Friedrich-Schiller-Universität Jena

SPIE PW 2018, Paper 10518-63

Non-paraxial Diffractive and Refractive Laser Beam Shaping

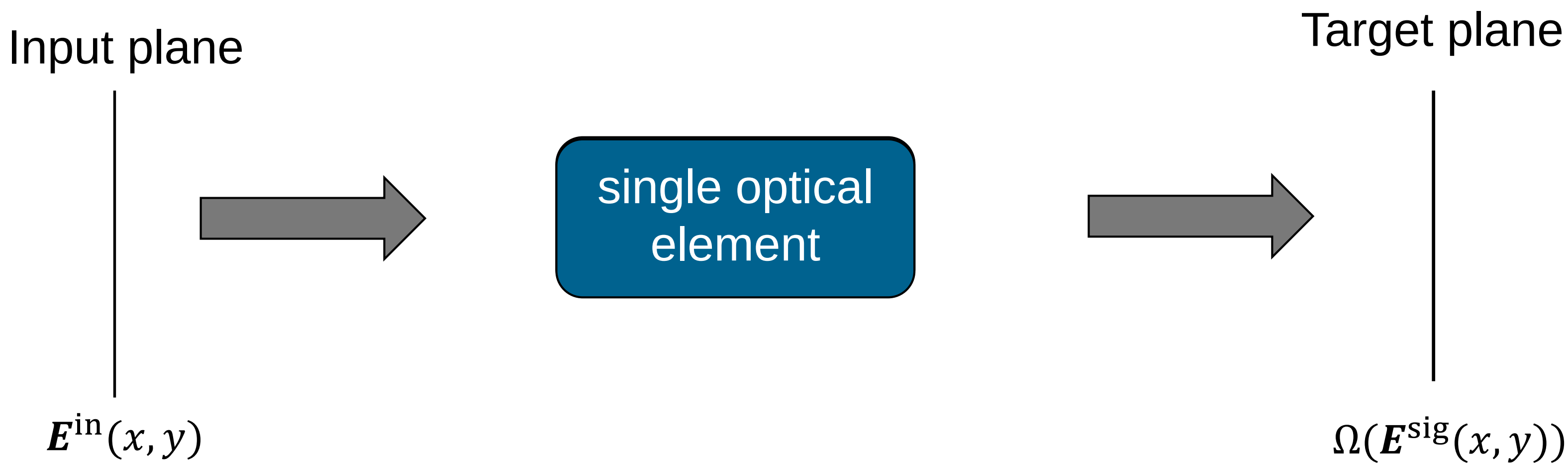
Liangxin Yang[1], Roberto Knoth[2], Christian Hellmann[3], Frank Wyrowski[1]

1. Friedrich-Schiller-Univ. Jena (Germany);
2. LightTrans International UG (Germany);
3. Wyrowski Photonics UG (Germany)

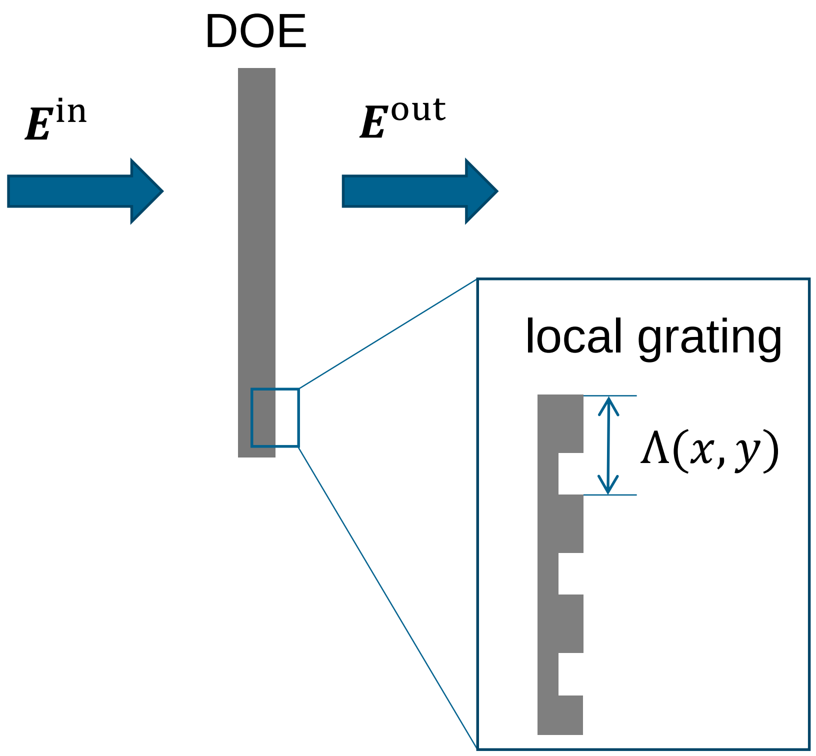
Introduction

In general, an optical design problem can be described as followed:

- given input field $\boldsymbol{E}^{\mathrm{in}}(x,y)$
- design an optical system: $\boldsymbol{E}^{\mathrm{in}}(x,y) \rightarrow \boldsymbol{E}^{\mathrm{sig}}(x,y)$
- obtain a detector function $\Omega(\boldsymbol{E}^{\mathrm{sig}}(x,y))$



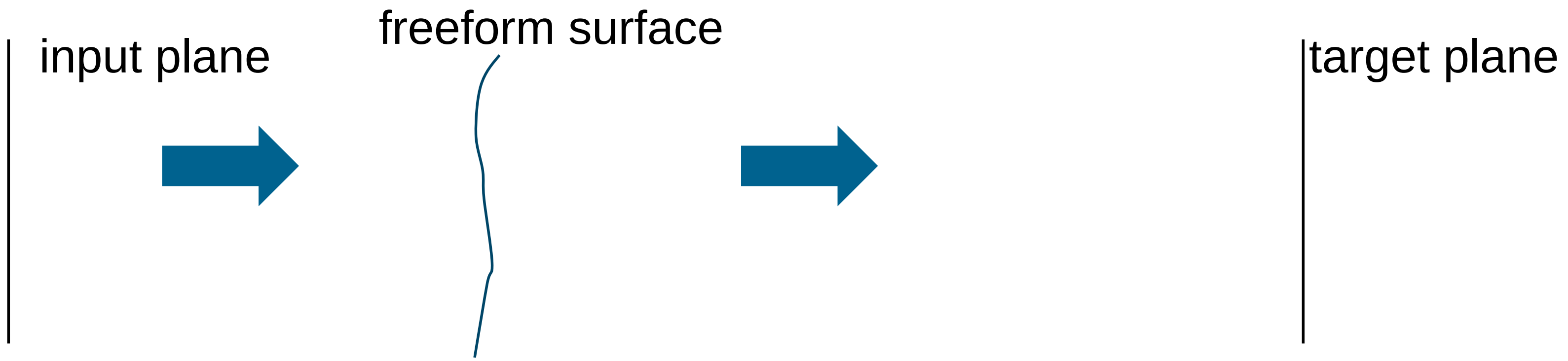
Modelling of Diffractive Optical Element



The Fourier Modal Method (FMM) is a rigorous technique to model the electric field propagation through a grating.

Lifeng Li, Use of Fourier series in the analysis of discontinuous periodic structures, J. Opt. Soc. Am. A 13, 1870-1876 (1996)

Modelling of Refractive Optical Element

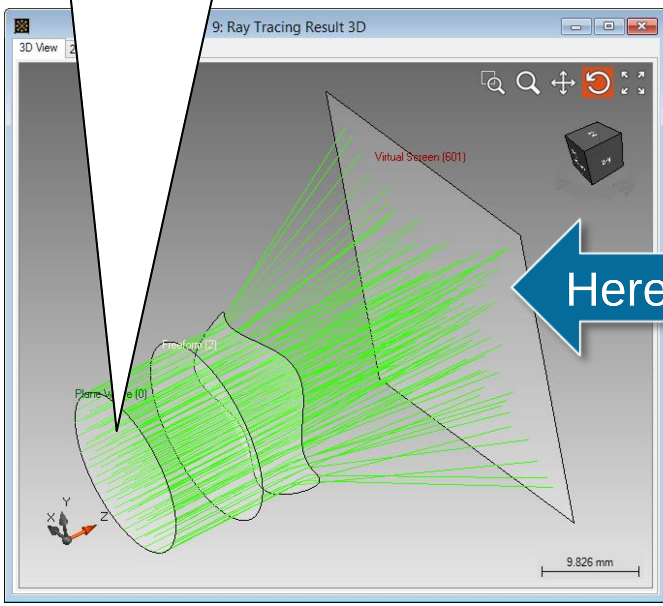


“Local plane-interface approximation“ a method for propagating electromagnetic fields through the smooth surface of an optical system.

Albrecht v. Pfeil, Frank Wyrowski, Andreas Drauschke, and Harald Aagedal, "Analysis of optical elements with the local plane-interface approximation," Appl. Opt. 39, 3304-3313 (2000)

