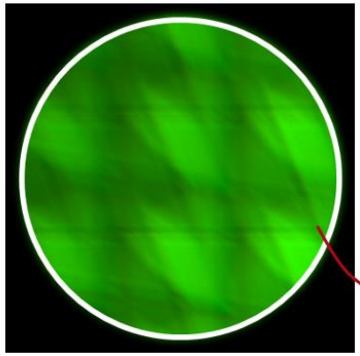
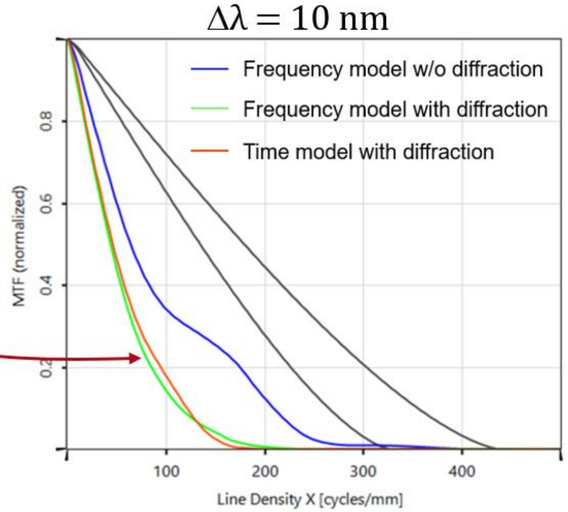
Control of Accuracy-Speed Balance for MTF Analysis in Complex Waveguide Devices for AR-applications

Abstract



Partially coherent, with diffraction



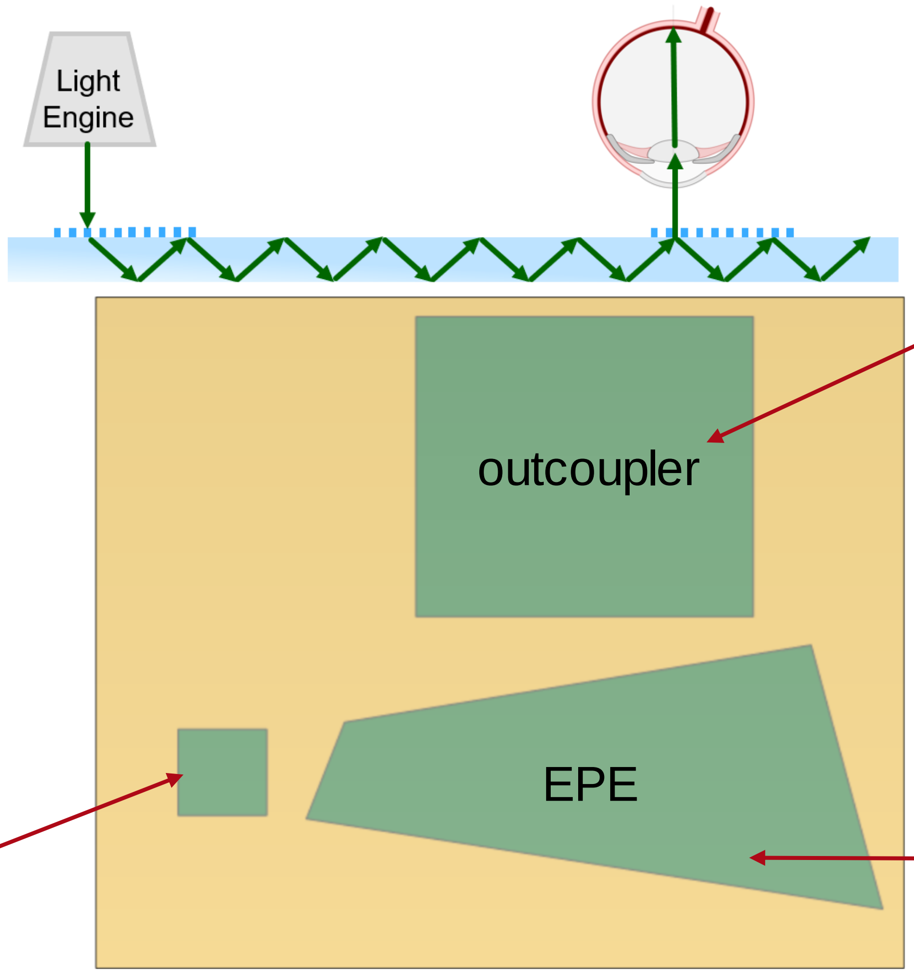
During the design process of waveguide devices in the field of augmented and mixed reality applications (AR/MR), the accurate calculation of the achievable optical performance is one of the major tasks. One very important quantity is, besides the spatial and angular uniformity, the modulation transfer function (MTF), which enables an assessment of the resolution capability of the final device. In this example, we point out the impact of diffraction and coherence effects on the accuracy of the calculated MTF. We further show that an accurate and fast inclusion of these effects necessitates a combination of highly interoperable simulation techniques on a single platform. This also enables the user to seamlessly control the accuracy and speed balance of complex optical systems.

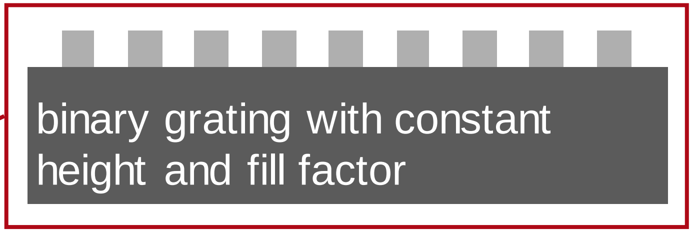
Task Description

Task: How to accurately calculate the MTF of a waveguide? What effects have to be considered?

Outcoupler

- binary grating
- 380 nm period
- height: 50 nm
- fill factor: 50%





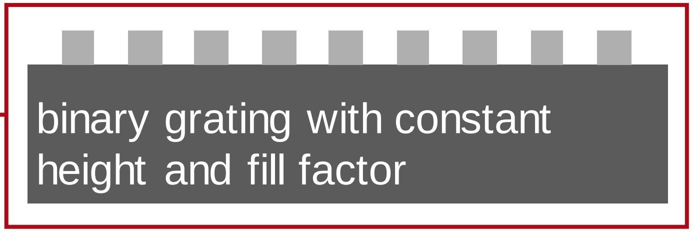
Layout & initial parameters:

Incoupler

- idealized grating
- 380 nm period
- efficiency +1st order: 50%
- efficiency 0th order: 50% (for backside illumination)

Eye Pupil Expander

- binary grating
- 268.7 nm period
- height: 50 nm
- fill factor: 50%

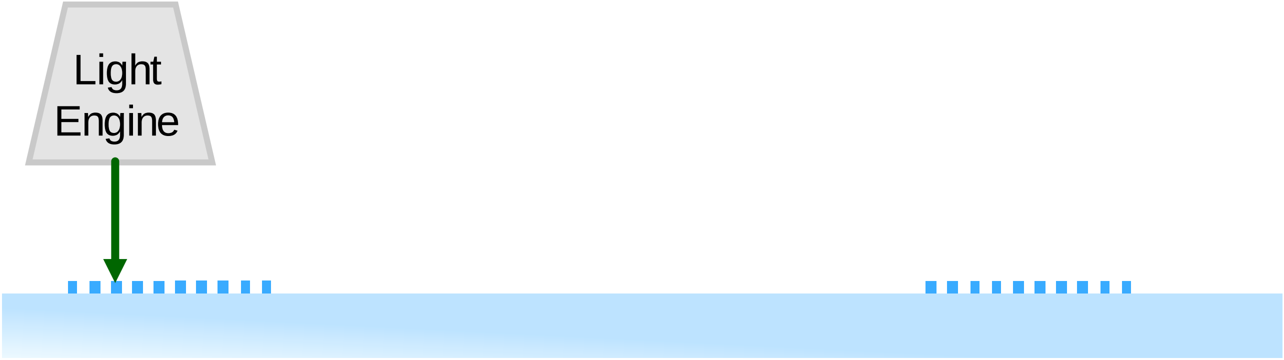


Simulation & Setup: Single Platform Interoperability

Connected Modeling Techniques: Source

Light Engine Model

- beam type: plane wave
- beam diameter: 3 mm (circular)
- polarization: linearly polarized
- wavelength: 532 nm
- bandwidth: 0 nm, 1 nm, 10 nm



