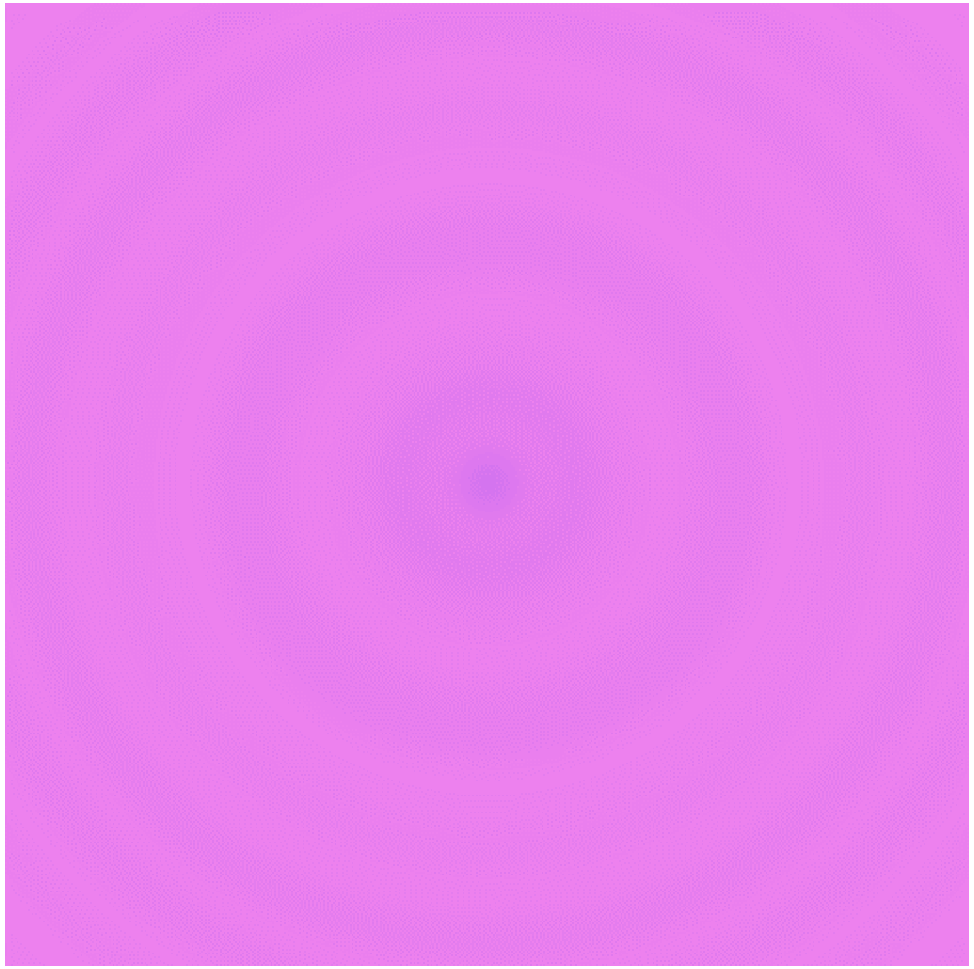
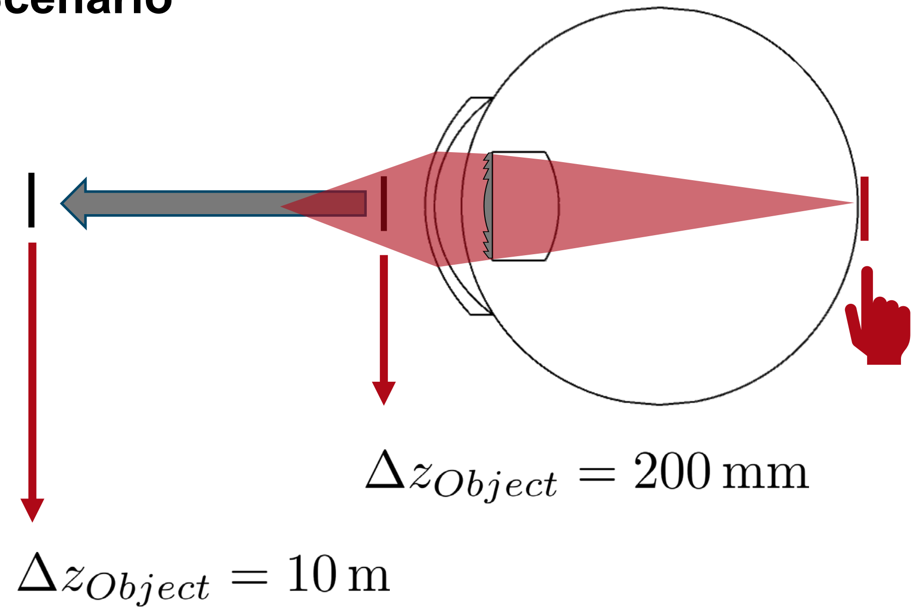
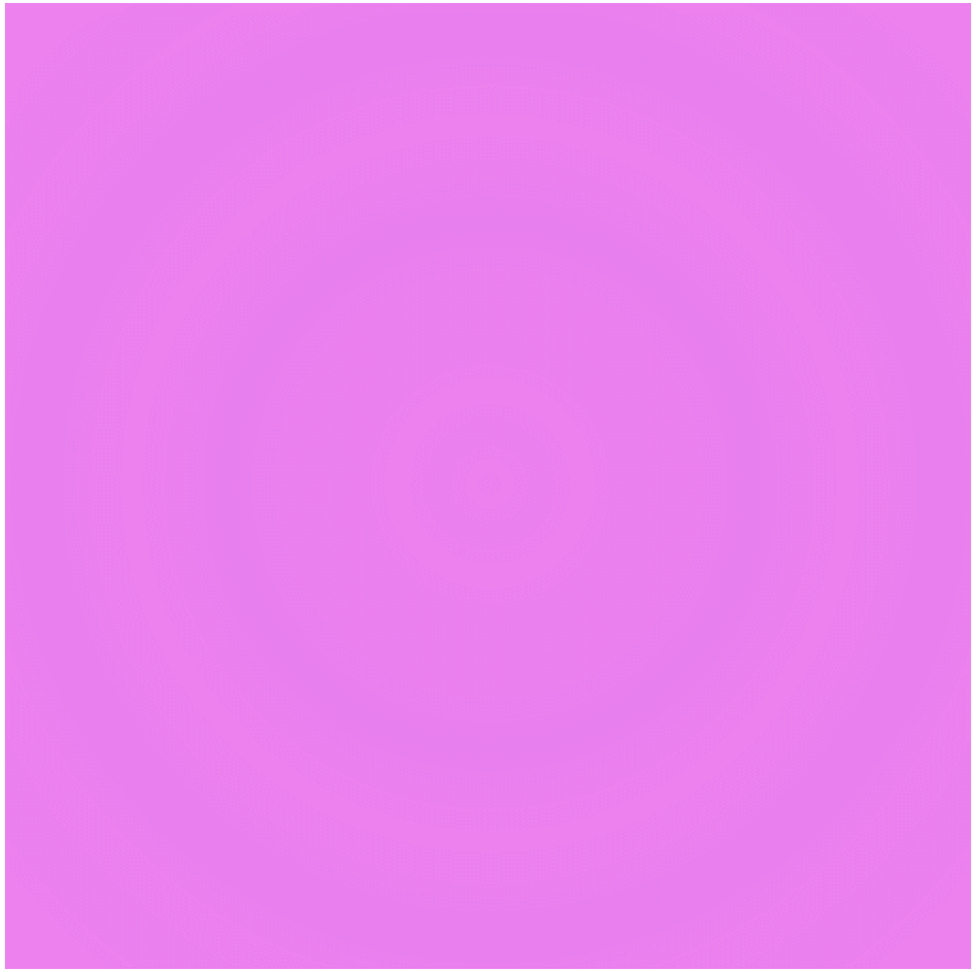


Illustration of Focus Development from Near to Far Region

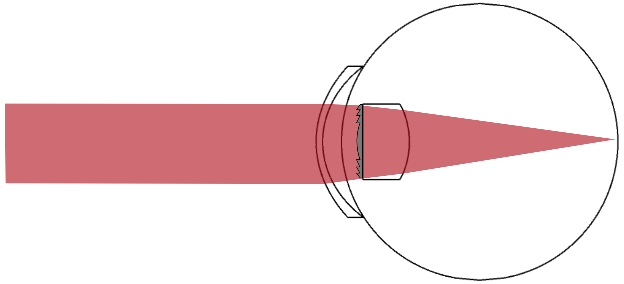
Near to Far View Scenario



step size 50 mm
→ 168 simulations
simulation time ~20 min

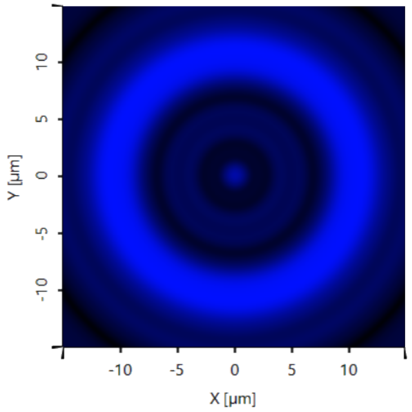


Far View Scenario: Analysis of the Focal Spots per Color

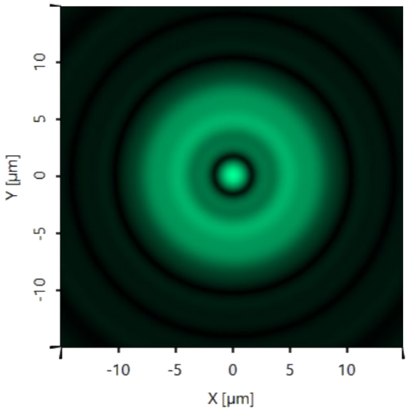


VirtualLab enables various analysis capabilities of the designed diffractive lens structure

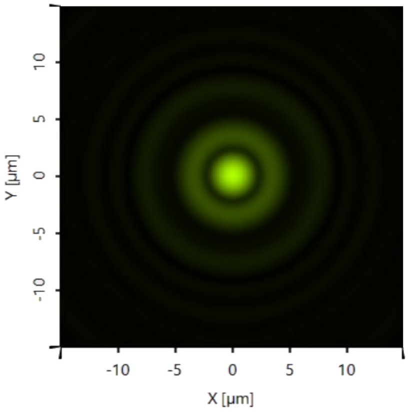
Wavelength 470 nm



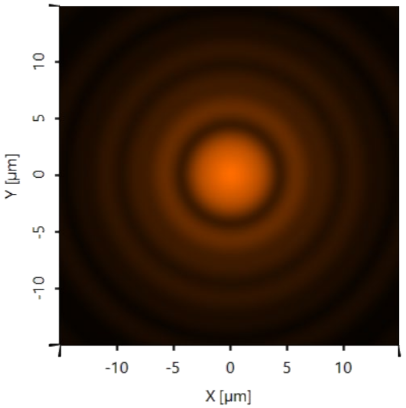
Wavelength 510 nm



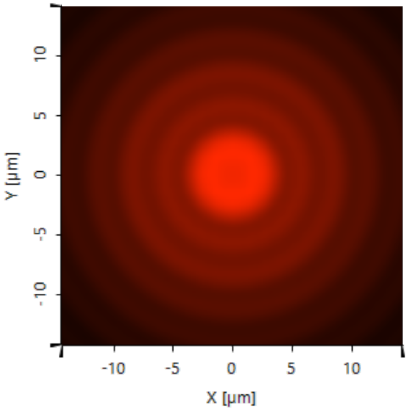
Wavelength 555 nm



Wavelength 610 nm



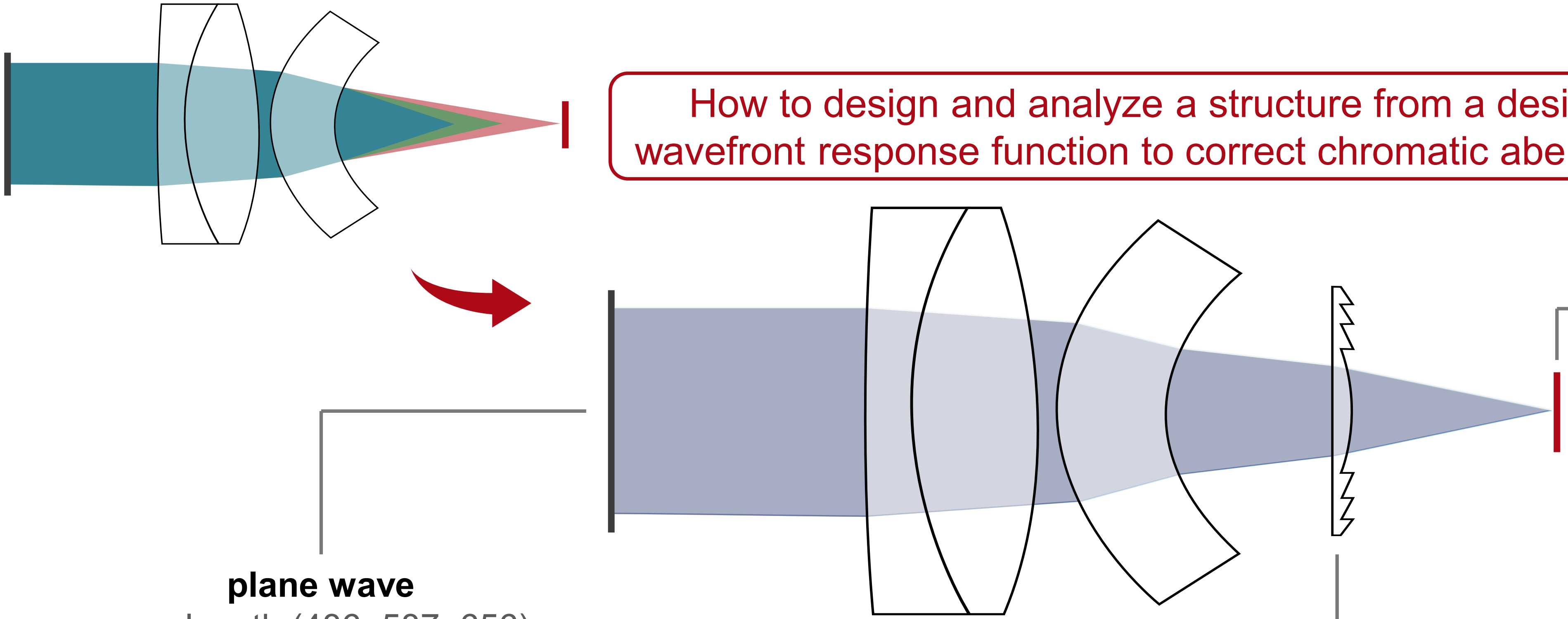
Wavelength 650 nm



An Example of Diffractive Layer Design

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

Modeling and Design Task



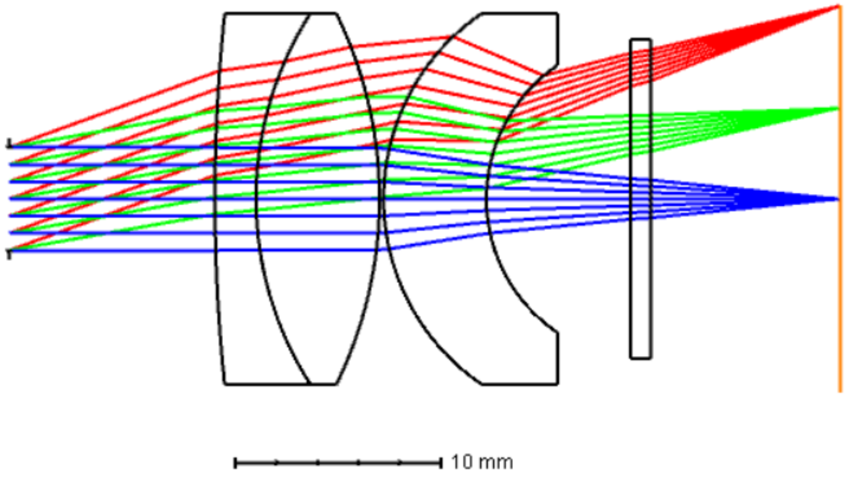
How to design and analyze a structure from a designed wavefront response function to correct chromatic aberration ?

detectors
- point spread function
- modulation transfer function (MTF)

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

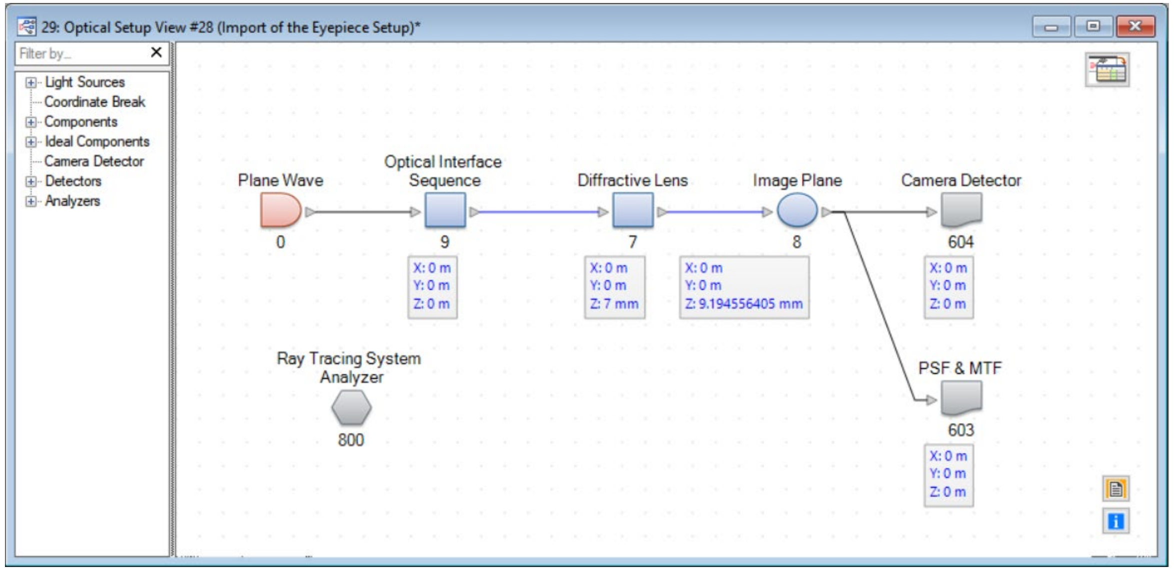
lens solution
- wavefront response function
- diffractive lens
- meta lens

Design of Wavefront Surface Response in OpticStudio



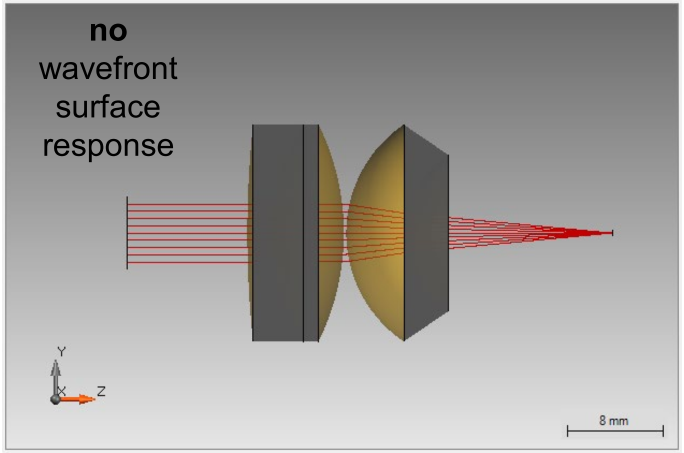
Optical setup including the wavefront surface response was originally designed in OpticStudio

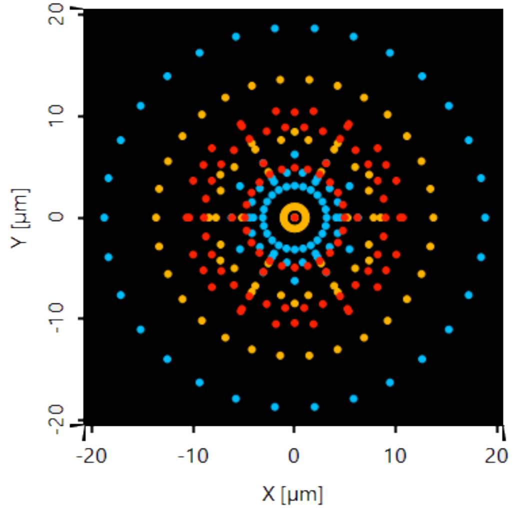
Import of the OpticStudio file to VirtualLab Fusion

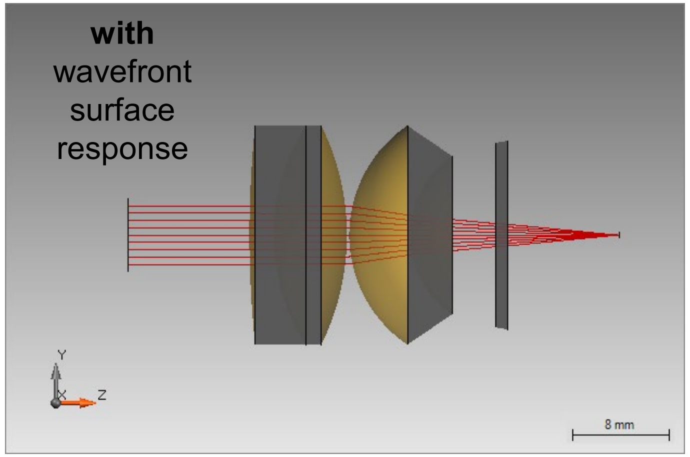


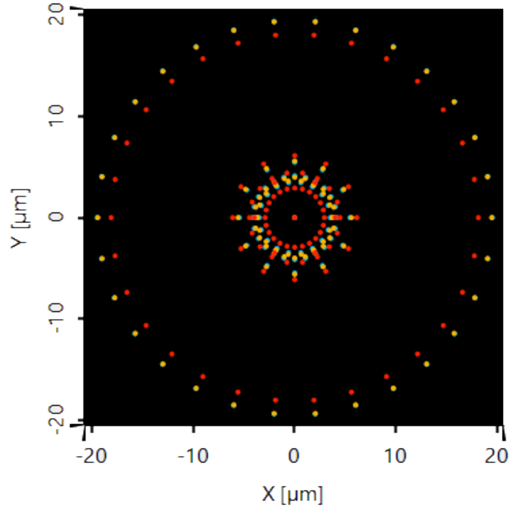
Wavefront Surface Response (WSR)