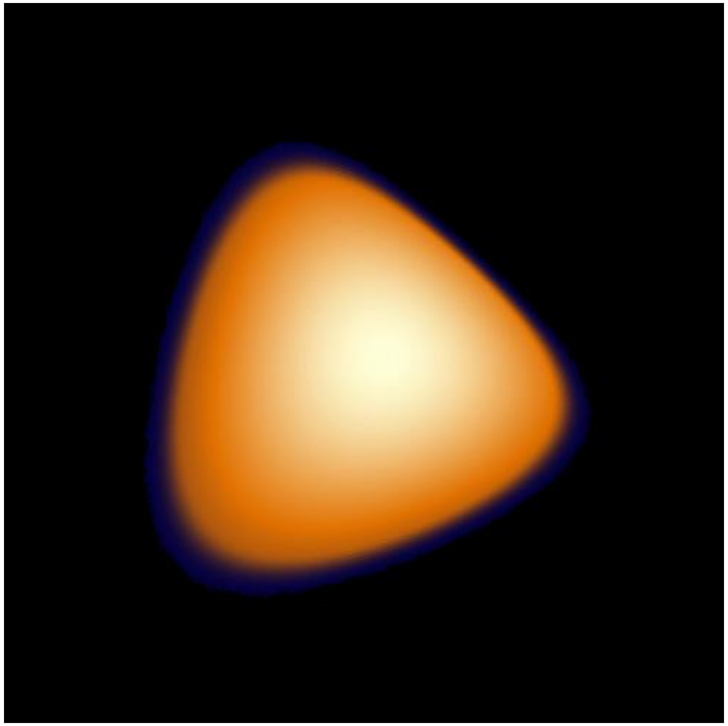
Modelling of Refractive Optical Element

Input: Gaussian beam
Diameter 10 mm



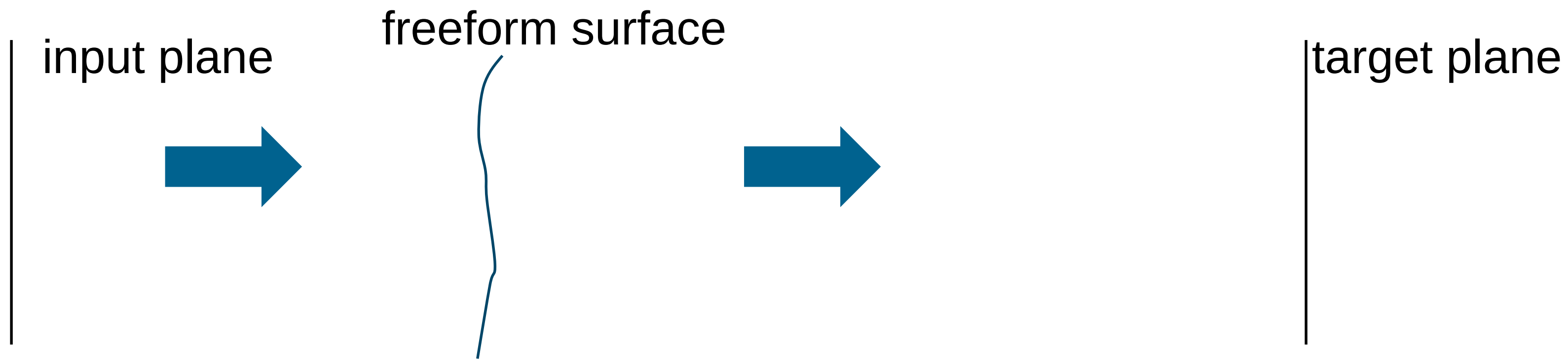
Here

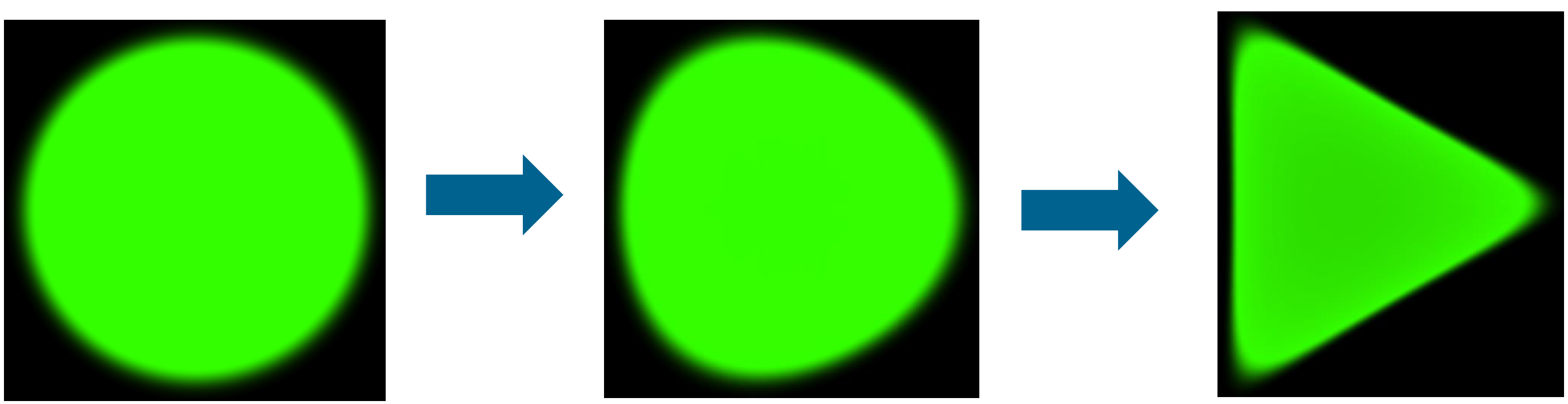
Amplitude $E_x(x,y)$



simulation time < 1 sec

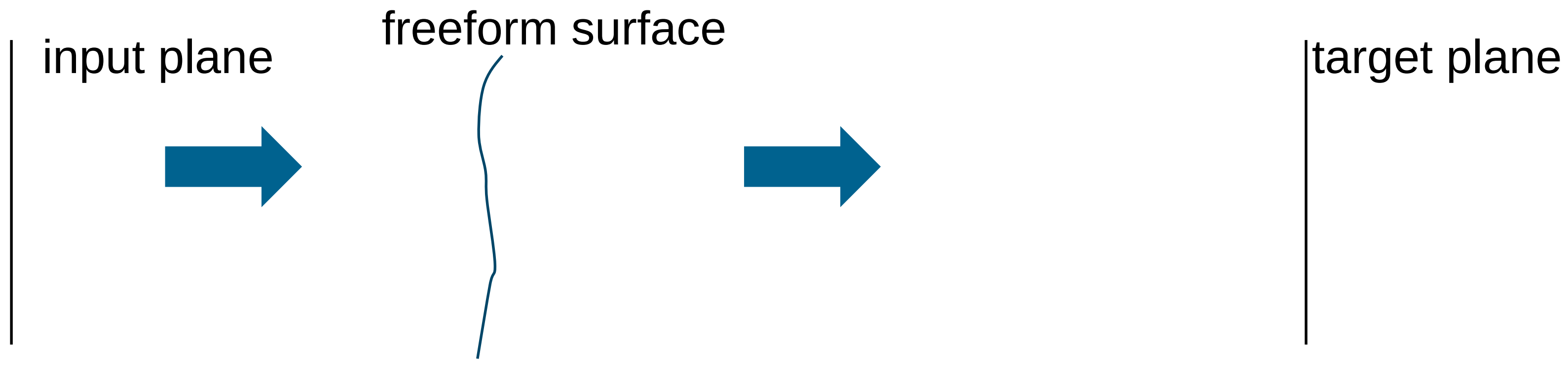
Modelling of Refractive Optical Element

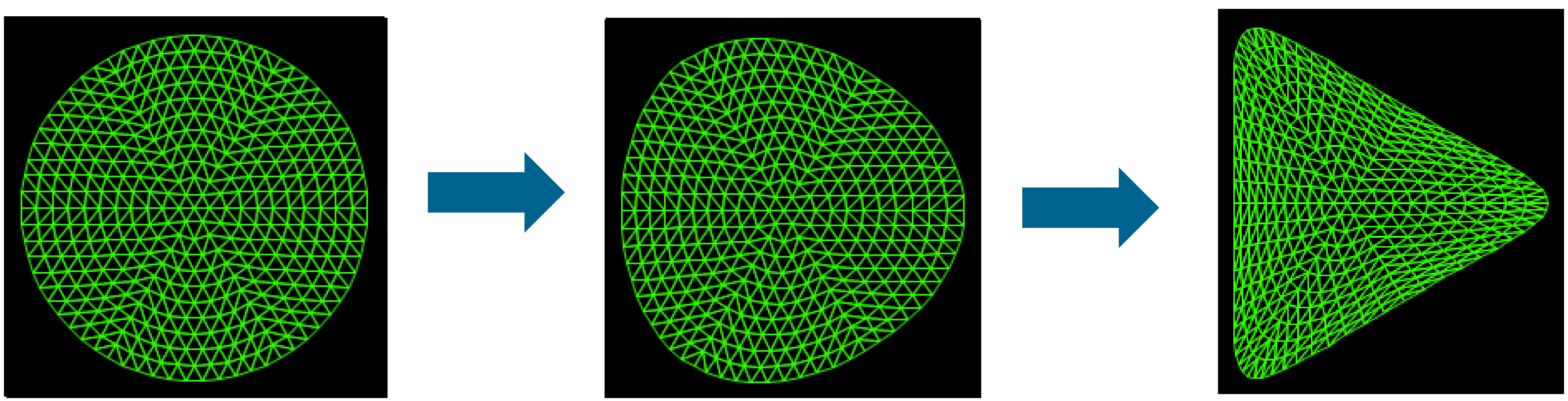




Irradiance pattern is morphing while propagation

Modelling of Refractive Optical Element

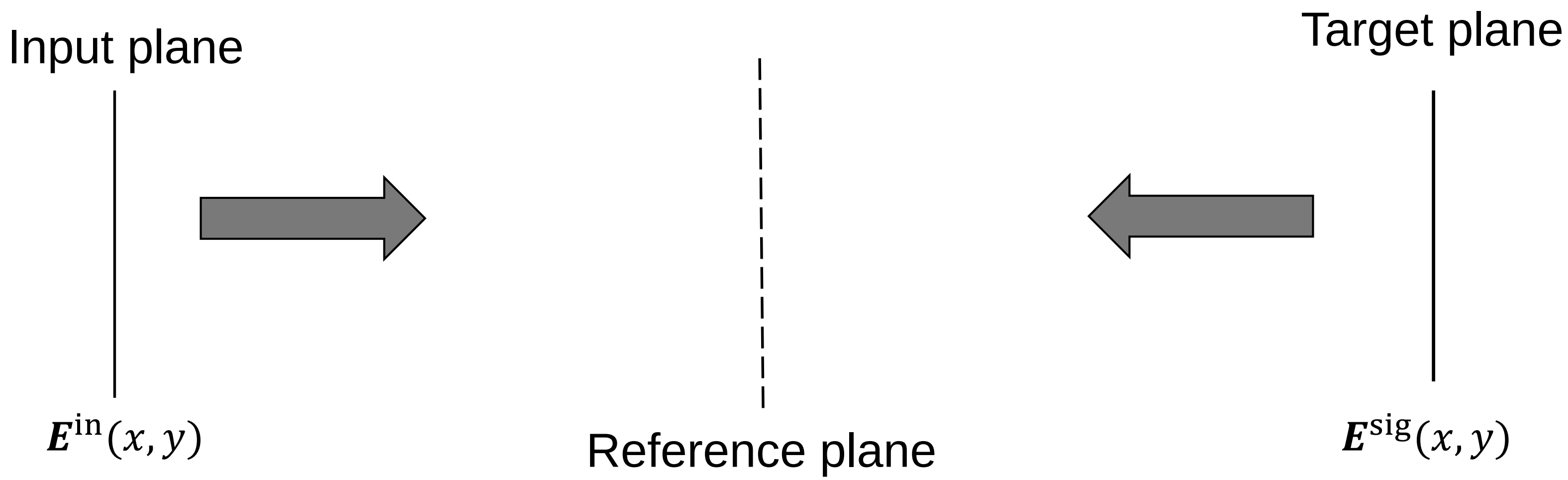




Introduction

Inverse approach

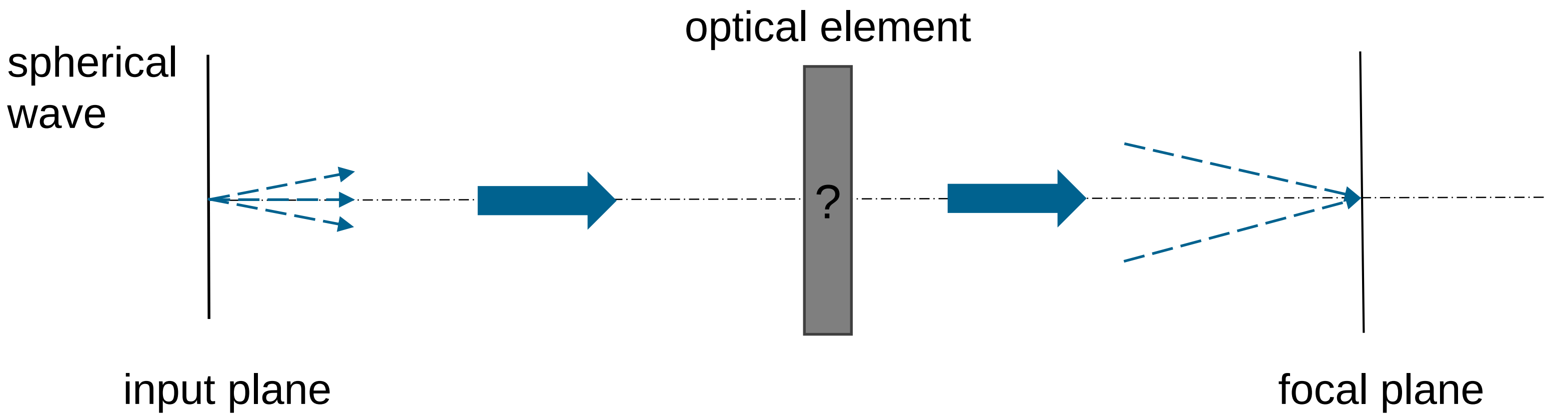
1. functional embodiment: an ideal component function is introduced to realize the transmission between the two fields;
2. structure embodiment: suitable structure is developed to realize the functionality of the component.