Available modeling techniques for sources with finite bandwidth (temporal coherence):

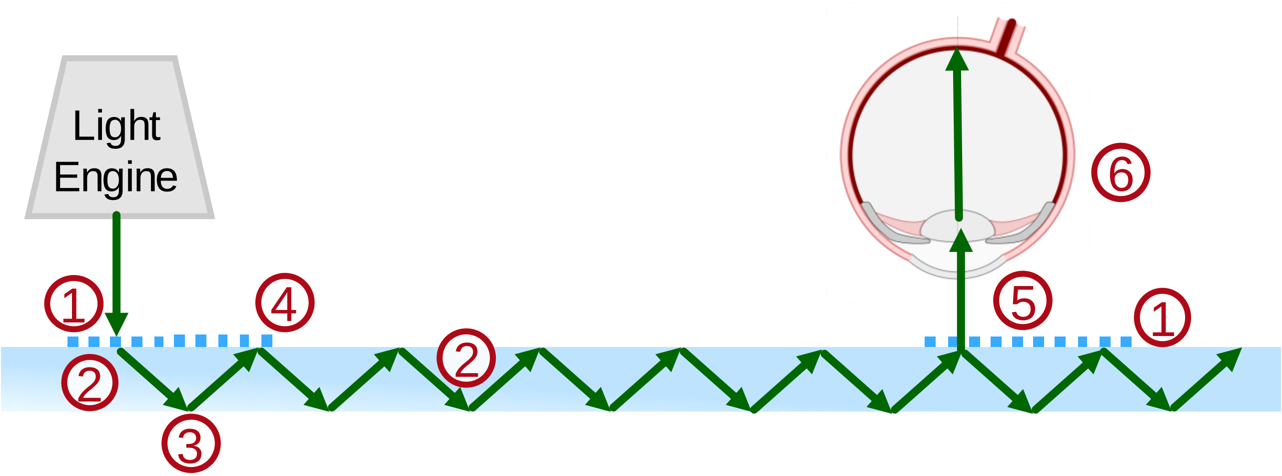
Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion & spectrum information not included	High	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

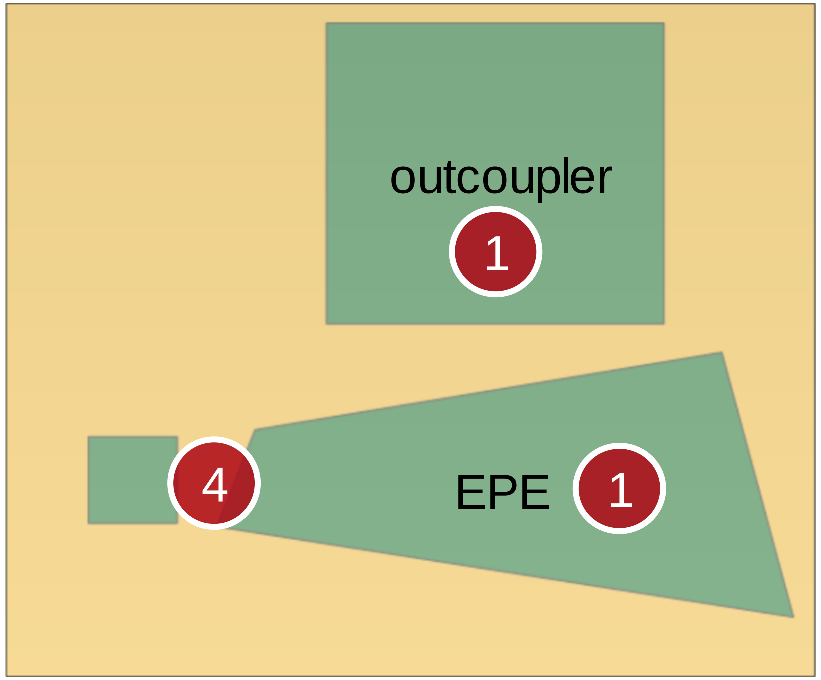
Two different techniques are available for modeling the source in this setup, the advantages and disadvantages of each one will be discussed later in the document.

Single-Platform Interoperability of Modeling Techniques

Each beam interacts with very different kinds of optical components while propagating through the complex system. Therefore, an accurate model requires a seamless interoperability of algorithms to be able to handle all aspects that arise:

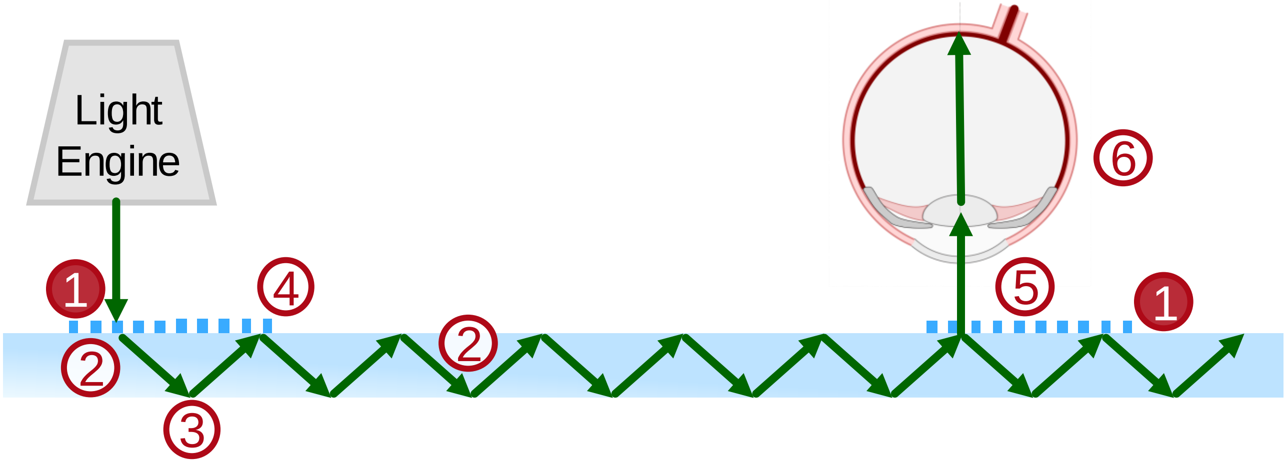
① gratings (incoupler, EPE, outcoupler)
② free space (propagation inside the glass slab)
③ reflection at surfaces of glass slab
④ region boundaries (at boundaries of a grating)
⑤ detector (uniformity measurement in eye box)
⑥ eye model (calculation of PSF & MTF)





Connected Modeling Techniques: Gratings

1 gratings (incoupler, EPE, outcoupler)
2 free space (propagation inside the glass slab)
3 reflection at surfaces of glass slab
4 region boundaries (at boundaries of a grating)
5 detector (uniformity measurement in eye box)
6 eye model (calculation of PSF & MTF)



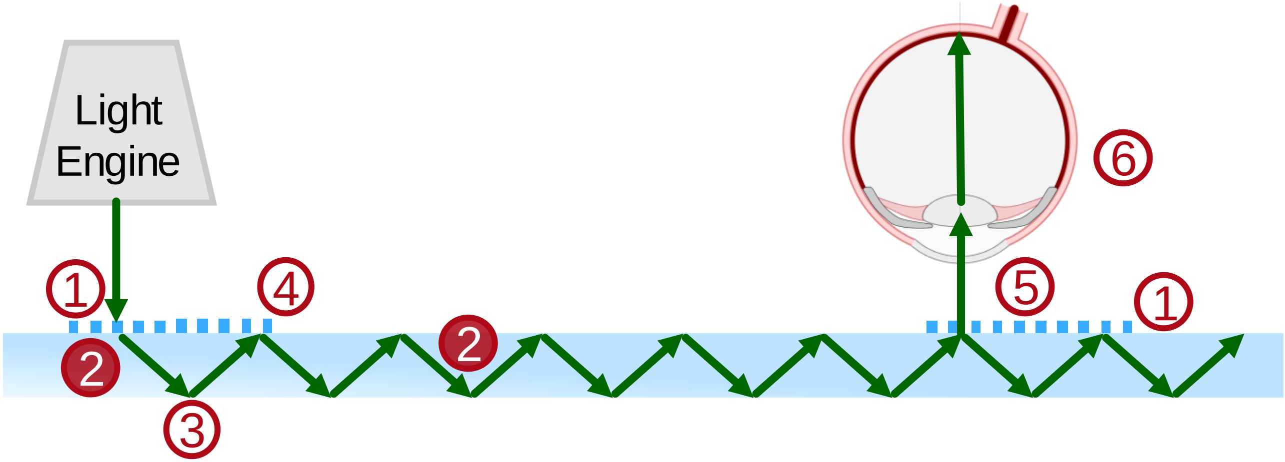
Available modeling techniques for periodic micro and nano structures:

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Modal Method (FMM)	None	High	High	**Small periods**
Thin Grating Approximation	**Large periods & features, thin**	High	High	Thickness about wavelength; period & features larger than about ten wavelengths
	Otherwise	Low	High	
FMM in Kogelnik Approximation	**Thick volume gratings; Bragg condition**	High	Very high	Method is electromagnetic formulation of Kogelnik's approach
	No Bragg condition	Low	Very high	

As a rigorous eigenmode solver, the Fourier modal method (also known as rigorous coupled wave analysis, RCWA) provides very high accuracy. Due to the small periods in this setup, the calculation speed is fast. FMM is therefore the best compromise of accuracy and speed.

Connected Modeling Techniques: Inside Waveguide Slab

1. gratings (incoupler, EPE, outcoupler)
2. free space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)
6. eye model (calculation of PSF & MTF)



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	

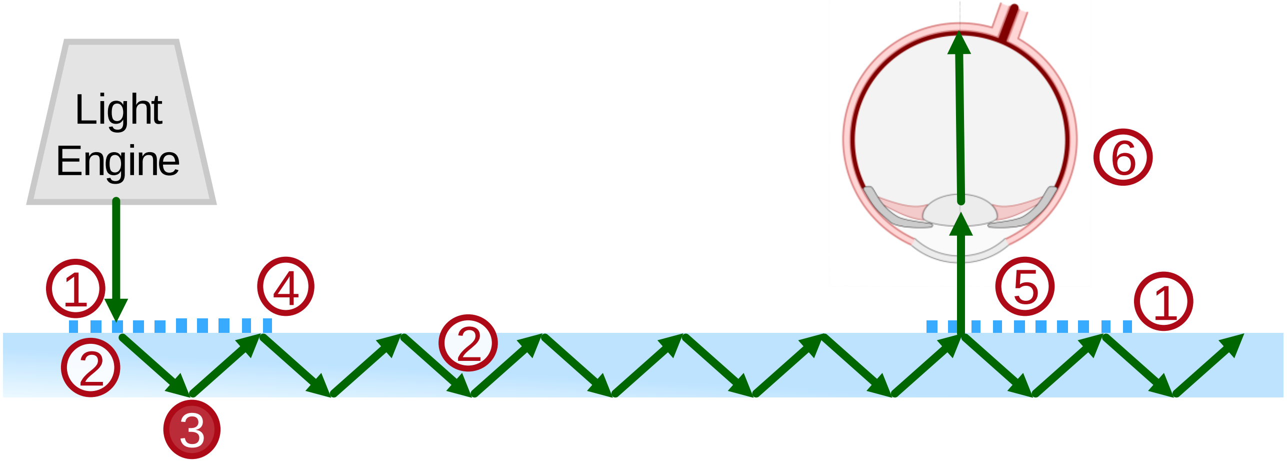
Two fast modeling techniques are available to calculate the propagation inside the glass plate:

- **Fourier Domain Techniques** (includes diffraction effects of boundaries and apertures)
- **Geometric Propagation** (neglects diffraction that arises from boundaries and apertures)

In order to choose the adequate technique, the results need to be considered!

Connected Modeling Techniques: Waveguide Surfaces

1. gratings (incoupler, EPE, outcoupler)
2. free space (propagation inside the glass slab)
3. reflection at surfaces of glass slab
4. region boundaries (at boundaries of a grating)
5. detector (uniformity measurement in eye box)
6. eye model (calculation of PSF & MTF)



Available modeling techniques interaction with surfaces:

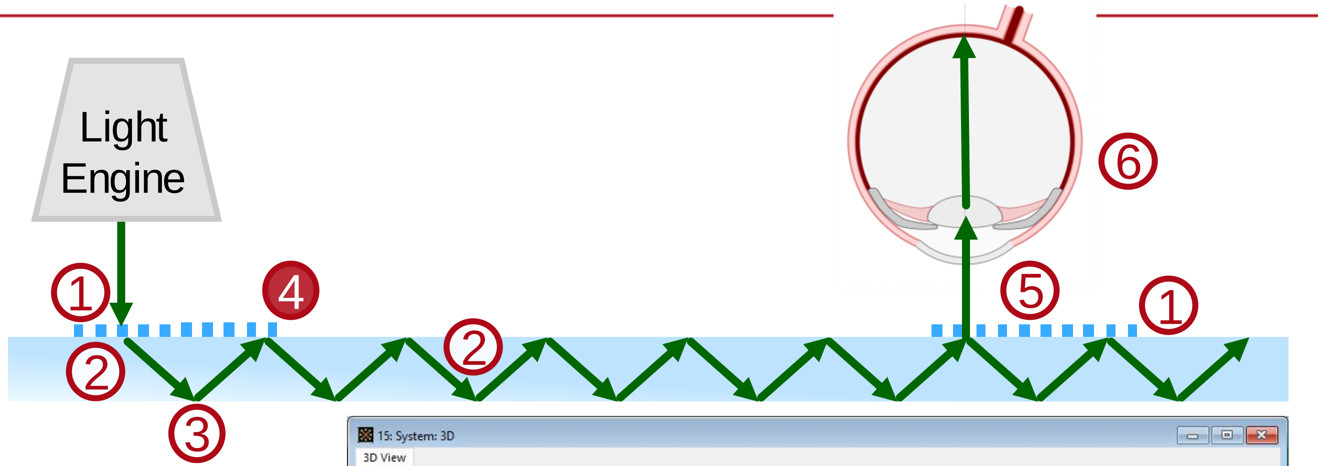
Methods	Preconditions	Accuracy	Speed	Comments
S matrix	Planar surface	High	Very High	Rigorous model; includes isotropic and birefringent coatings; k-domain
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

Two modeling techniques are available to calculate the interaction with the surfaces.

Since both are fast, and the **Local Planar Interface Approximation** allows us in addition to consider curved surfaces (e.g. for tolerance analysis), this technique is chosen.

