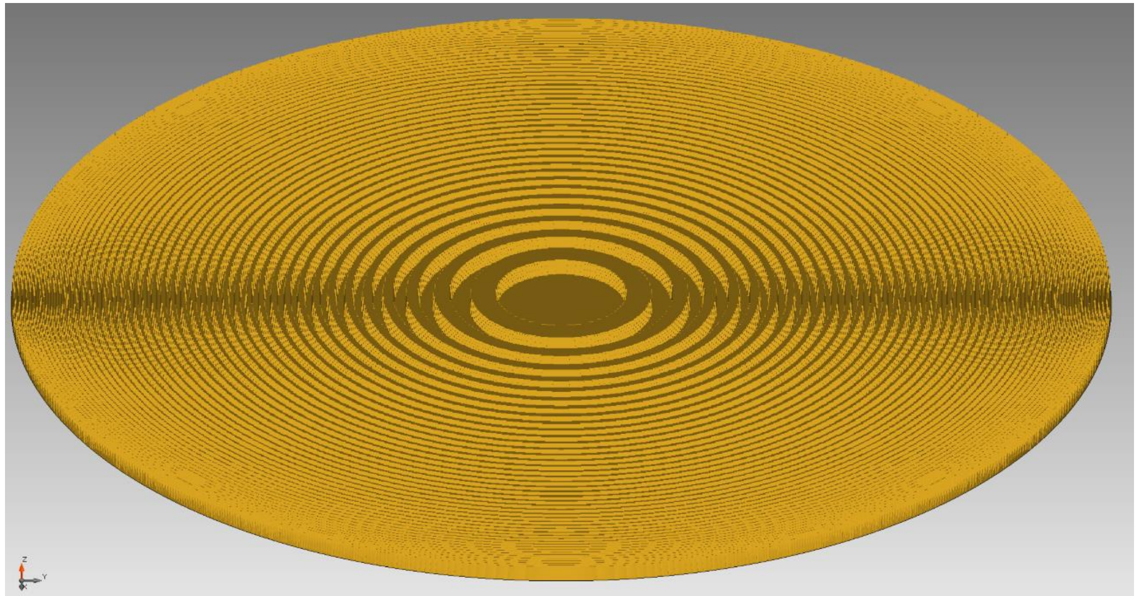
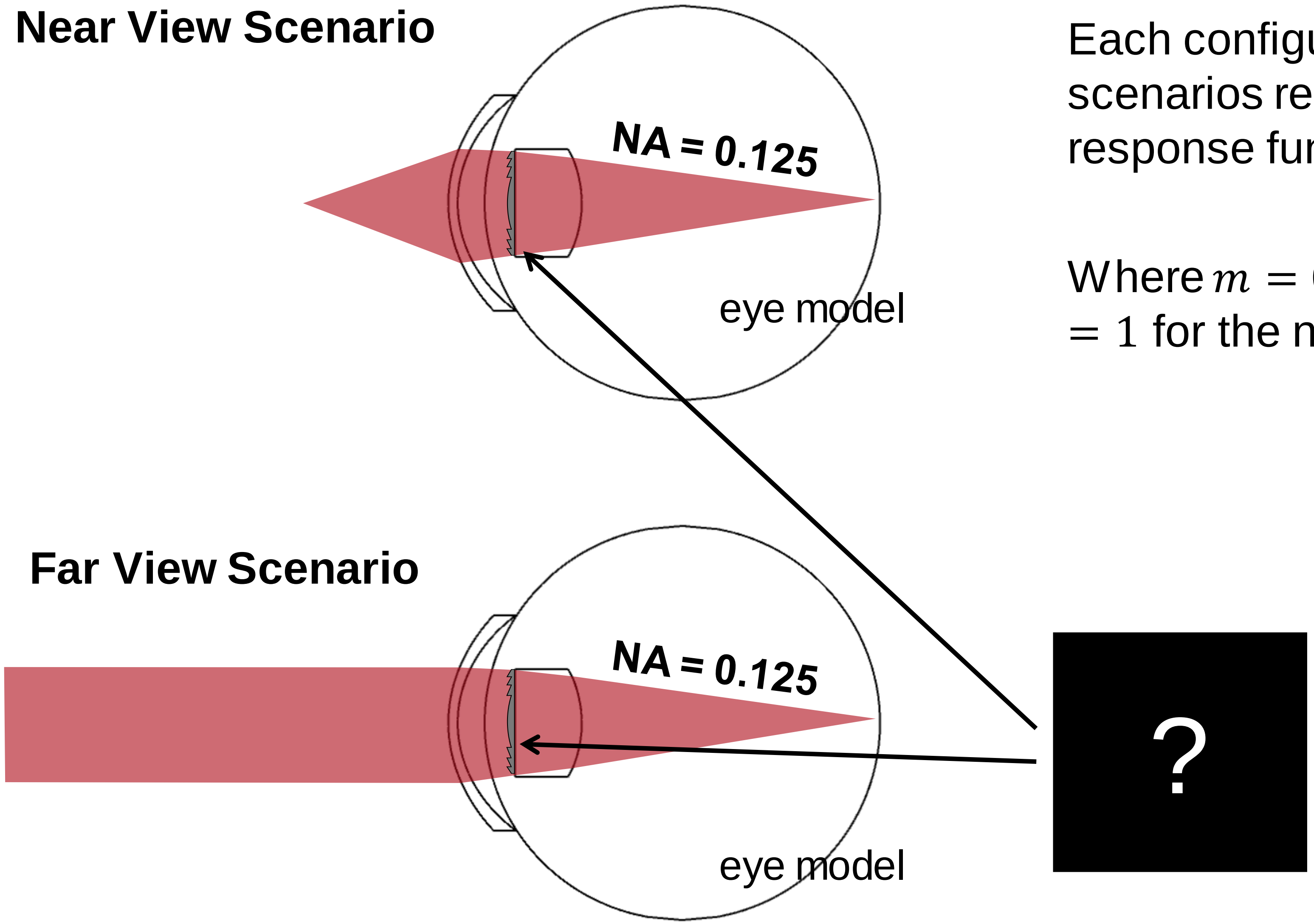
Design and Analysis of Intraocular Diffractive Lens

Abstract



Multifocal intraocular lens implantation is now widely applied for the treatment of cataracts. As one of its advantages, the diffractive intraocular lens provides good far and near vision for the patients. Such lenses are usually designed e.g., using Binary 2 surfaces in Zemax OpticStudio®. In this example, we demonstrate how to import the initial designs into VirtualLab Fusion and model the lens system with the actual binary structures taken into account. The performance of the diffractive lens is further investigated by varying the height of binary structures.

Design Task



Each configuration of the two intraocular lens scenarios requires a certain wavefront phase response function.

$$\Delta\psi(\rho) = m\Delta\psi(\rho)$$

Where $m = 0$ for the far view scenario and $m = 1$ for the near view scenario.

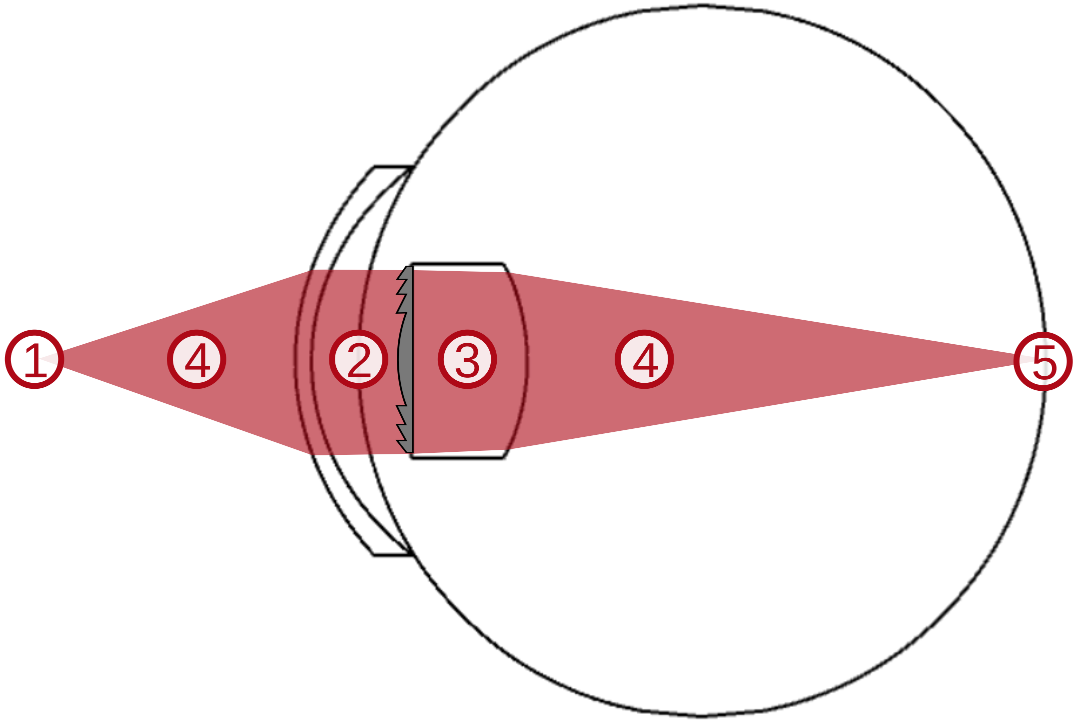
How to design and analyze the diffractive lens providing two different wavefront phase responses for the two configurations?