Pfeil, A. V. & Wyrowski, F. Wave-optical structure design with the local plane-interface approximation *Journal of Modern Optics*, **2000**, *47*, 2335-2350

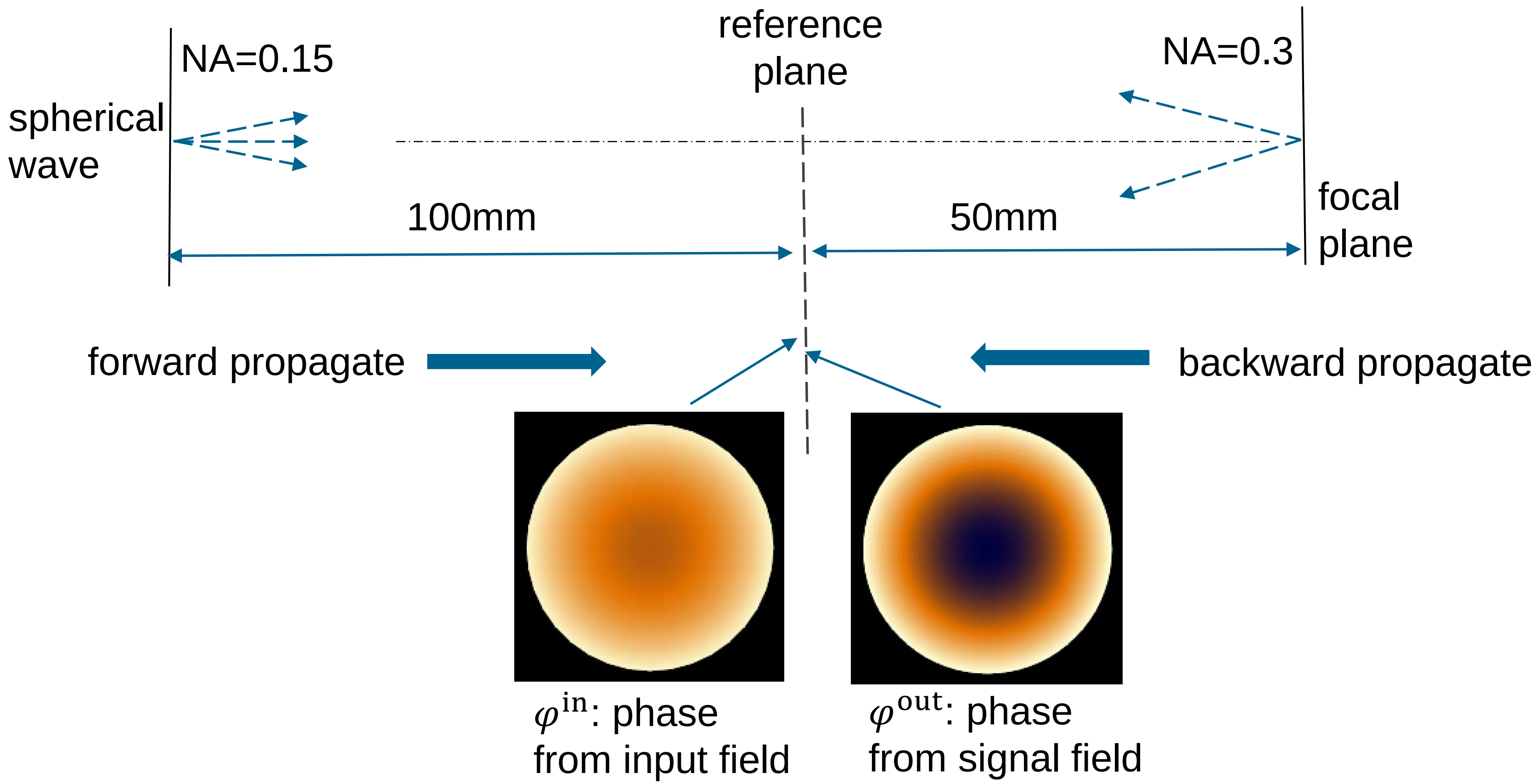
Design Task: Focusing System

Task description: for an given spherical wave, to design an optical element to focus it with a specific NA



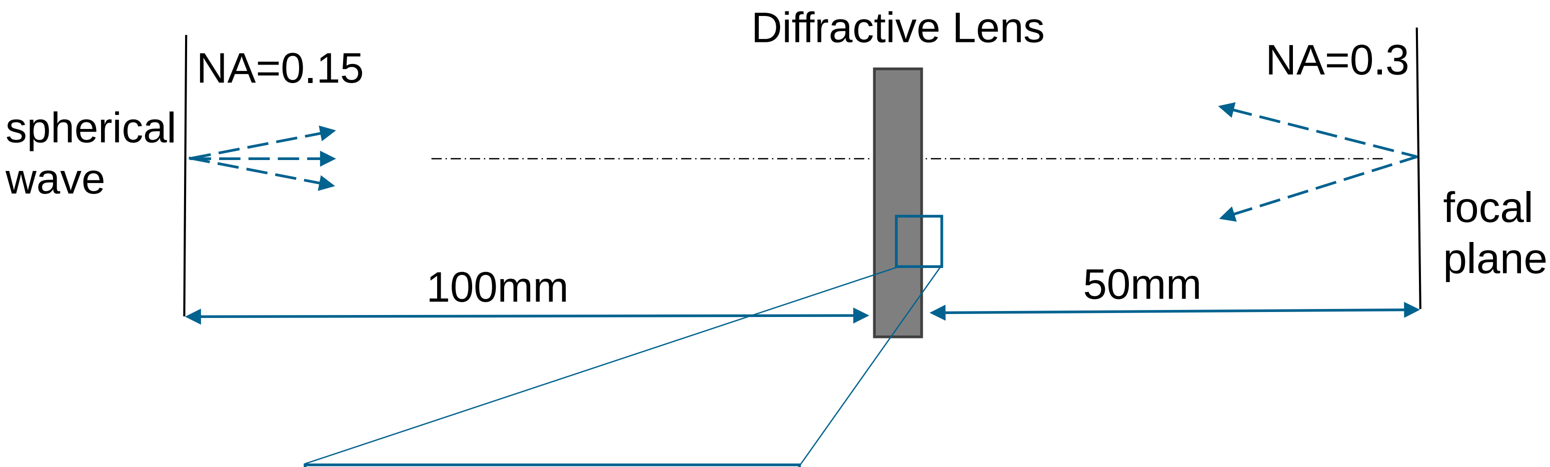
The signal field is considered as a spherical wave.

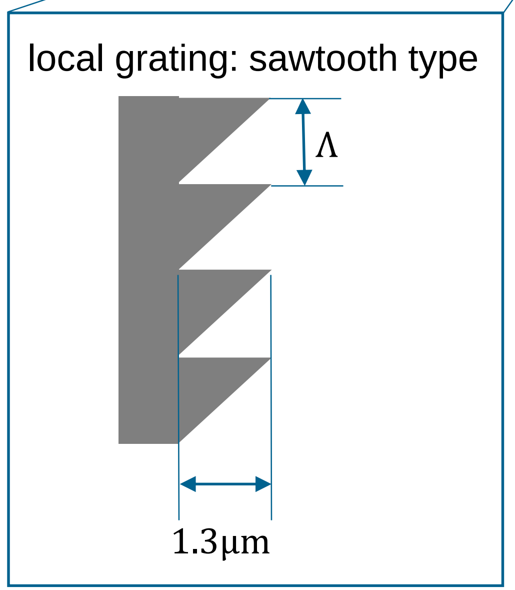
Design Process: Functional Embodiment



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

Design Process: Structure Embodiment



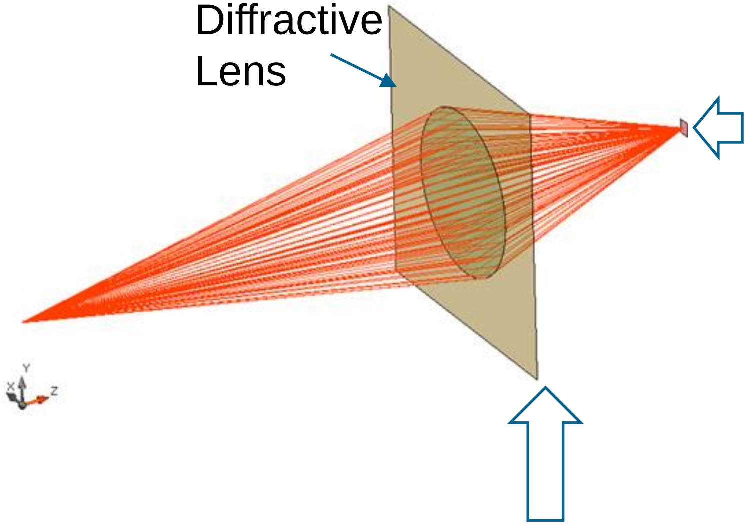


- The local grating of the diffracitve lens is chosed as sawtooth type.
- The 1st order is selected as working order.
- Local grating period $\Lambda(x, y)$ of the diffractive lens is obtained with the phase function.

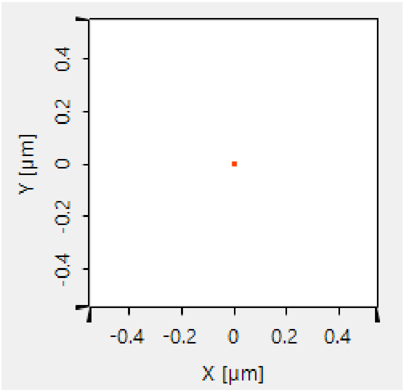
$$\Lambda(x, y) = \frac{2\pi}{|\nabla\varphi(x, y)|}$$

Simulation with Designed Result

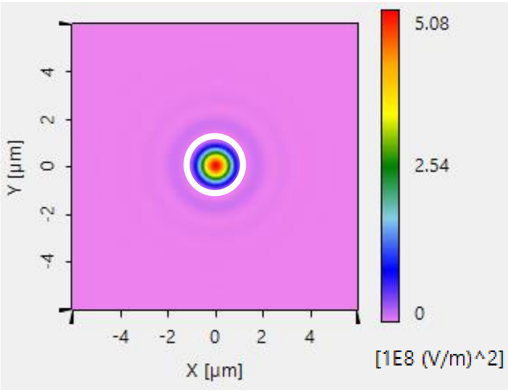
Diffractive
Lens



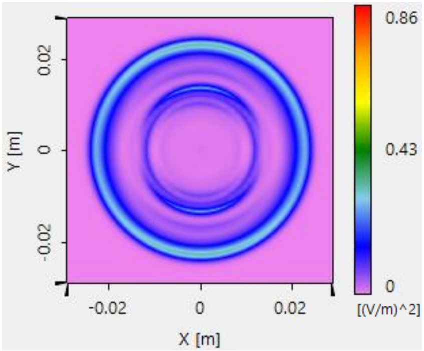
dot diagram



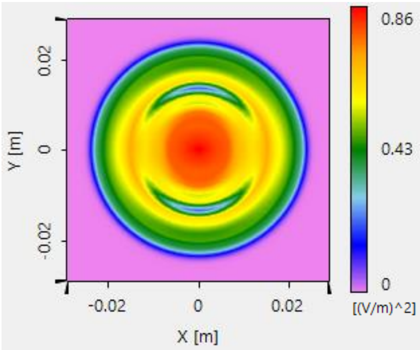
PSF
(Airy disk diameter $\approx 2.5\mu m$)