On-Axis Analysis: Comparison of Spot Diagram

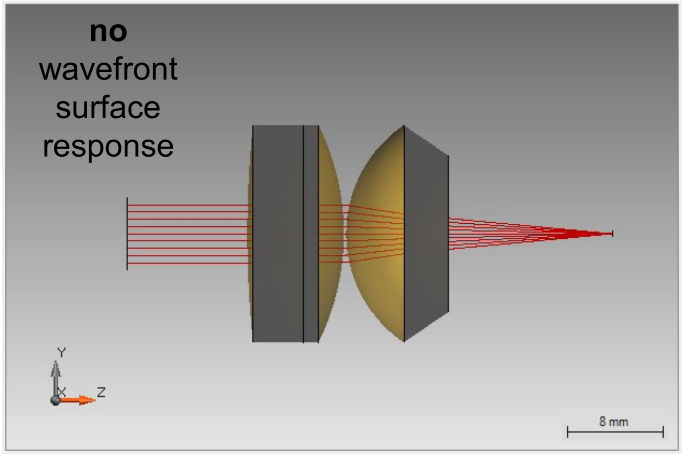




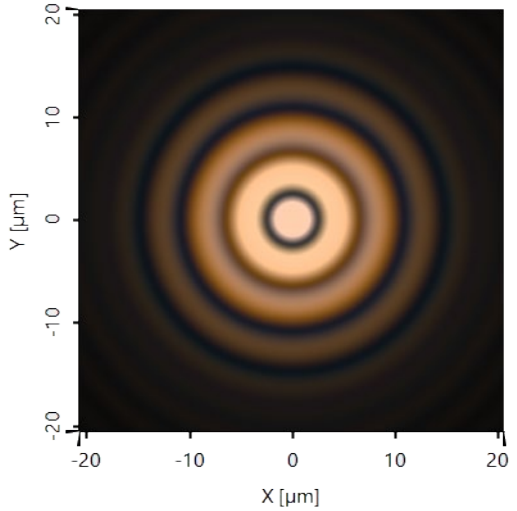




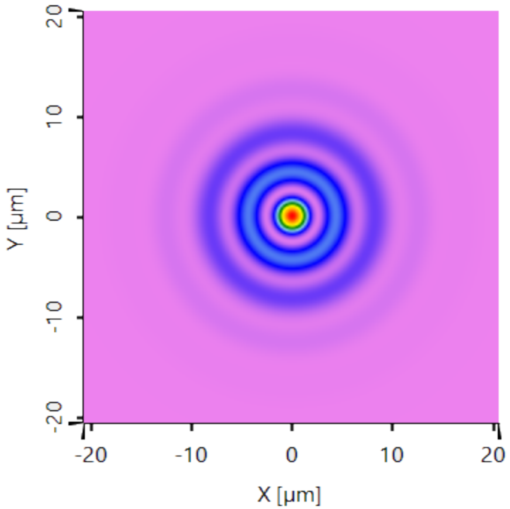
On-Axis Analysis: Comparison of PSF

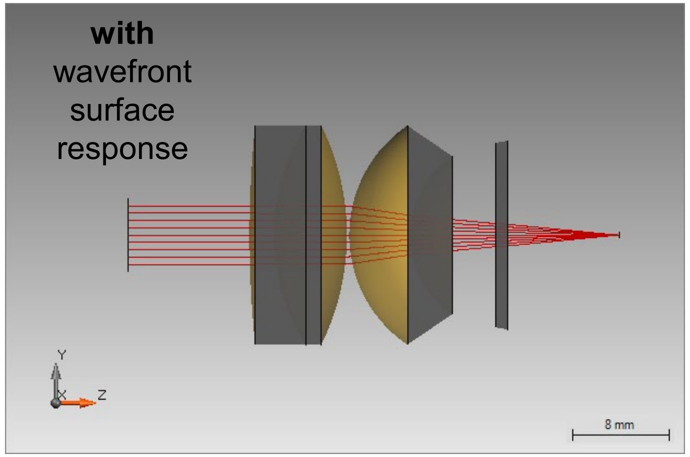


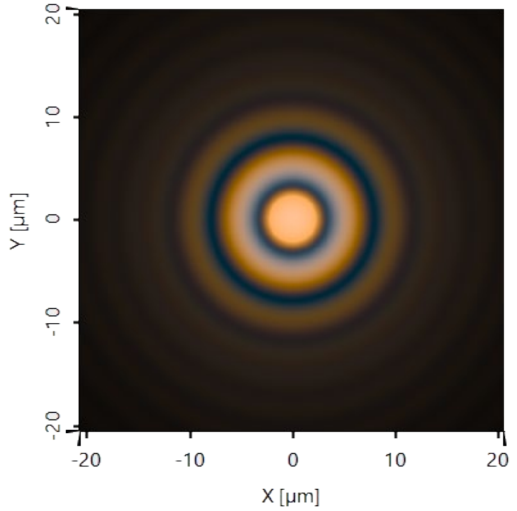
Real Color View

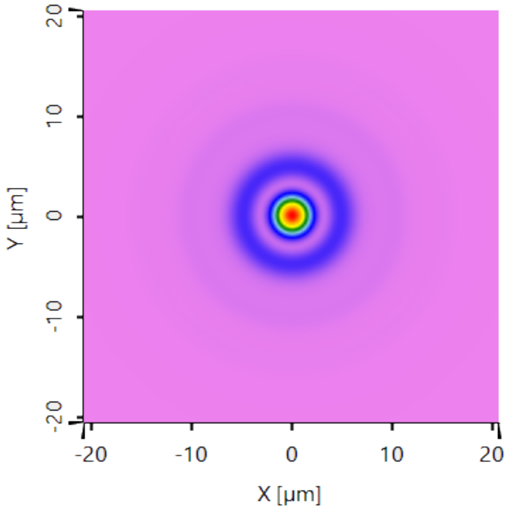


False Color View

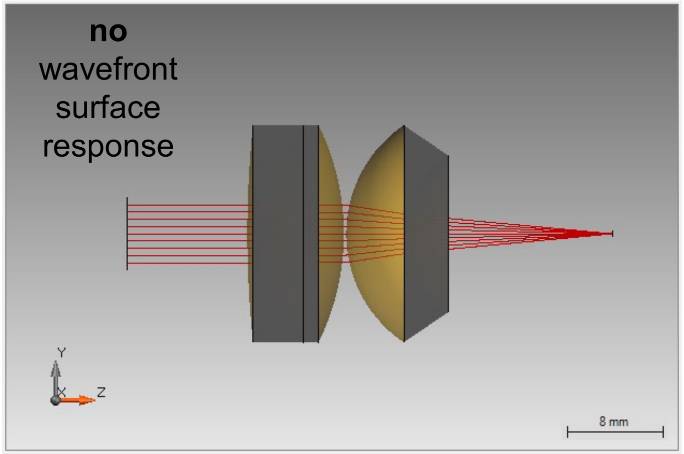


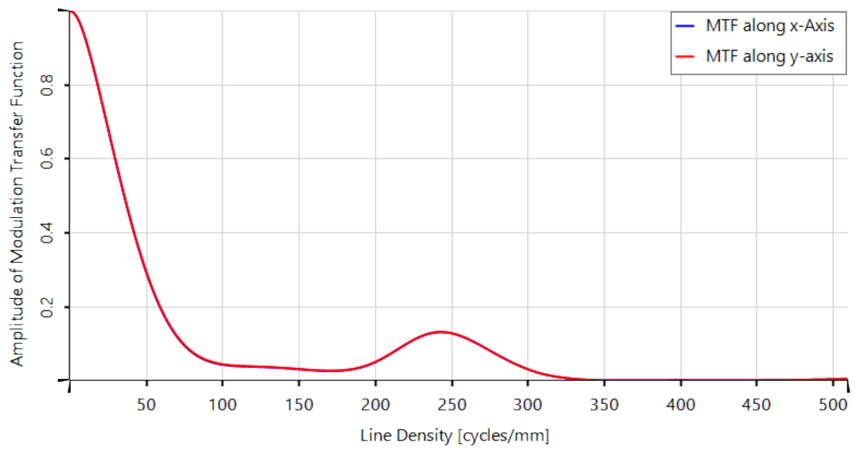


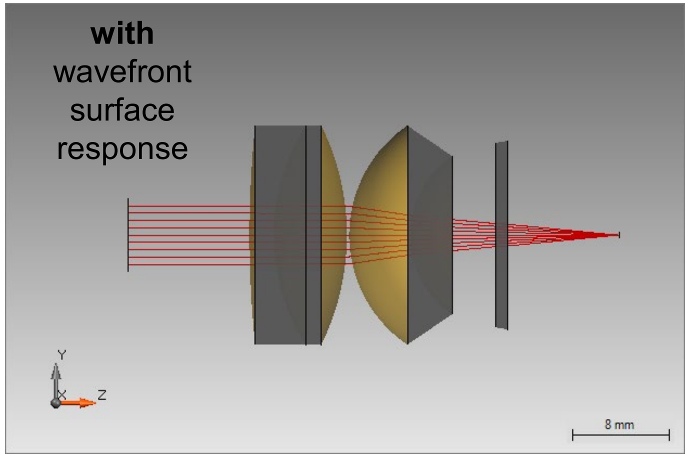


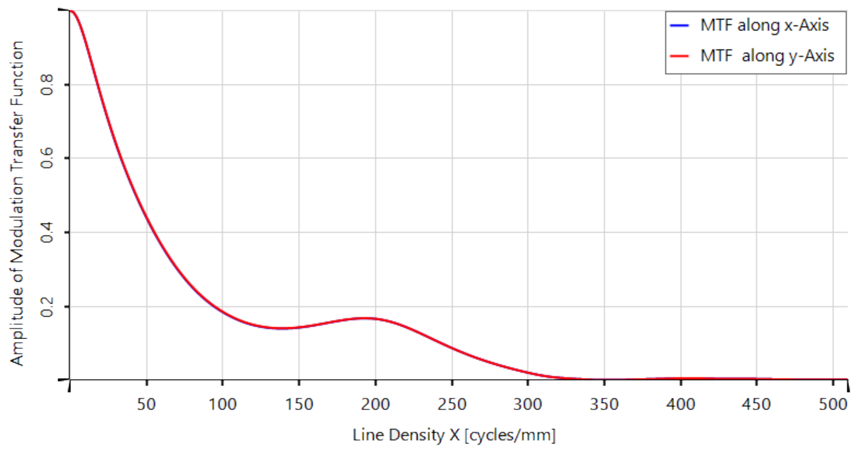


On-Axis Analysis: Comparison of MTF

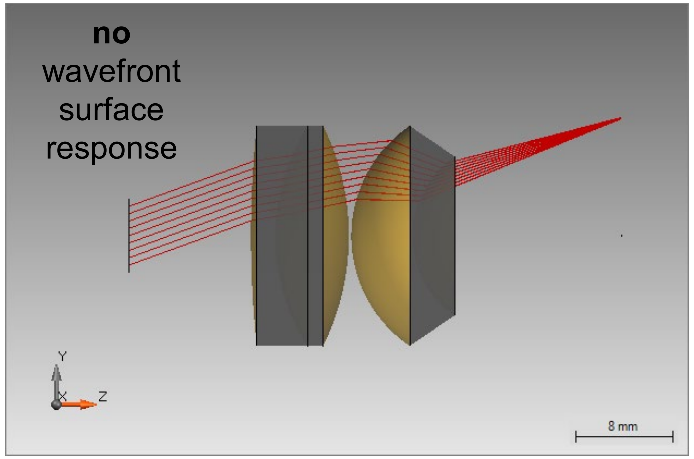


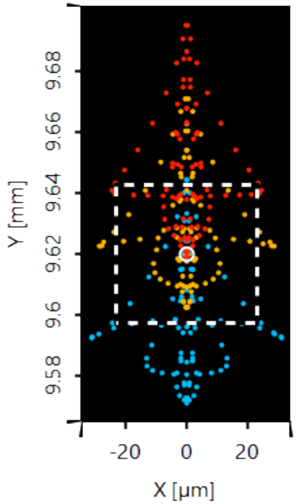


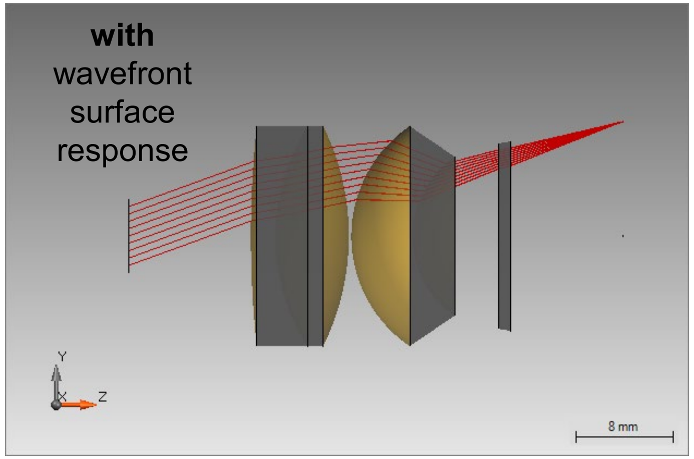


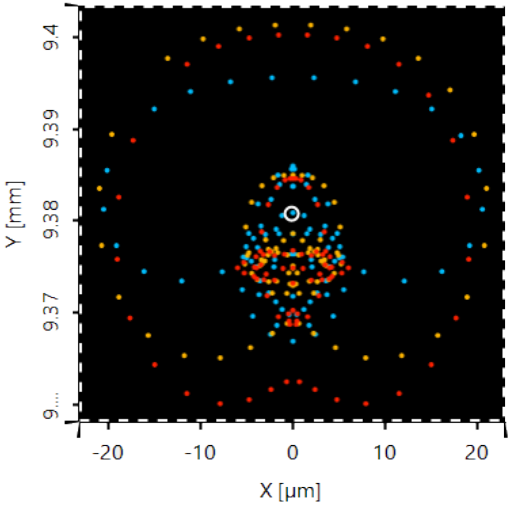


Off-Axis Analysis: Comparison of Spot Diagram

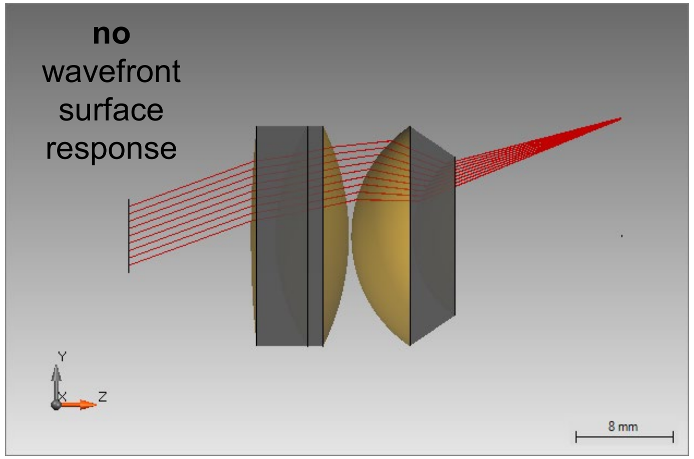


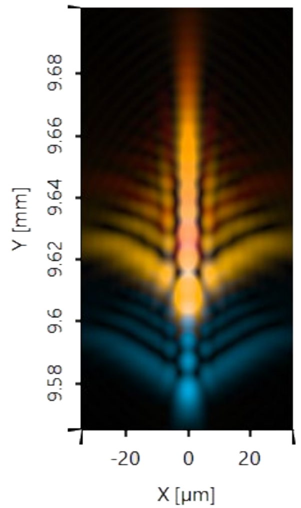


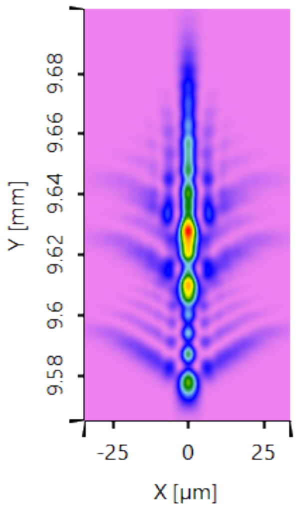


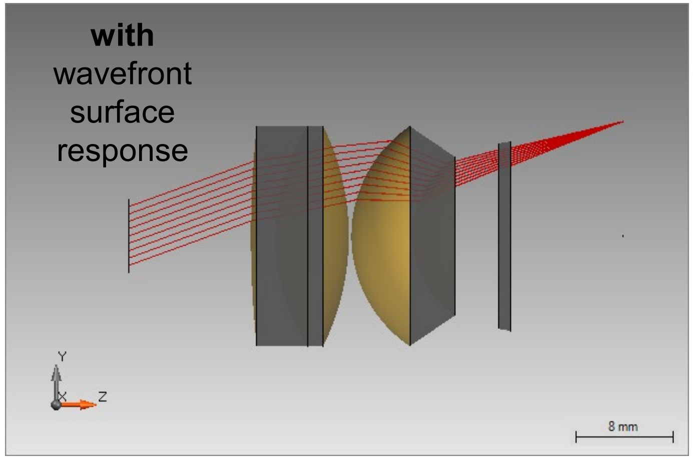


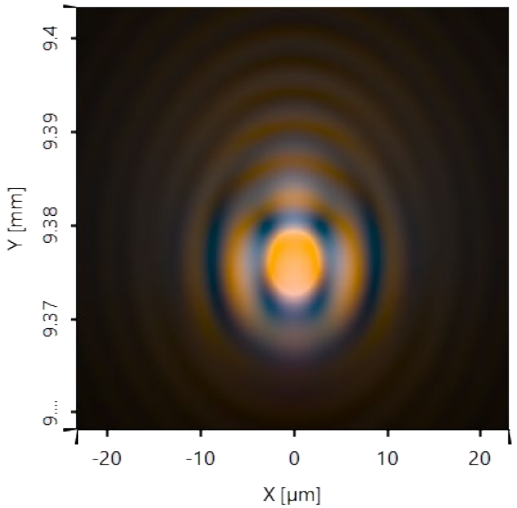
Off-Axis Analysis: Comparison of PSF

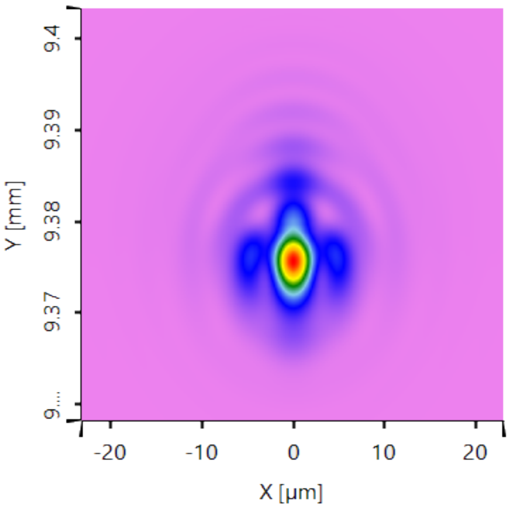




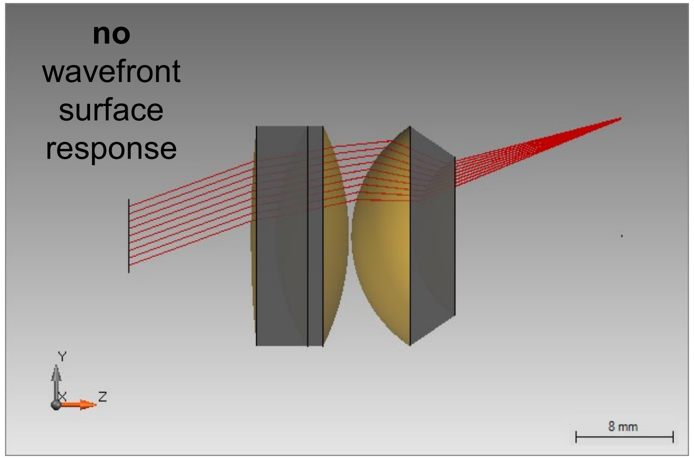


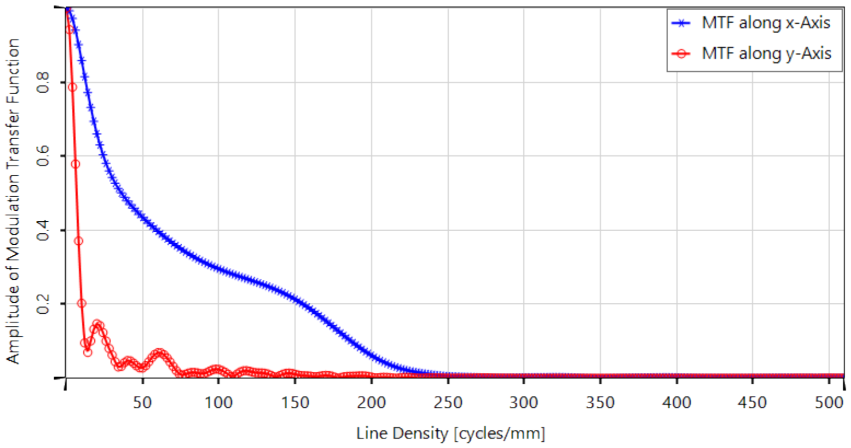


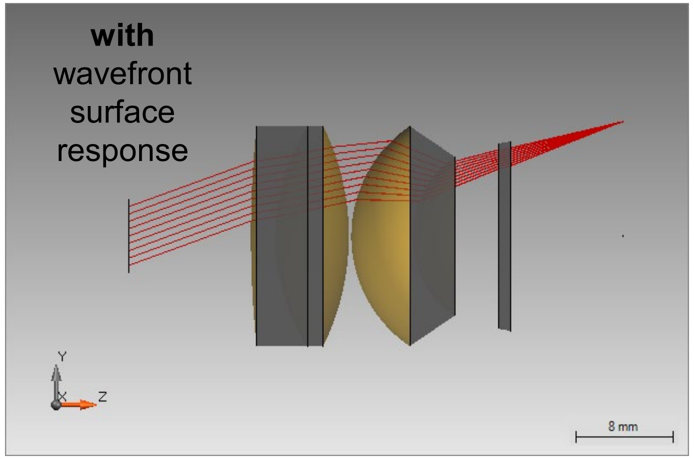


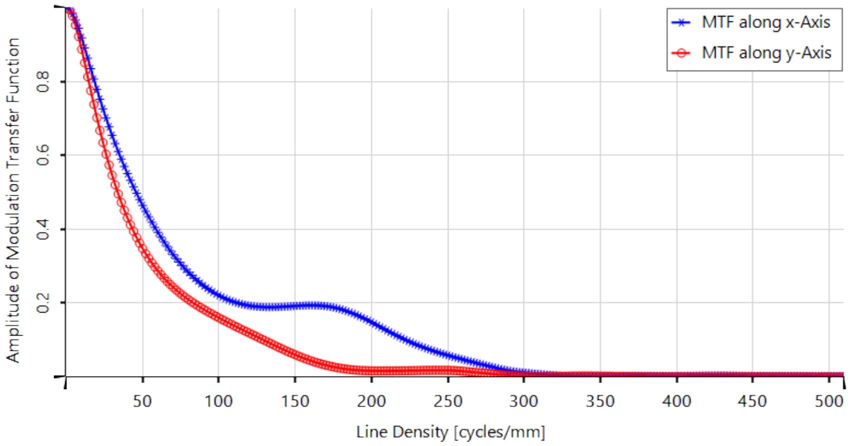


Off-Axis Analysis: Comparison of MTF