Connected Modeling Techniques: Region Boundaries

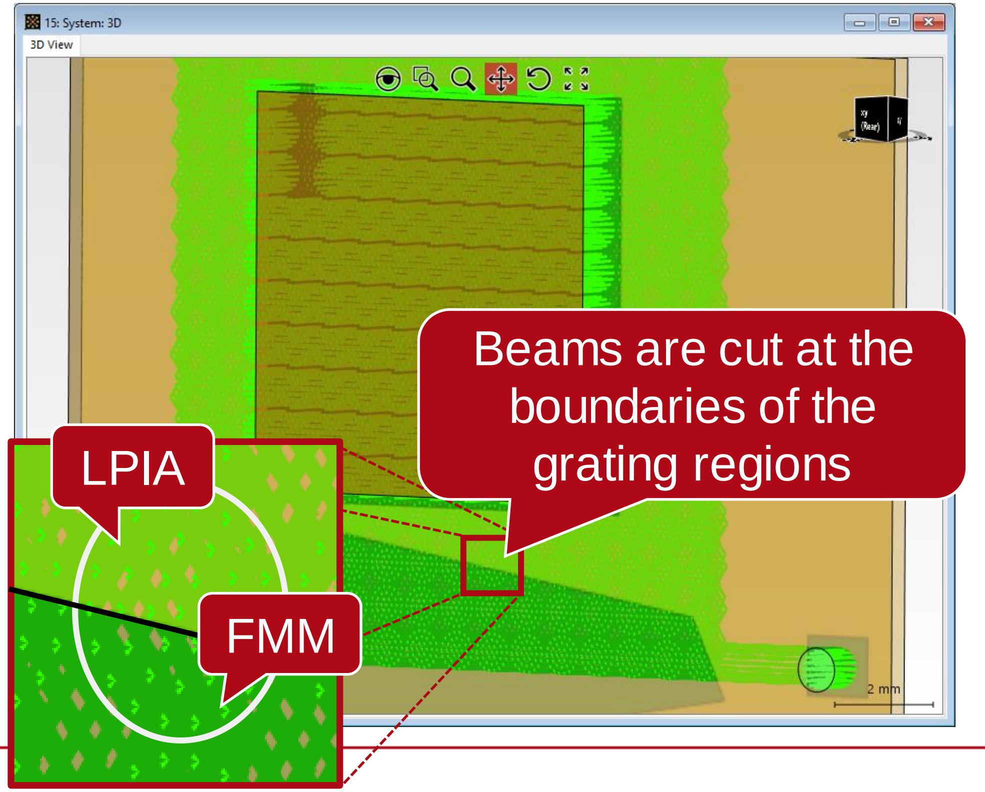
① gratings (incoupler, EPE, outcoupler)
② free space (propagation inside the glass slab)
③ reflection at surfaces of glass slab
④ region boundaries (at boundaries of a grating)
⑤ detector (uniformity measurement in eye box)
⑥ eye model (calculation of PSF & MTF)



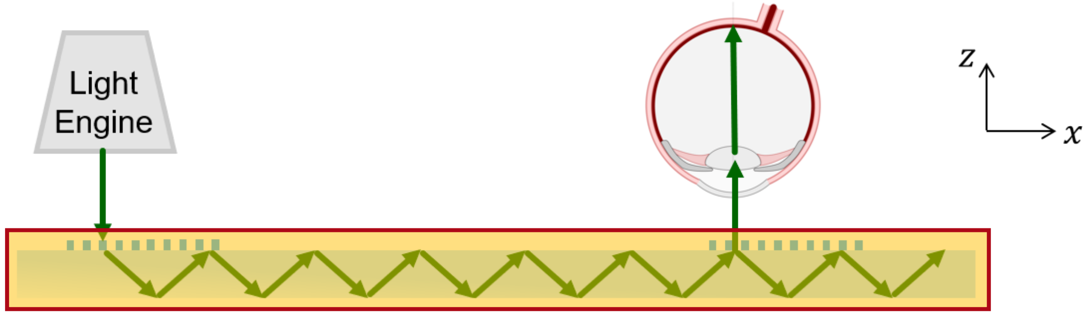
Available modeling techniques for interaction with region boundaries:

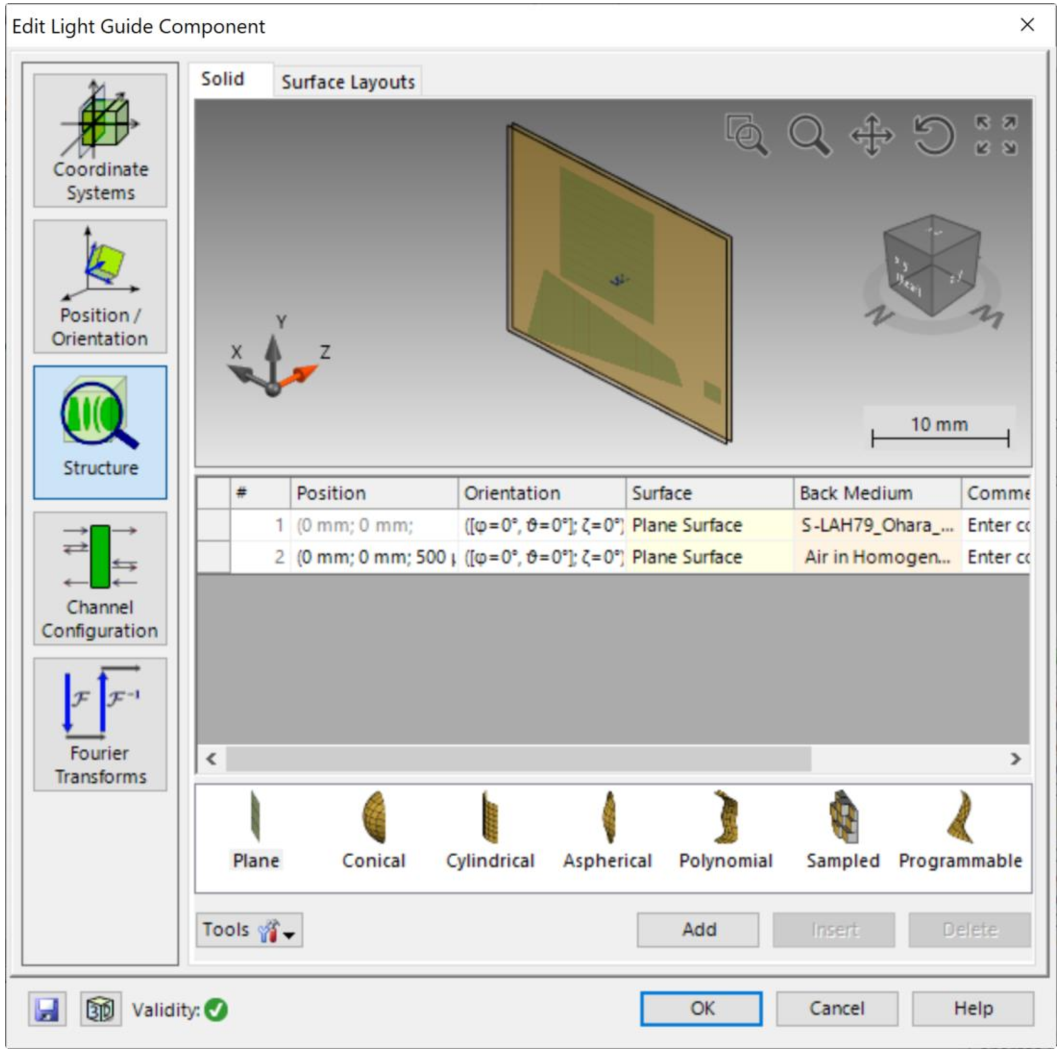
Methods	Preconditions	Accuracy	Speed	Comments
Local application of LPIA and FMM	Region extent not close to a few wavelengths	High	Very High	Beam profile cut along region boundaries; **high resolution**

With the local application of LPIA and FMM we can take into account the interactions with the boundaries of grating regions.



Light Guide Component

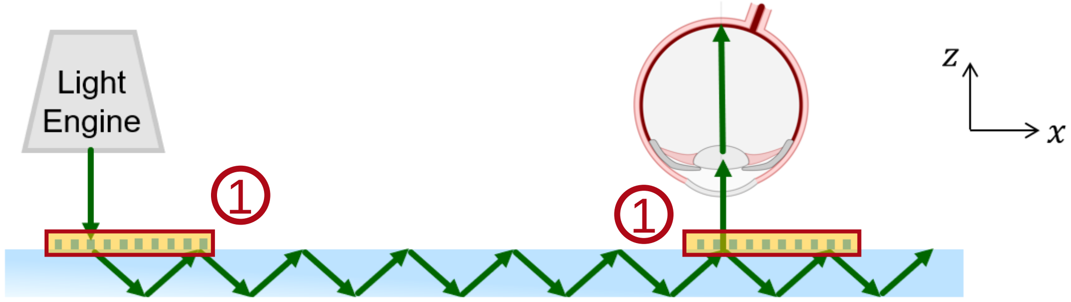




Modeling techniques 1 to 4 are combined in the *Light Guide Component.* With this element, grating-based lightguide systems with complex-shaped grating regions can easily be defined. Furthermore, these regions can be equipped with idealized or real grating structures (1D or 2D-periodic) to act as incoupler, outcoupler or exit pupil expanders. More information under:

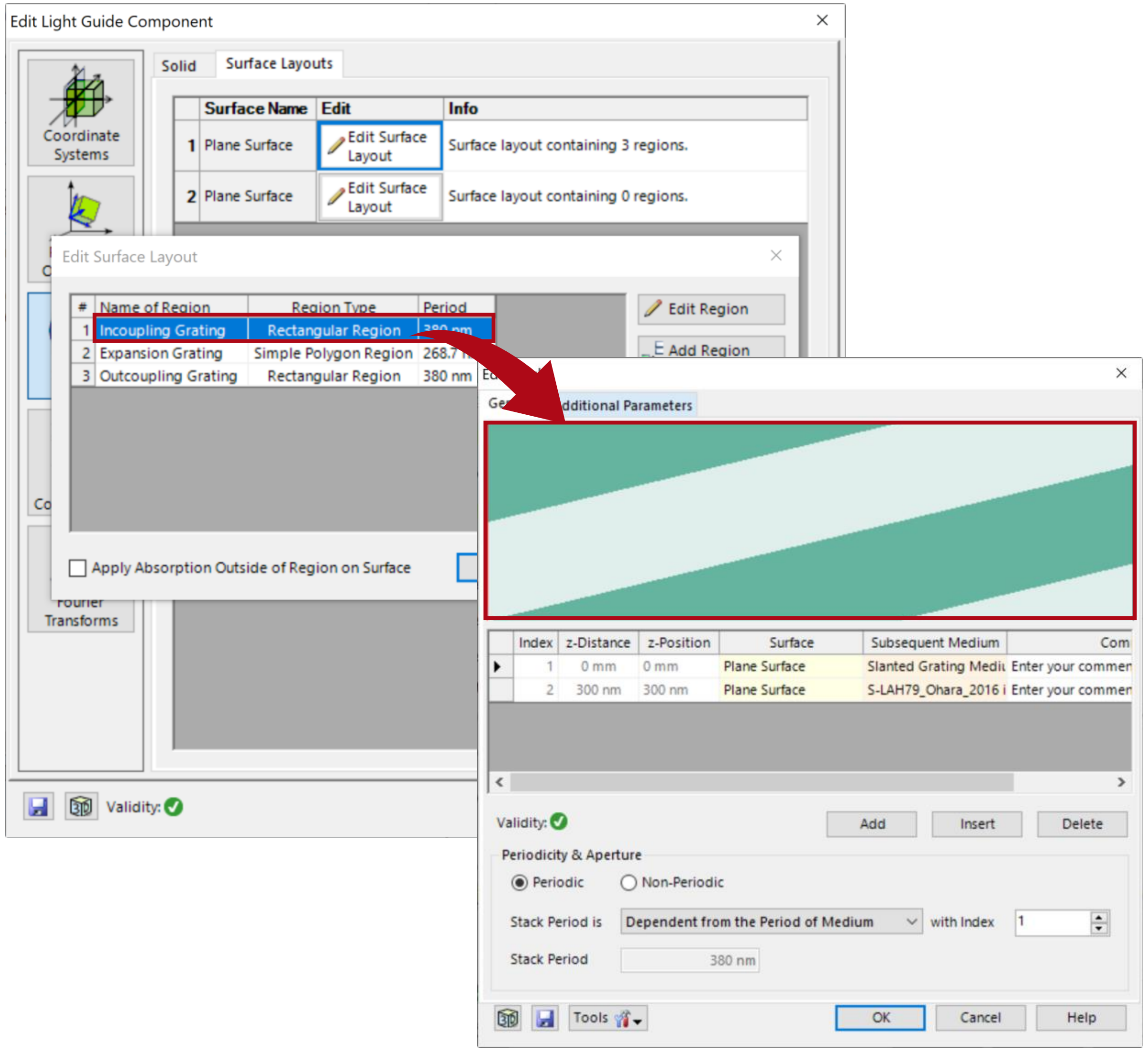
Construction of a Light Guide

Grating Regions



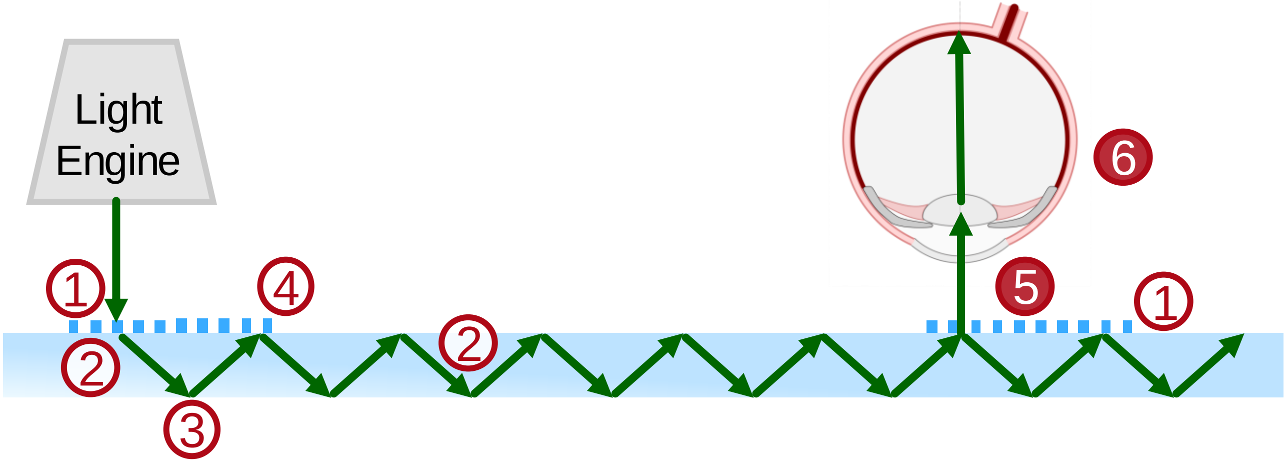
For the incoupler, outcoupler and eye pupil expander (EPE) real gratings were used. Their Rayleigh matrices and the corresponding diffraction efficiencies are calculated rigorously by applying FMM (RCWA). You can find more information on how to set this up under:

[How to Set Up a Lightguide with Real Grating Structures]



Connected Modeling Techniques: Detector Eyebox

① gratings (incoupler, EPE, outcoupler)
② free-space (propagation inside the glass slab)
③ reflection at surfaces of glass slab
④ region boundaries (at boundaries of a grating)
⑤ detector (uniformity measurement in eye box)
⑥ eye model (calculation of PSF & MTF)



⑤ Full flexibility in detector modeling:

- Radiometry, e.g., irradiance per FOV or all FOVs, radiance
- Photometry, e.g., illuminance per FOV or all FOVs, luminance
- Uniformity measures

⑥ Eye model for

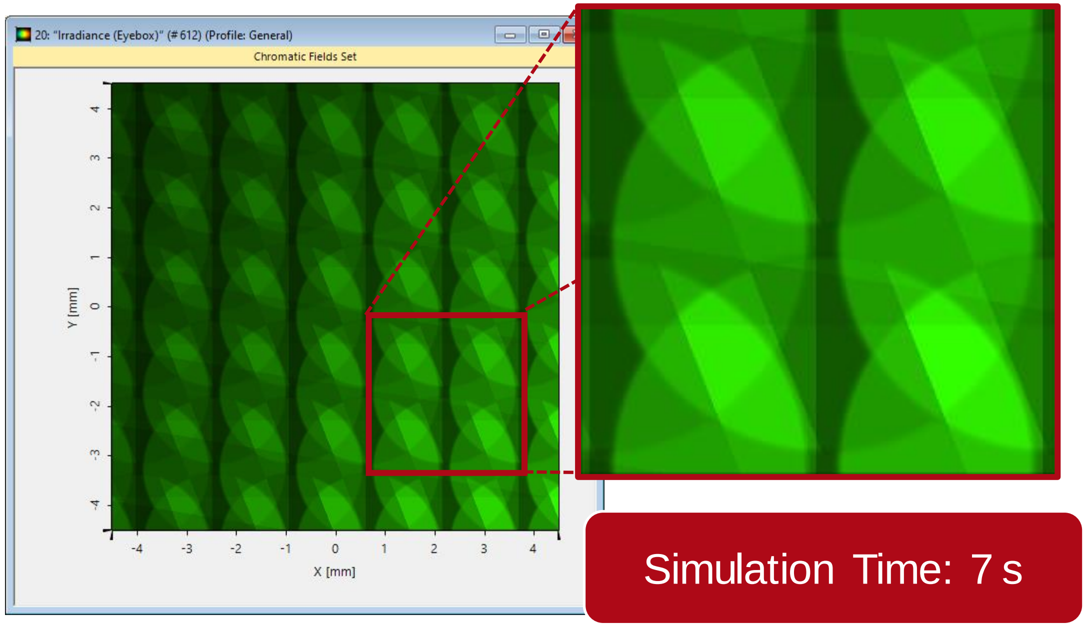
- Point spread function (PSF)
- Modulation Transfer Function (MTF)