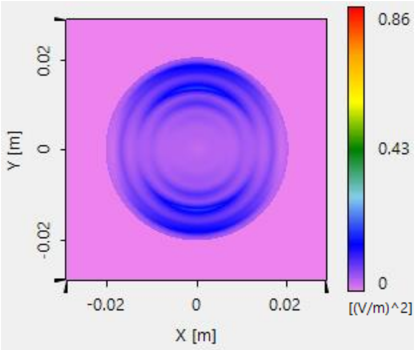
Intensity After the Diffractive Lens



0th order

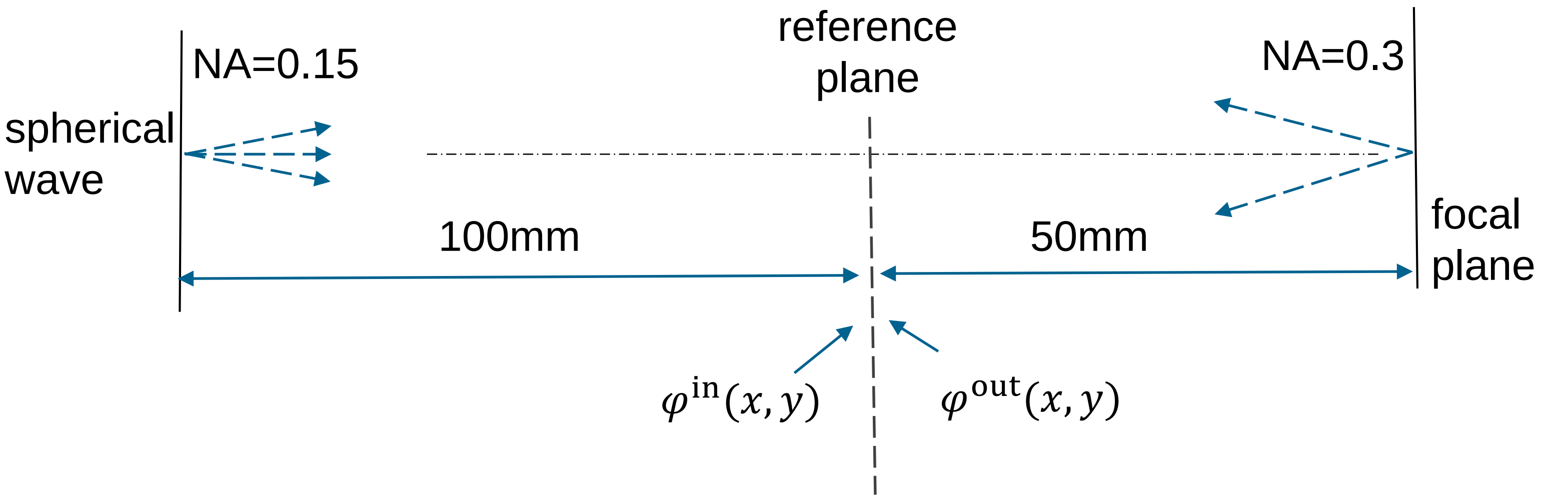


1st order



2nd order

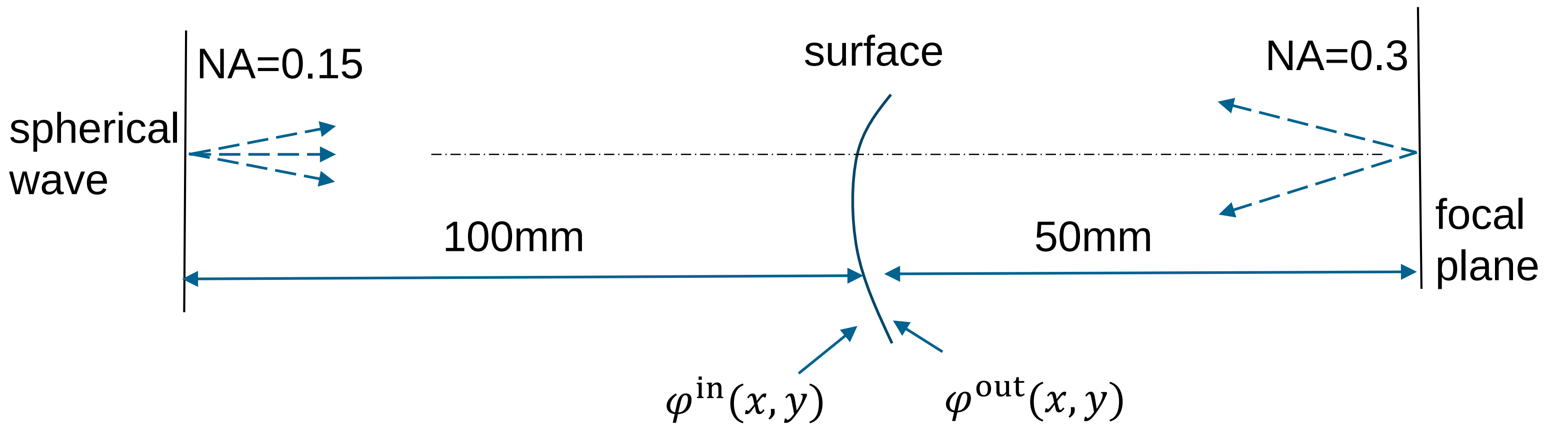
Design Process: Structure Embodiment



Algorithm in brief:

1. propagate → phase on reference plane $\varphi^{\mathrm{in}}(x,y)$, $\varphi^{\mathrm{out}}(x,y)$
2. $\varphi^{\mathrm{in}}(x,y)$, $\varphi^{\mathrm{out}}(x,y)$ → local wave vectors $\boldsymbol{k}^{\mathrm{in}}(x,y)$, $\boldsymbol{k}^{\mathrm{out}}(x,y)$;
3. $\boldsymbol{k}^{\mathrm{in}}(x,y)$, $\boldsymbol{k}^{\mathrm{out}}(x,y)$ → gradient of the surface $\nabla H(x,y)$;

Design Process: Structure Embodiment



Algorithm in brief:

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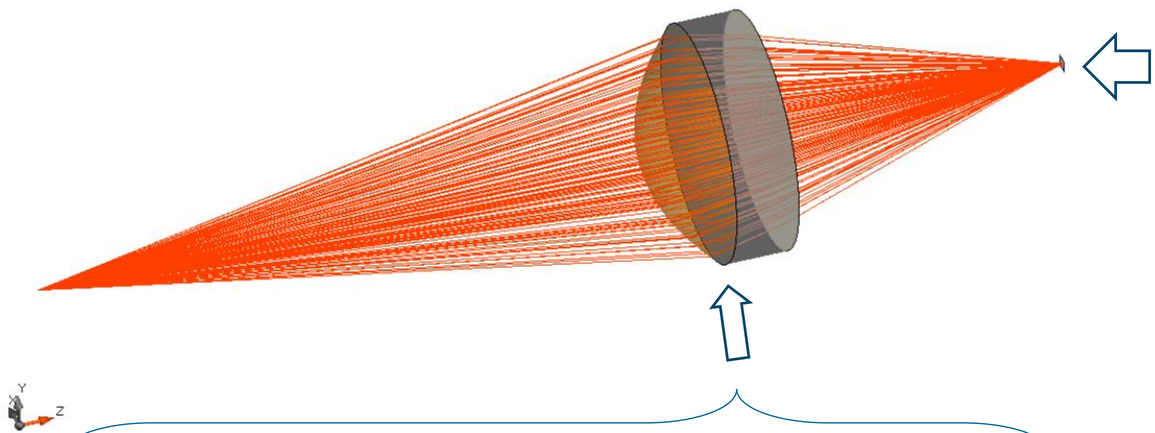
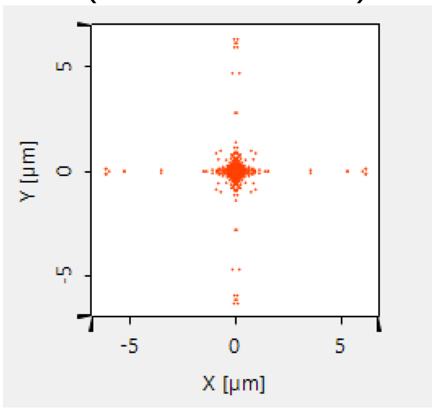
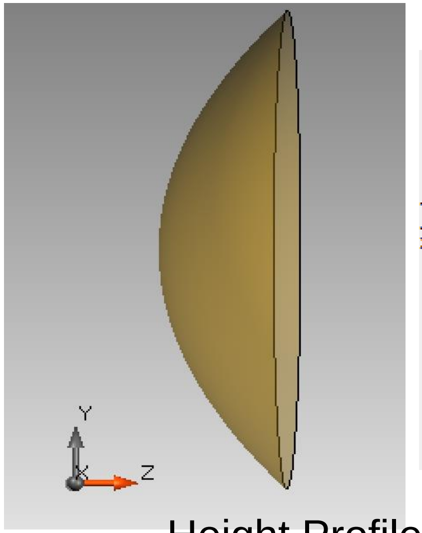
2. $\varphi^{\mathrm{in}}(x,y)$, $\varphi^{\mathrm{out}}(x,y)$ → local wave vectors $\boldsymbol{k}^{\mathrm{in}}(x,y)$, $\boldsymbol{k}^{\mathrm{out}}(x,y)$;
3. $\boldsymbol{k}^{\mathrm{in}}(x,y)$, $\boldsymbol{k}^{\mathrm{out}}(x,y)$ → gradient of the surface $\nabla H(x,y)$;
4. fit the gradient by B-spline to obtain a surface;
5. update the reference plane with the surface, and iteratively perform step 1 to 4 until a proper surface is obtained.

Designed Result and Simulation

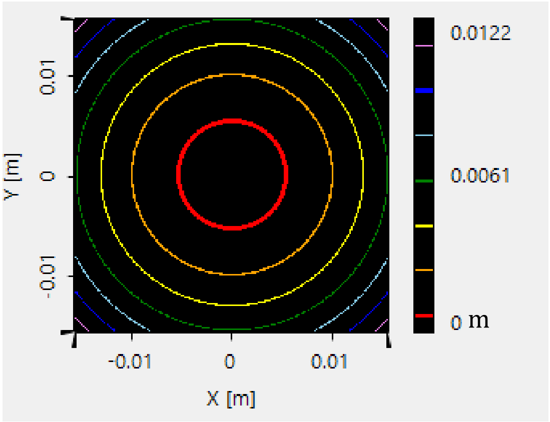


dot diagram
$(RMS \approx 4110nm)$



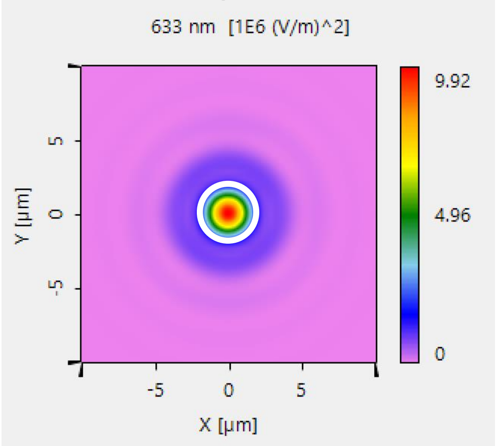


Height Profile
(3D view)



Height Profile
(2D Contour line)

PSF



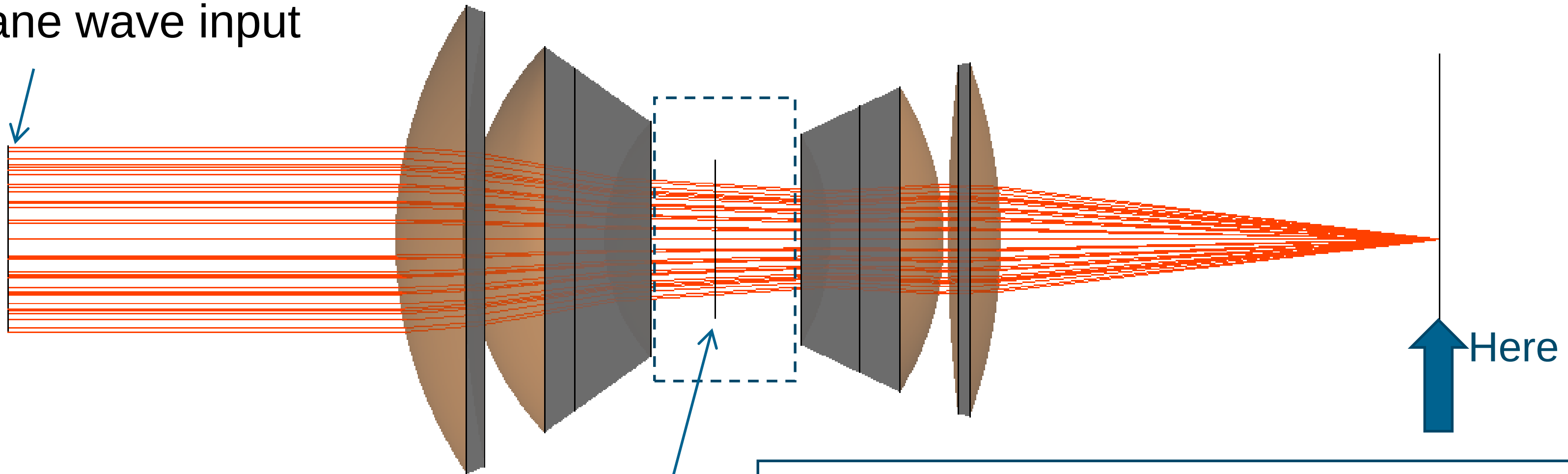
(Airy disk diameter $\approx 2.5\mu m$)