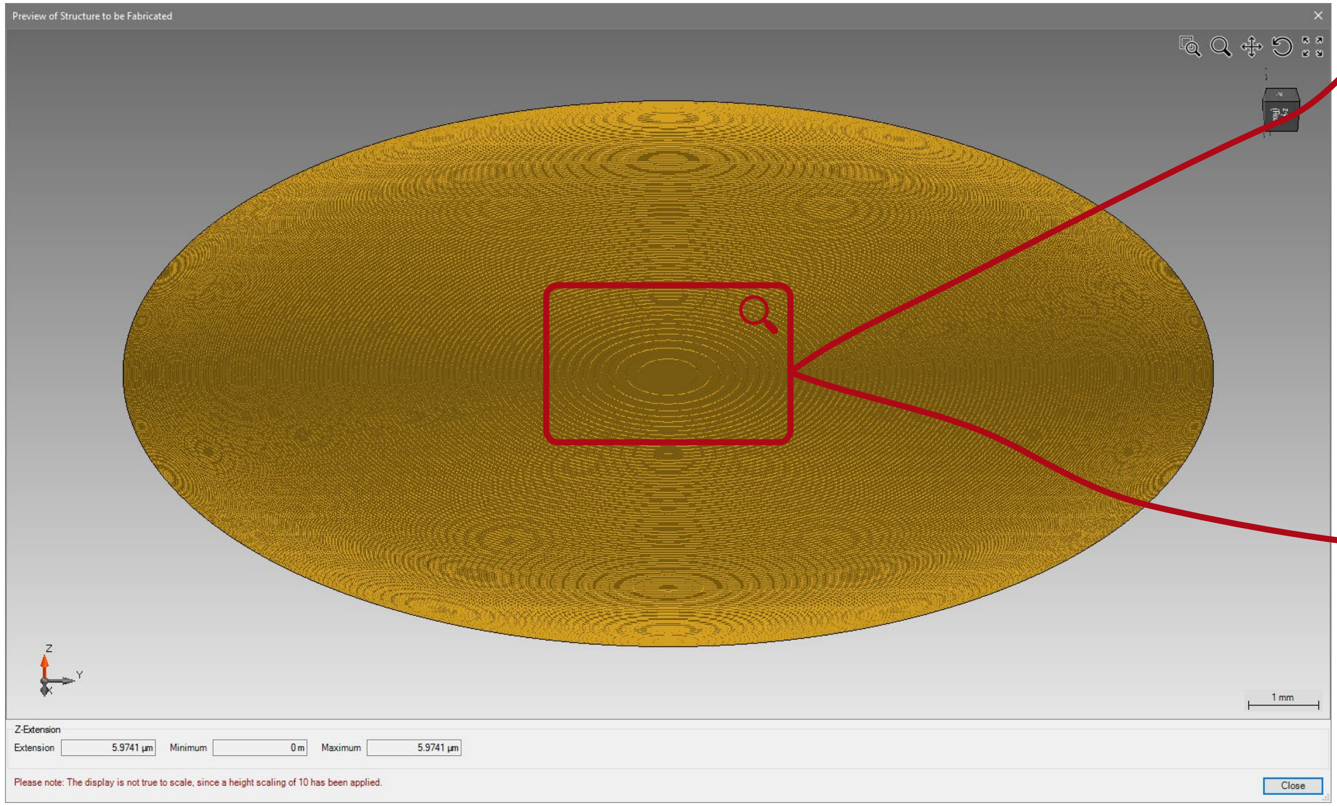


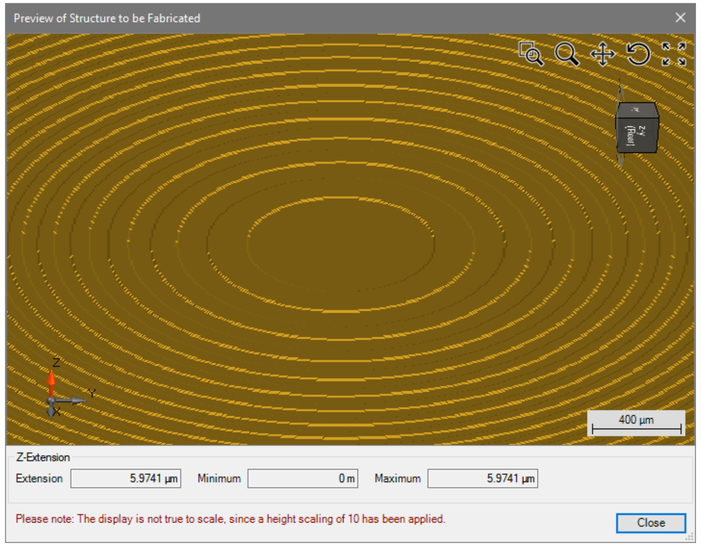
Structure Design – Diffractive Lens

Visualization of Quantized Diffractive Lens Structure

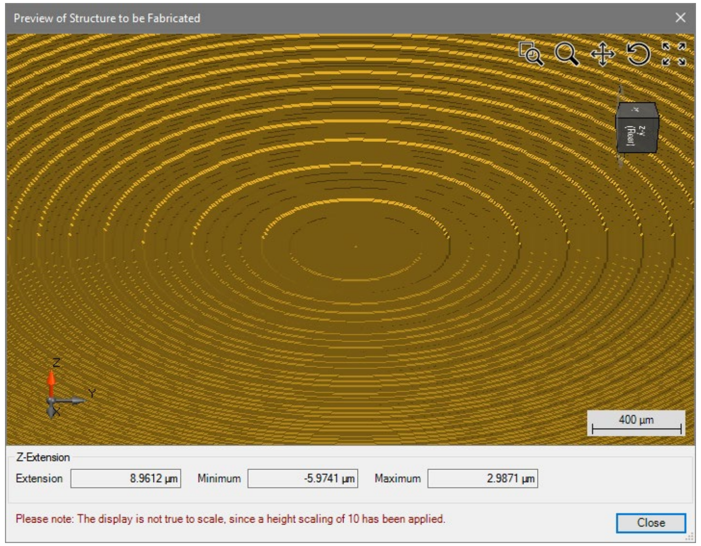
The structure is designed by TEA:

$$h^{DOE}(\rho) = \frac{\lambda}{2\pi\Delta n}\Delta\psi(\rho)^{DOE}$$



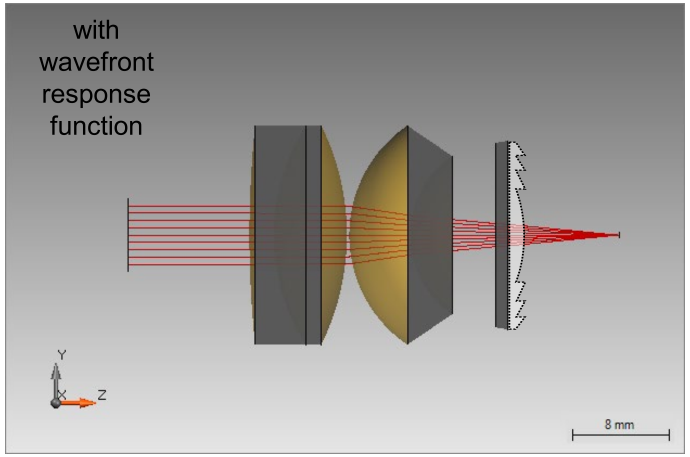


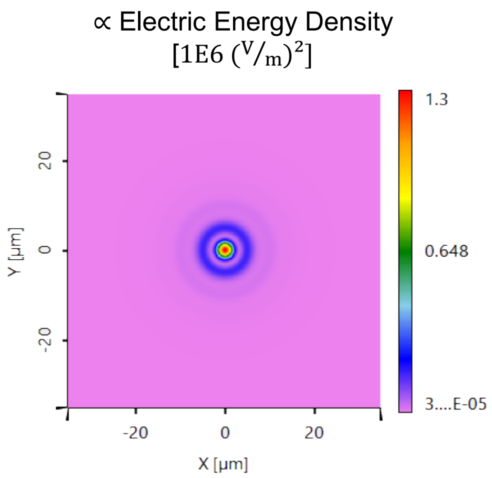
Preview for 2 quantization levels

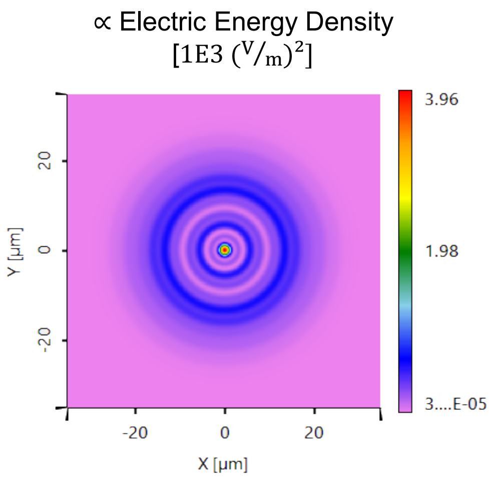


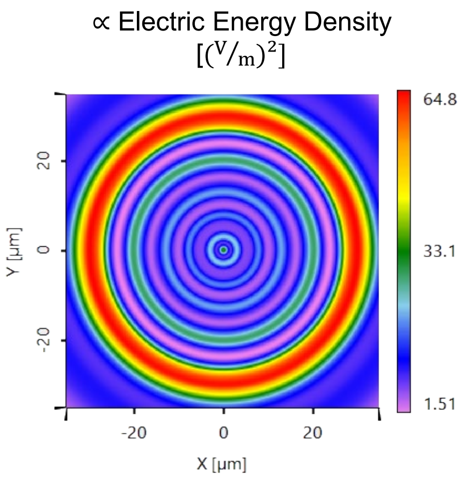
Preview for 4 quantization levels

On-Axis Analysis: Inclusion of Higher Orders

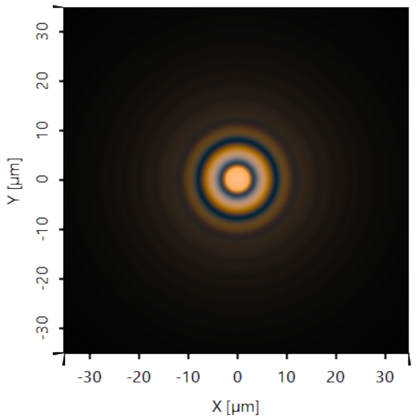




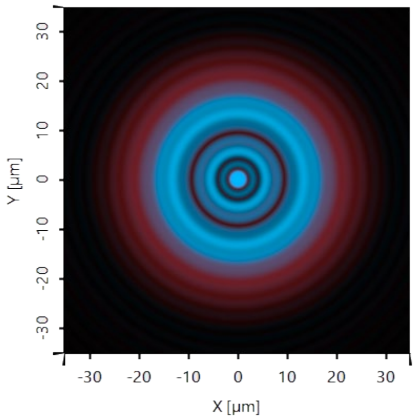




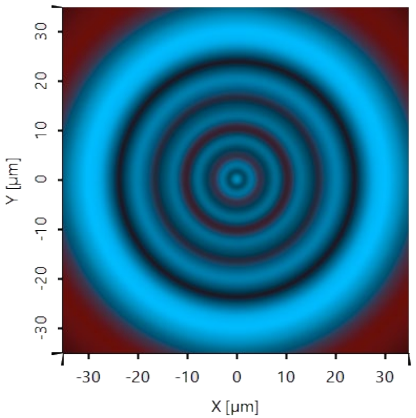
simulation time per order ~seconds



+1st diffraction order

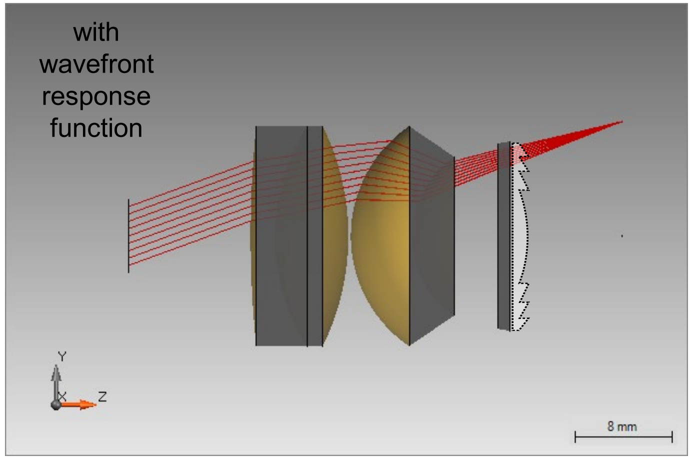


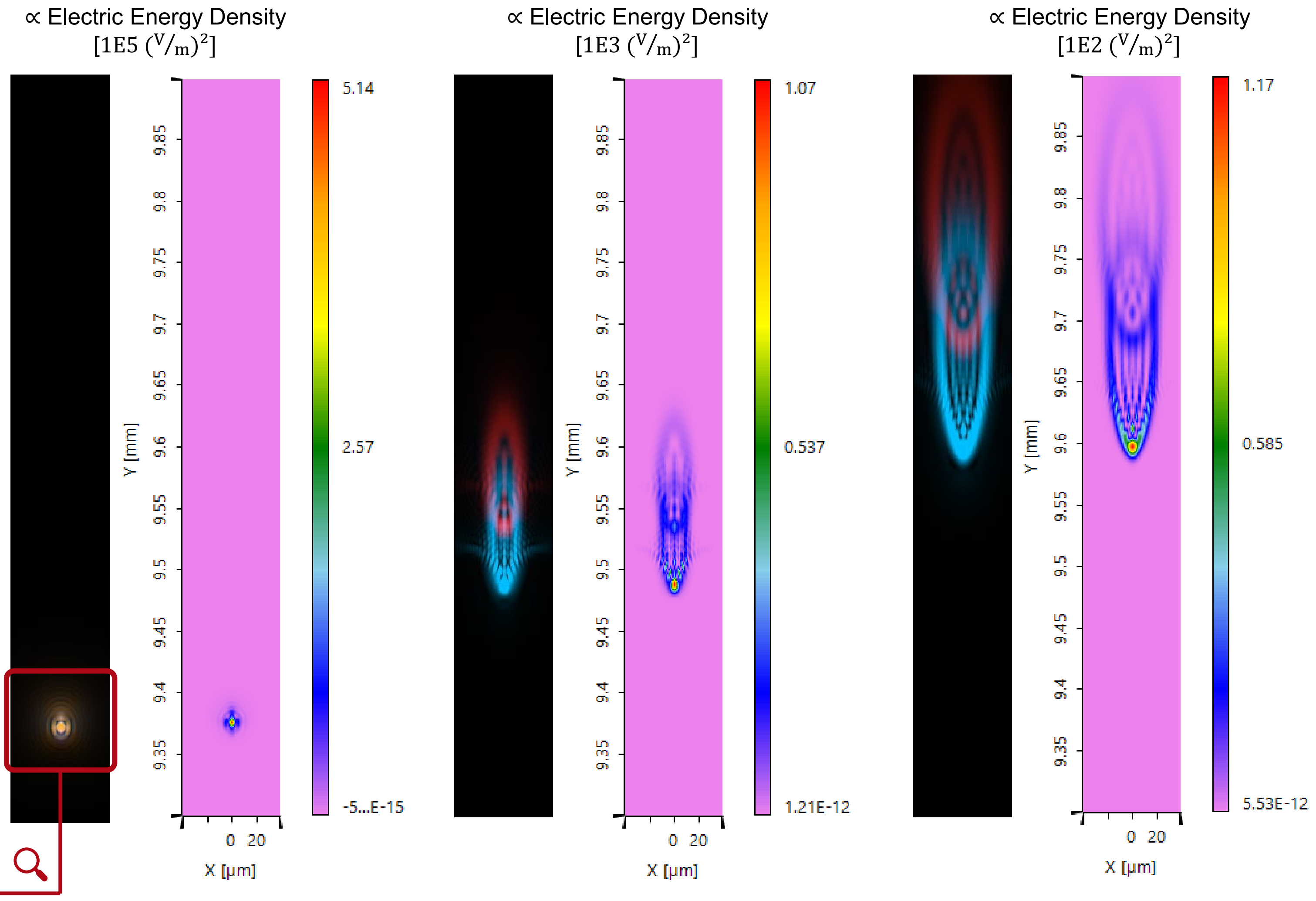
0th diffraction order



-1st diffraction order

Off-Axis Analysis: Inclusion of Higher Orders

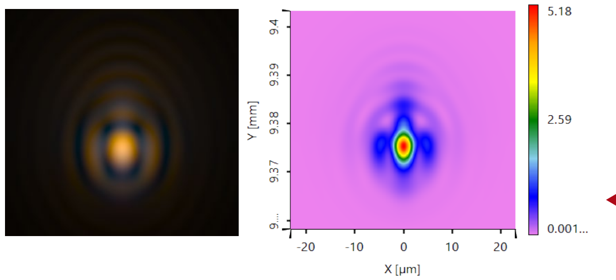




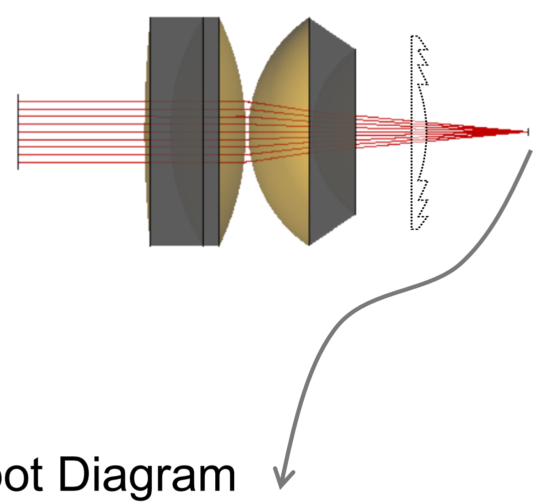
+1st diffraction order

0th diffraction order

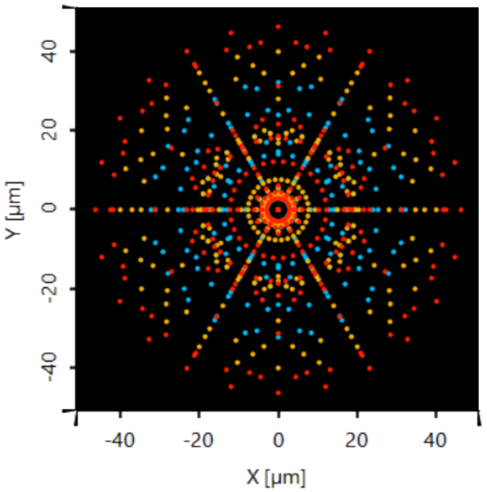
-1st diffraction order

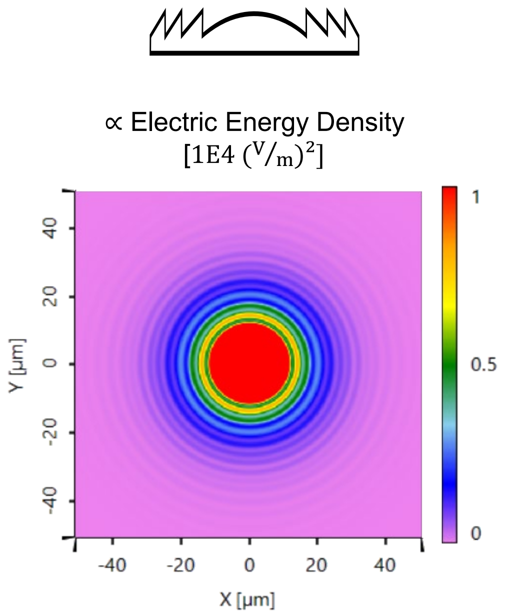


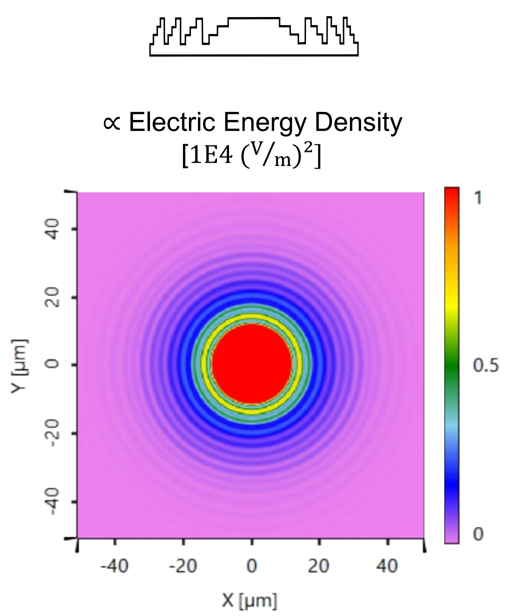
On-Axis Analysis: Inclusion of Height Profile Quantization