Diffraction Inside Waveguide: Irradiance Eye Box

① grating (incoupler)

② free-space (propagation inside the glass slab)

irradiance in eye box without diffraction:

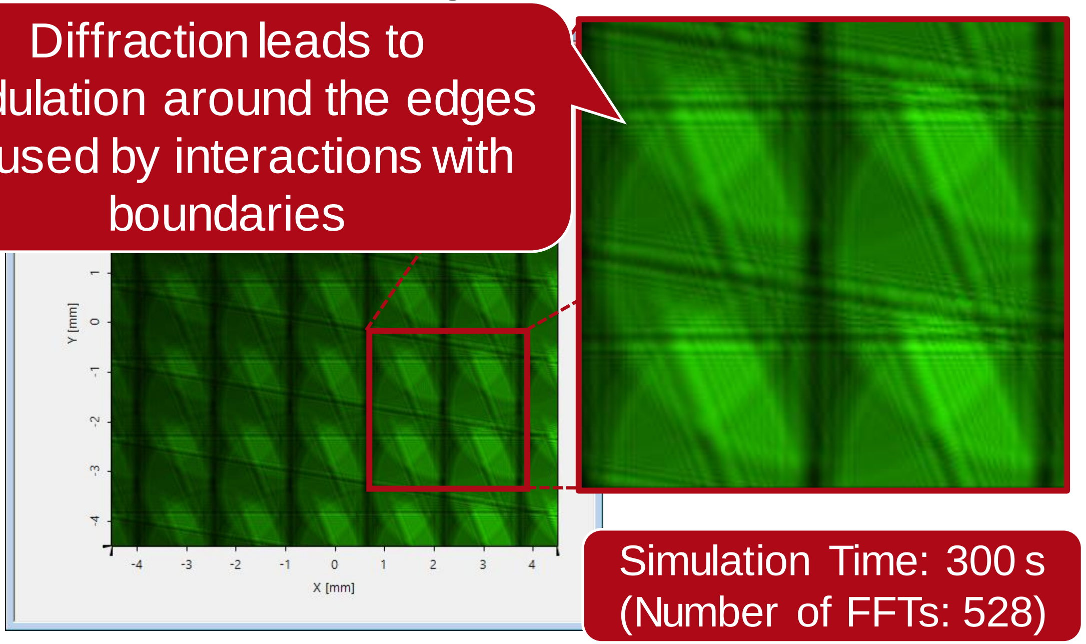


Simulation Time: 7 s

Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

irradiance in eye box with diffraction:

Diffraction leads to modulation around the edges caused by interactions with boundaries



Simulation Time: 300 s
(Number of FFTs: 528)

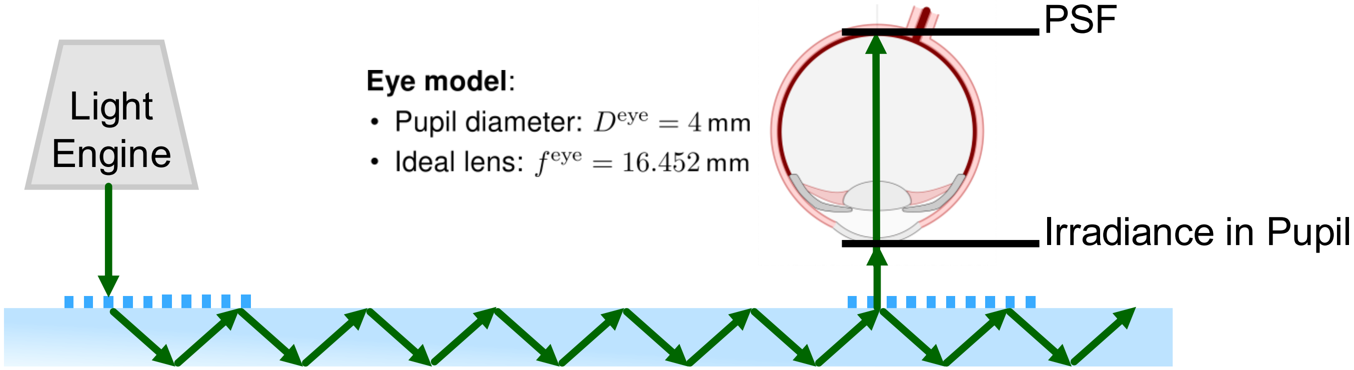
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

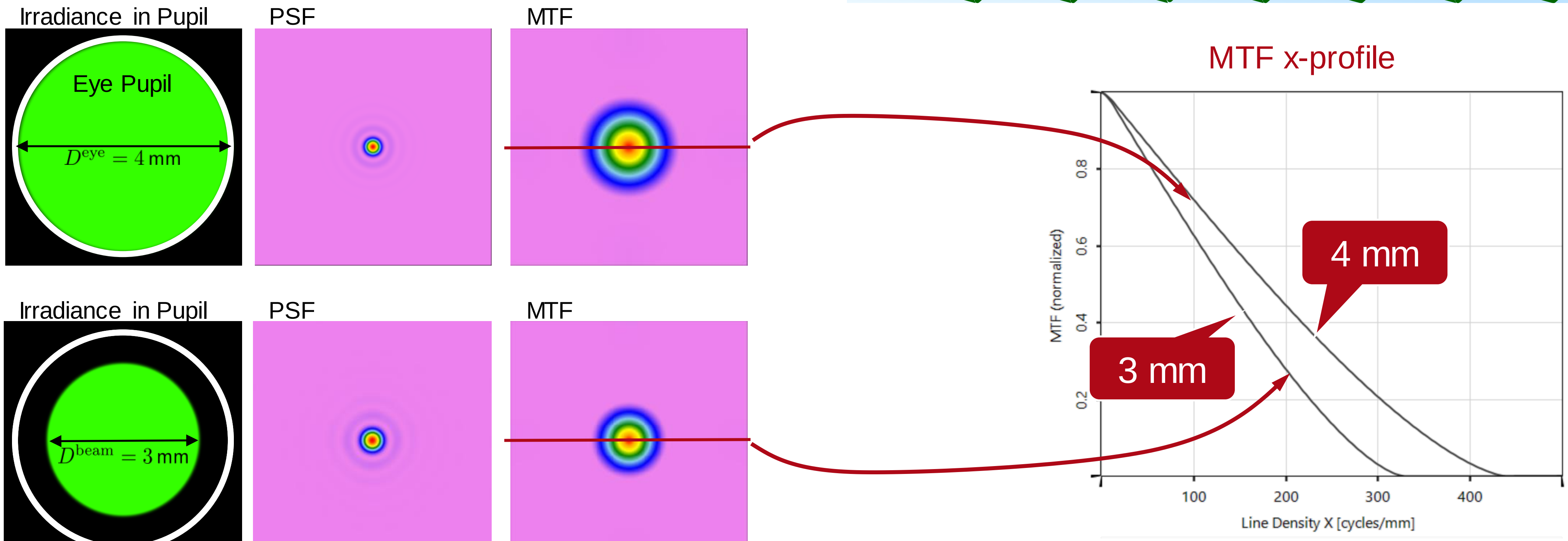
sample files: “01 Irradiance in Eyebox wo Diffraction.os” & “01a Irradiance in Eyebox w Diffraction.os”