Simulation & Setup: Single Platform Interoperability

Single-Platform Interoperability of Modeling Techniques

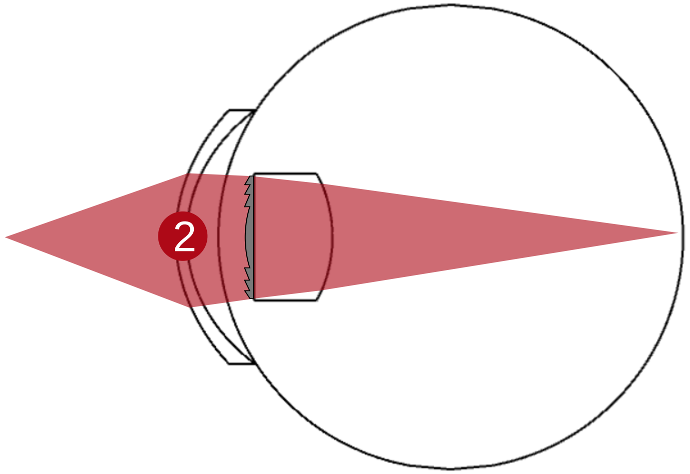
Light will encounter and interact with different components as it propagates through the system. A suitable and flexible model is required that provides a good compromise between accuracy and speed for each of these elements of the system:

① source
② cornea and pupil of human eye
③ intraocular diffractive lens
④ free-space propagation
⑤ detector



Connected Modeling Techniques: Cornea and Pupil of Eye

① source
② cornea and pupil of human eye
③ intraocular diffractive lens
④ free-space propagation
⑤ detector

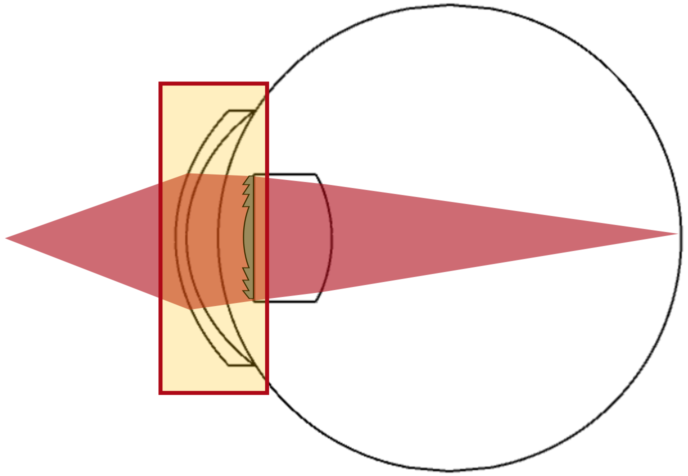


Available modeling techniques for lens systems :

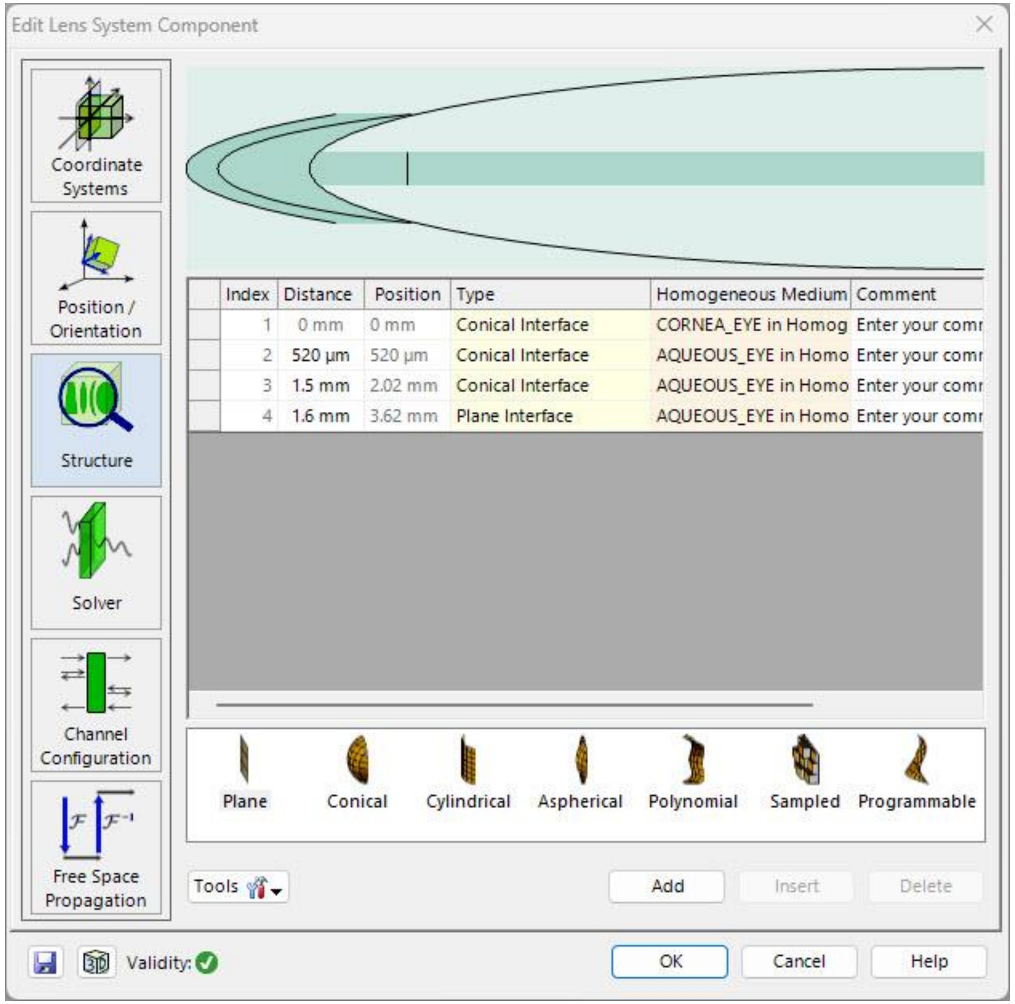
Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	-	low	very High	no Fresnel losses
Thin Element Approximation (TEA)	smallest structure > ~10λ	high	high	inaccurate for larger NA and thick elements; x-domain
	smallest structure < ~5λ	low	high	
Local Planar Interface Approximation (LPIA)	surface not in focal region of beam	high	high	local application of S matrix; x-domain
	otherwise	low	high	

Since considering the cornea and pupil of the eye (and the aqueous humor in between) as a thin element would result in a large inaccuracy, the **Local Linear Interface Approximation (LPIA)** is selected to ensure an appropriate accuracy.

Lens System Component

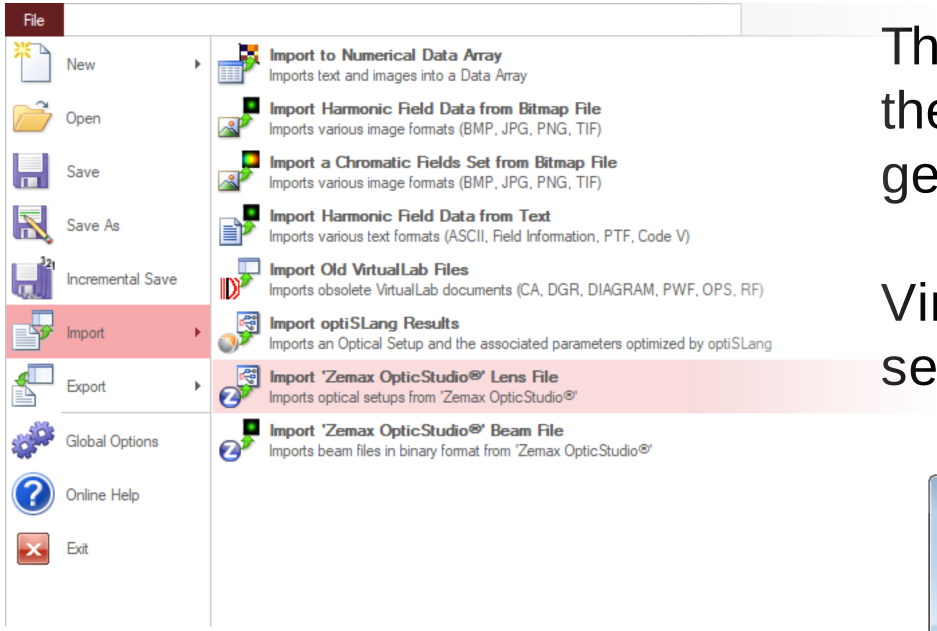


The *Lens System Component* allows the user to easily define a component consisting of an alternating sequence of smooth surfaces and homogeneous, isotropic media. For both interfaces and materials, you can choose ready-made entries from the built-in catalogs or customize your own for maximum flexibility.



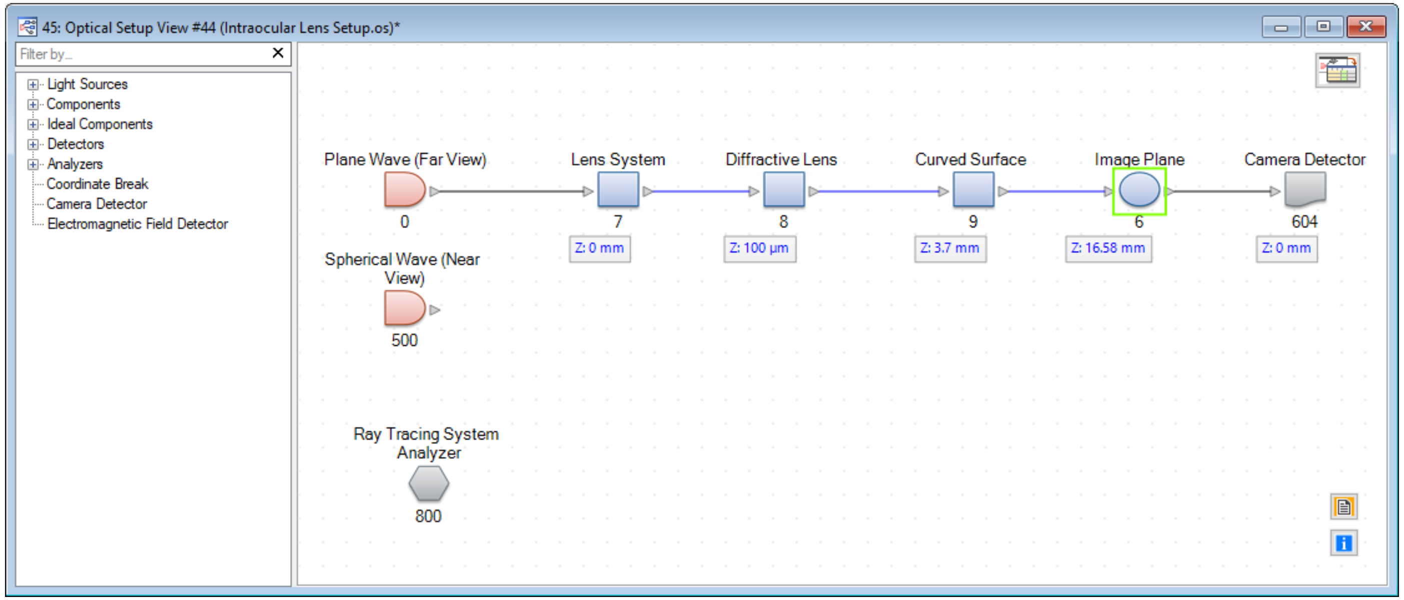
Index	Distance	Position	Type	Homogeneous Medium	Comment
1	0 mm	0 mm	Conical Interface	CORNEA_EYE in Homog	Enter your comr
2	520 µm	520 µm	Conical Interface	AQUEOUS_EYE in Homo	Enter your comr
3	1.5 mm	2.02 mm	Conical Interface	AQUEOUS_EYE in Homo	Enter your comr
4	1.6 mm	3.62 mm	Plane Interface	AQUEOUS_EYE in Homo	Enter your comr

Import of Optical System from OpticStudio



The configuration of the optical setup as well as the design of the wavefront phase response by a Binary 2 surface was generated in Zemax OpticStudio®.*

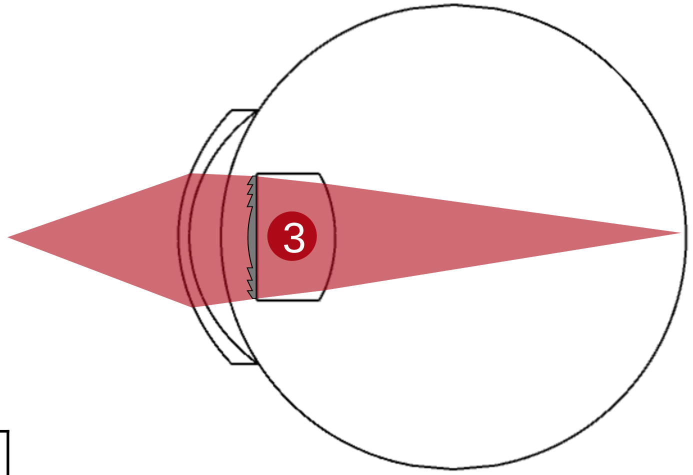
VirtualLab Fusion provides the capability to import the optical setups and merge them in a single optical setup configuration.