Application: Aberration Control in Image System

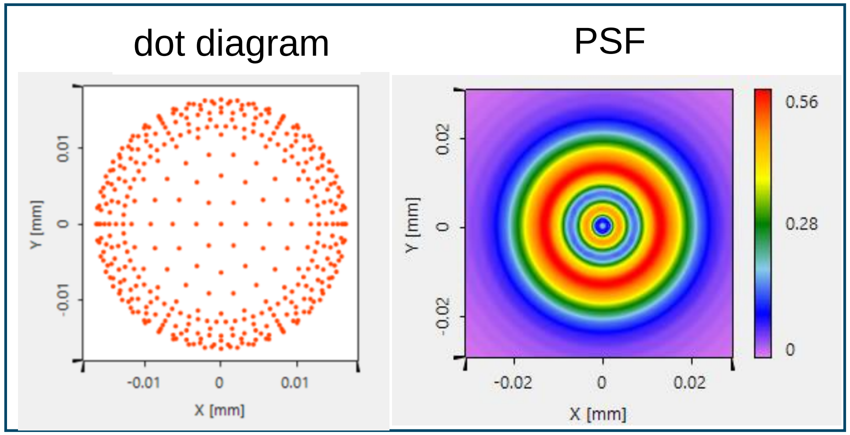
1. Spherical Aberration

double-Gauss lens system

plane wave input

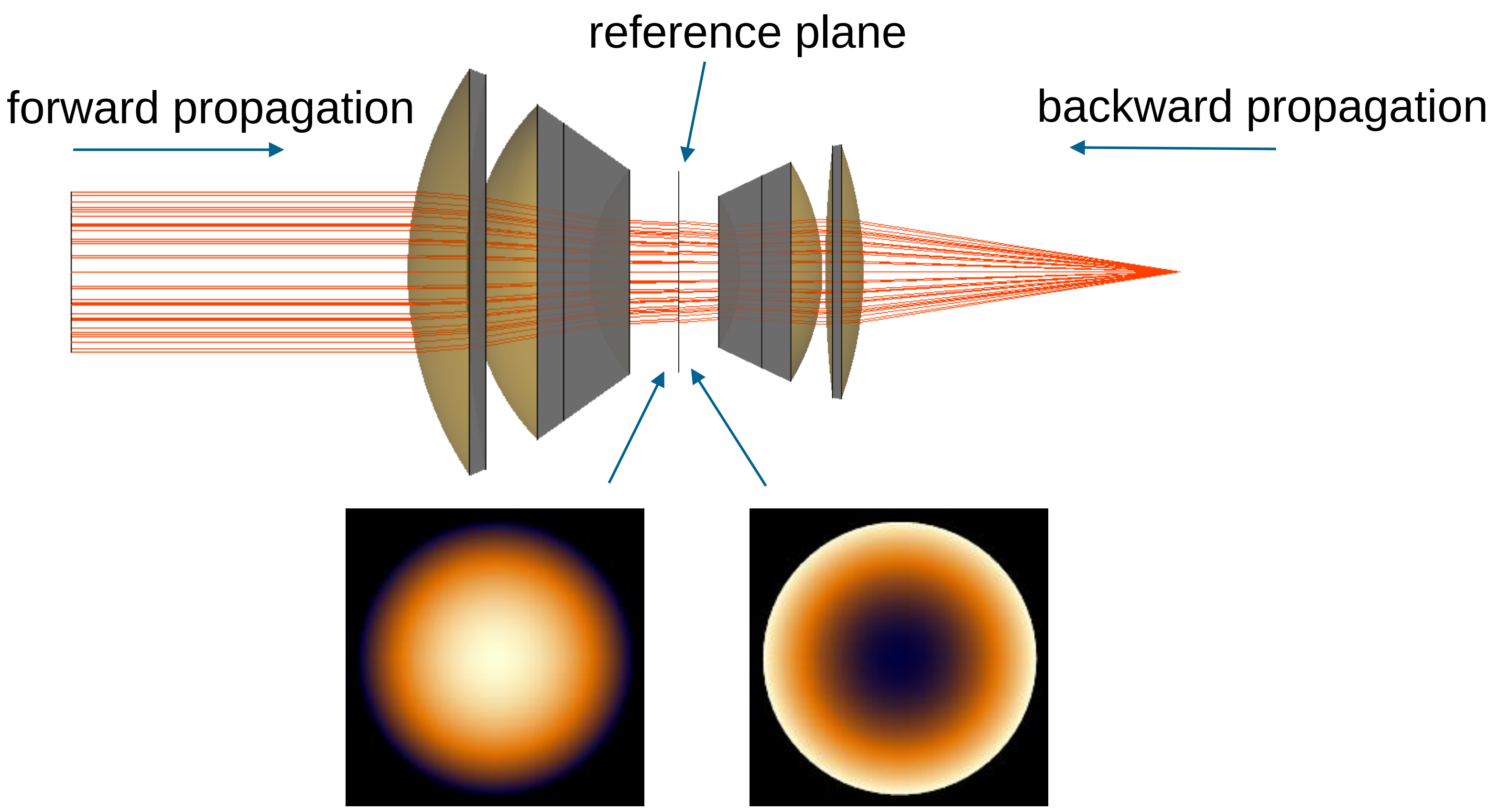


Freeform Structure?



Application: Aberration Control in Image System

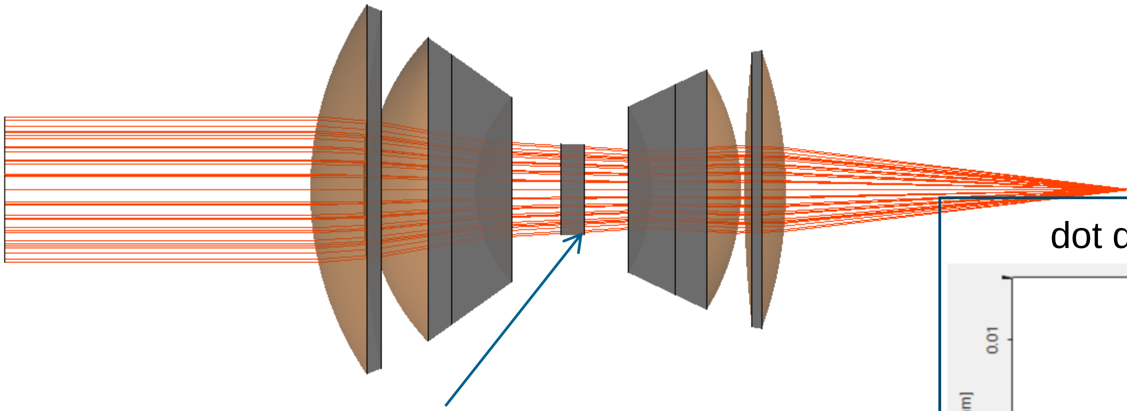
Design Process



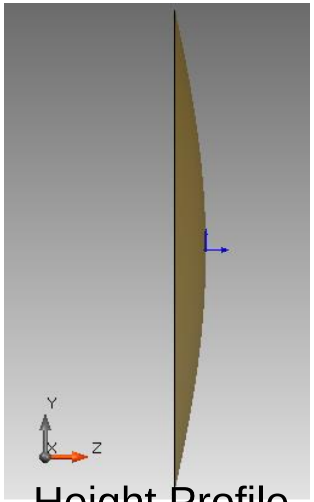
phase
from input field

phase
from target field

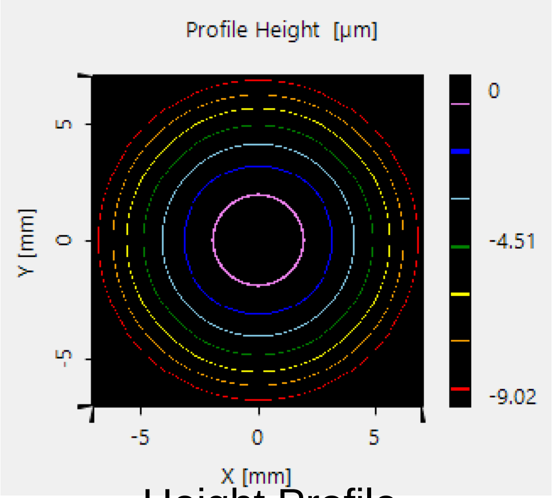
Design and Simulation Result



freeform surface

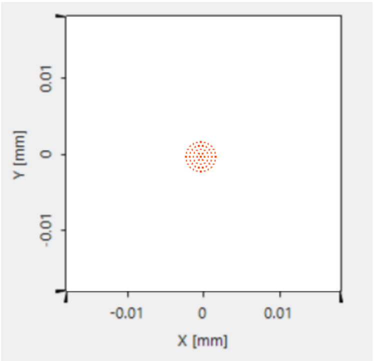


Height Profile
(3D view)

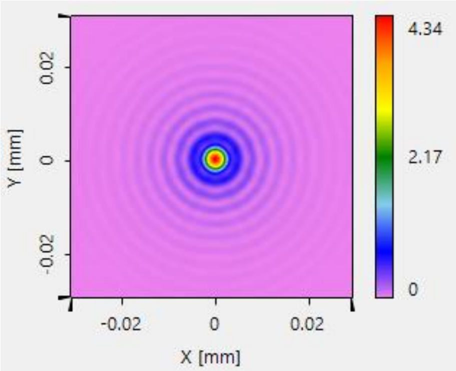


Height Profile
(2D Contour line)