PSF & MTF Analysis – Part #1: Diffraction Effects

PSF and MTF Calculation: One Beam in Pupil

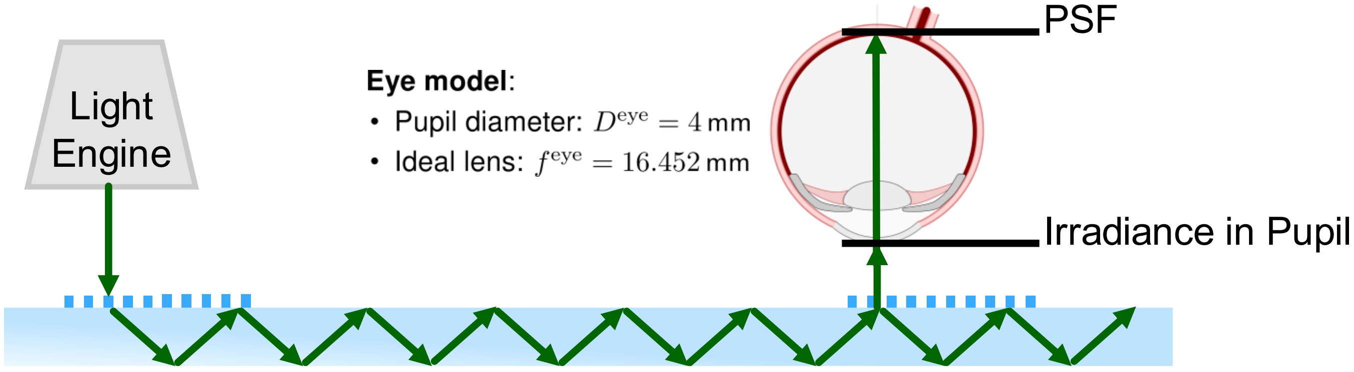
In case of a uniformly filled pupil, the resulting PSF and MTF are rotation symmetric and exhibit a continuous decay. For a smaller beam diameter, the decay of the MTF is stronger, but the general behavior does not change.

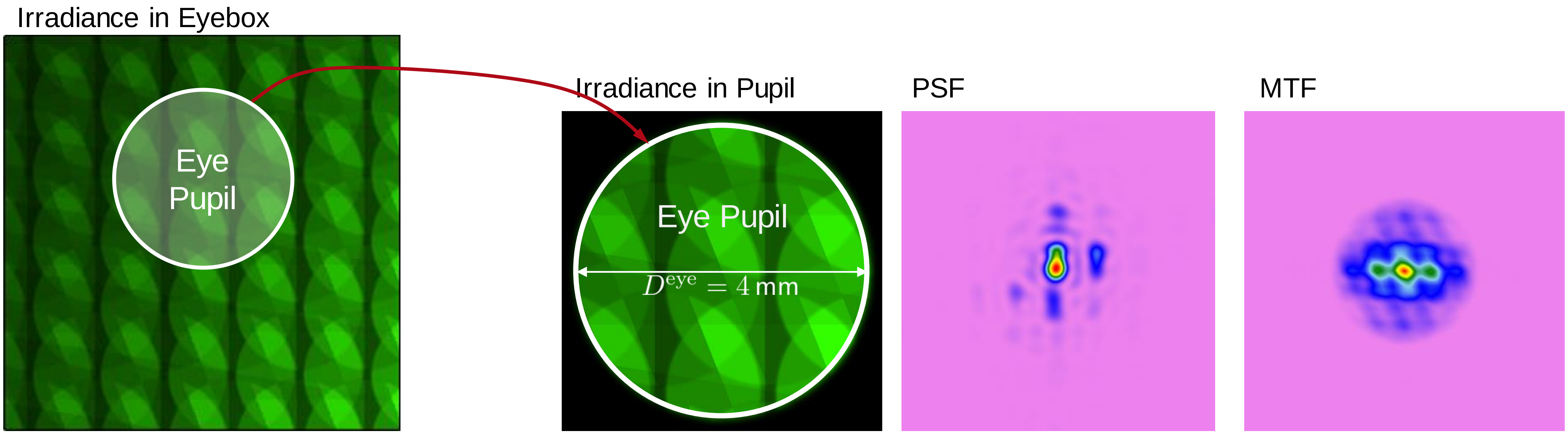




PSF and MTF Calculation: Multiple Beams in Pupil

For a pupil filled with multiple beams, which are affected by numerous interactions with region boundaries, the resulting (two dimensional) PSF and MTF are much more complex and no longer rotationally symmetric.

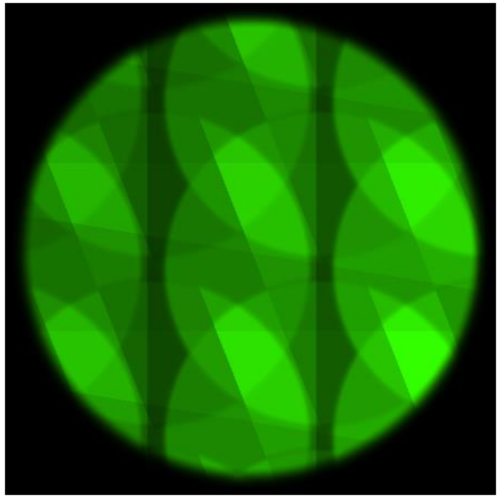




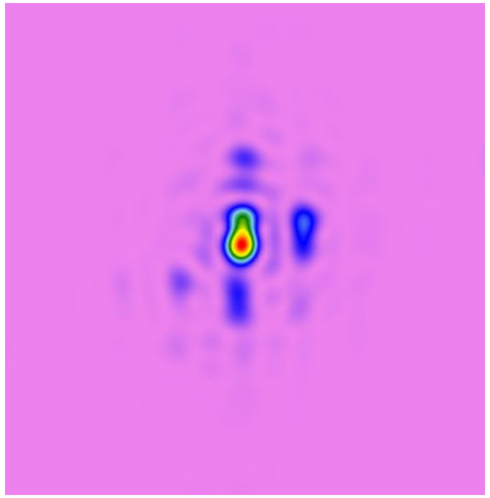
sample file: "01b PSF&MTF wo Diffraction.os"

PSF and MTF Calculation: w/o Diffraction in Waveguide

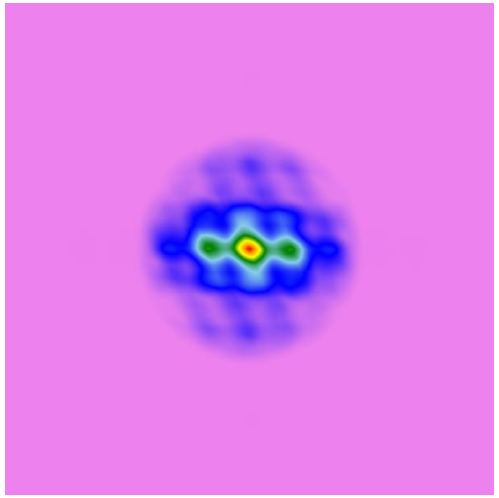
Irradiance in Pupil



PSF

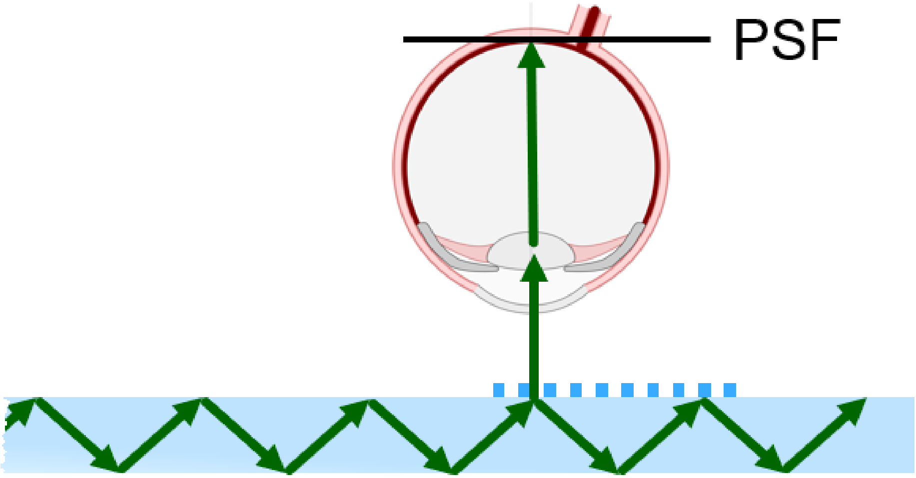


MTF



In case the geometric propagation technique is chosen, diffraction effects introduced by apertures and region boundaries are neglected. However, the resulting (two dimensional) PSF and MTF exhibit a complex behavior and are not longer rotationally symmetric.