** Note: the design of the wavefront phase response can be achieved in VirtualLab Fusion as well.*

Connected Modeling Techniques: Intraocular Diffractive Lens

① source
② cornea and pupil of human eye
❸ intraocular diffractive lens
④ free-space propagation
⑤ detector

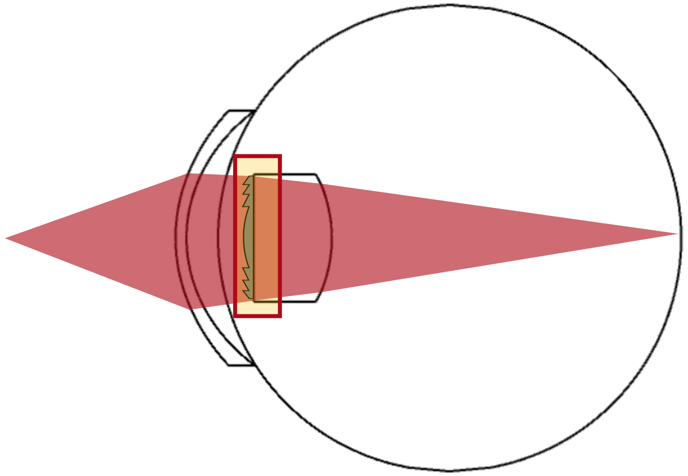


Available modeling techniques for micro structured gratings:

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Modal Method (FMM)	period < ~ (5λ × 5λ)	very high	high	rigorous solution; fast for structures and periods similar to the wavelength; more demanding for larger periods; k-domain
	period > ~ (15λ × 15λ)	very high	slow	
Thin Grating Approximation (TGA)	smallest structure > ~10λ	high	high	accurate for shallow structures (thickness ~λ); non-paraxial incidence increases inaccuracy; x-domain
	smallest structure < ~5λ	low	high	
Local Linear Grating Approximation (LLGA)	-	high	high	local application of either FMM or TGA according to local period

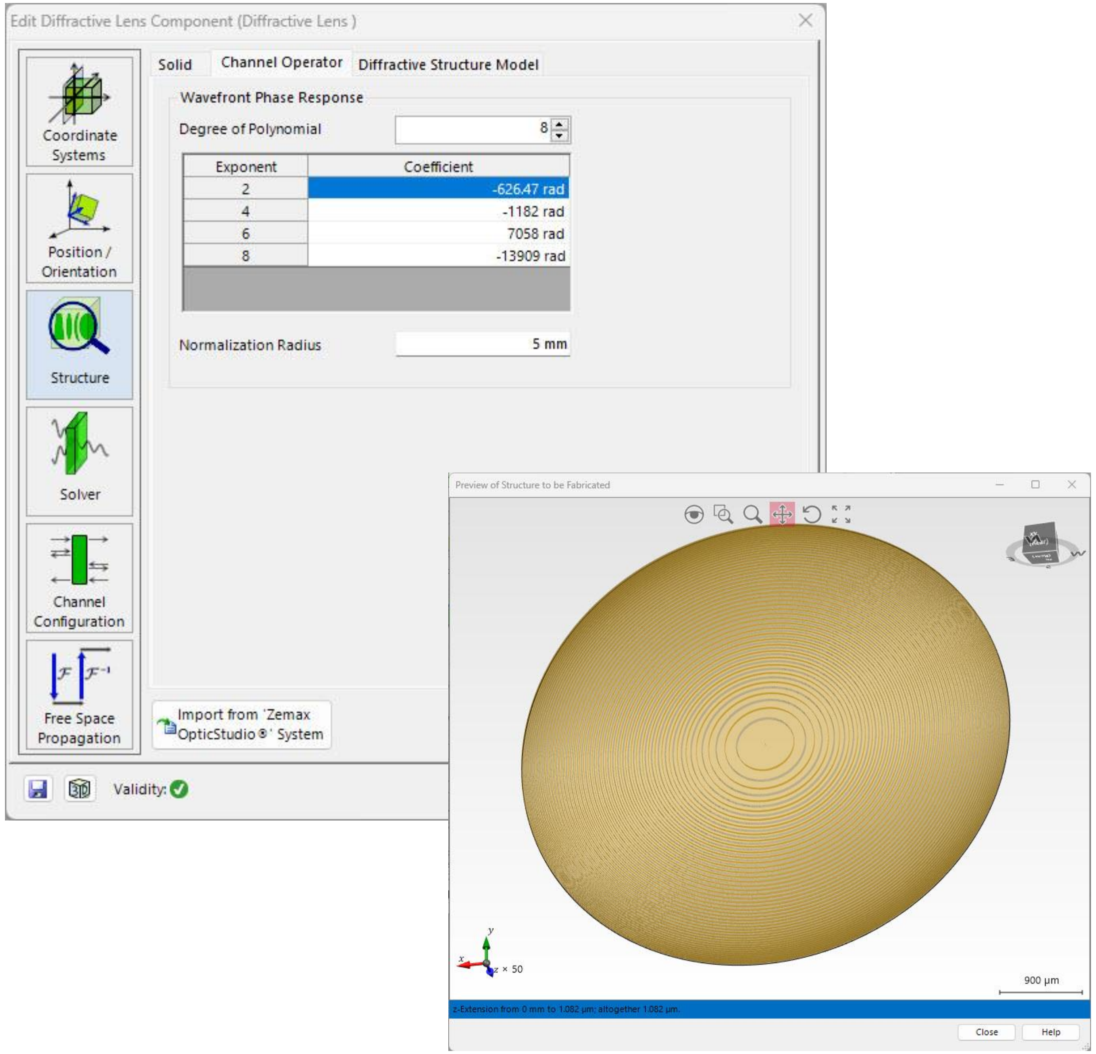
By design, the local period of a diffractive lens is not constant. The **Local Linear Grating Approximation (LLGA)** algorithm automatically determines the local period at each point and applies TEA or FMM accordingly, providing an optimal combination of speed and accuracy.

Diffractive Lens Component



The intraocular diffractive lens is modeled by the *Diffractive Lens* component, which allows for the definition of a specific wavefront phase response, which then also can be translated in a real structure with a height profile.

The propagation through the real diffractive lens is then modeled by the *Local Linear Grating Approximation (LLGA)*. For further information, please see Diffractive Lens Component.



Edit Diffractive Lens Component (Diffractive Lens)

Wavefront Phase Response

Degree of Polynomial: 8

Exponent	Coefficient
2	-626.47 rad
4	-1182 rad
6	7058 rad
8	-13909 rad

Normalization Radius: 5 mm

Validity: ✓

Preview of Structure to be Fabricated

z-Extension from 0 mm to 1.082 µm; altogether 1.082 µm.

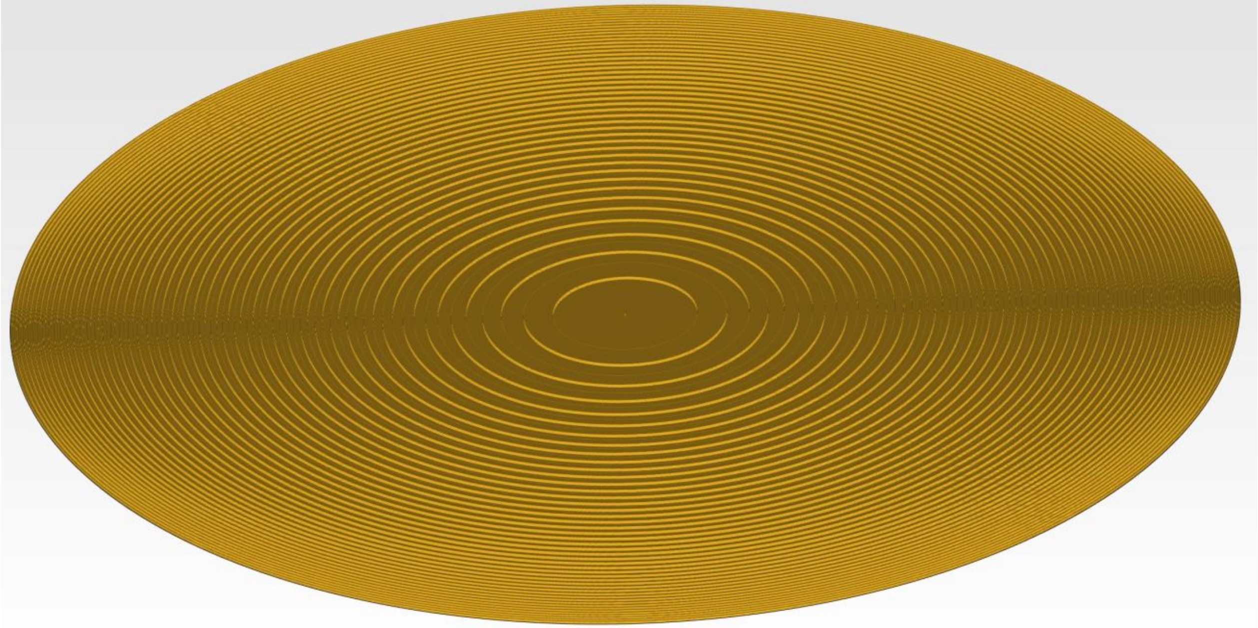
Structure Design: Diffractive Lens Profile Height

The structure profile of the diffractive lens is calculated by Thin Element Approximation (TEA) according to the defined wavefront phase response:

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

with a scaling factor β to modulate the height and control the efficiency of the diffraction orders.