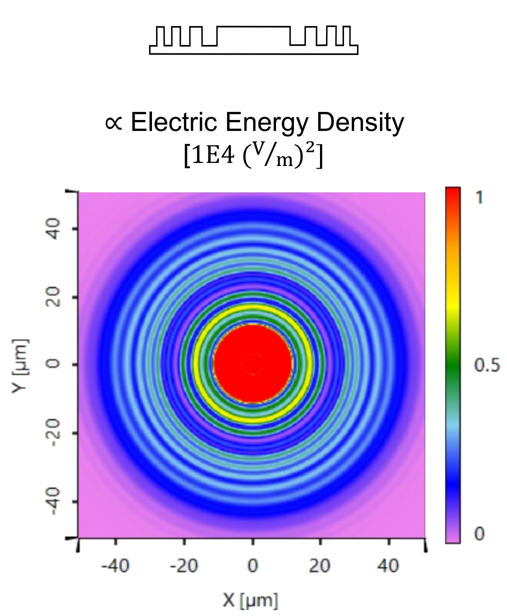


Spot Diagram



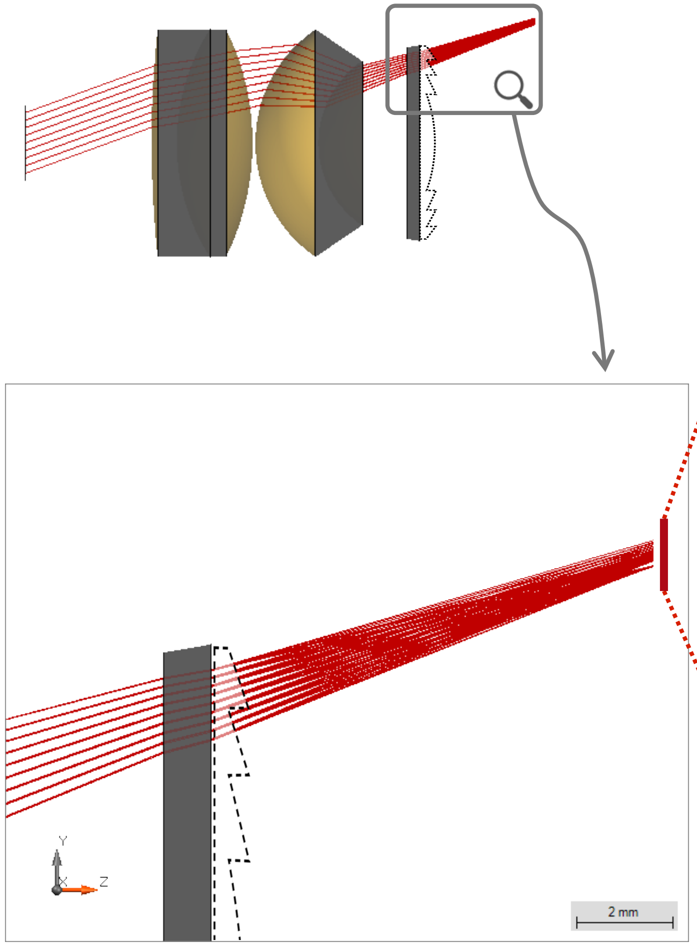




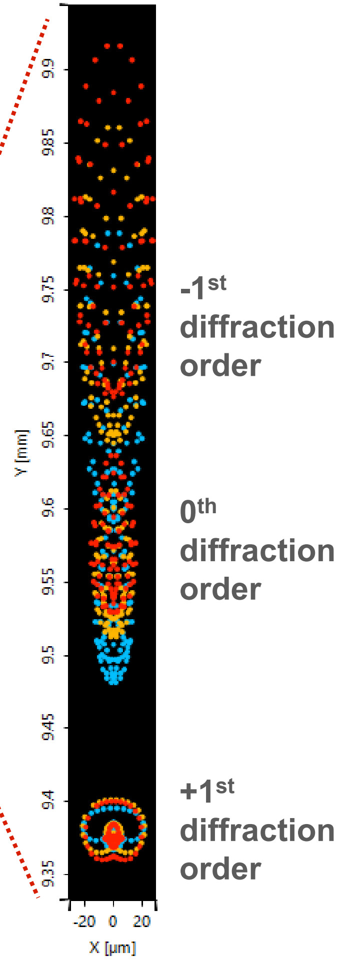


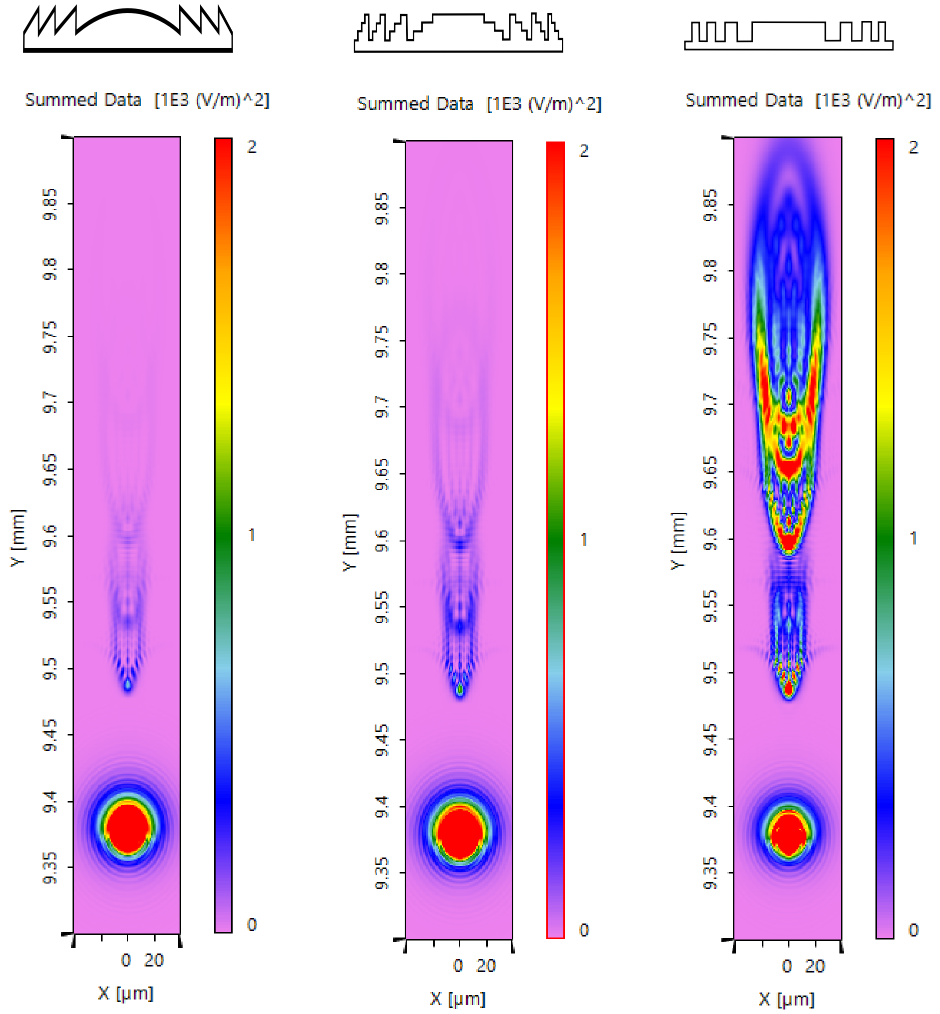
PSF scaled by factor of ~1/100 to maximum

Off-Axis Analysis: Inclusion of Height Profile Quantization



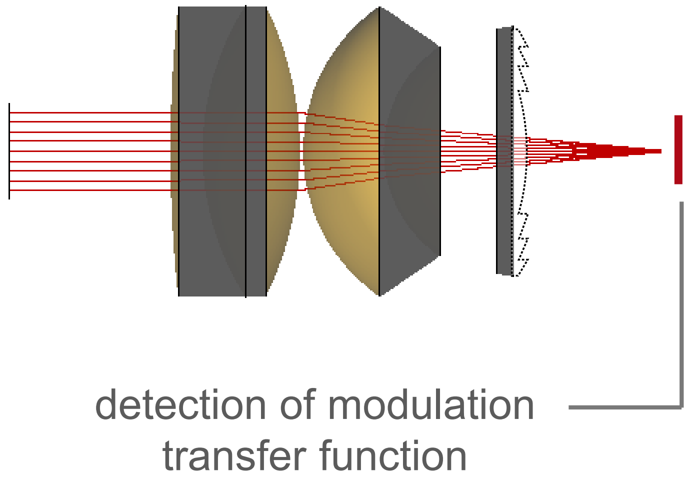
Spot Diagram

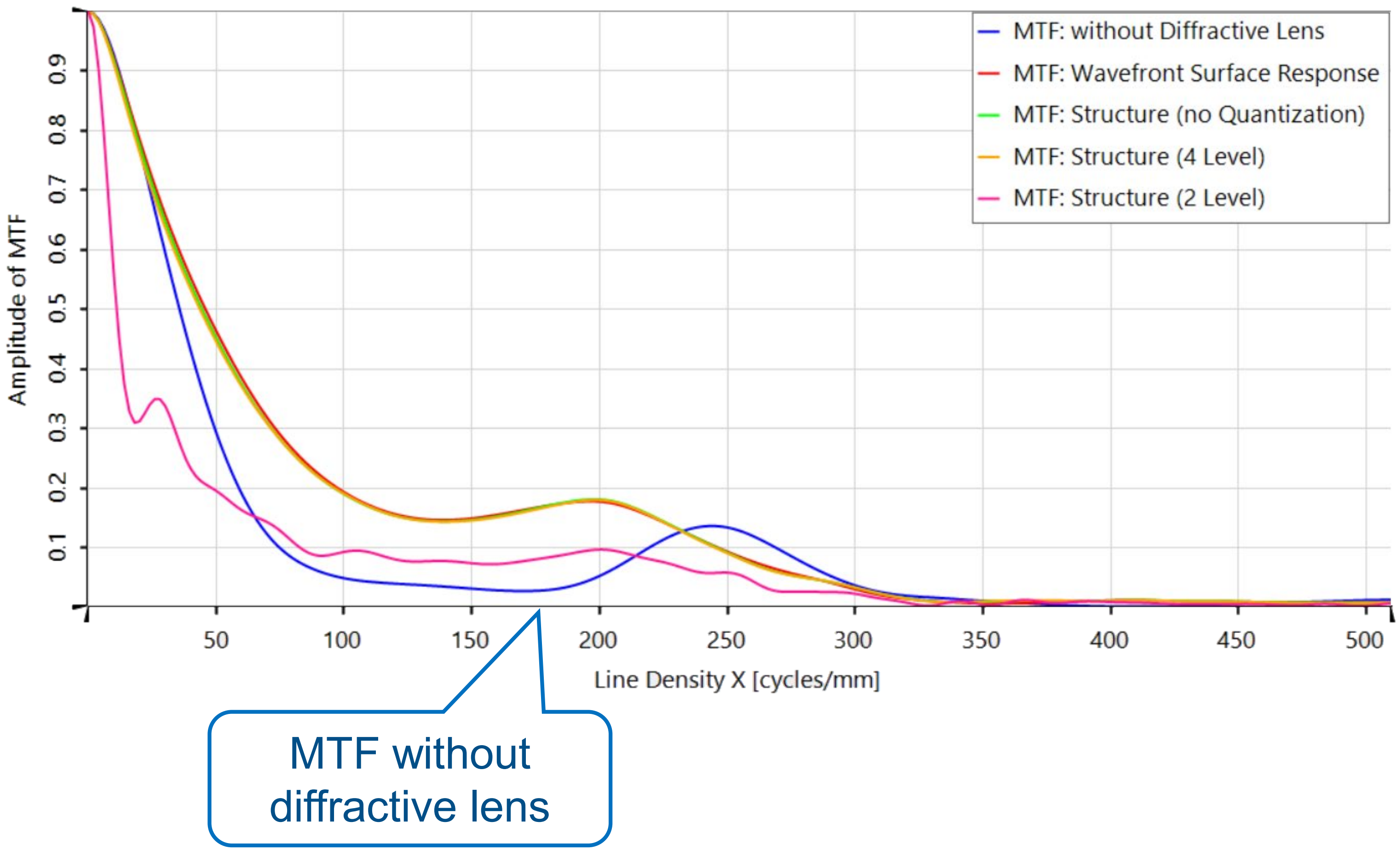




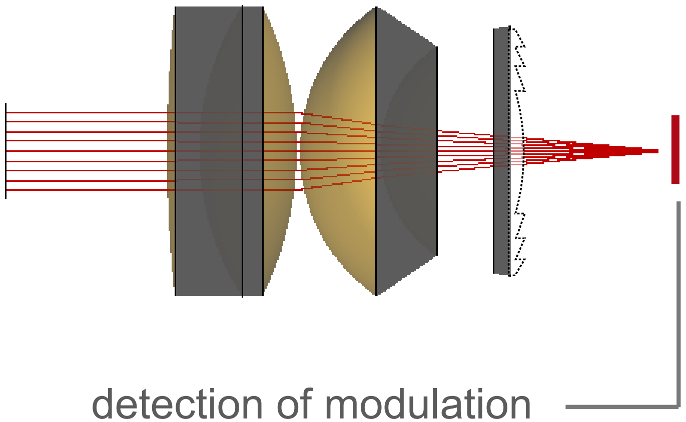
PSF scaled by factor of ~1/100 to maximum

MTF for Various Diffractive Lens Structures

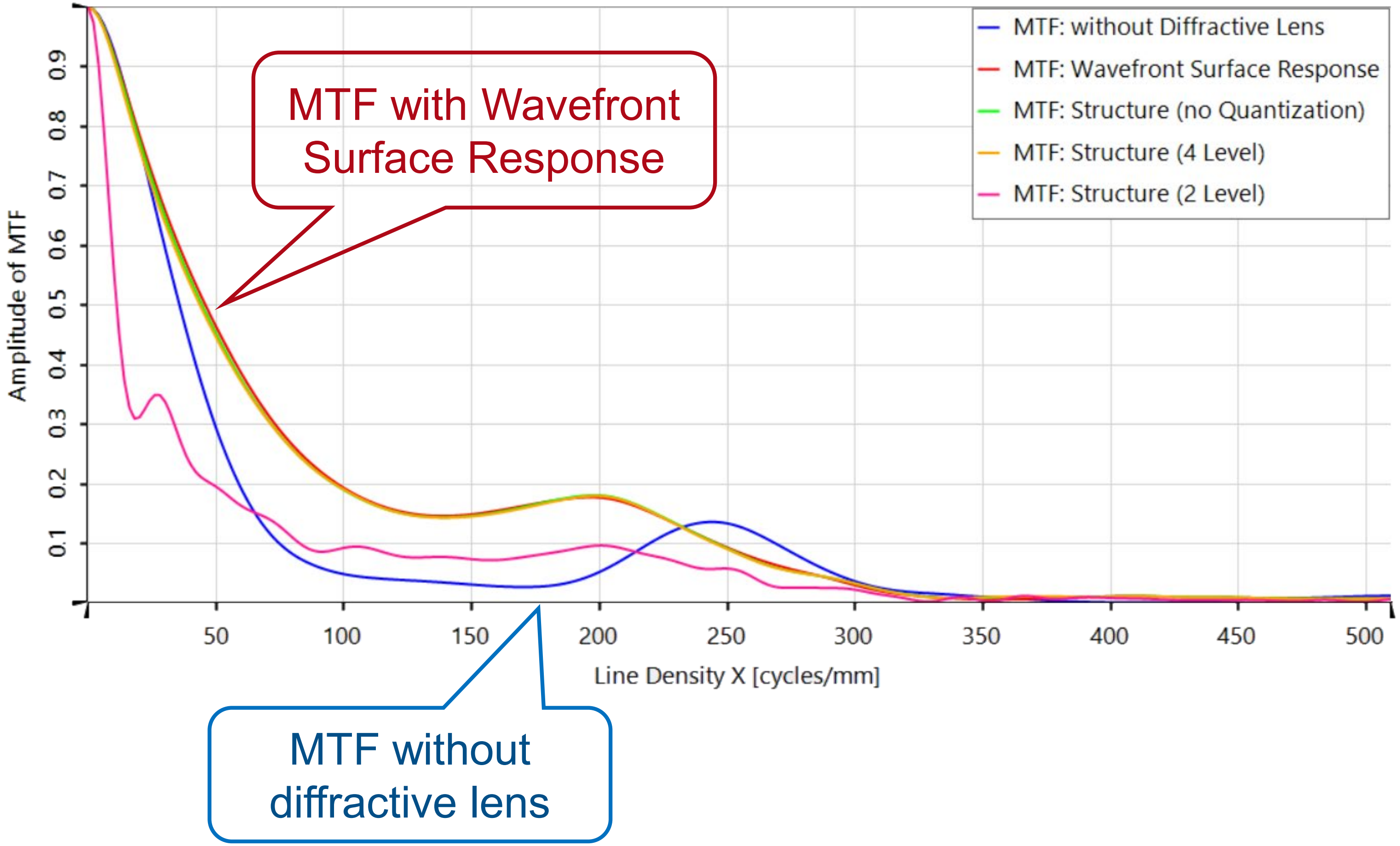




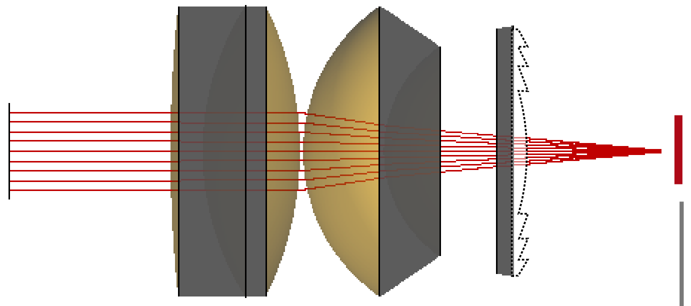
MTF for Various Diffractive Lens Structures