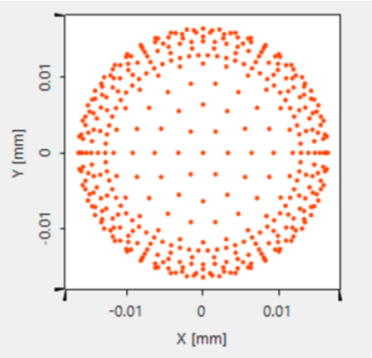
dot diagram

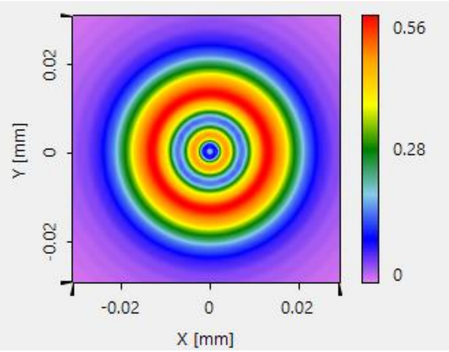


PSF



$RMS = 2.08\mu m$

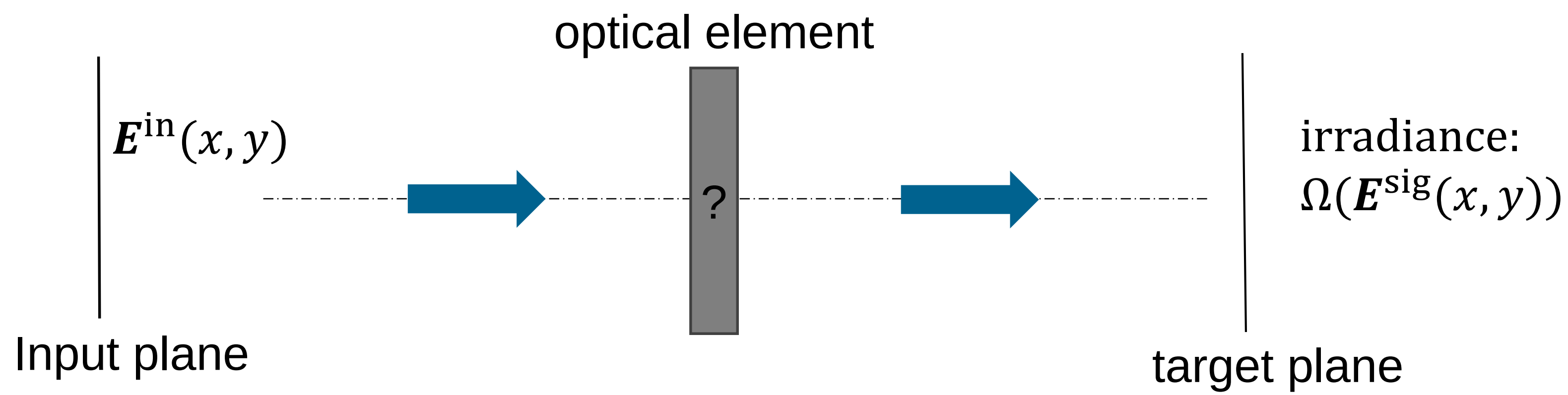




$RMS = 42.27\mu m$

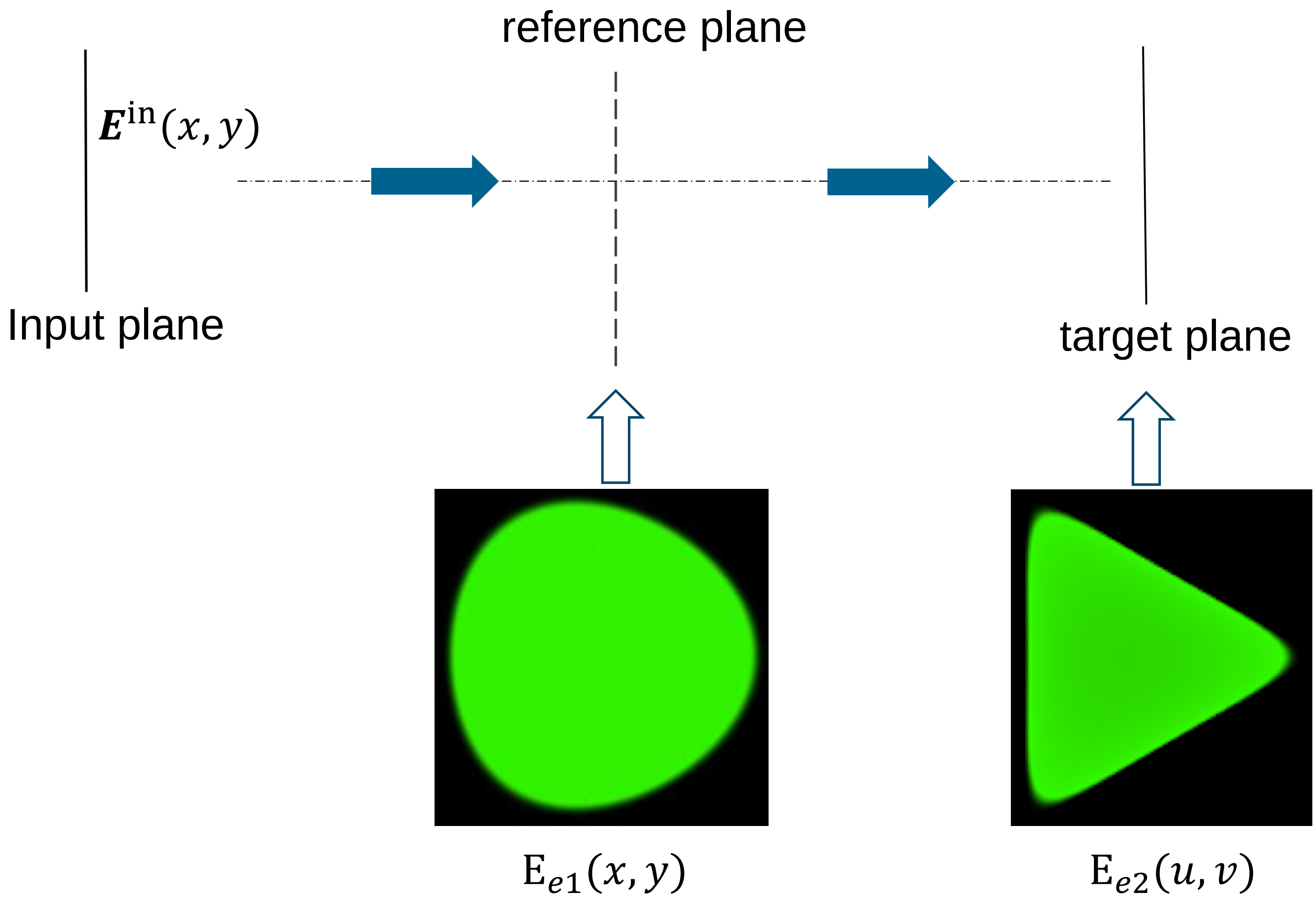
Design Task: Irradiance Redistribution

Task description: for a given input field, design an optical element to achieve required irradiance on target plane

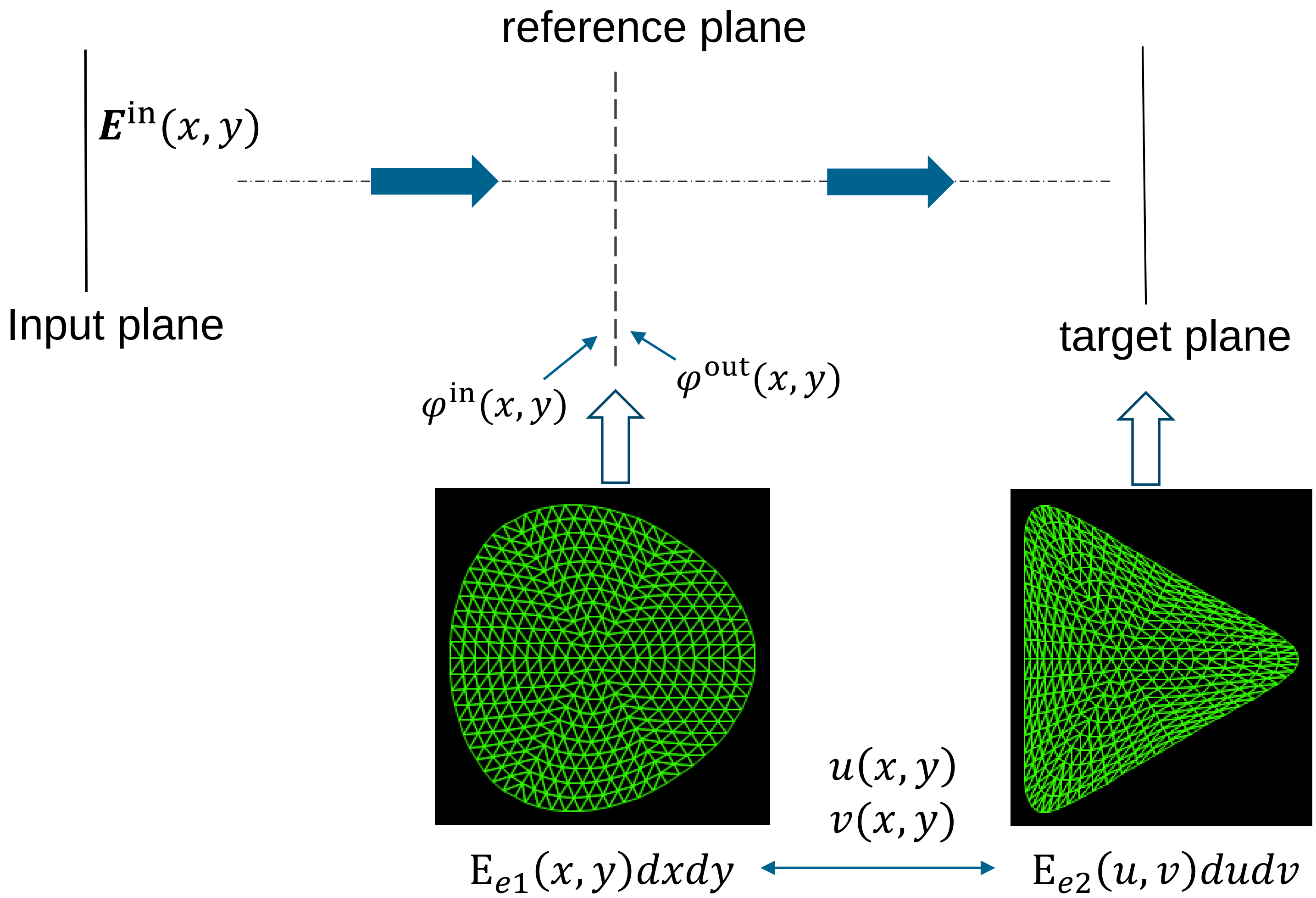


The input field is given.
The signal field is a freedom for the design.

Design Process: Functional Embodiment



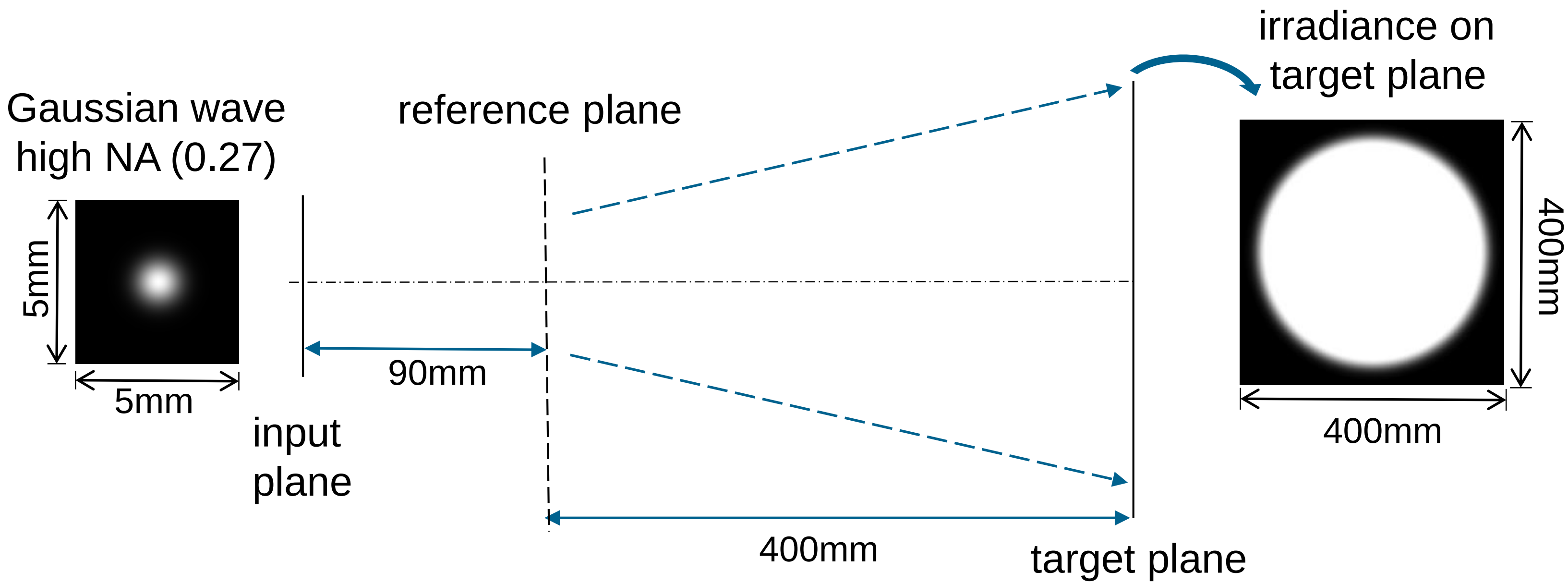
Design Process: Functional Embodiment



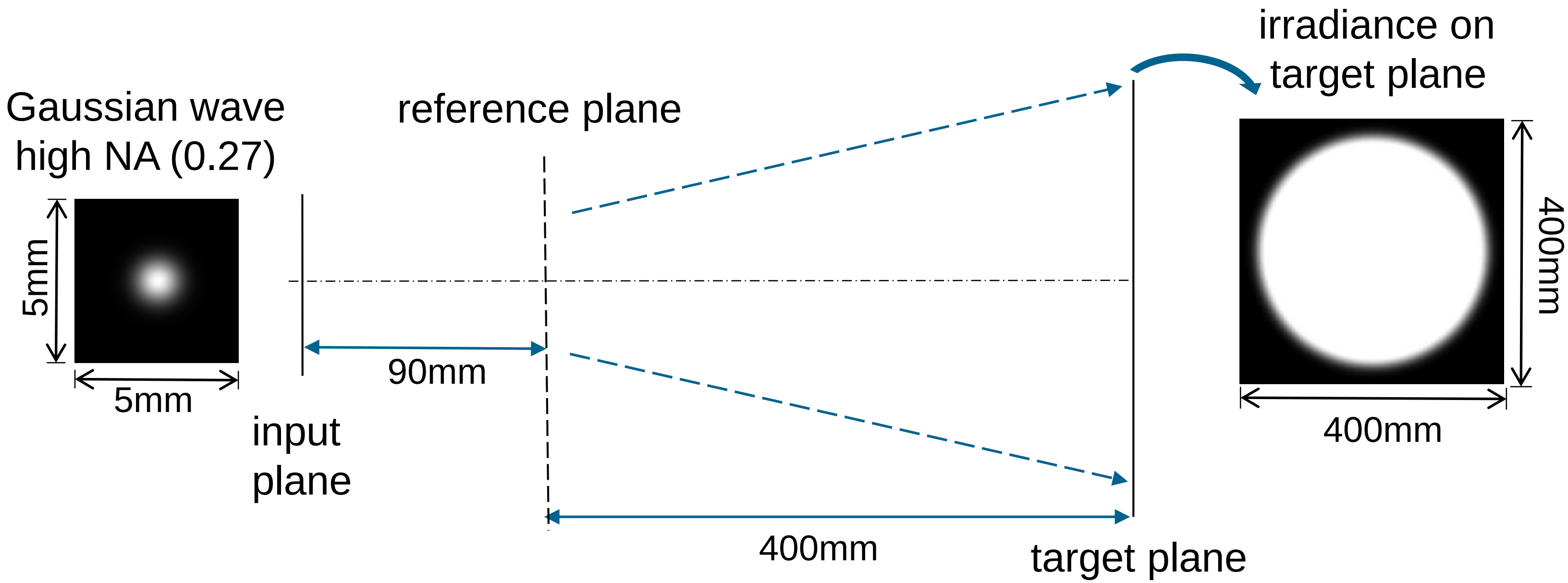
Sulman, M. M; et al. An efficient approach for the numerical solution of the Monge-Ampere equation
Applied Numerical Mathematics, **2011**, *61*, 298 - 307