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

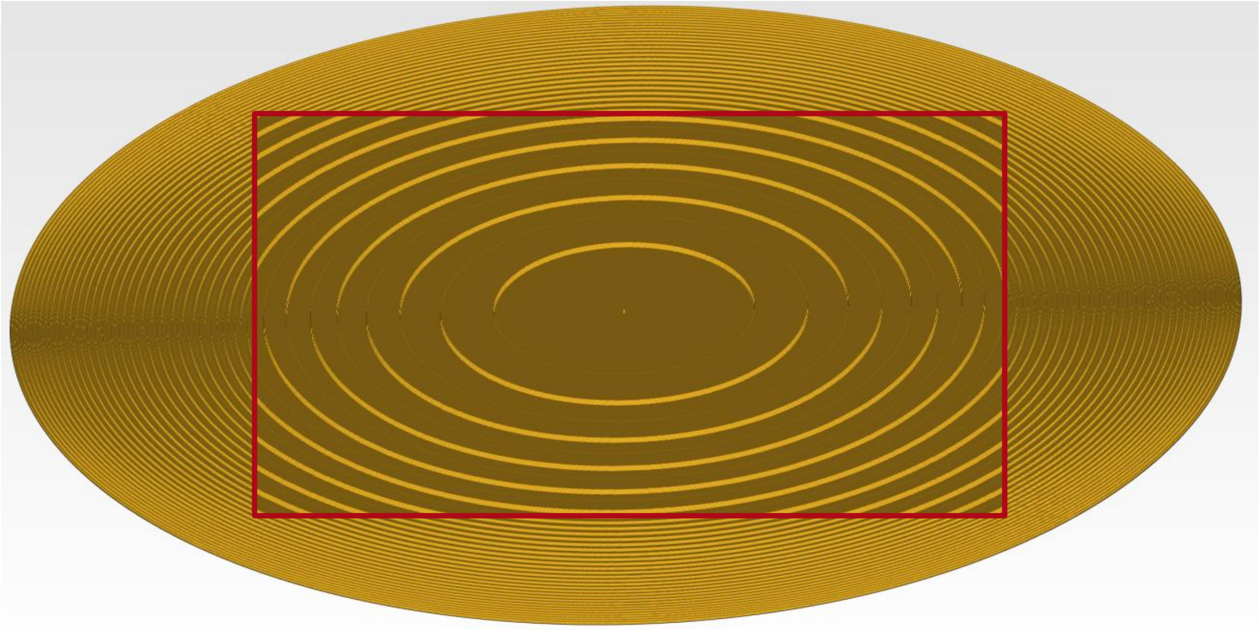


Structure Design: Diffractive Lens Profile Height

A quantization of the structure with 2 height levels is chosen because the binary diffractive lens

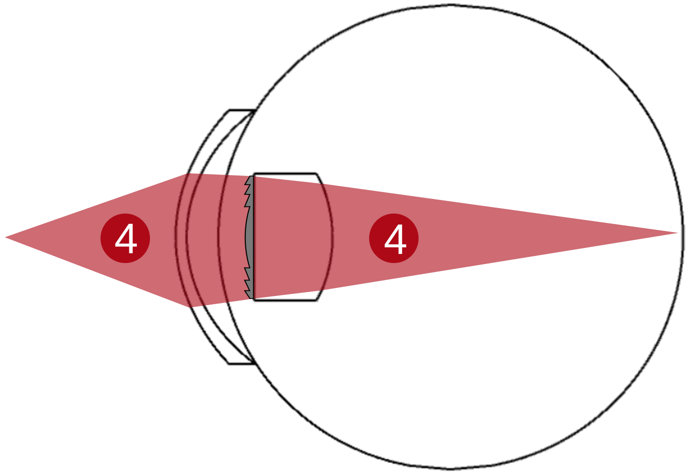
- is beneficial for manufacturing (costs, easier to fabricate);
- gives a better control of the efficiencies, especially for the 0th and 1st order using the height variation approach.

⇨



Connected Modeling Techniques: Free-Space Propagation

① source
② cornea and pupil of human eye
③ intraocular diffractive lens
④ free-space propagation
⑤ detector



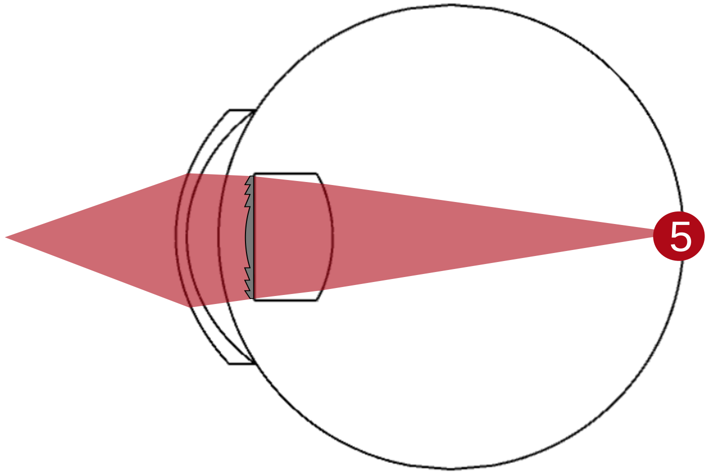
Available modeling techniques for free-space propagation:

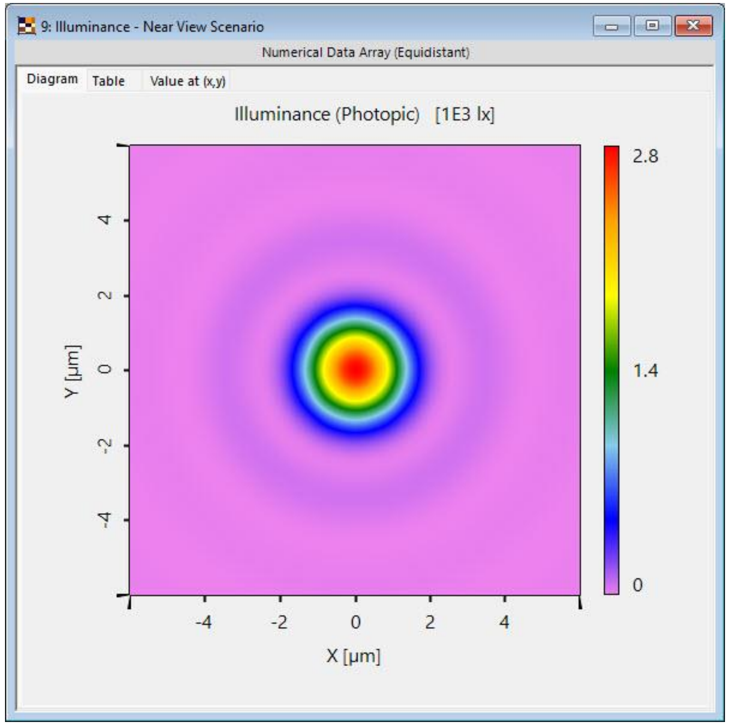
Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	none	high	low	rigorous solution
Fourier Domain Techniques	None	high	high	rigorous mathematical reformulation of RS integral
Fresnel Integral	**paraxial**	high	high	assumes paraxial light; moderate speed for very short distances
	non-paraxial	low	high	
Geometric Propagation	**low diffraction**	high	very high	neglects diffraction effects
	otherwise	low	very high	

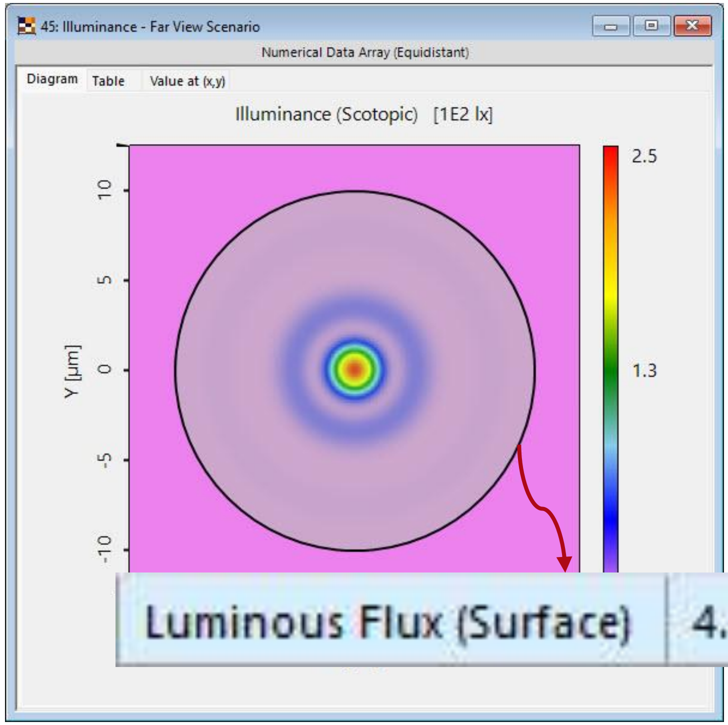
Diffractive effects are a major part of the simulation when propagating into the focus. Hence, we choose **Fourier Domain Techniques** as simulation technique.

Detector

- ① source
- ② eye pupil
- ③ intraocular diffractive lens
- ④ free-space propagation
- ❺ detector







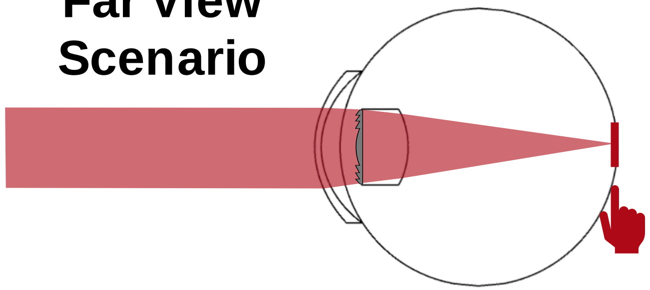
Luminous Flux (Surface) | 4.8016E-09 lm

VirtualLab Fusions flexible Universal Detector combined with convenient tools to define regions allows for the calculation of many different physical values, such as illuminance or luminous flux.