detection of modulation transfer function



MTF for Various Diffractive Lens Structures



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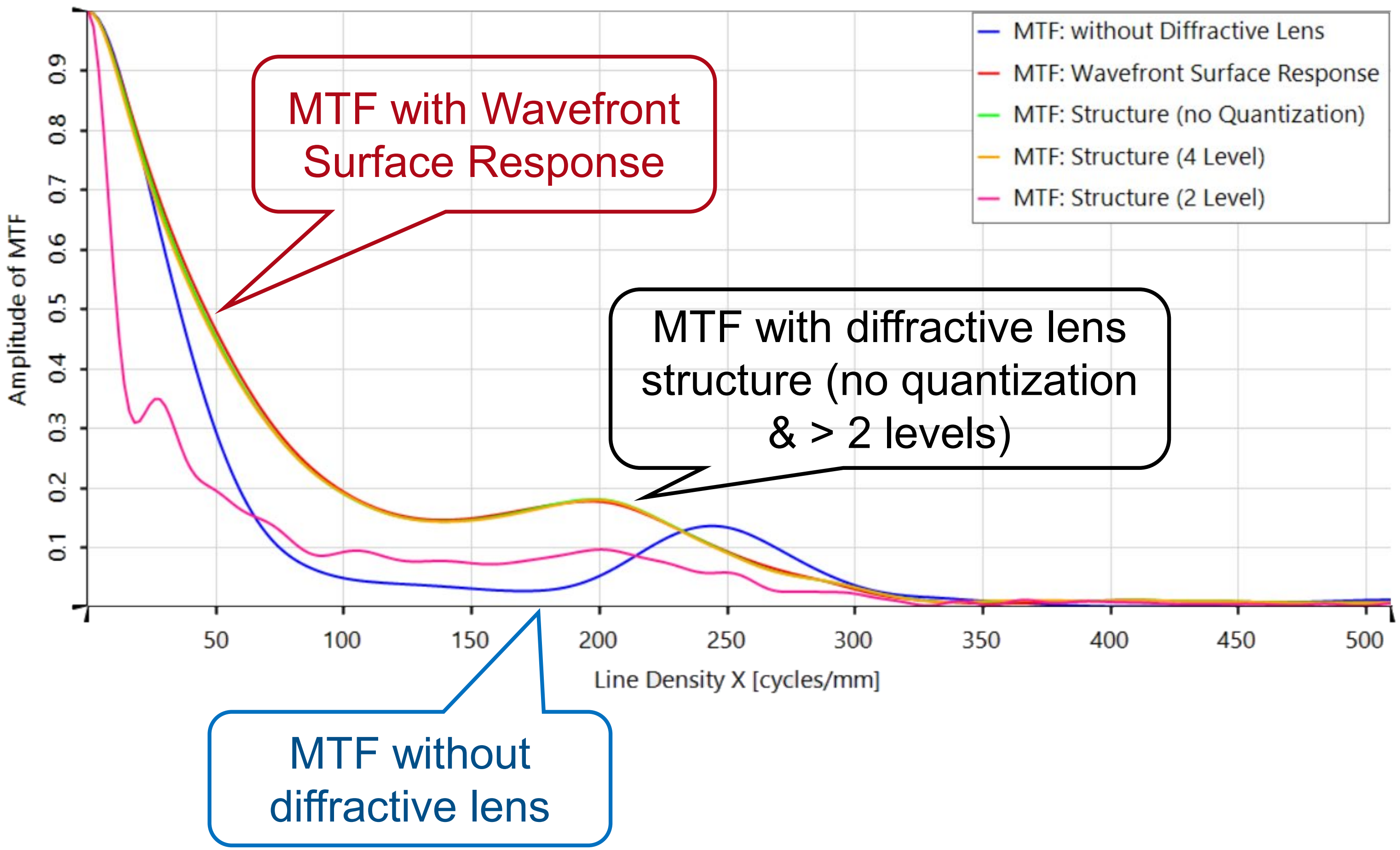
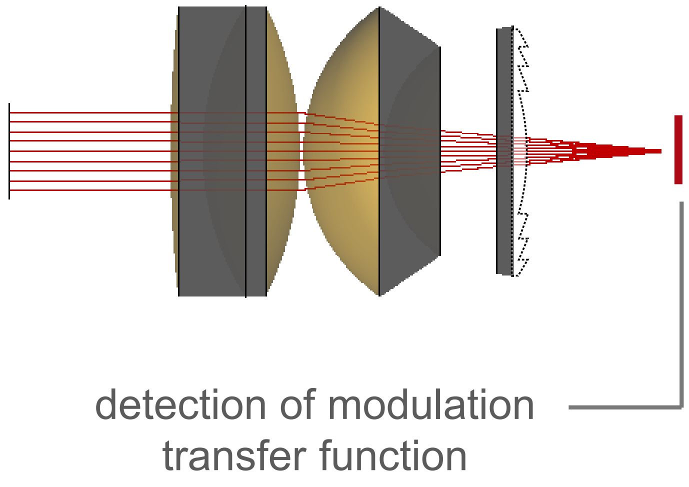
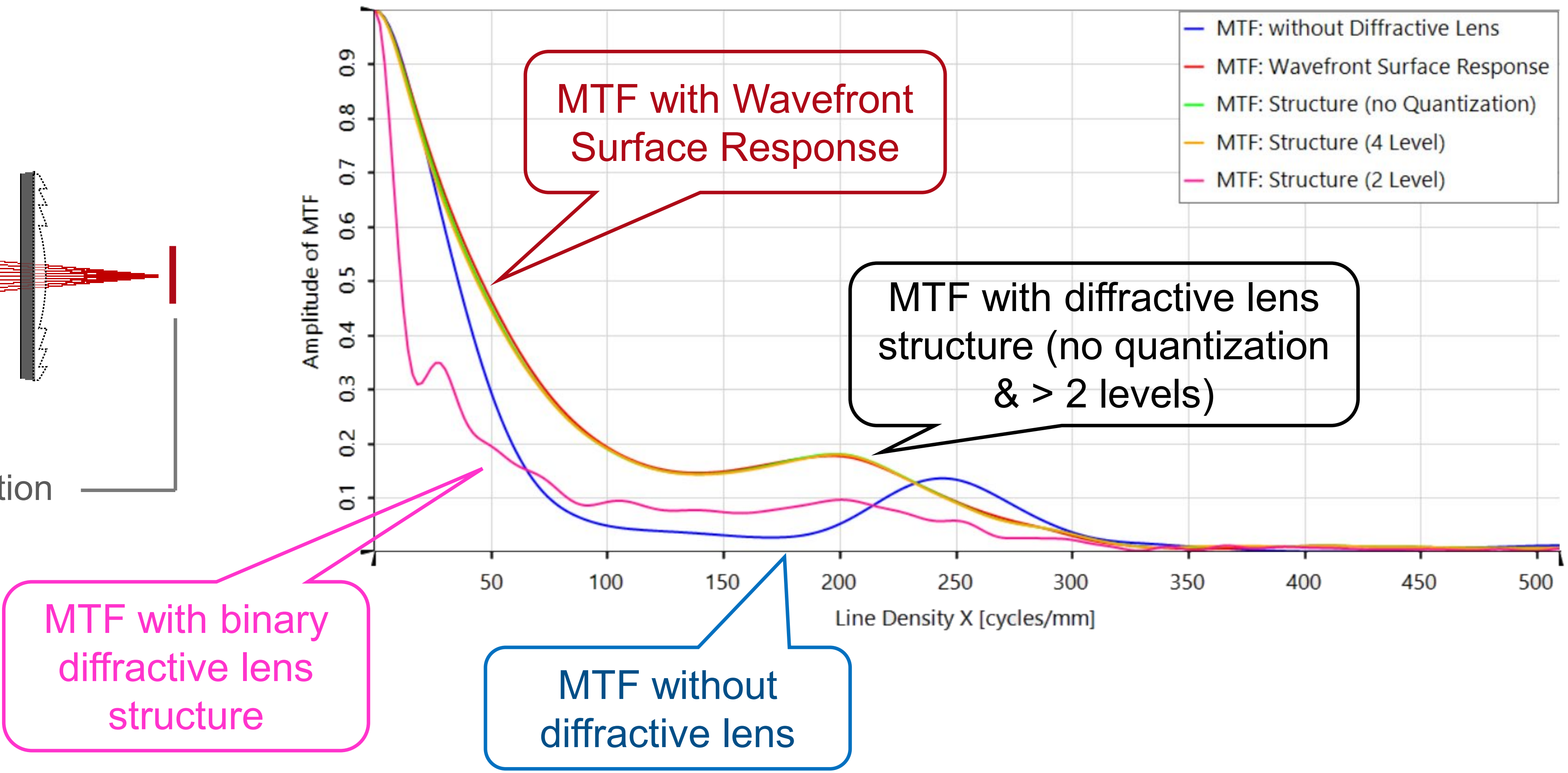
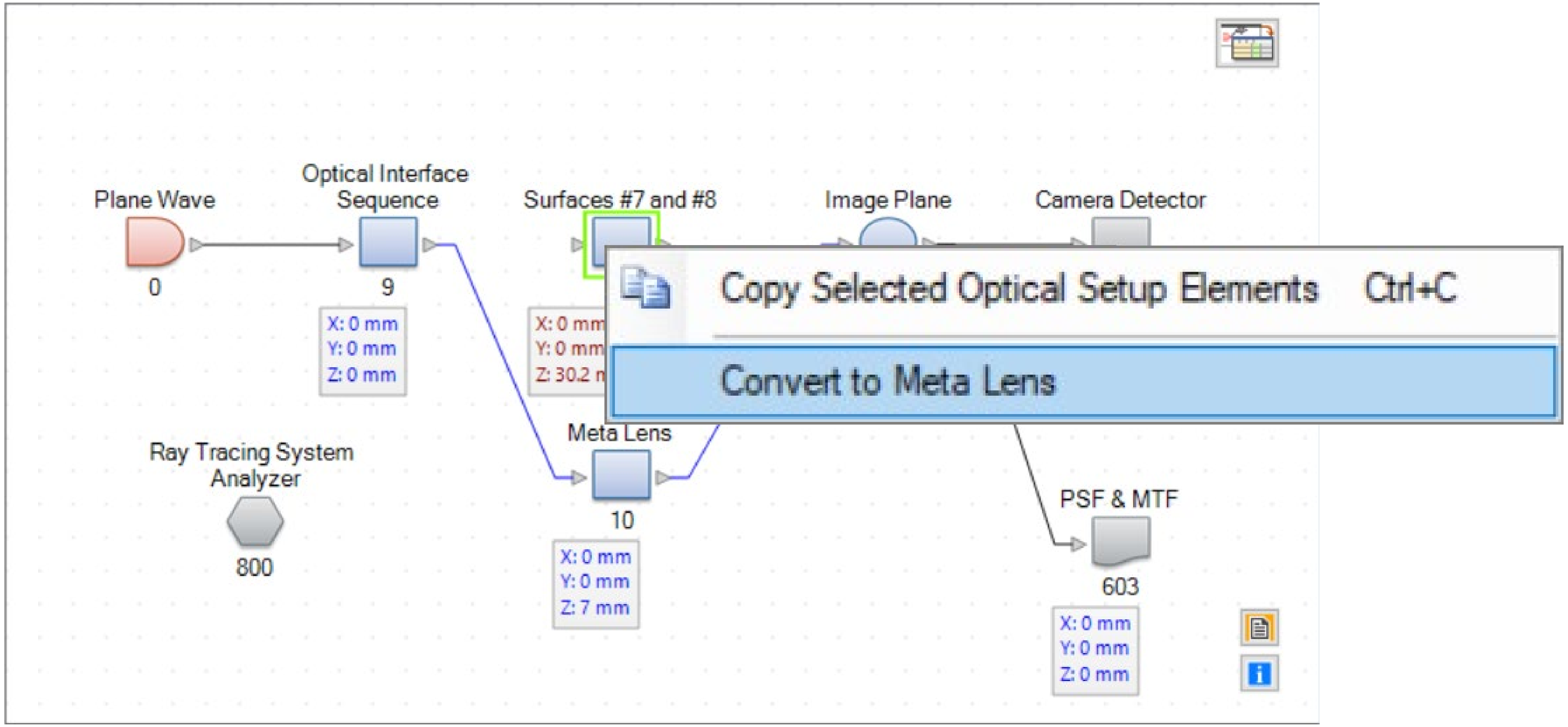


MTF for Various Diffractive Lens Structures





… convert to metalens



Structure of Workshop

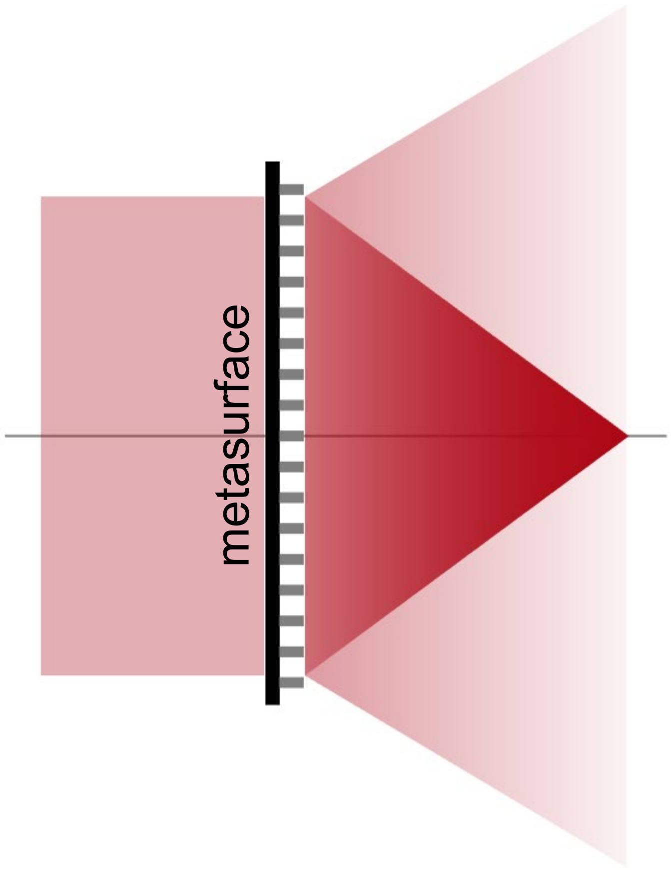
- Introduction of theory
  - Frank Wyrowski
- Design of binary surfaces in OpticStudio
  - Akil Bhagat
- Physical-optics analysis of imported systems from OpticStudio: Diffractive lenses
  - Roberto Knoth
- **Metalenses theory and modeling**
  - **Site Zhang**
- Fabrication export
  - Roberto Knoth

Metasurface Theory and Modeling

- In general a real surface layer structure does not just realize the desired wavefront response but additional effects and fields

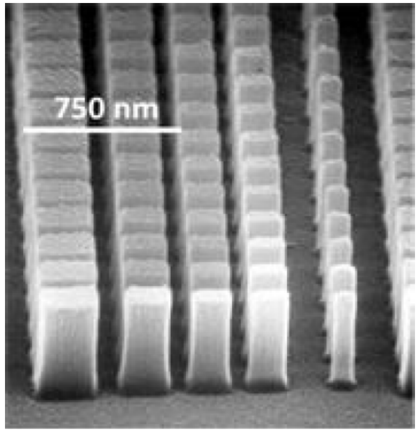
$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \left\{\mathbf{B}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right) + \boldsymbol{V}_{\perp}^{\text{res}}(\boldsymbol{\rho})\,.$$

- There are different types of metasurfaces that can be used to realize the desired $\Delta\psi(\boldsymbol{\rho})$. The exact form of the B-operator and the residual terms depends on the employed type of metasurfaces.



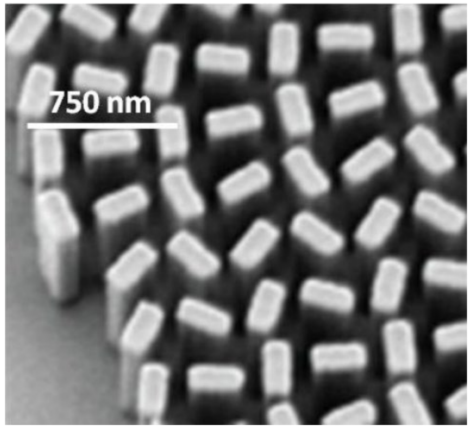
Physical Effects for Realizing Metasurfaces

- Propagation phase delay
  - Centrosymmetric (polarization insensitive)



P. Lalanne *et al.*, J. Opt. Soc. Am. A **16**, 1143-1156 (1999).

  - Rotationally asymmetric (form birefringence)



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

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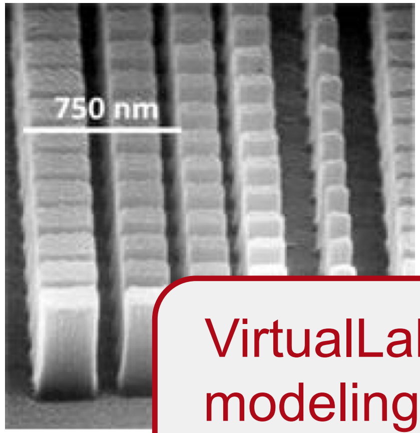

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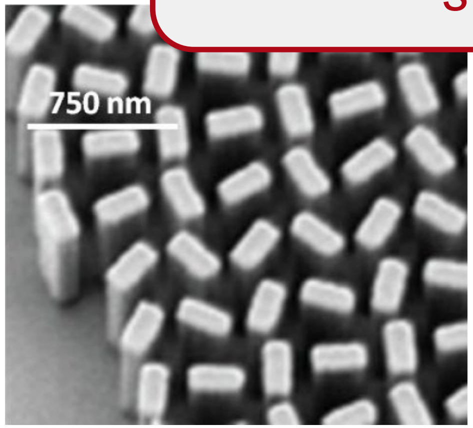
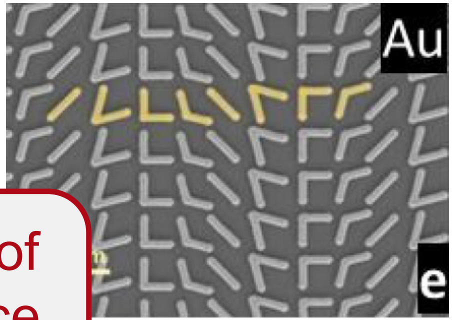


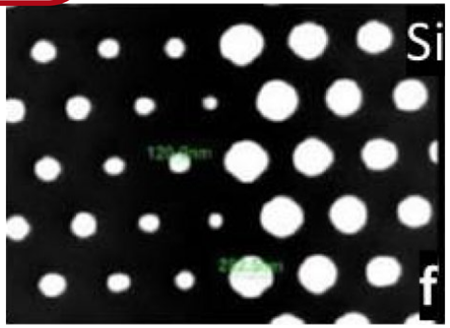
M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

VirtualLab Fusion is capable of modeling different metasurface structures.

- Resonance phase delay



u *et al.*, Science **334**,
337 (2011).



Y. F. Yu *et al.*, Laser Photonics Rev. **9**, 412-418 (2015).

Physical Effects for Realizing Metasurfaces

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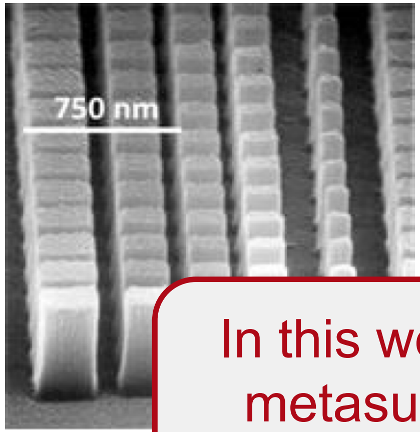

P. Lalanne *et al*., J. Opt. Soc. Am. A **16**, 1143-1156 (1999).

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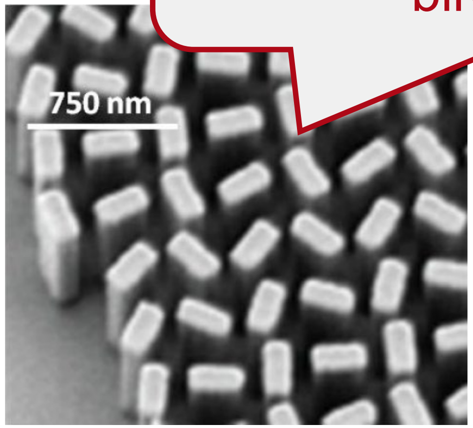
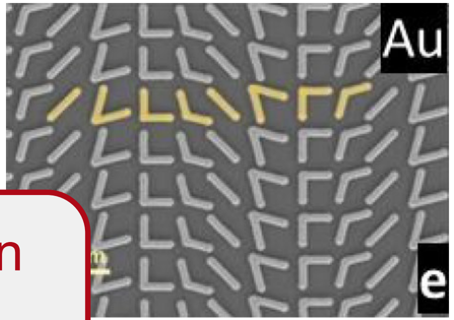


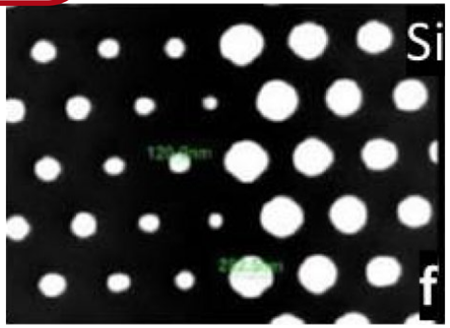
M. Khorasaninejad *et al*., Science **352**, 1190-1194 (2016).

In this workshop, we focus on metasurface based on form birefringence

- Resonance phase delay



u *et al*., Science **334**, 337 (2011).



Y. F. Yu *et al*., Laser Photonics Rev. **9**, 412-418 (2015).

Metasurface Modeling

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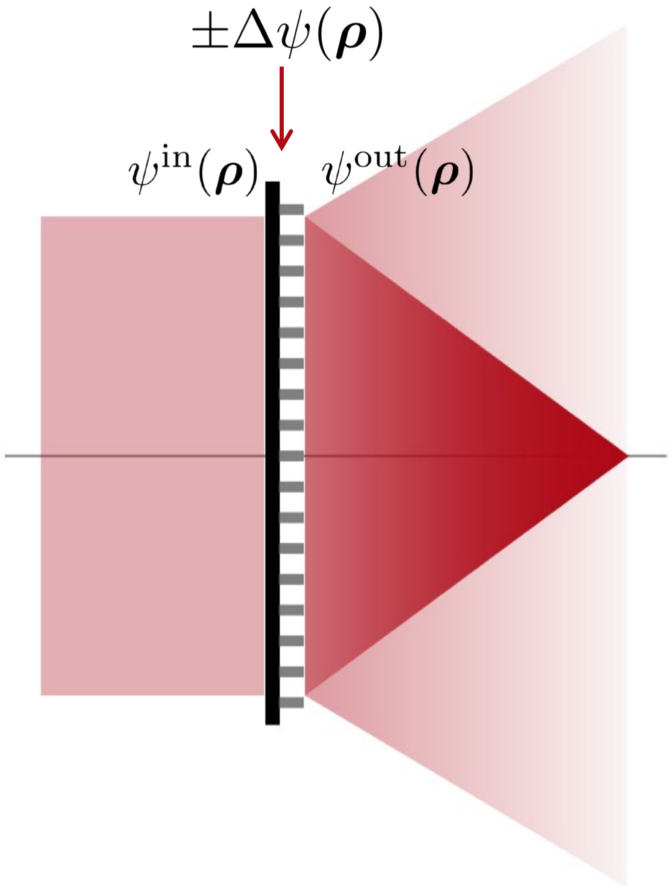
- For metasurfaces made of rotated nanofins, the typical results can be written as

$$\begin{aligned}\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = &\left\{\mathbf{B}^{+}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right)\\ &+ \left\{\mathbf{B}^{-}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\right\}\exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) - \Delta\psi(\boldsymbol{\rho}))\right)\,.\end{aligned}$$

- We will show that $+\Delta\psi$ occurs for R-circularly polarized input fields and the conjugate phase $-\Delta\psi$ for L-circularly polarized input.