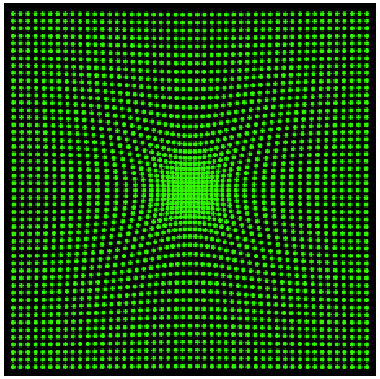
Example: Homogeneous Irradiance

Task description: for an input Gaussian wave, design an optical element to achieve homogeneous irradiance on target plane

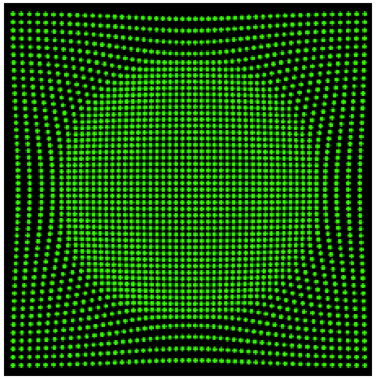


Example: Homogeneous Irradiance



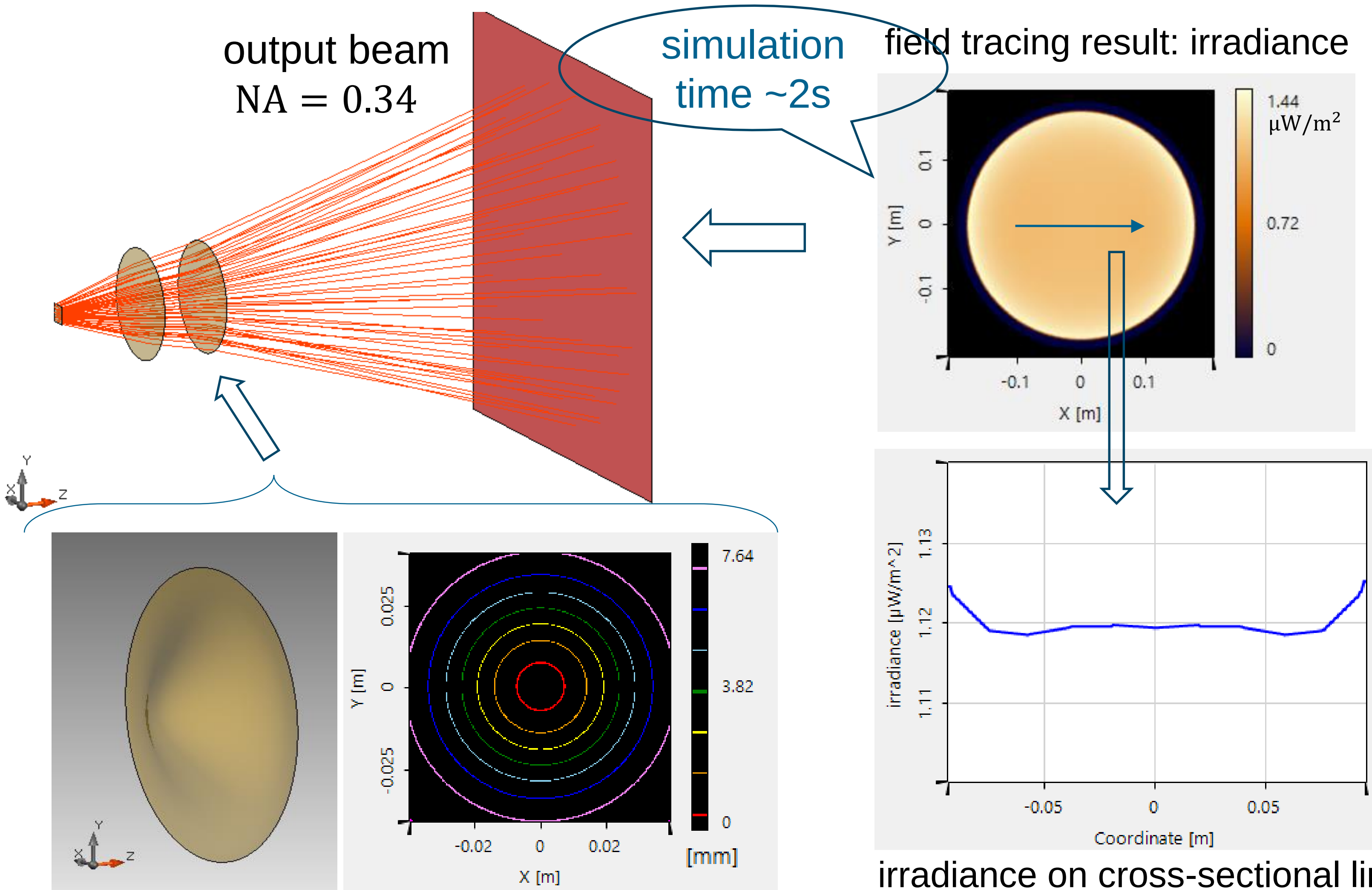


mesh nodes for input irradiance



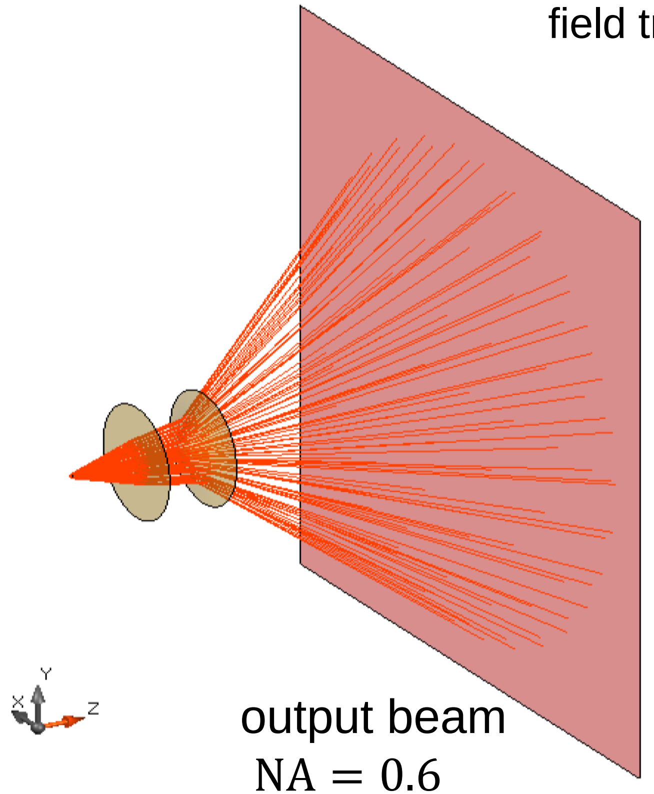
mesh nodes for target irradiance

Designed Result and Simulation



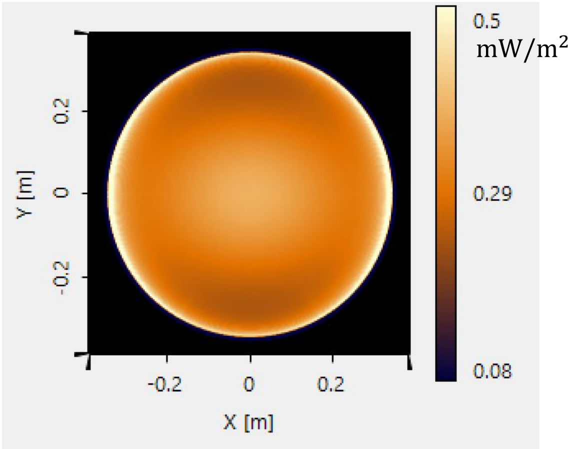
3D View   2D Contour line

Designed Result and Simulation

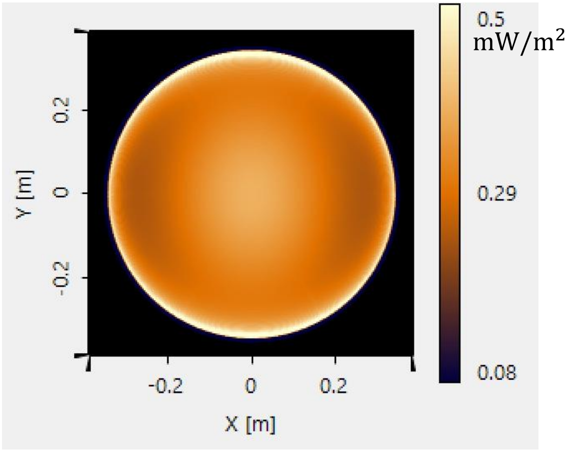


output beam
$\mathrm{NA} = 0.6$

field tracing result: irradiance with different polarization input field

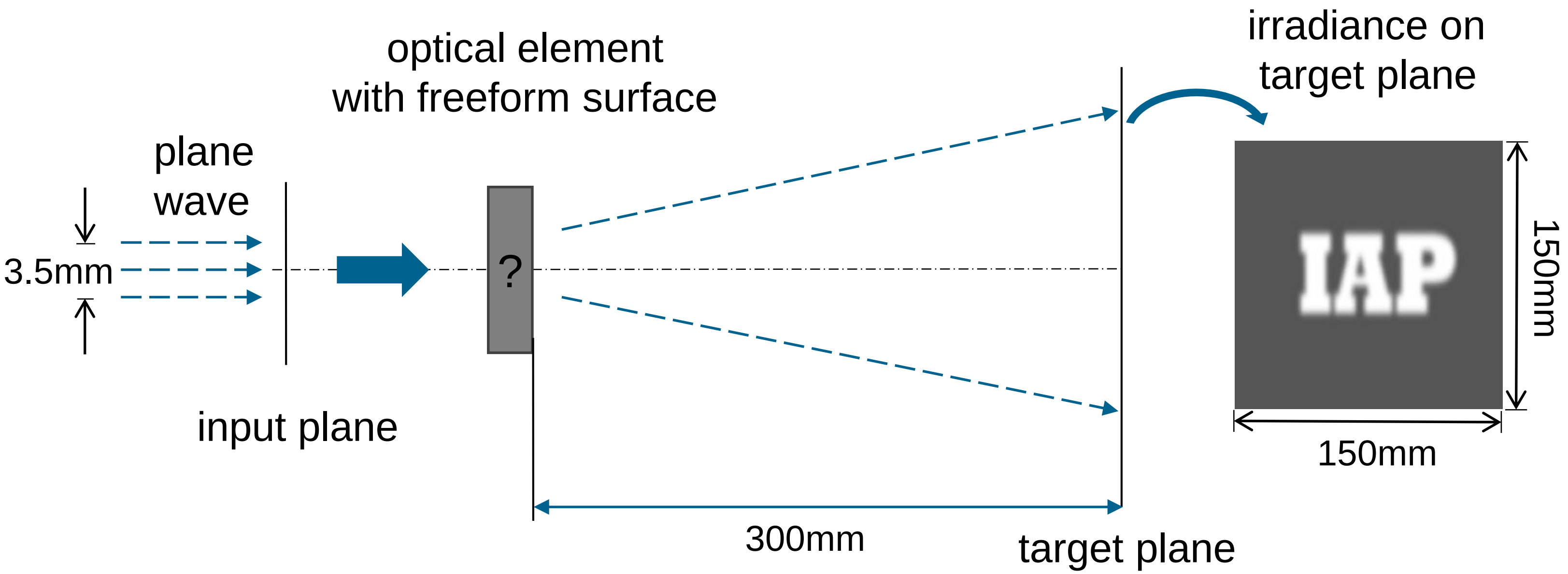


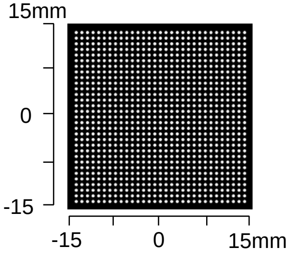
x-polarized

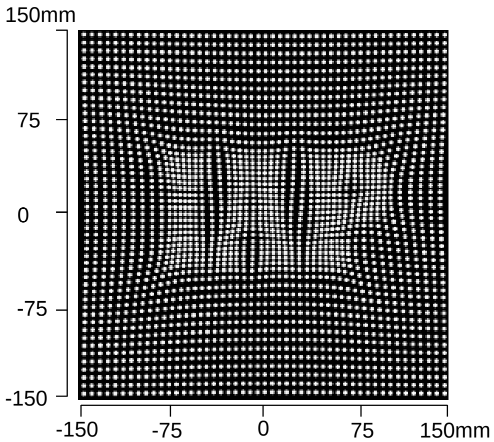


y-polarized

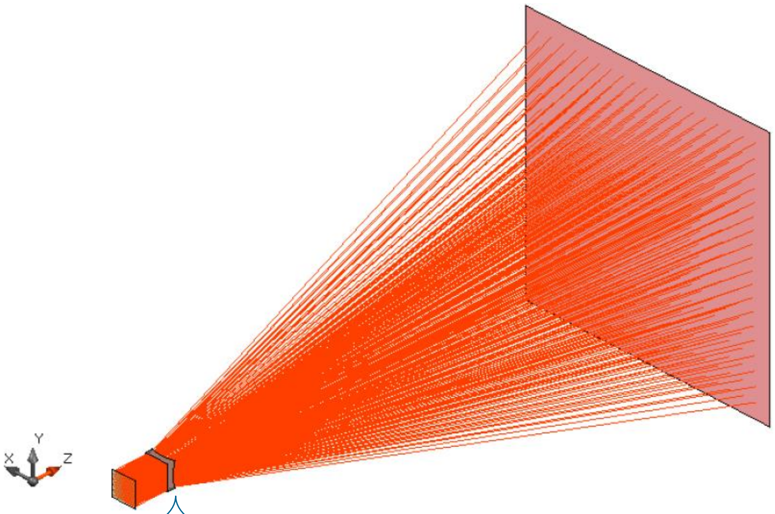
Example: Specific Irradiance

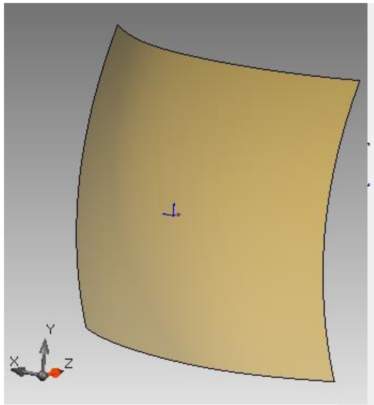


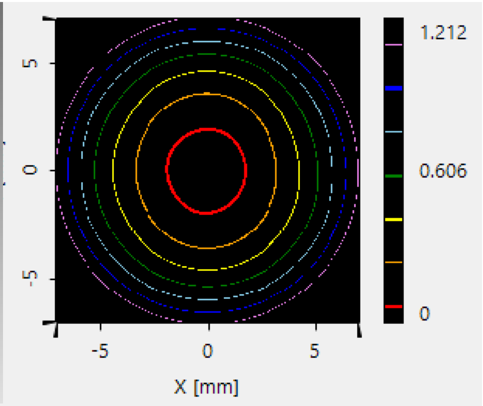