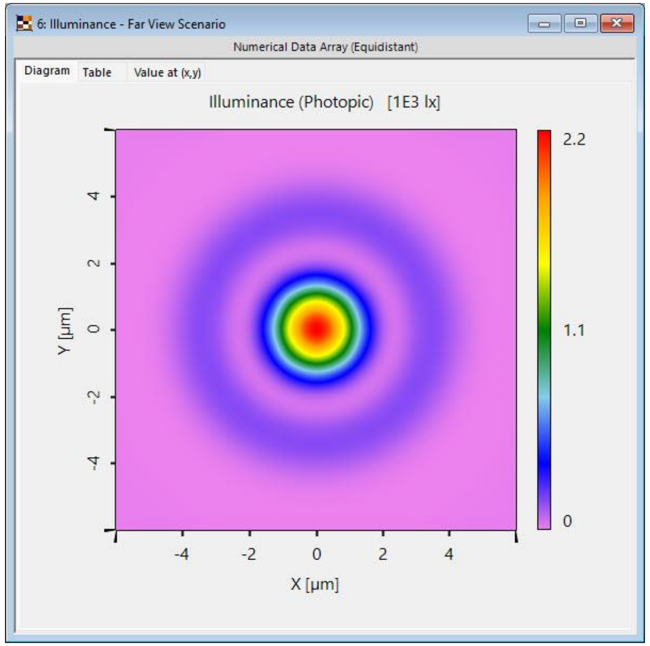
Simulation Results

Far View: Conformity of OpticStudio Import

Far View Scenario

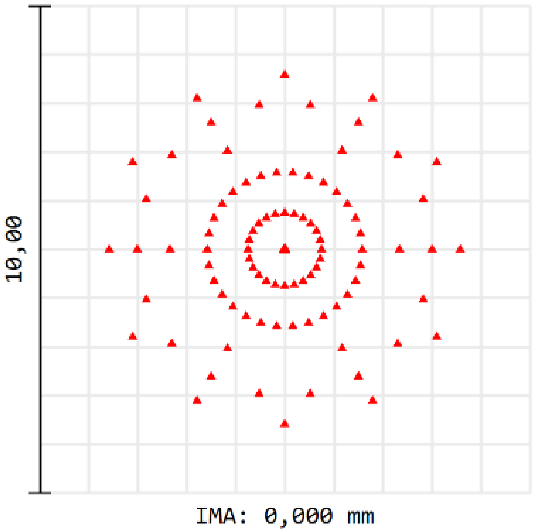


Illuminance (photopic) calculation by **VirtualLab Fusion** (idealized diffractive lens)

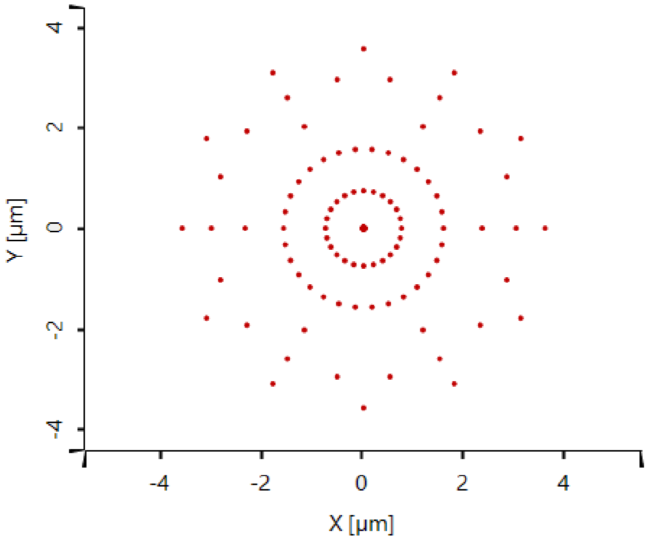


spot diagram of central wavelength (555 nm) calculated by:

OpticStudio

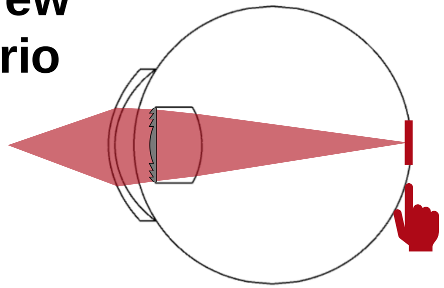


VirtualLab Fusion

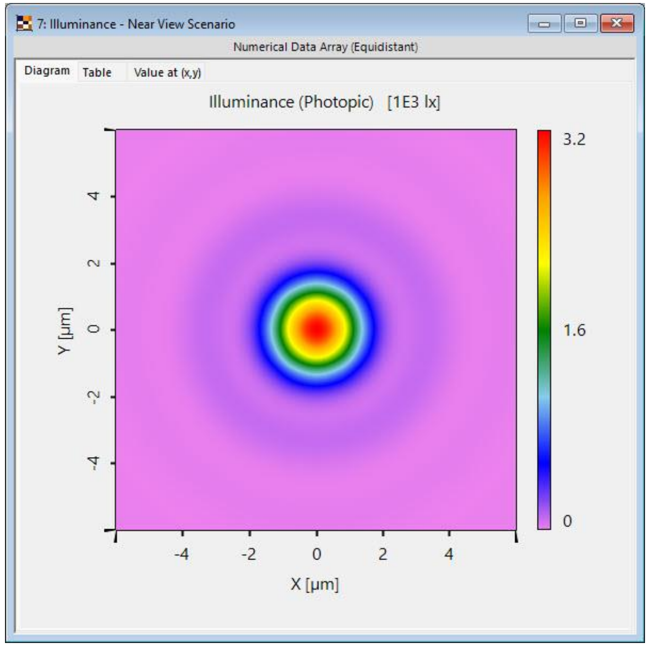


Near View: Conformity of OpticStudio Import

Near View Scenario



Illuminance (photopic) calculation by **VirtualLab Fusion** (ideal diffractive lens)

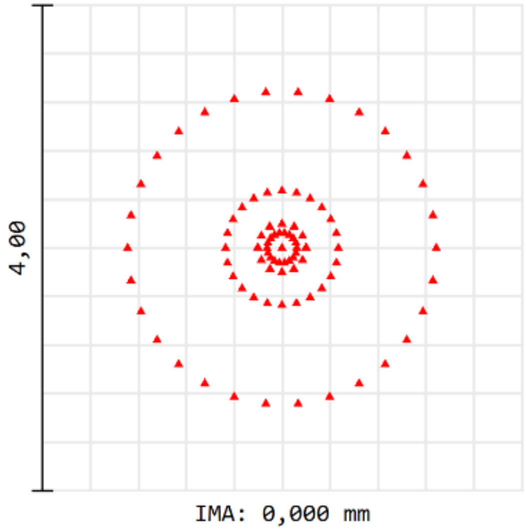

7: Illuminance - Near View Scenario

Numerical Data Array (Equidistant)

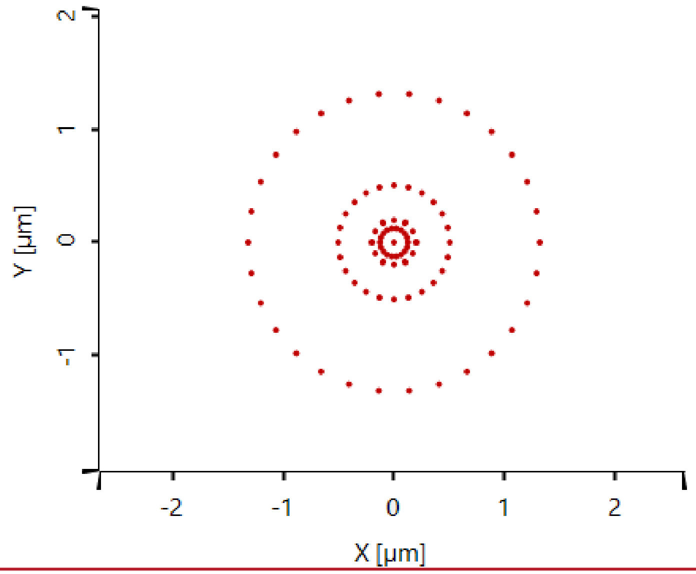
Illuminance (Photopic) [1E3 lx]

spot diagram of central wavelength (555 nm) calculated by:

OpticStudio

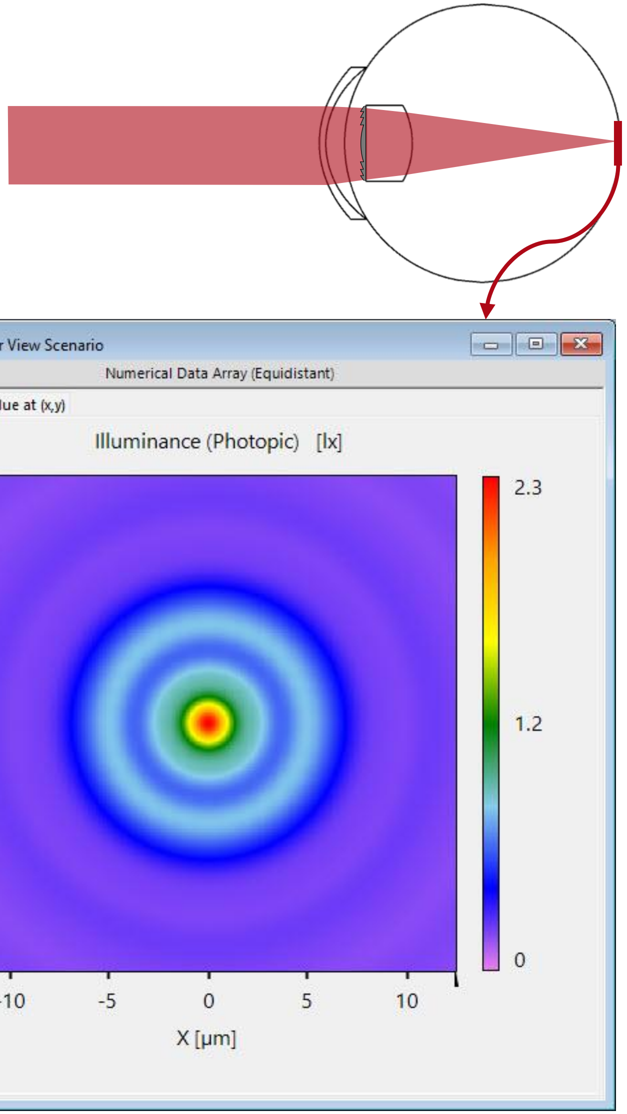


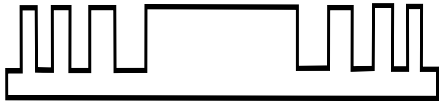
VirtualLab Fusion



Structure Design: Height Scaling Factor of 1.00

Far View Scenario



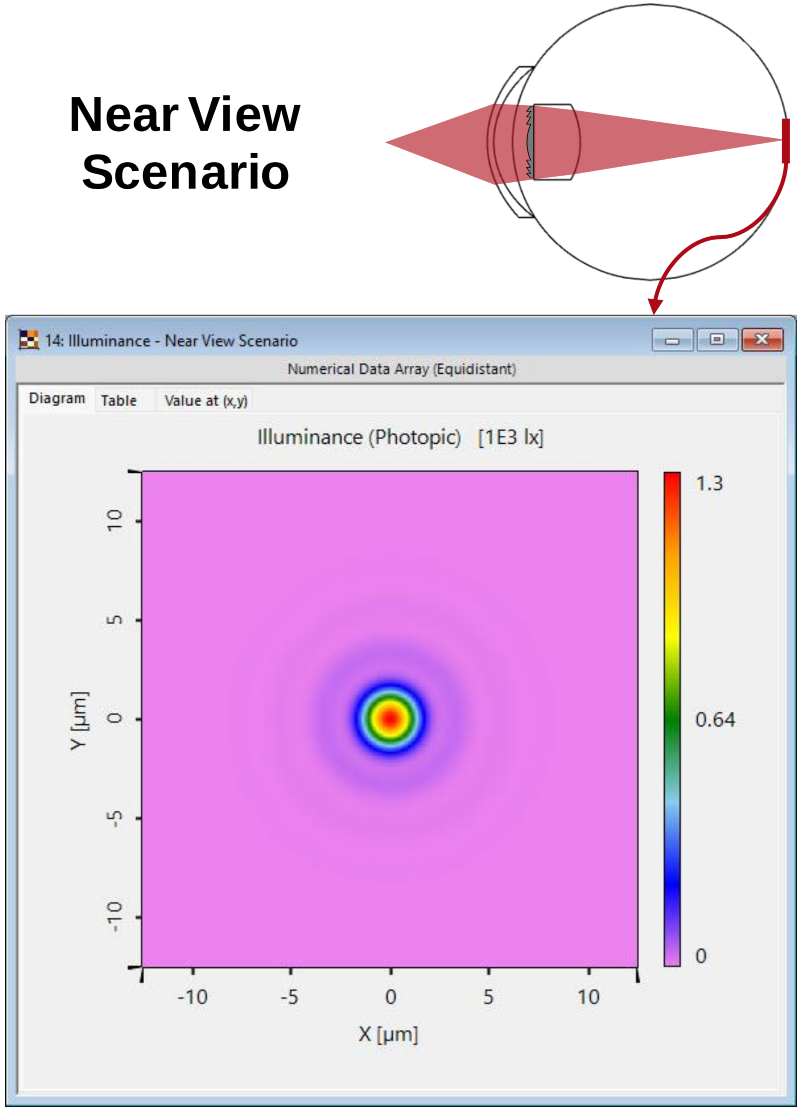


scaling of modulation height by

$\boldsymbol{\beta = 1.00}$

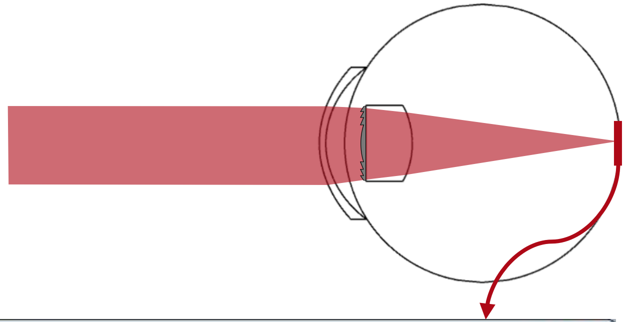
A real structure with height scaling 1.0 shows that the near view scenario produces a focal spot, while the far view one does not.

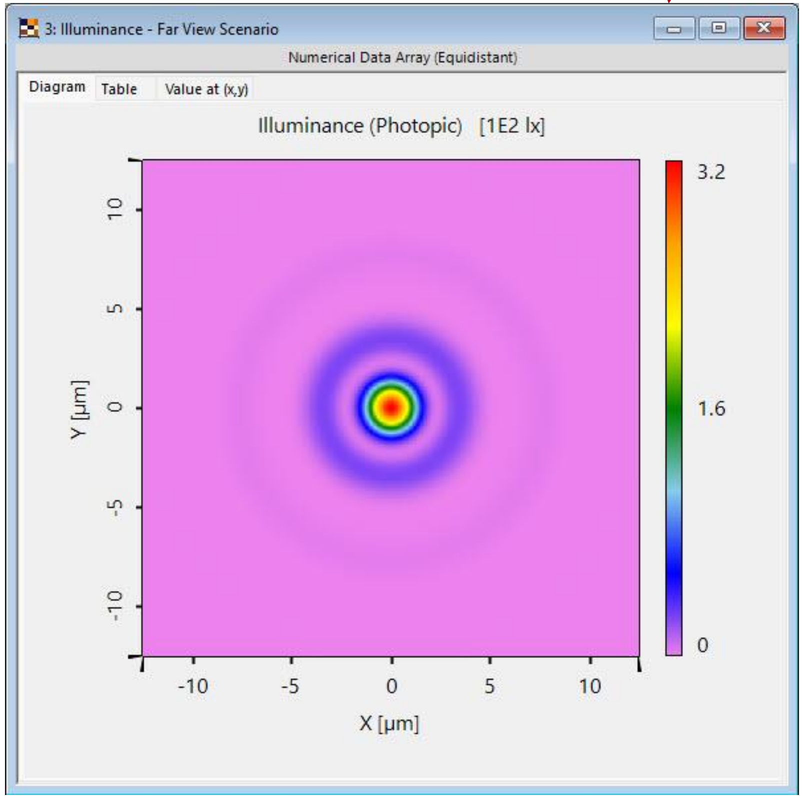
Near View Scenario

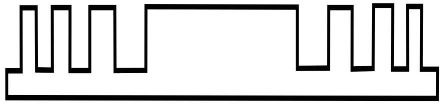


Structure Design: Height Scaling Factor of 0.75

Far View Scenario





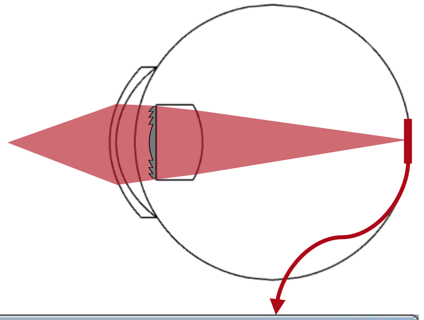


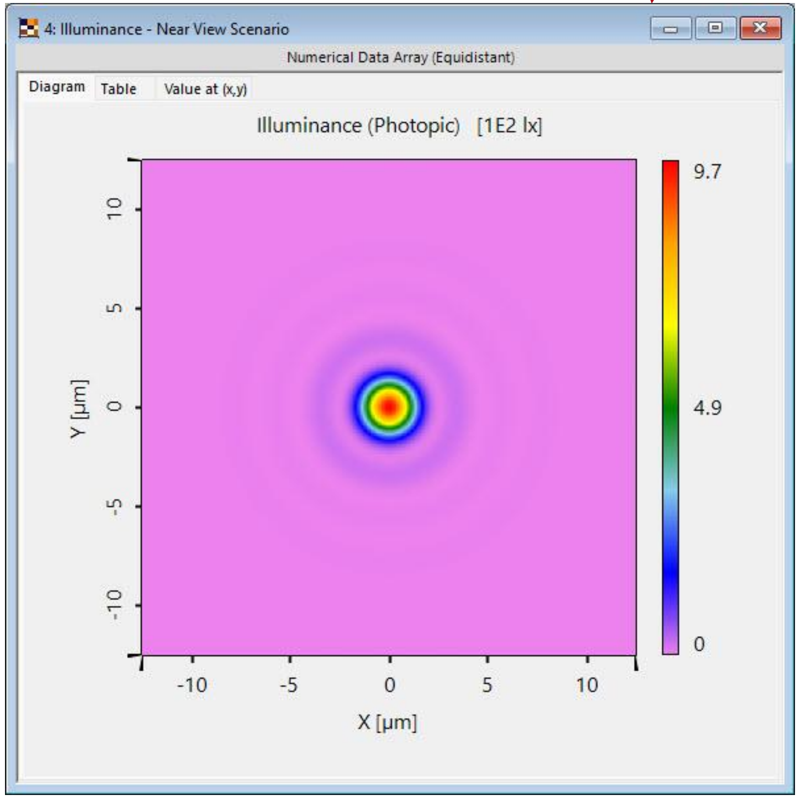
scaling of modulation height by

$\boldsymbol{\beta = 0.75}$

Decreasing the height scaling factor helps drastically in the far view scenario while only minorly affecting the near view one.