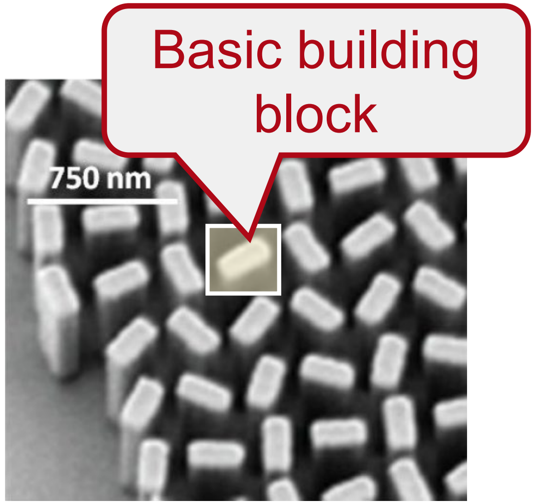
Metasurface Building Block

- Locally at $\boldsymbol{\rho}$, the B-operator for a single meta building block is

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \boldsymbol{\mathcal{B}}(\boldsymbol{\rho};\psi^{\text{in}})\boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho})\,,$$

  and writting down the 2×2-matrix B-operator explicity, we have

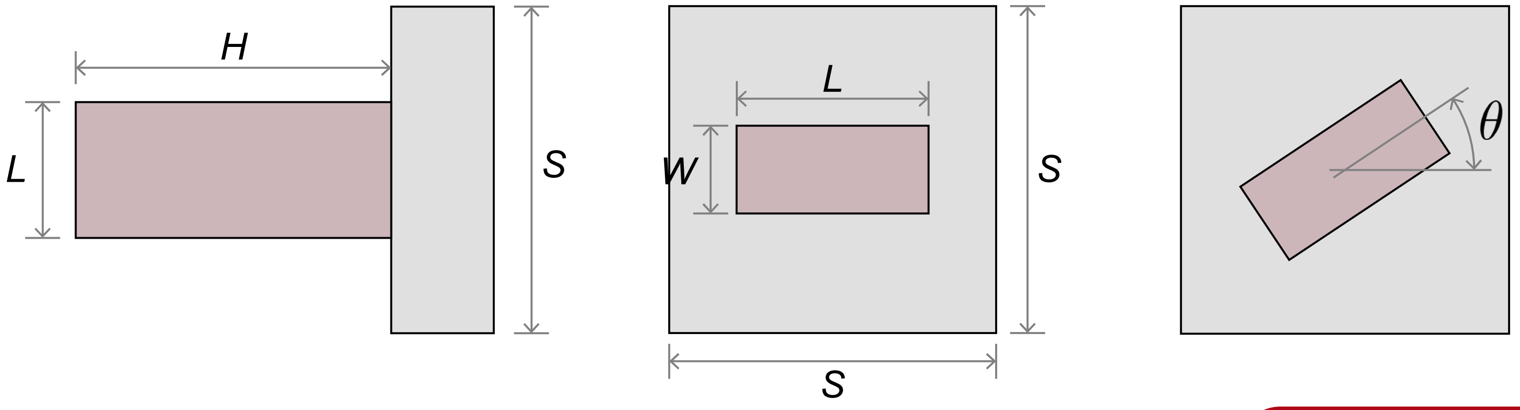
$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} B_{xx}(\boldsymbol{\rho};\psi^{\text{in}}) & B_{xy}(\boldsymbol{\rho};\psi^{\text{in}}) \\ B_{yx}(\boldsymbol{\rho};\psi^{\text{in}}) & B_{yy}(\boldsymbol{\rho};\psi^{\text{in}}) \end{pmatrix} \boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho})\,.$$

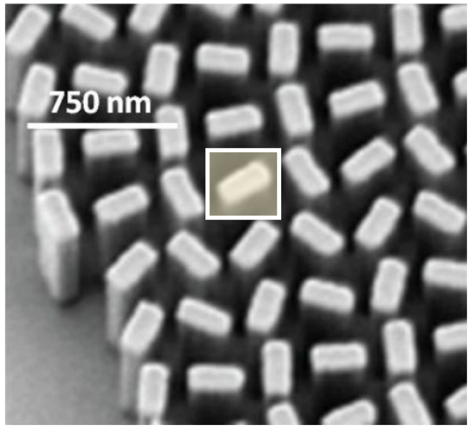


- Building blocks over the whole surface are same, but with different rotation angle $\theta(\boldsymbol{\rho})$. That can be expressed as

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} \cos\theta(\boldsymbol{\rho}) & -\sin\theta(\boldsymbol{\rho}) \\ \sin\theta(\boldsymbol{\rho}) & \cos\theta(\boldsymbol{\rho}) \end{pmatrix} \begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} \begin{pmatrix} \cos\theta(\boldsymbol{\rho}) & \sin\theta(\boldsymbol{\rho}) \\ -\sin\theta(\boldsymbol{\rho}) & \cos\theta(\boldsymbol{\rho}) \end{pmatrix} \boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho})$$

Metasurface Building Block





- Building blocks over the whole surface are same, ferent rotation angle $\theta(\boldsymbol{\rho})$. That can be expressed

… in the "eigen" coordinate system of the structure

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} \cos\theta(\boldsymbol{\rho}) & -\sin\theta(\boldsymbol{\rho}) \\ \sin\theta(\boldsymbol{\rho}) & \cos\theta(\boldsymbol{\rho}) \end{pmatrix} \begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} \begin{pmatrix} \cos\theta(\boldsymbol{\rho}) & \sin\theta(\boldsymbol{\rho}) \\ -\sin\theta(\boldsymbol{\rho}) & \cos\theta(\boldsymbol{\rho}) \end{pmatrix} \boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho})$$

Metasurface Building Block

- Omitting the variables for conciseness in the expr

… to be analyzed in detail later

$$\boldsymbol{V}_\perp^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho}),$$

and, without introducing any approximation, but rearrange the terms so that the rotation angle θ can be extracrted, we obtain the following result

$$\begin{aligned} \boldsymbol{V}_\perp^{\text{out}}(\boldsymbol{\rho}) =& \frac{1}{2}\left[(b_{xx}+b_{yy})\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + (b_{xy}-b_{yx})\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\right]\boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho}) \\ &+ \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & -\mathrm{i} \\ -\mathrm{i} & -1 \end{pmatrix} + (b_{xy}+b_{yx})\begin{pmatrix} \mathrm{i} & 1 \\ 1 & -\mathrm{i} \end{pmatrix}\right]\boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho})\exp(\mathrm{i}2\theta) \\ &+ \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & -1 \end{pmatrix} + (b_{xy}+b_{yx})\begin{pmatrix} -\mathrm{i} & 1 \\ 1 & \mathrm{i} \end{pmatrix}\right]\boldsymbol{V}_\perp^{\text{in}}(\boldsymbol{\rho})\exp(-\mathrm{i}2\theta)\,. \end{aligned}$$

Metasurface Modeling

- Omitting the variables for conciseness in the expression

$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \boldsymbol{V}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}),$$

and, without introducing any approximation, but rearrange the terms so that the rotation ang… the following result

$$\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = \frac{1}{2}\Big[(b_{xx}+b_{yy})\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \ldots$$

$$+\frac{1}{4}\Big[(b_{xx}-b_{yy})\begin{pmatrix} 1 & \ldots \\ -\mathrm{i} & -1 \end{pmatrix} \ldots \begin{pmatrix} \ldots & \ldots \\ 1 & -\mathrm{i} \end{pmatrix}\Big] \boldsymbol{V}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \exp(\mathrm{i}\Delta\psi(\boldsymbol{\rho}))$$

$$+\frac{1}{4}\Big[(b_{xx}-b_{yy})\begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & \ldots \end{pmatrix} \ldots (b_{xy}+b_{yx})\begin{pmatrix} -\mathrm{i} & 1 \\ 1 & \mathrm{i} \end{pmatrix}\Big] \boldsymbol{V}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \exp(-\mathrm{i}\Delta\psi(\boldsymbol{\rho})),$$

with $\Delta\psi(\boldsymbol{\rho}) := 2\theta(\boldsymbol{\rho})$, and $\theta(\boldsymbol{\rho})$ is the rotation angle.

With spatially varying rotation angles, the desired wavefront surface response can be realized!

Metasurface Modeling

- Omitting the variables for conciseness in the expression

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho}),$$

and, without introducing any approximation, but rearrange the terms so that the rotation angle θ can be extracrted, we obtain the following result

$$\begin{aligned}\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) =& \frac{1}{2}\left[(b_{xx}+b_{yy})\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + (b_{xy}-b_{yx})\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\exp(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho})) \\ &+ \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & -\mathrm{i} \\ -\mathrm{i} & -1 \end{pmatrix} + (b_{xy}+b_{yx})\begin{pmatrix} \mathrm{i} & 1 \\ 1 & -\mathrm{i} \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right) \\ &+ \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & -1 \end{pmatrix} + (b_{xy}+b_{yx})\begin{pmatrix} -\mathrm{i} & 1 \\ 1 & \mathrm{i} \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\text{in}}(\boldsymbol{\rho})\exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) - \Delta\psi(\boldsymbol{\rho}))\right),\end{aligned}$$

desired response $\Delta\psi(\boldsymbol{\rho})$

conjugate part $-\Delta\psi(\boldsymbol{\rho})$

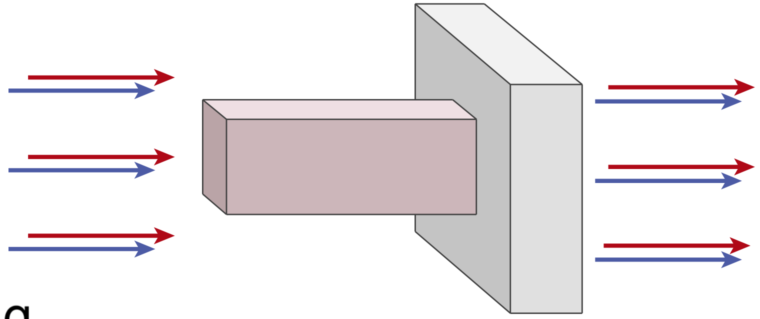
with $\Delta\psi(\boldsymbol{\rho}) := 2\theta(\boldsymbol{\rho})$, and $\theta(\boldsymbol{\rho})$ is the rotation angle.

Form Birefringence Analysis

- Next, we would like to examine the matrix

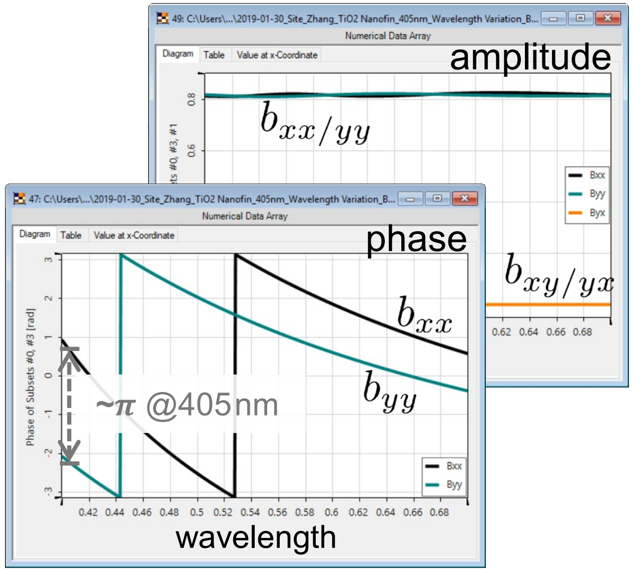
$$\begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix}$$

  that describes the fundamental property of the meta building block, and we analyze it rigorously.



- Ideally, the building block is supposed to work as a half-wave plate, i.e.

$$b_{xy} \approx 0\,,$$
$$b_{yx} \approx 0\,,$$
$$b_{xx} \approx -b_{yy}\,.$$

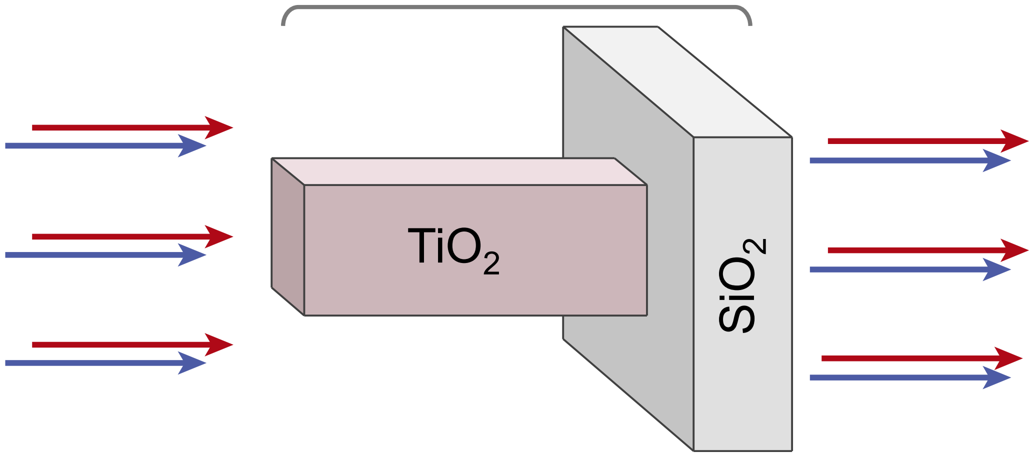


- We will substitute these approximations step by step in what follows.

Form Birefringence Analysis

$$\begin{pmatrix} b_{xx}(\omega) & b_{xy}(\omega) \\ b_{yx}(\omega) & b_{yx}(\omega) \end{pmatrix} = ?$$

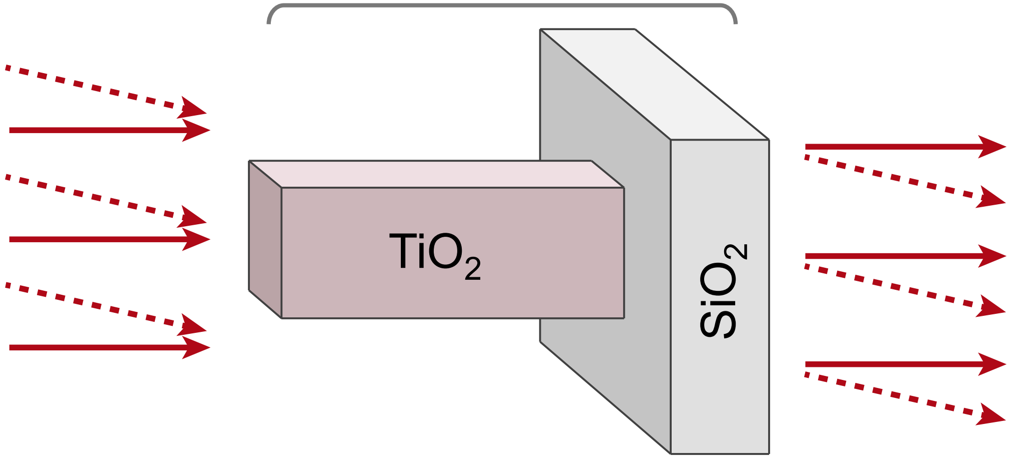
plane wave
- normal incidence
- wavelengths 405, 532, 660 nm



How to analyze the form birefringence for the metasurface building block – nanofin structure?

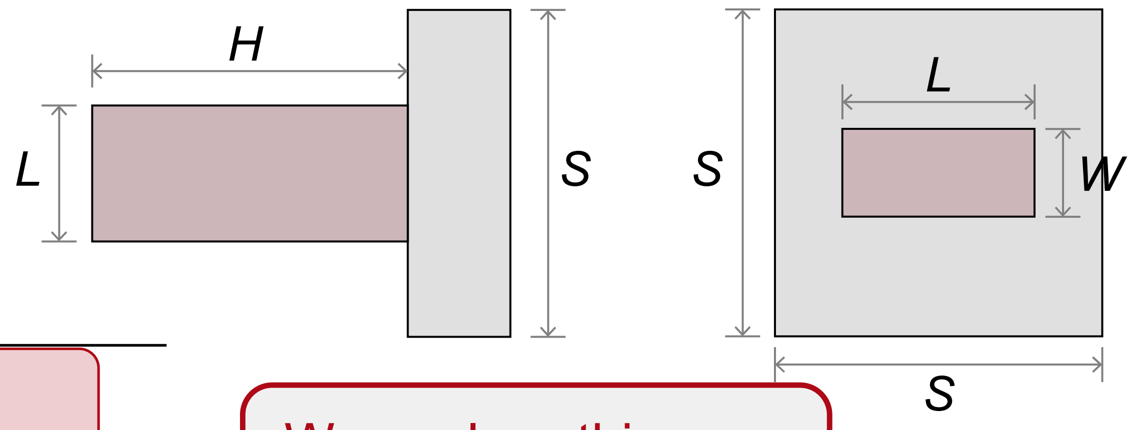
$$\begin{pmatrix} b_{xx}(\alpha) & b_{xy}(\alpha) \\ b_{yx}(\alpha) & b_{yx}(\alpha) \end{pmatrix} = ?$$

plane wave
- wavelength @405 nm
- incidence angle [-25°, 25°]



VirtualLab Fusion Demonstration

Nanofin Structural Designs



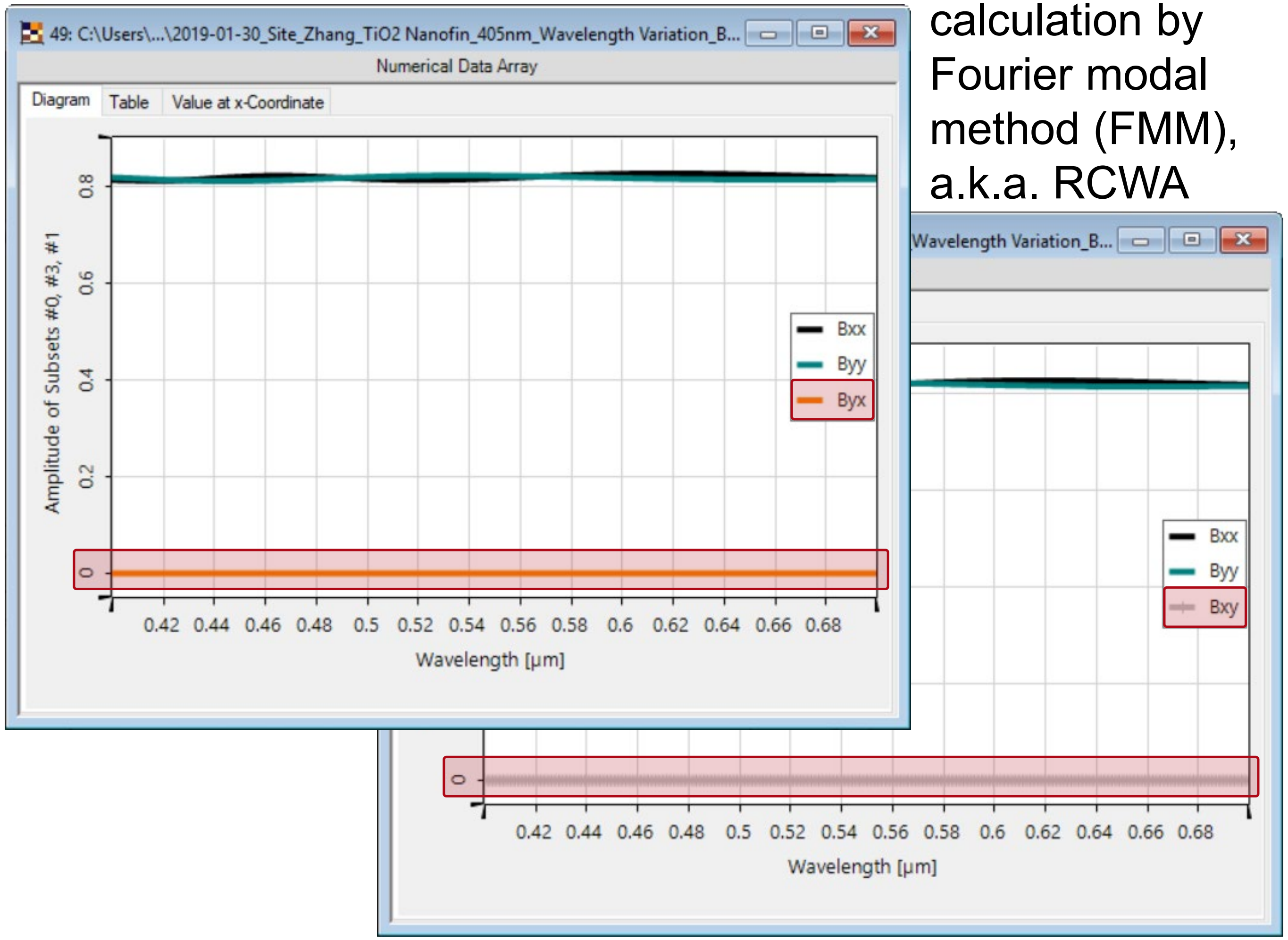
structural parameters

Case	660 nm Design	532 nm Design	405 nm Design
refractive index	n=2.36	n=2.43	n=2.63
W	85 nm	95 nm	40 nm
L	410 nm	250 nm	150 nm
H	600 nm	600 nm	600 nm
S	430 nm	325 nm	200 nm

We analyze this case as an example.

M. Khorasaninejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, F. Capasso, *Science* **2016**, 352 (6290), 1190-1194

Spectral Analysis for Nanofin – 405nm Design



calculation by Fourier modal method (FMM), a.k.a. RCWA

- B-matrix for metasurface building block

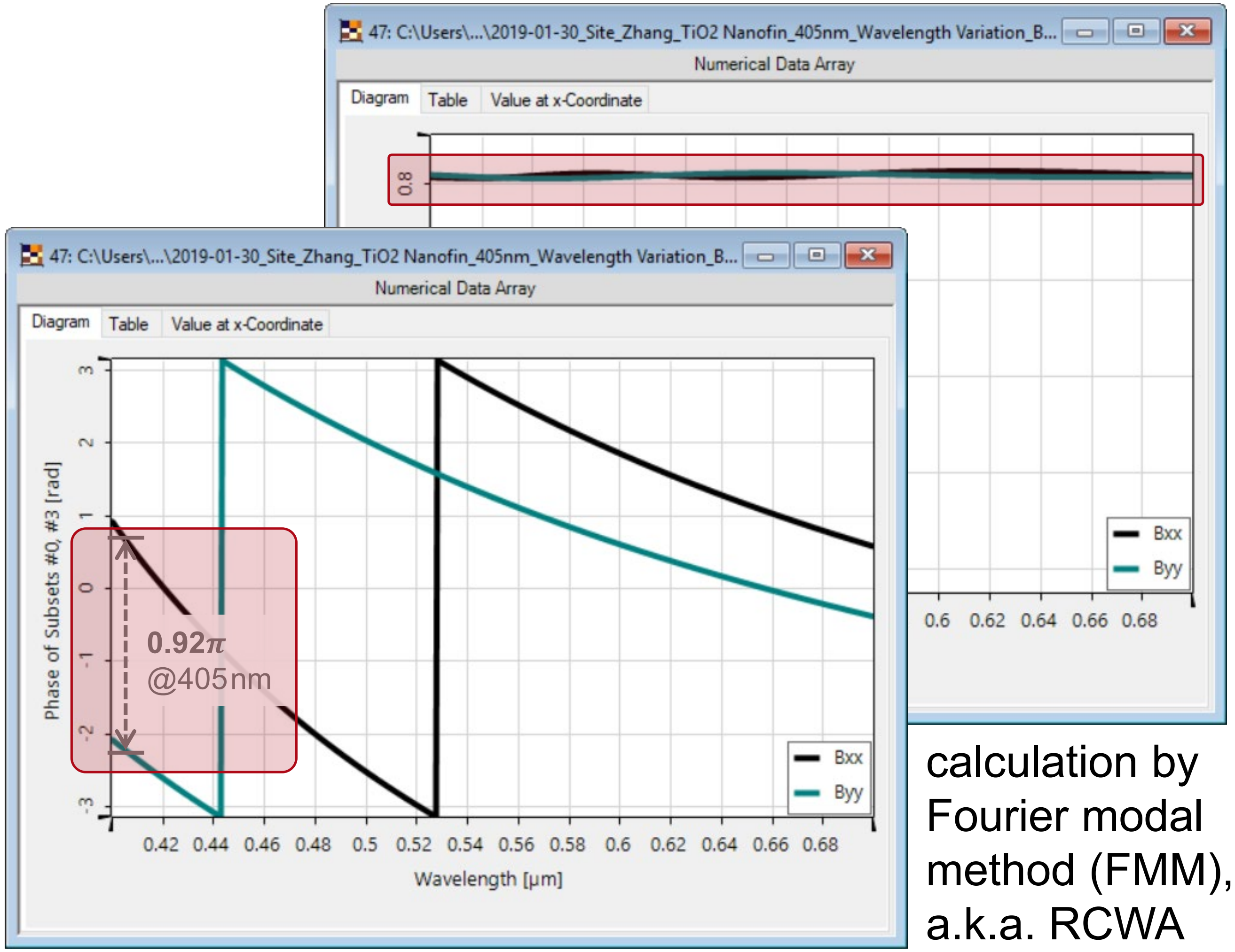
$$\begin{pmatrix} b_{xx} & b_{xy} \\ \end{pmatrix} .$$

Almost no polarization crosstalk

...unction as a half-wave ...ate, i.e.

$$b_{xy} \approx 0 \,,$$
$$b_{yx} \approx 0 \,,$$
$$b_{xx} \approx -b_{yy} \,.$$

Spectral Analysis for Nanofin – 405nm Design



calculation by Fourier modal method (FMM), a.k.a. RCWA

- B-matrix for metasurface building block

$$\begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} .$$

- Ideally, it should function as ... .e.