Designed Result and Simulation



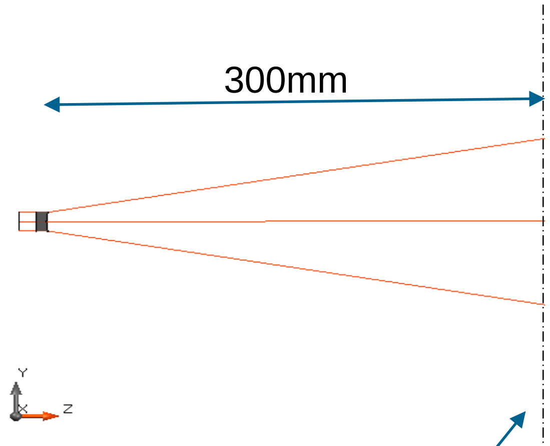


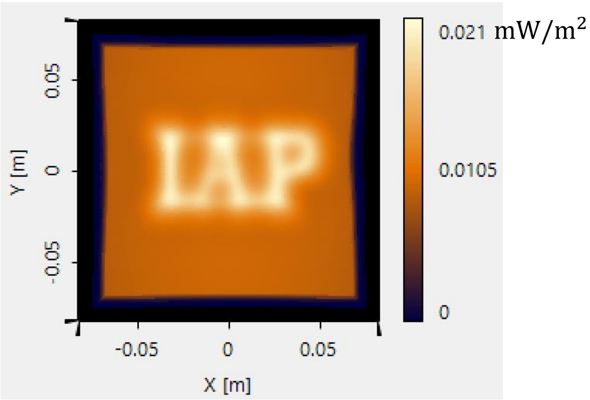


3D View

2D Contour line

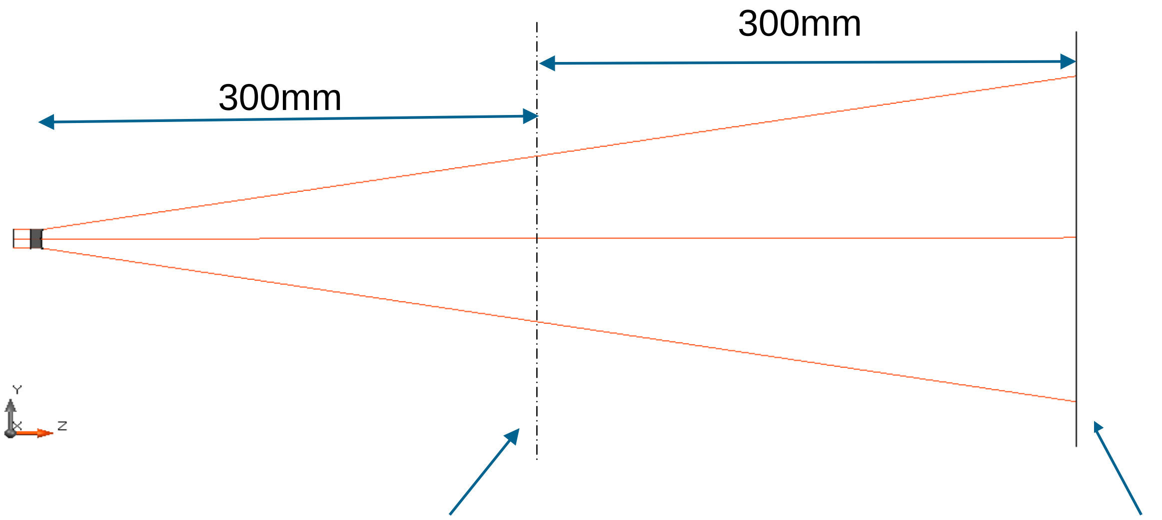
Designed Result and Simulation

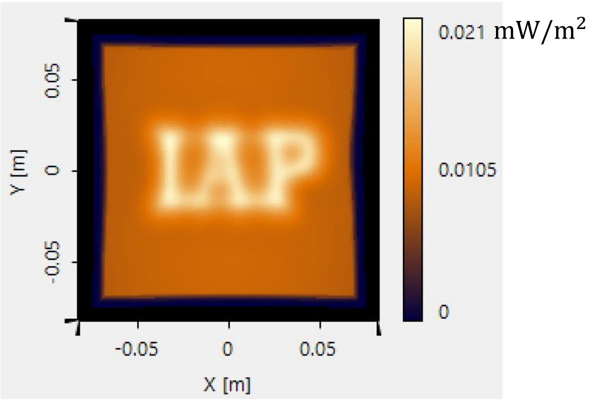




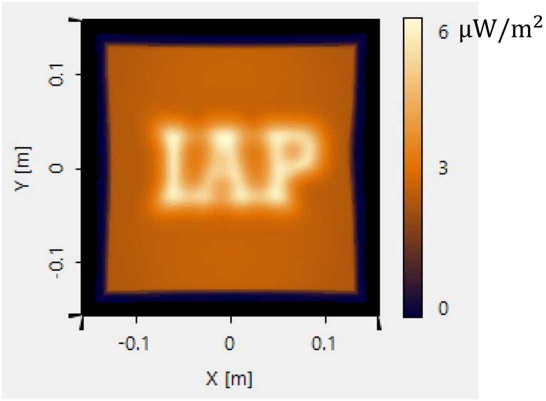
field tracing result:
irradiance on target plane

Designed Result and Simulation





field tracing result:
irradiance on target plane



field tracing result:
irradiance on further plane

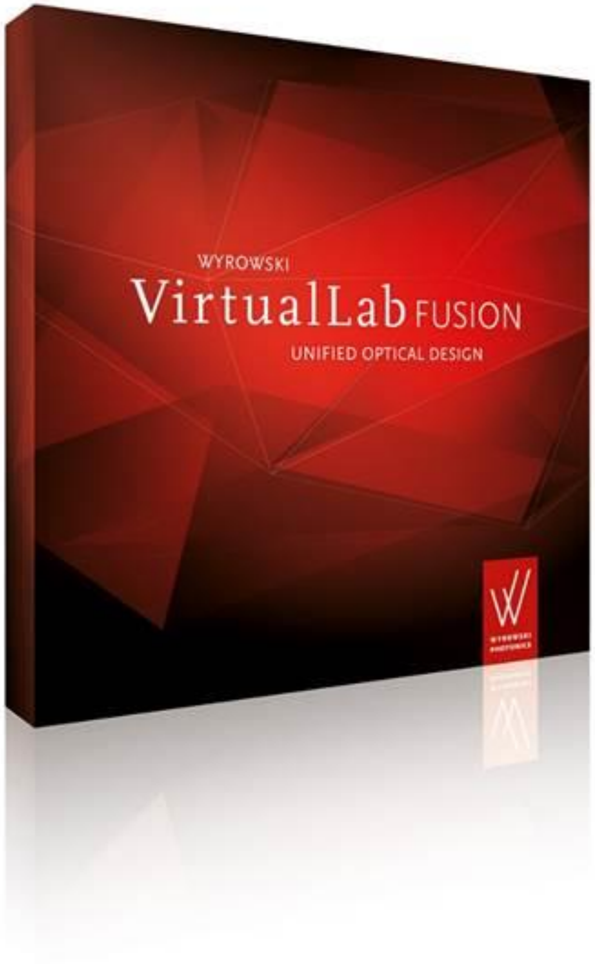
Conclusion

In summary:

- Modelling method is the basic for optical design;
- Base on the inverse approach, the directly design for the element structure is done in a fast way;
- The designed results can be used as the initial structure for further optimization.

Implementation

- All algorithms are implemented in the physical optics simulation and design software **VirtualLab Fusion**
- VirtualLab Fusion is developed, following the field tracing concept, by Wyrowski Photonics UG, Jena, Germany



Thank you