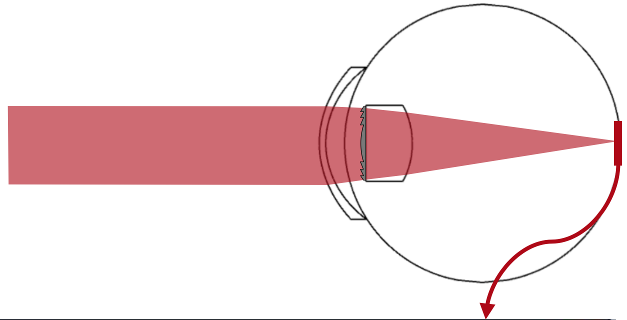
Near View Scenario

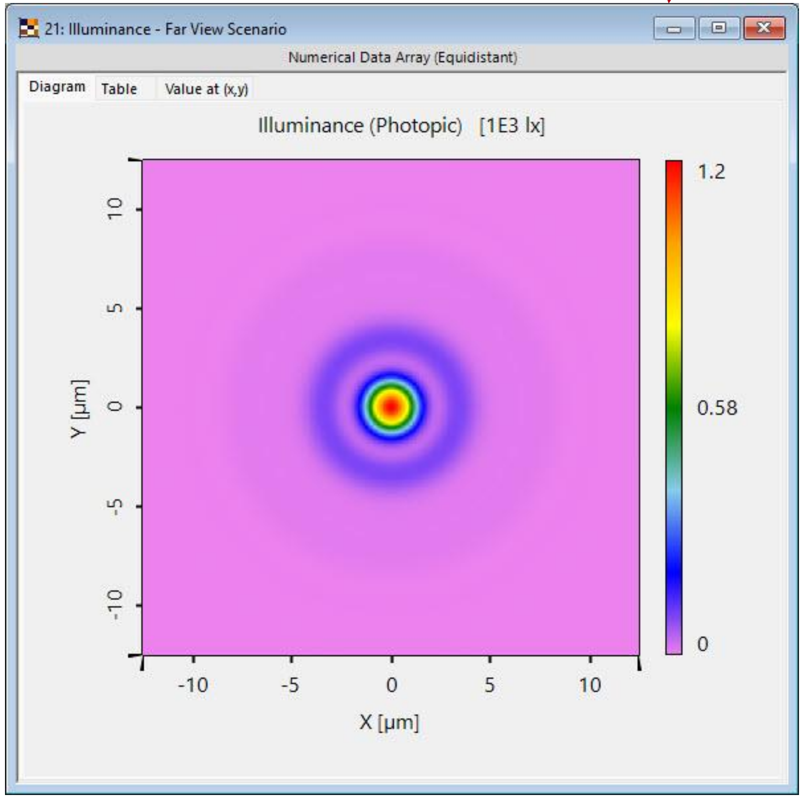


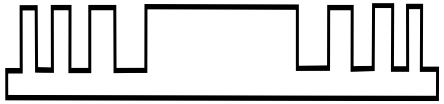


Structure Design: Height Scaling Factor of 0.50

Far View Scenario





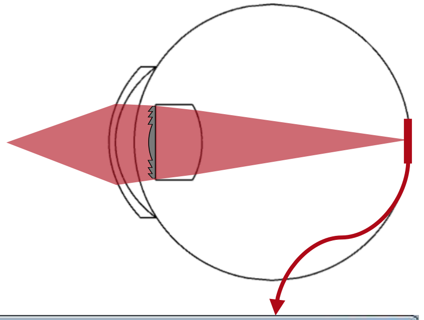


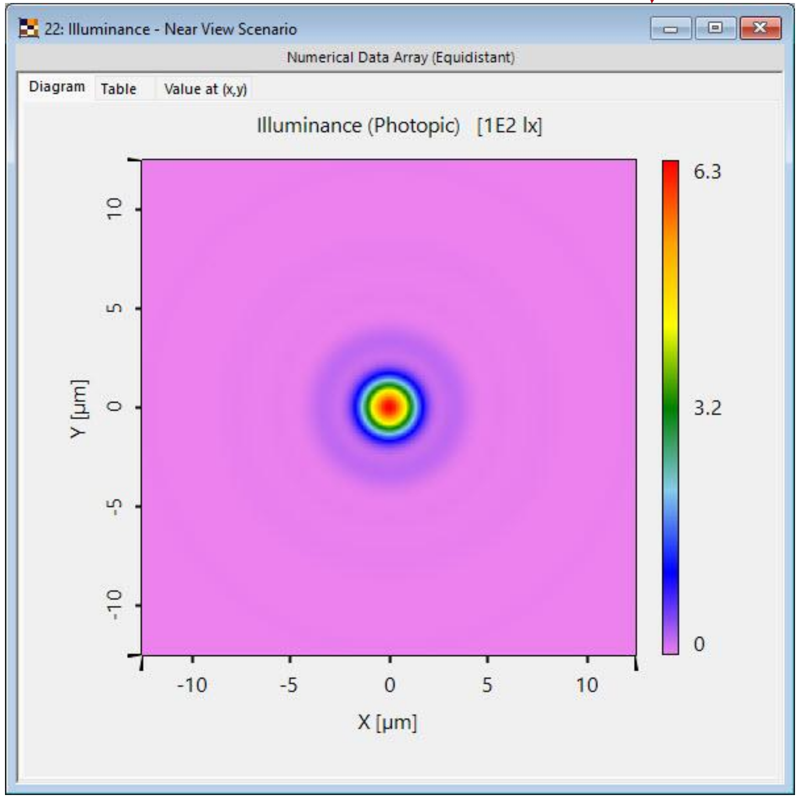
scaling of modulation height by

$\boldsymbol{\beta = 0.5}$

At a height scaling factor of 0.5, peak irradiance of the far view scenario exceeds that of the near view one. As a conclusion, there must be a height scaling factor to optimize both scenarios.

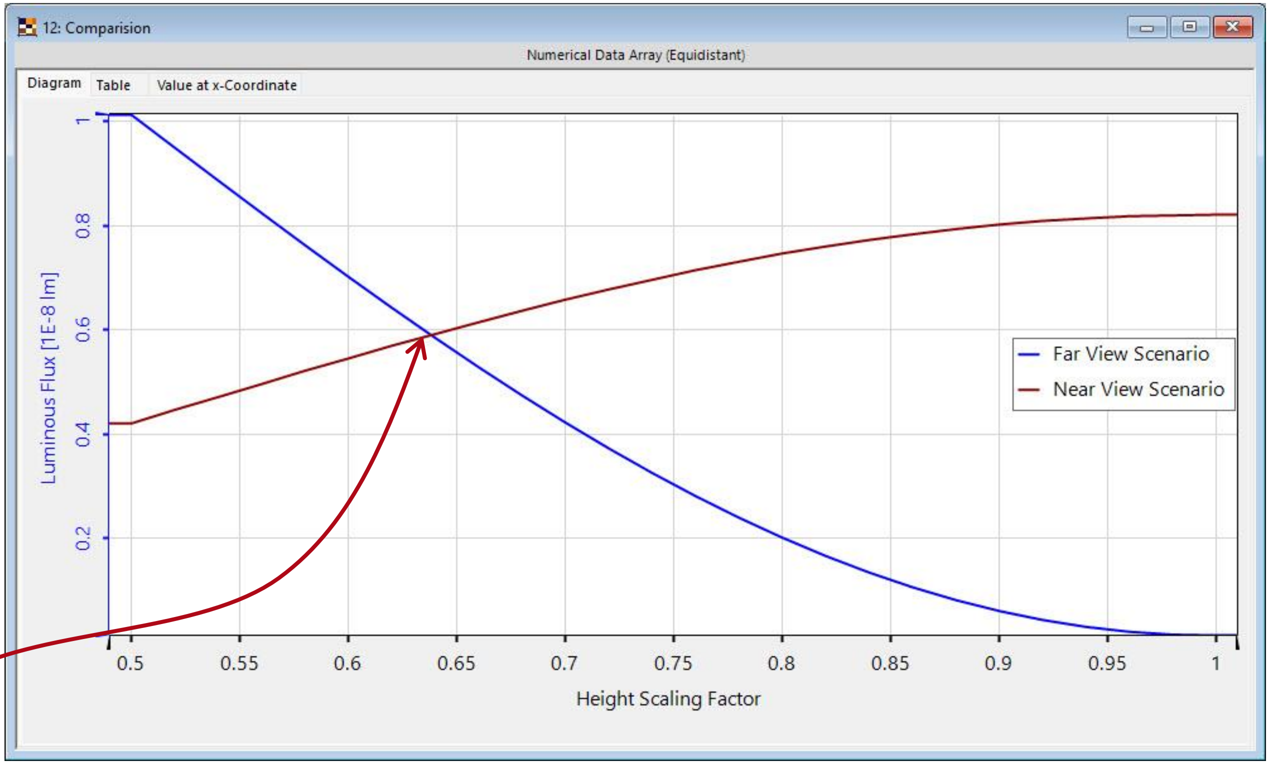
Near View Scenario





Structure Design: Determine the Optimum Scaling Factor

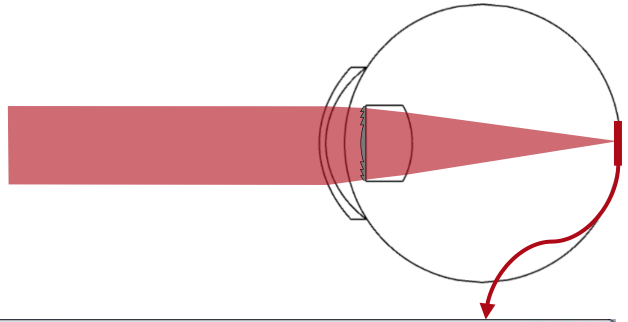
- The human eye is a quite complex organ with many different cells contributing to its ability of sight, which also differ in shape and size.
- Therefore, for sake of simplicity, we define a region of 10 µm around the center in which the luminous flux is optimized.



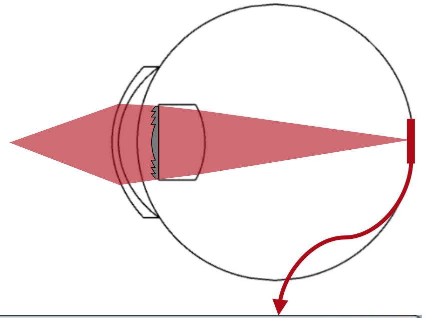
Optimum of the scaling factor for equivalent peak luminous flux for both foci (near and far view).

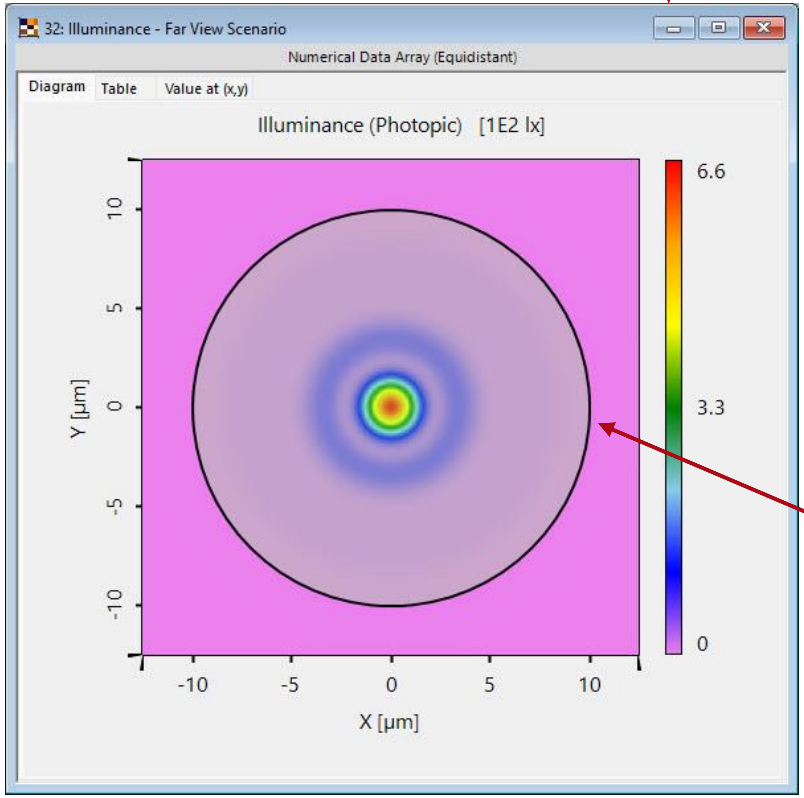
Structure Design: Optimized Height Factor of 0.60