Almost half-wave plate effect

$$... 0 ,$$

$$b_{yx} ... 0 ,$$

$$b_{xx} \approx -b_{yy} .$$

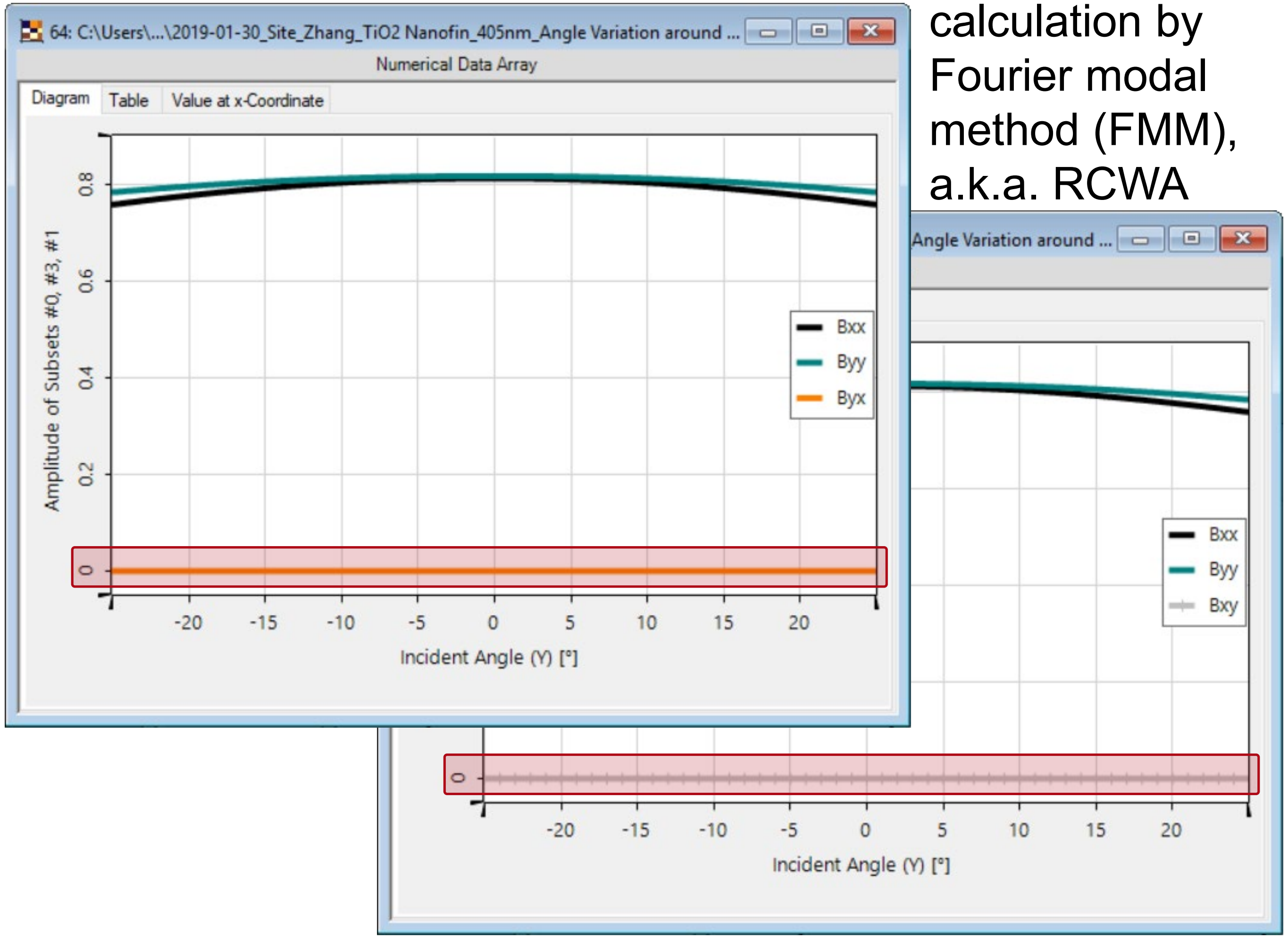
Angular Analysis for Nanofin – 405nm Design

- B-matrix for metasurface building block

$$\begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix}.$$

- Ideally, it should function as a half-wave plate, i.e.

$$b_{xy} \approx 0\,,$$
$$b_{yx} \approx 0\,,$$
$$b_{xx} \approx -b_{yy}\,.$$



calculation by Fourier modal method (FMM), a.k.a. RCWA

Angular Analysis for Nanofin – 405nm Design

- B-matrix for metasurface building block

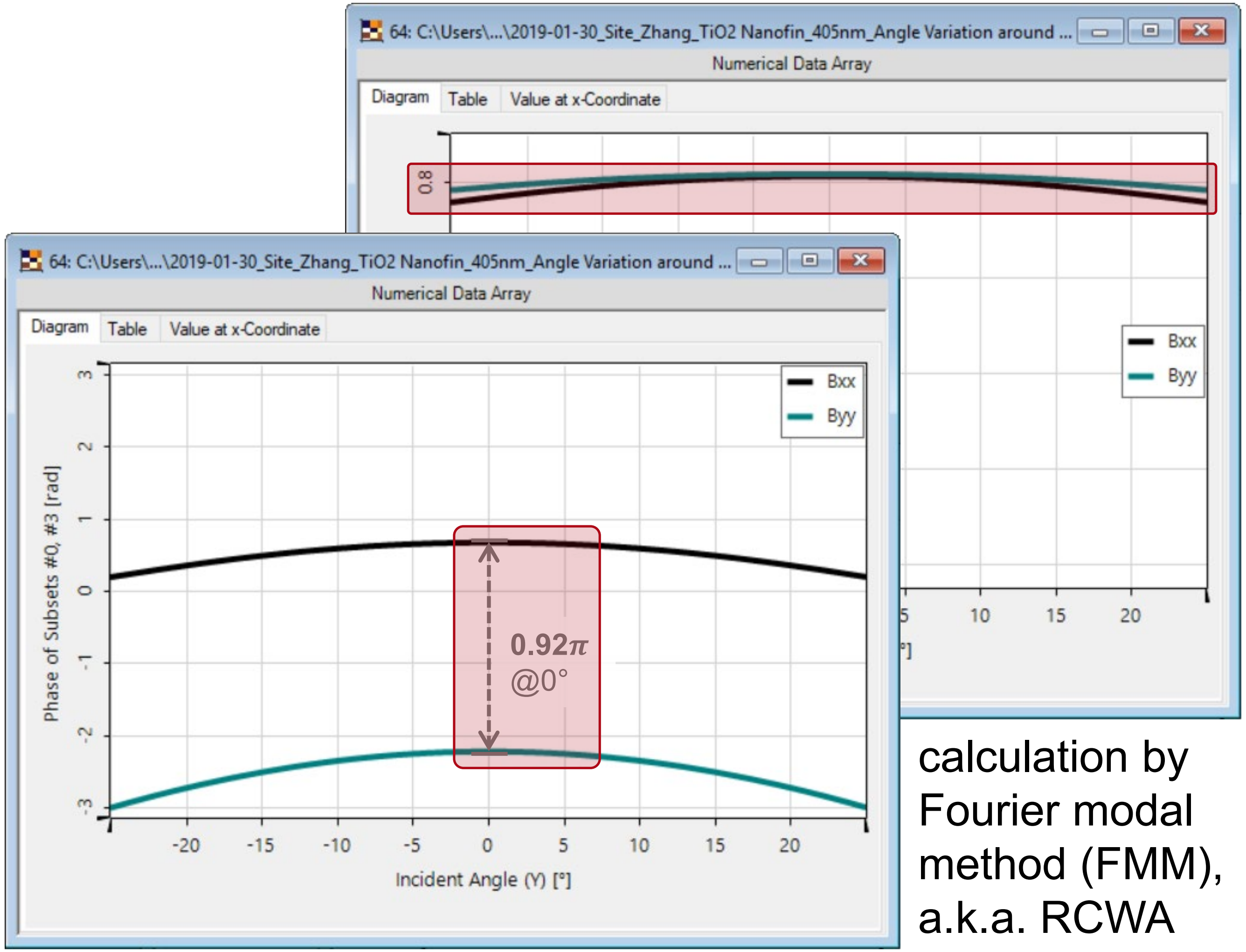
$$\begin{pmatrix} b_{xx} & b_{xy} \\ b_{yx} & b_{yy} \end{pmatrix} .$$

- Ideally, it should function as a half-wave plate, i.e.

$$b_{xy} \approx 0 ,$$

$$b_{yx} \approx 0 ,$$

$$b_{xx} \approx -b_{yy} .$$



calculation by Fourier modal method (FMM), a.k.a. RCWA

Metasurface Modeling

As shown before, valid for certain wavelength and angle range

- Use the half-wave plate approximations

$$\left.\begin{aligned} b_{xy} \approx 0\,, \quad & b_{yx} \approx 0\,, \\ b_{xx} \approx -b_{yy}\,. & \end{aligned}\right\}$$

- Then, the metasurface response can be written as

desired response $\Delta\psi(\boldsymbol{\rho})$

$$\begin{aligned}\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) = & \frac{1}{2}\left[\xcancel{(b_{xx}+b_{yy})}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \xcancel{(b_{xy}-b_{yx})}\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\exp(\mathrm{i}\psi^{\mathrm{in}}(\boldsymbol{\rho})) \\ & + \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & -\mathrm{i} \\ -\mathrm{i} & -1 \end{pmatrix} + \xcancel{(b_{xy}+b_{yx})}\begin{pmatrix} \mathrm{i} & 1 \\ 1 & -\mathrm{i} \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\exp\Big(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\Big) \\ & + \frac{1}{4}\left[(b_{xx}-b_{yy})\begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & -1 \end{pmatrix} + \xcancel{(b_{xy}+b_{yx})}\begin{pmatrix} -\mathrm{i} & 1 \\ 1 & \mathrm{i} \end{pmatrix}\right]\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\exp\Big(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) - \Delta\psi(\boldsymbol{\rho}))\Big)\,.\end{aligned}$$

conjugate part $-\Delta\psi(\boldsymbol{\rho})$

Metasurface Modeling

- Use the half-wave plate approximations

$$
\begin{aligned}
&b_{xy} \approx 0\,, \quad b_{yx} \approx 0\,,\\
&b_{xx} \approx -b_{yy}\,.
\end{aligned}
$$

- Then, the metasurface response can be written as

$$
\begin{aligned}
\boldsymbol{V}_{\perp}^{\mathrm{out}}(\boldsymbol{\rho}) =& \frac{1}{4}\,(b_{xx}-b_{yy}) \begin{pmatrix} 1 & -\mathrm{i} \\ -\mathrm{i} & -1 \end{pmatrix} \boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right) \\
&+ \frac{1}{4}\,(b_{xx}-b_{yy}) \begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & -1 \end{pmatrix} \boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) - \Delta\psi(\boldsymbol{\rho}))\right) \\
=& \left\{\mathbf{B}^{+}(\boldsymbol{\rho};\psi^{\mathrm{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\right\} \exp\left(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right) \\
&+ \left\{\mathbf{B}^{-}(\boldsymbol{\rho};\psi^{\mathrm{in}})\boldsymbol{U}_{\perp}^{\mathrm{in}}(\boldsymbol{\rho})\right\} \exp\left(\mathrm{i}(\psi^{\mathrm{in}}(\boldsymbol{\rho}) - \Delta\psi(\boldsymbol{\rho}))\right)
\end{aligned}
$$

$+\Delta\psi(\boldsymbol{\rho})$ → desired $\Delta\psi(\boldsymbol{\rho})$

$-\Delta\psi(\boldsymbol{\rho})$ → conjugate part

Metasurface Modeling – Polarization Effect

- If the input field is R-circularly polarized, i.e.

$$\boldsymbol{V}_{\perp}^{\text{in}}(\boldsymbol{\rho}) = \begin{pmatrix} 1 \\ \mathrm{i} \end{pmatrix} U^{\text{in}}(\boldsymbol{\rho}) \exp(\mathrm{i}\psi^{\text{in}}(\boldsymbol{\rho}))\,,$$

Hint:

$$\begin{pmatrix} 1 & \mathrm{i} \\ \mathrm{i} & -1 \end{pmatrix} \begin{pmatrix} 1 \\ \mathrm{i} \end{pmatrix} = 0$$

substituting it into the B-operator expression, yields the output field in the following form

$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \frac{1}{2}(b_{xx} - b_{yy}) \begin{pmatrix} 1 \\ -\mathrm{i} \end{pmatrix} U^{\text{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right)\,.$$

→ desired $\Delta\psi(\boldsymbol{\rho})$ only

- In the idealized case, with $b_{xx} = 1$ and $b_{yy} = -1$, one gets

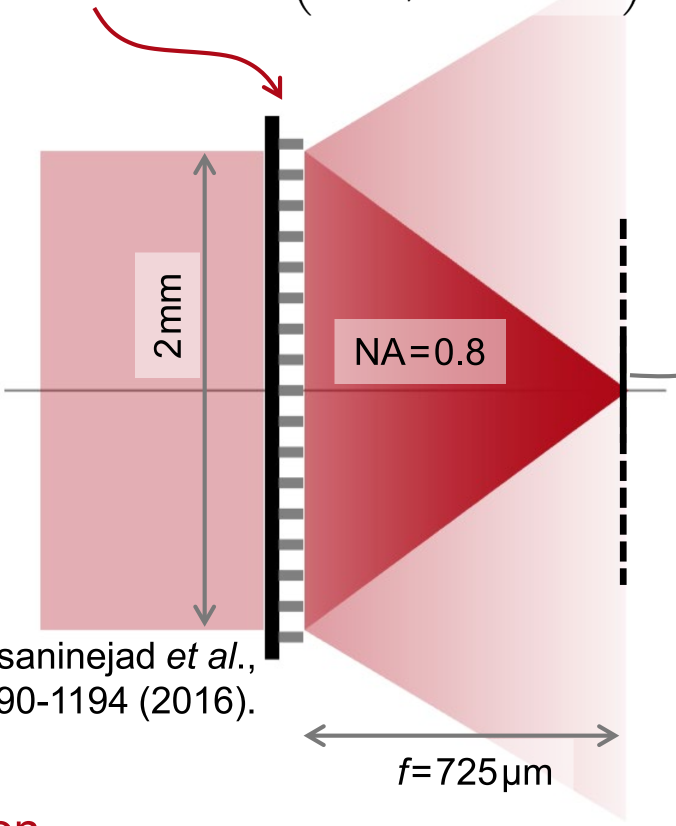
$$\boldsymbol{V}_{\perp}^{\text{out}}(\boldsymbol{\rho}) = \begin{pmatrix} 1 \\ -\mathrm{i} \end{pmatrix} U^{\text{in}}(\boldsymbol{\rho}) \exp\left(\mathrm{i}(\psi^{\text{in}}(\boldsymbol{\rho}) + \Delta\psi(\boldsymbol{\rho}))\right)\,.$$

High-NA Metalens Simulation

$$\Delta\psi(\boldsymbol{\rho}) = k_0 n \left(f - \sqrt{||\boldsymbol{\rho}||^2 + f^2}\right)$$

Desired to function as a focusing lens

input plane wave
- normal incidence
- wavelength @532 nm
- beam diameter 2 mm
- polarization state
  a) R-circular
  b) Linear
  c) L-circular

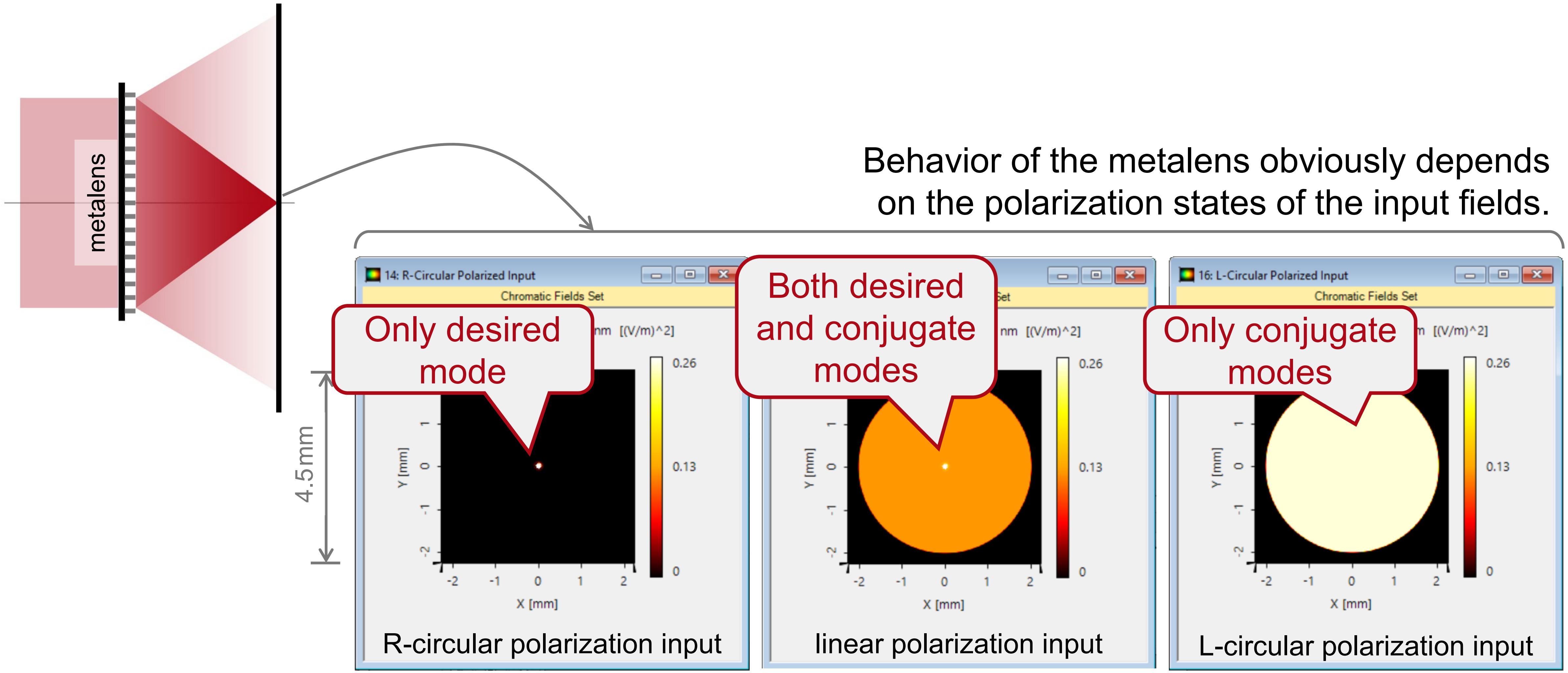


M. Khorasaninejad *et al.*, Science **352**, 1190-1194 (2016).

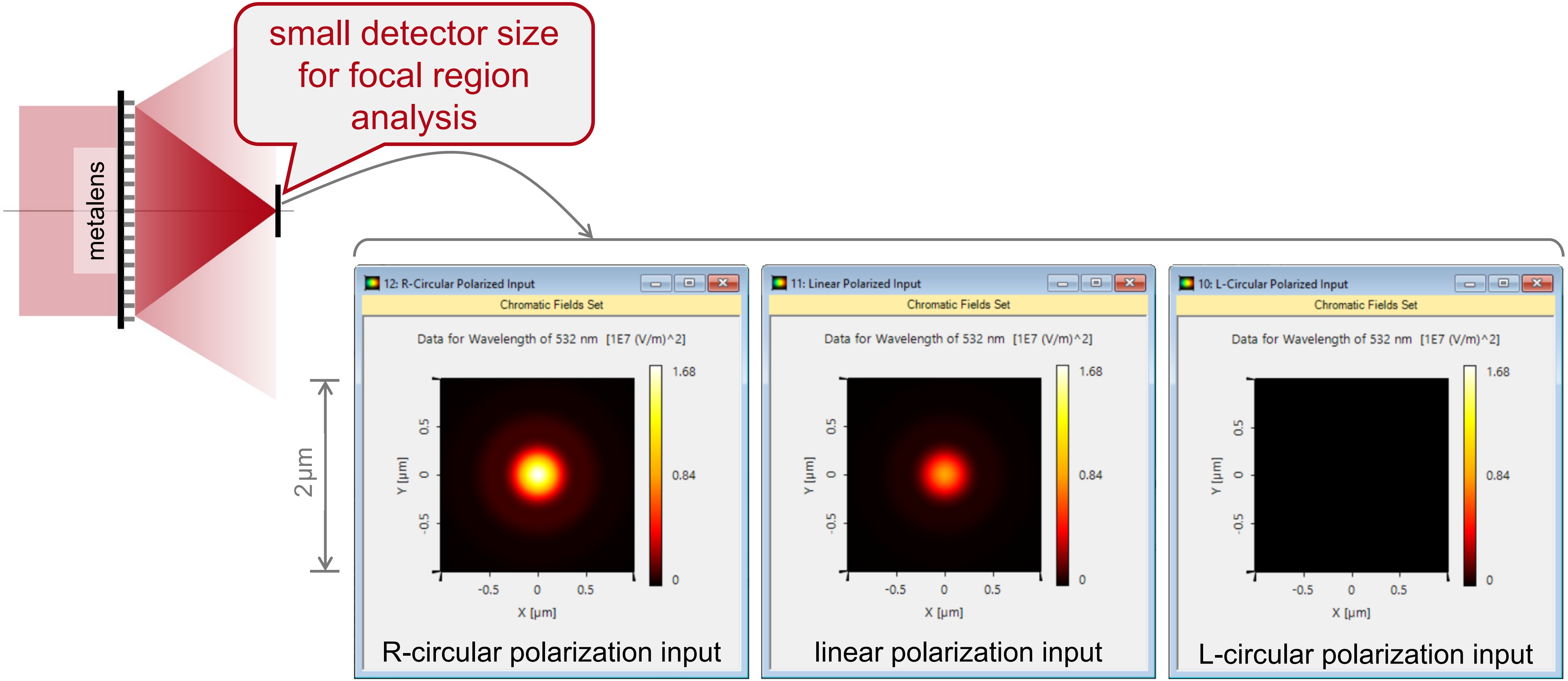
How to calculate the point spread function (PSF) at the focal plane of a metalens, with polarization effects considered?

VirtualLab Fusion Demonstration

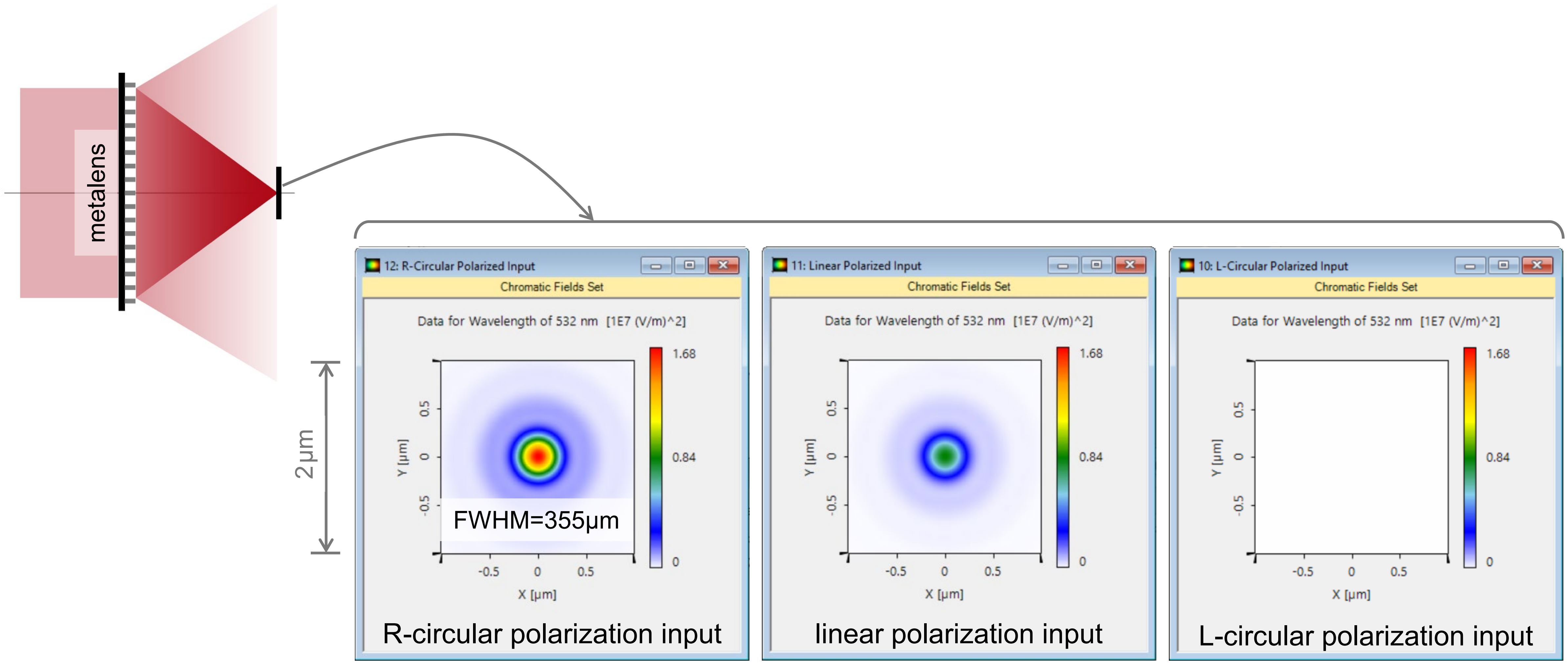
High-NA Metalens Simulation



High-NA Metalens Simulation



High-NA Metalens Simulation

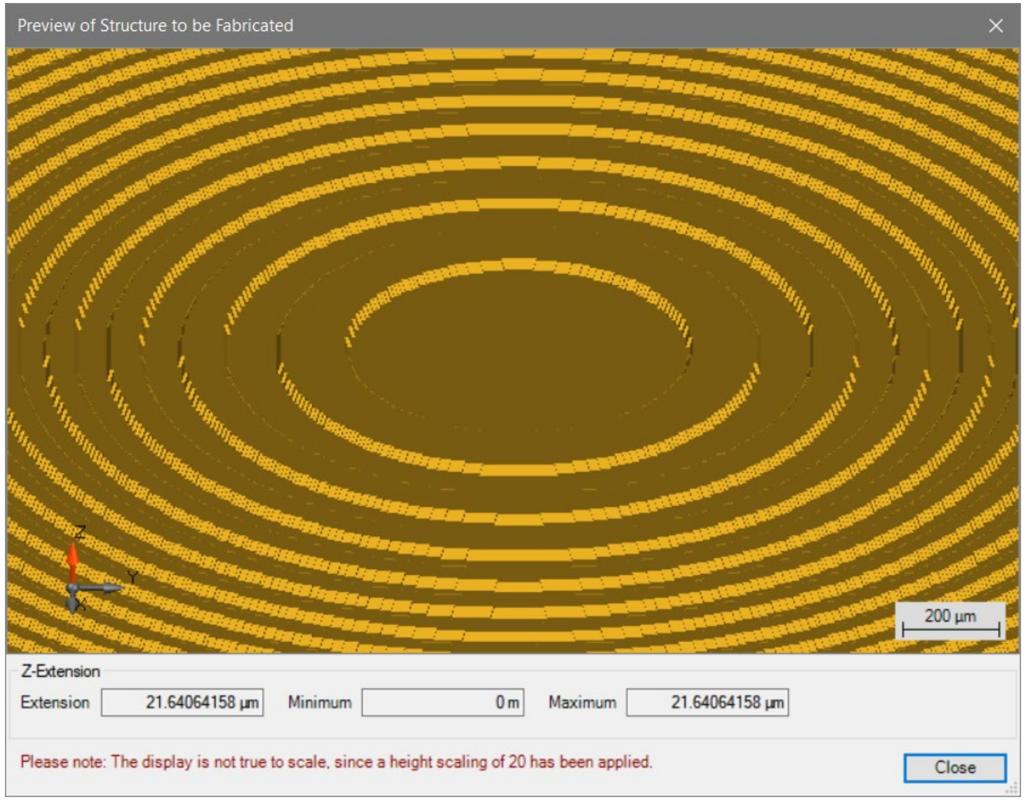


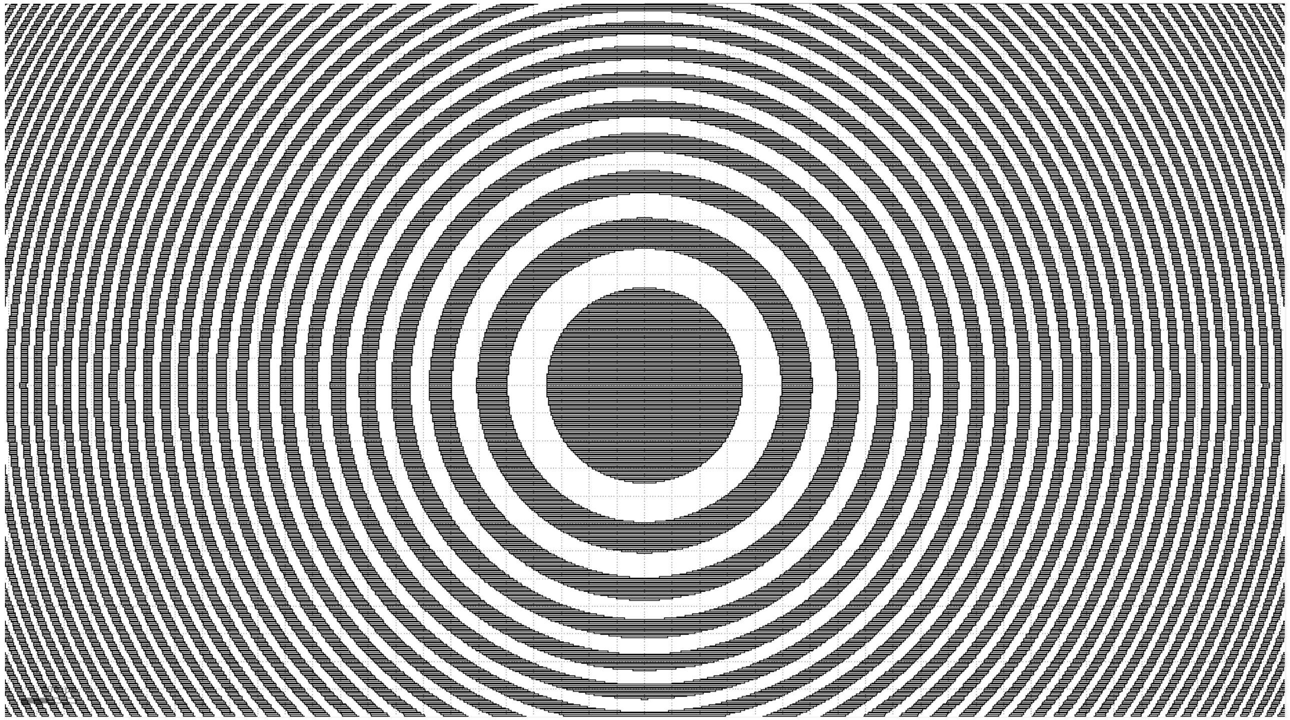
Structure of Workshop

- Introduction of theory
  - Frank Wyrowski
- Design of binary surfaces in OpticStudio
  - Akil Bhagat
- Physical-optics analysis of imported systems from OpticStudio: Diffractive lenses
  - Roberto Knoth
- Metalenses theory and modeling
  - Site Zhang
- **Fabrication export**
  - **Roberto Knoth**

Fabrication Export: Intraocular Lens (Binary → 1 Mask)

Sampled Data Export



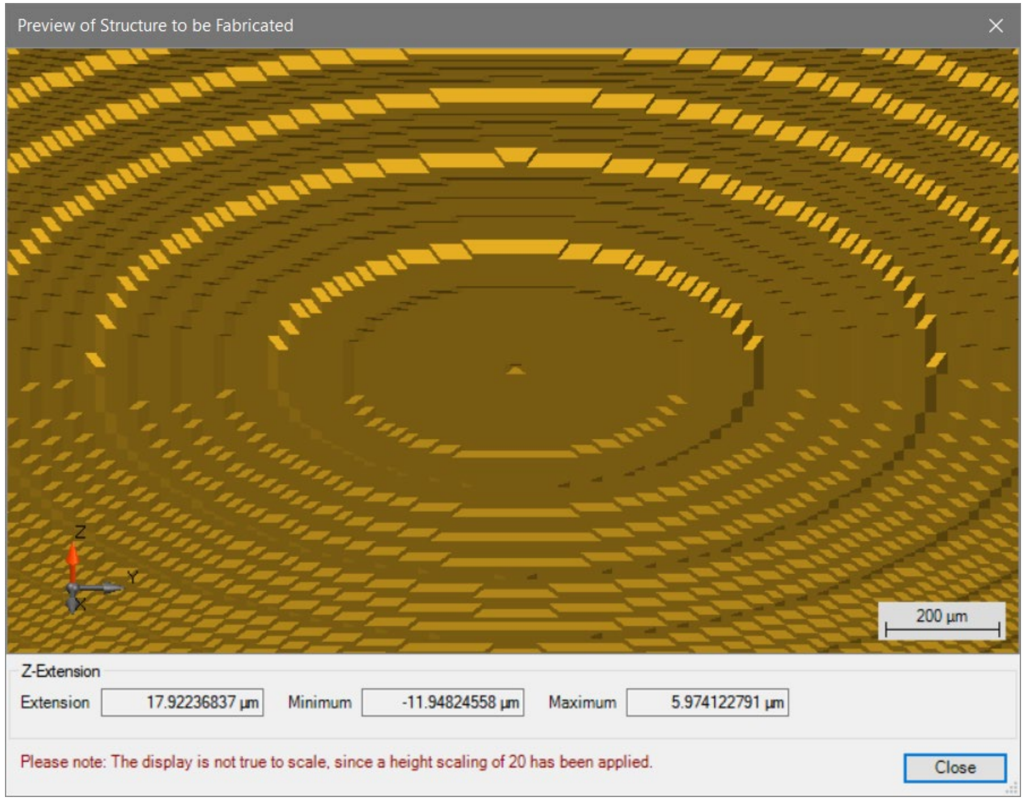


Structure Preview in VirtualLab Fusion

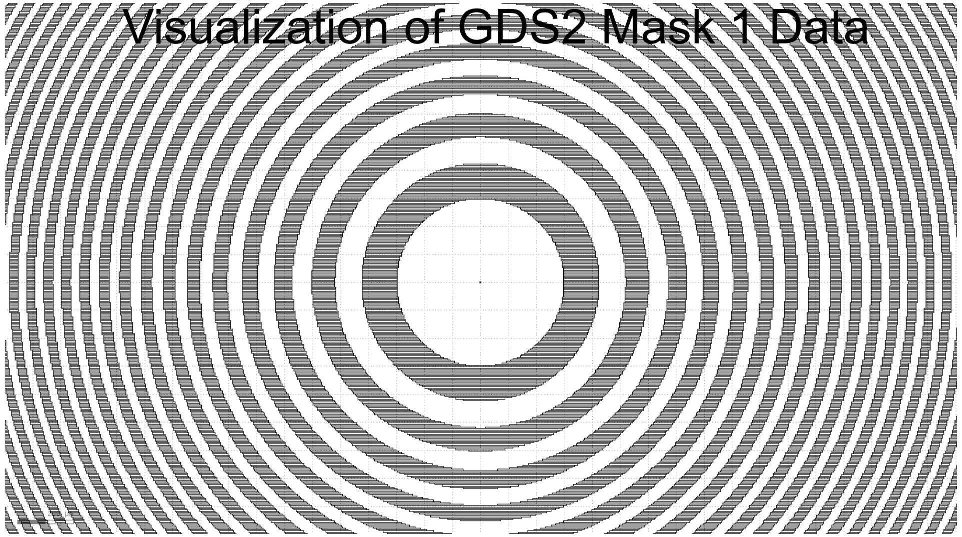
Visualization of GDS2 Mask Data

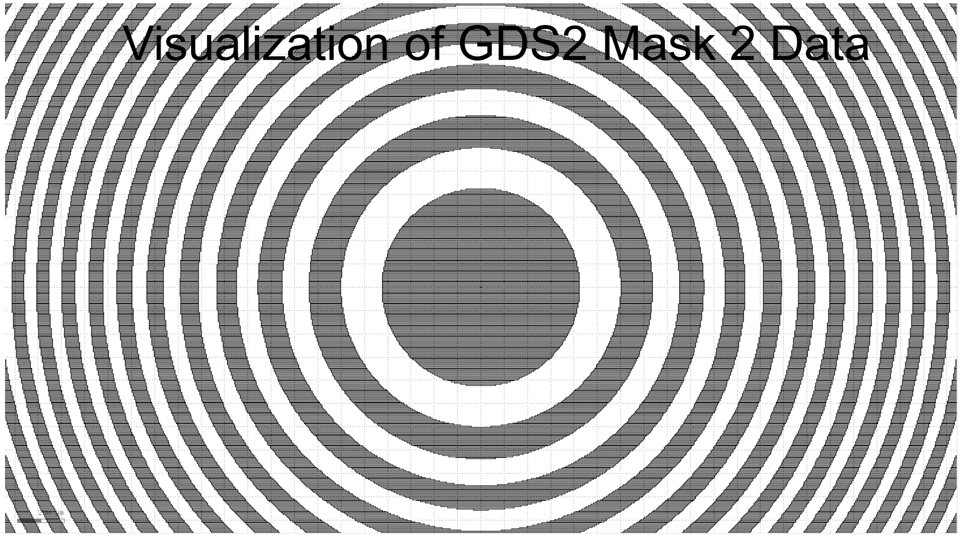
Fabrication Export: Eyepiece (4 Level → 2 Masks)

Sampled Data Export



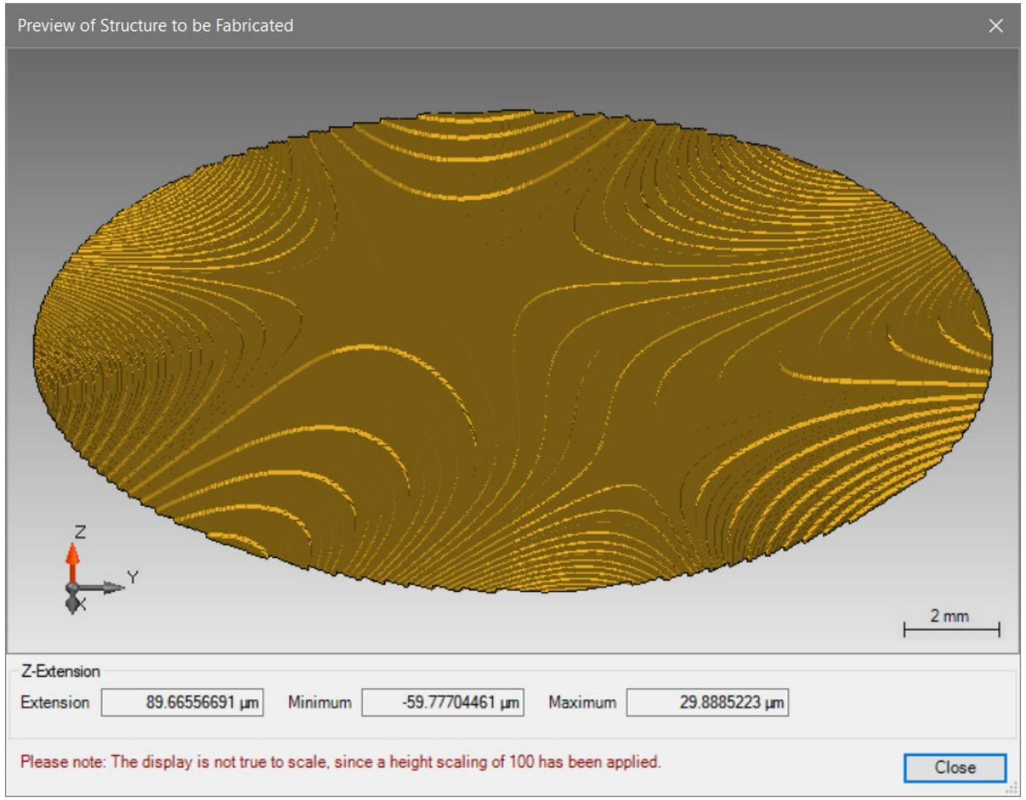
Structure Preview in VirtualLab Fusion



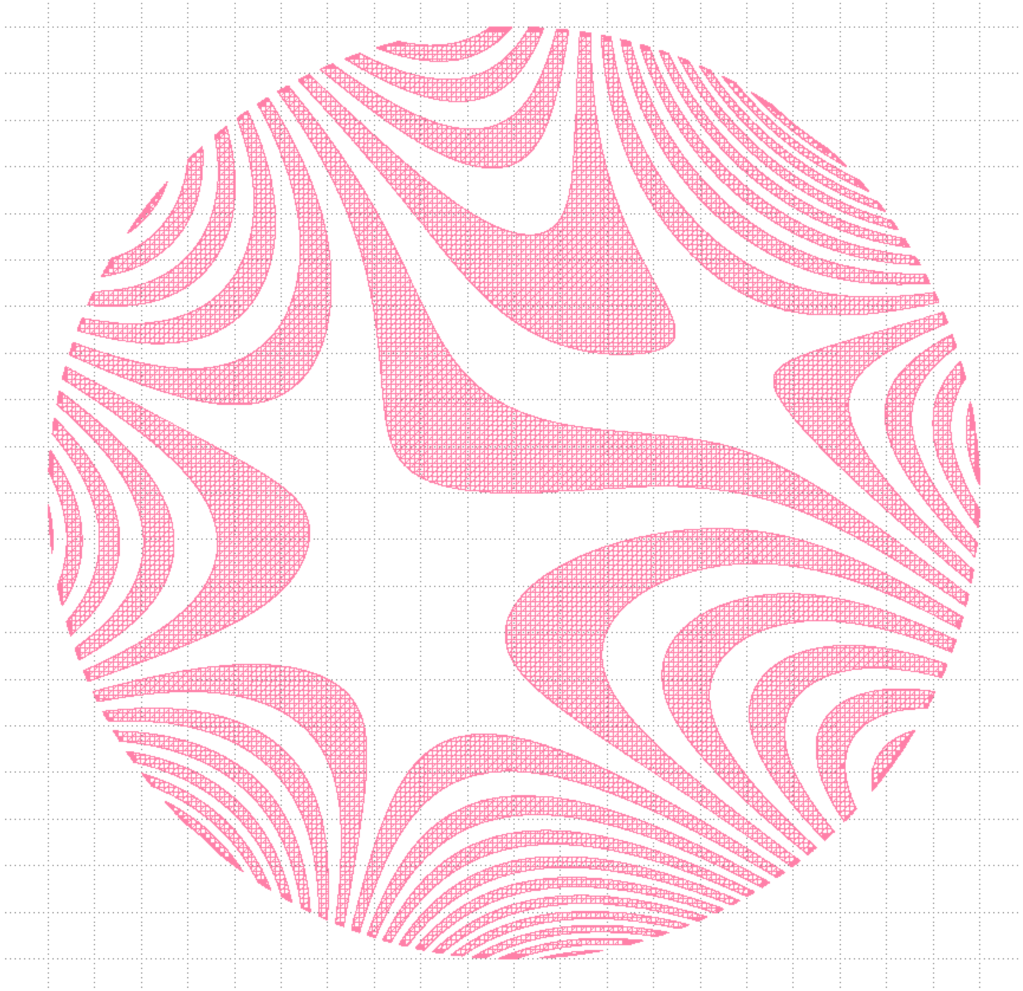


Fabrication Export: HOE (Binary → 1 Mask)

Polygon Data Export



Structure Preview in VirtualLab Fusion



Visualization of GDS2 Mask Data