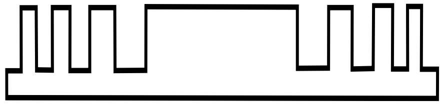
Far View Scenario



Near View Scenario

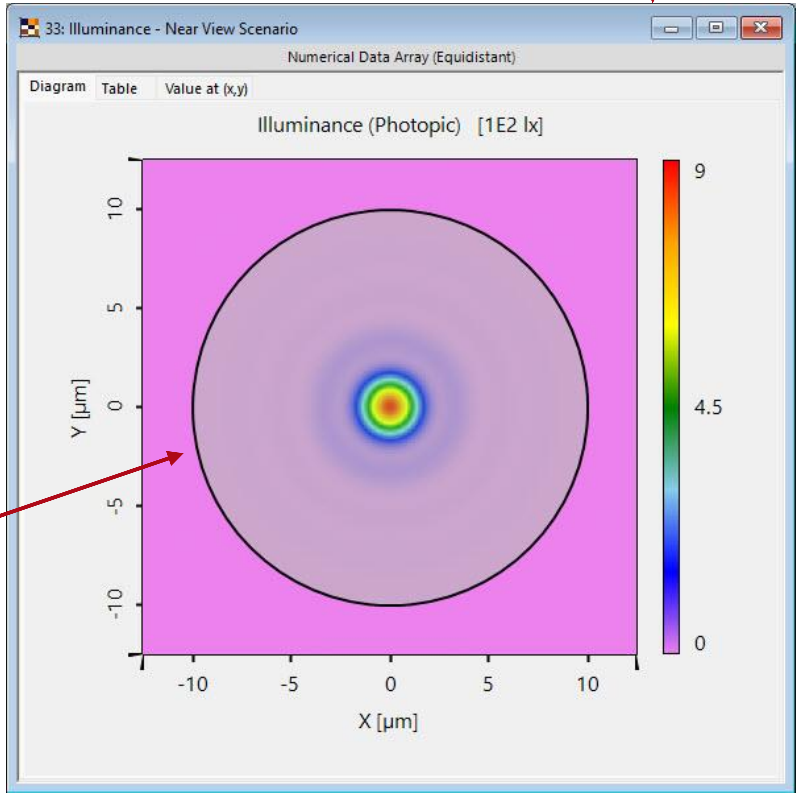






scaling of modulation height by
$\boldsymbol{\beta = 0.6}$

Same luminous flux in these two regions! (6.05 E-9 lm)

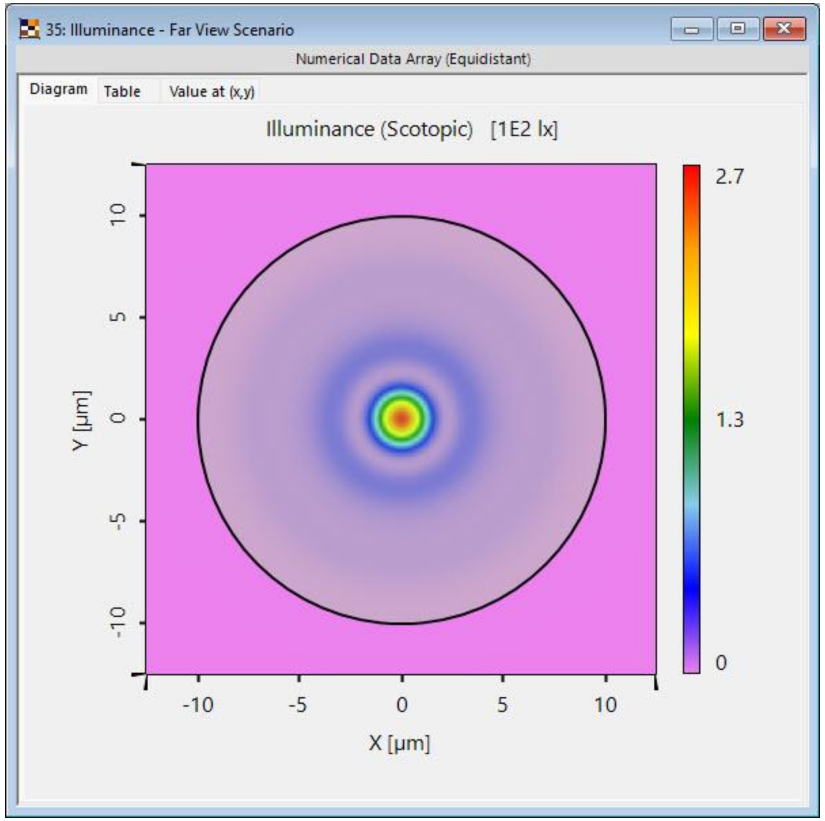


Scotopic Perception

Photometric physical values (such as the illuminance or luminous flux) can be defined in two different ways, namely photopic and scotopic. While we have used the photopic definition so far – since it describes the vision of the eye under normal daylight conditions – it might also be of interest to see how the lens performs under scotopic – meaning nighttime – conditions.

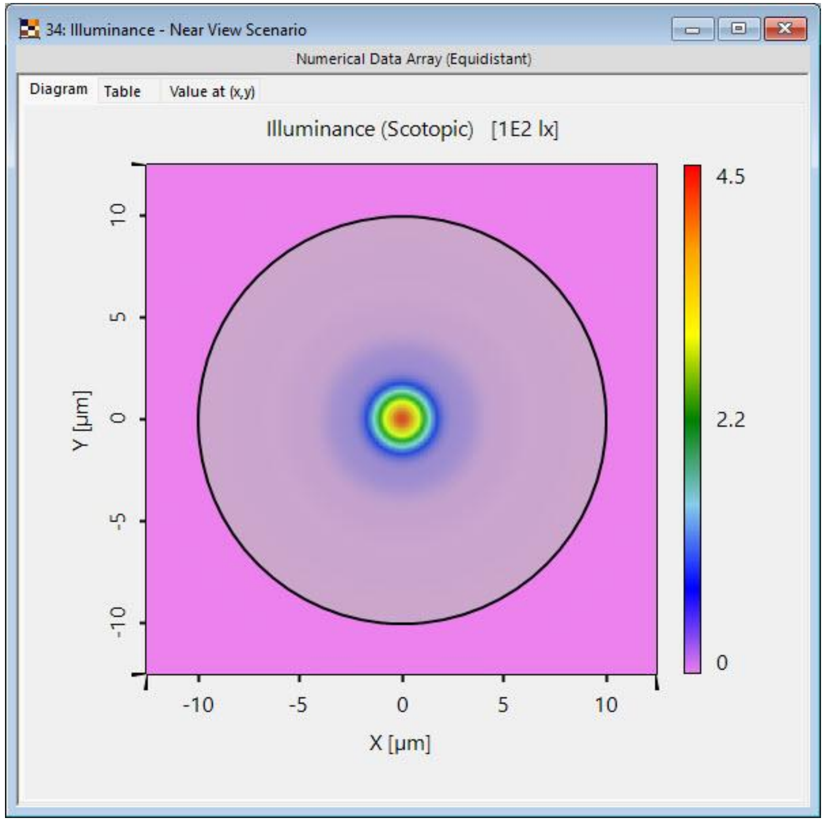
In this example, the design provides similar, but slightly different results under scotopic vision.

far view scenario



($3.33 \cdot 10^{-9}$ lumen in region)

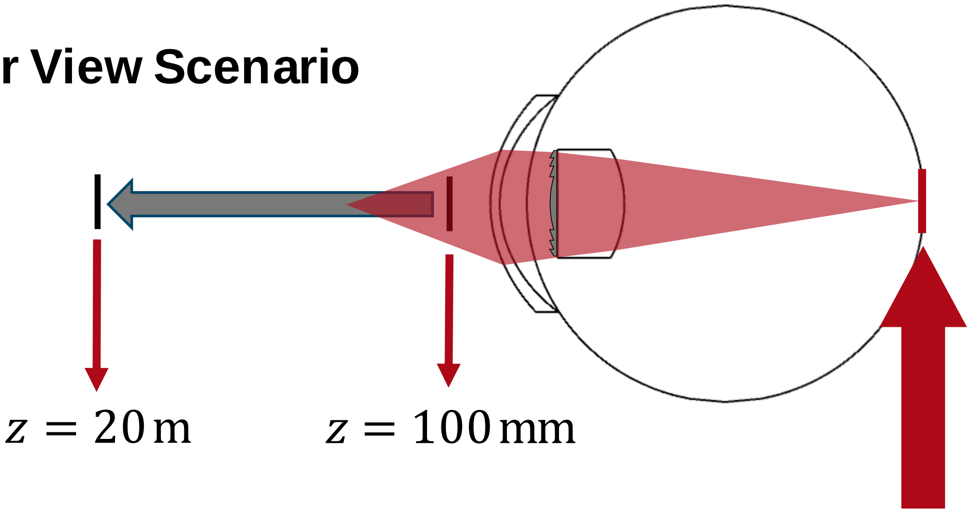
near view scenario



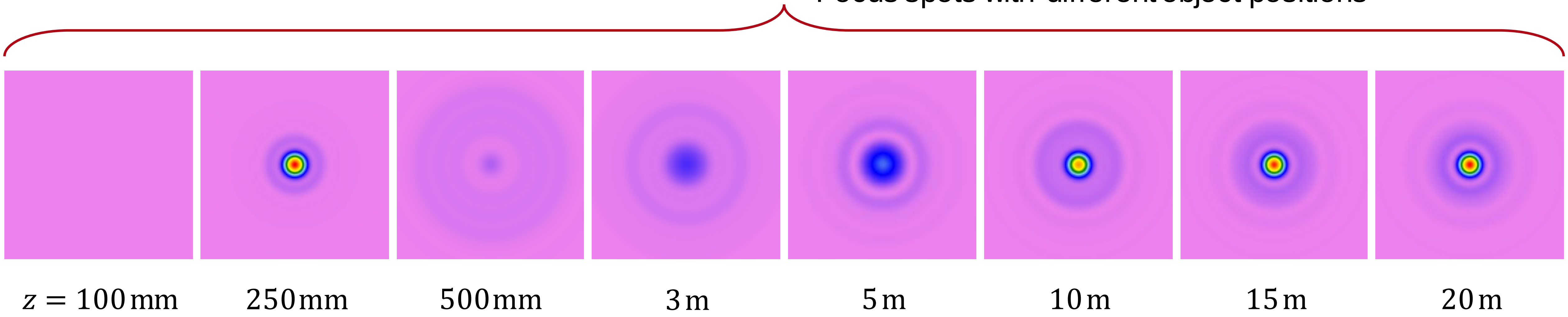
($2.84 \cdot 10^{-9}$ lumen in region)

Illustration of Focus Development from Near to Far Region

Near to Far View Scenario



Focus spots with different object positions*



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* *shown quantity: illuminace with equal scaling*

Document Information

title	Design and Analysis of Intraocular Diffractive Lens
document code	DFL.0001
version	2.2
edition	VirtualLab Fusion Advanced
toolbox(es)	Diffractive Optics Toolbox Gold
software version	2023.1 (Build 1.242)
category	Application Use Case
further reading	- Modeling of a Hybrid Eyepiece with Diffractive Lens Surface for Chromatic Aberration Correction - Import Optical Systems from Zemax OpticStudio®