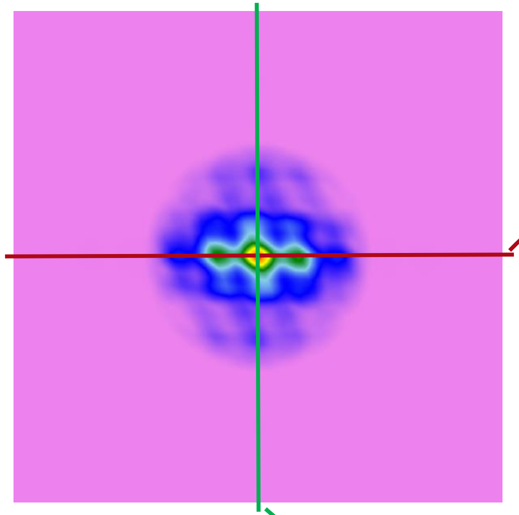
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	



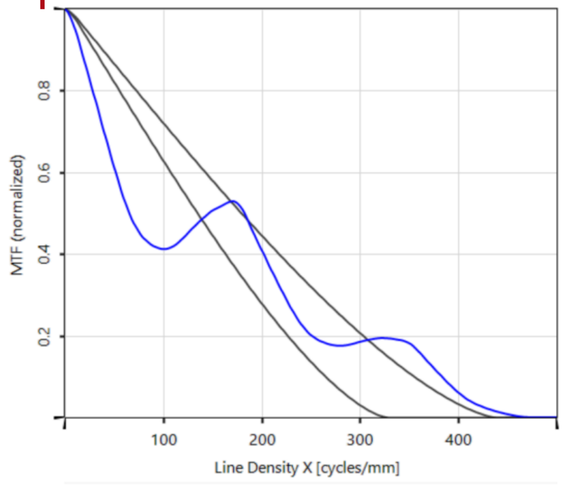
PSF and MTF Calculation: w/o Diffraction in Waveguide

In contrast to the MTF of a uniformly filled aperture, the cross-sections along x and y show different profiles and no monotonous decay anymore.

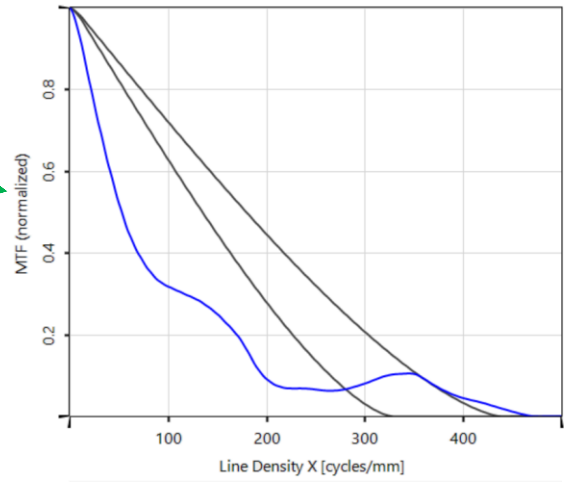
MTF



MTF x-profile



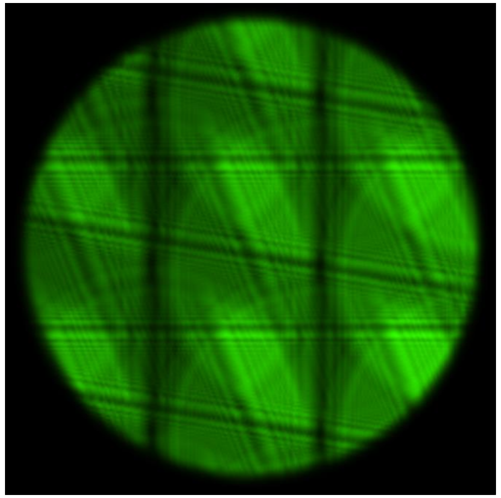
MTF y-profile



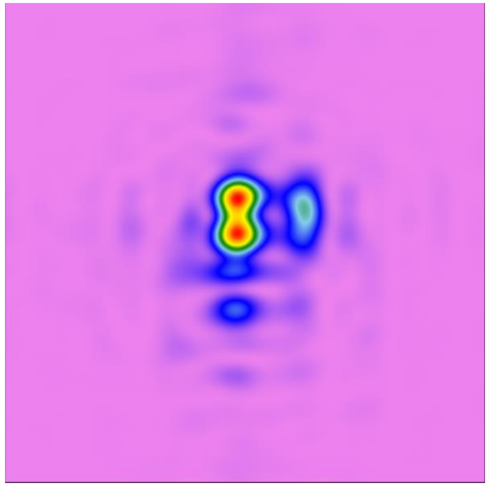
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

PSF and MTF Calculation: with Diffraction in Waveguide

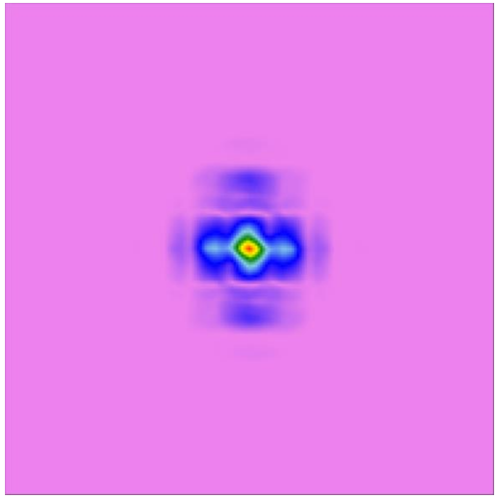
Irradiance in Pupil



PSF

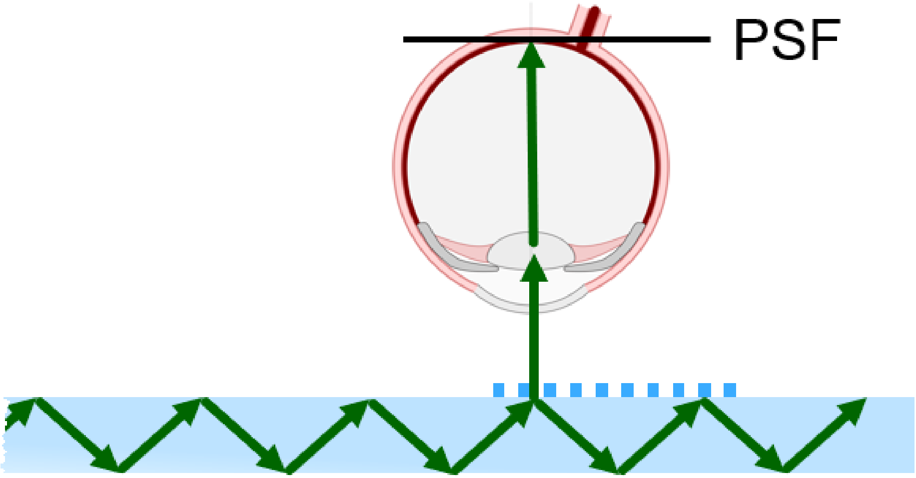


MTF



By applying a rigorous propagation technique, such as VirtualLab's Fourier domain techniques, diffraction effects introduced by apertures and region boundaries can be considered. The resulting PSF and MTF are very different from the non-diffractive case.

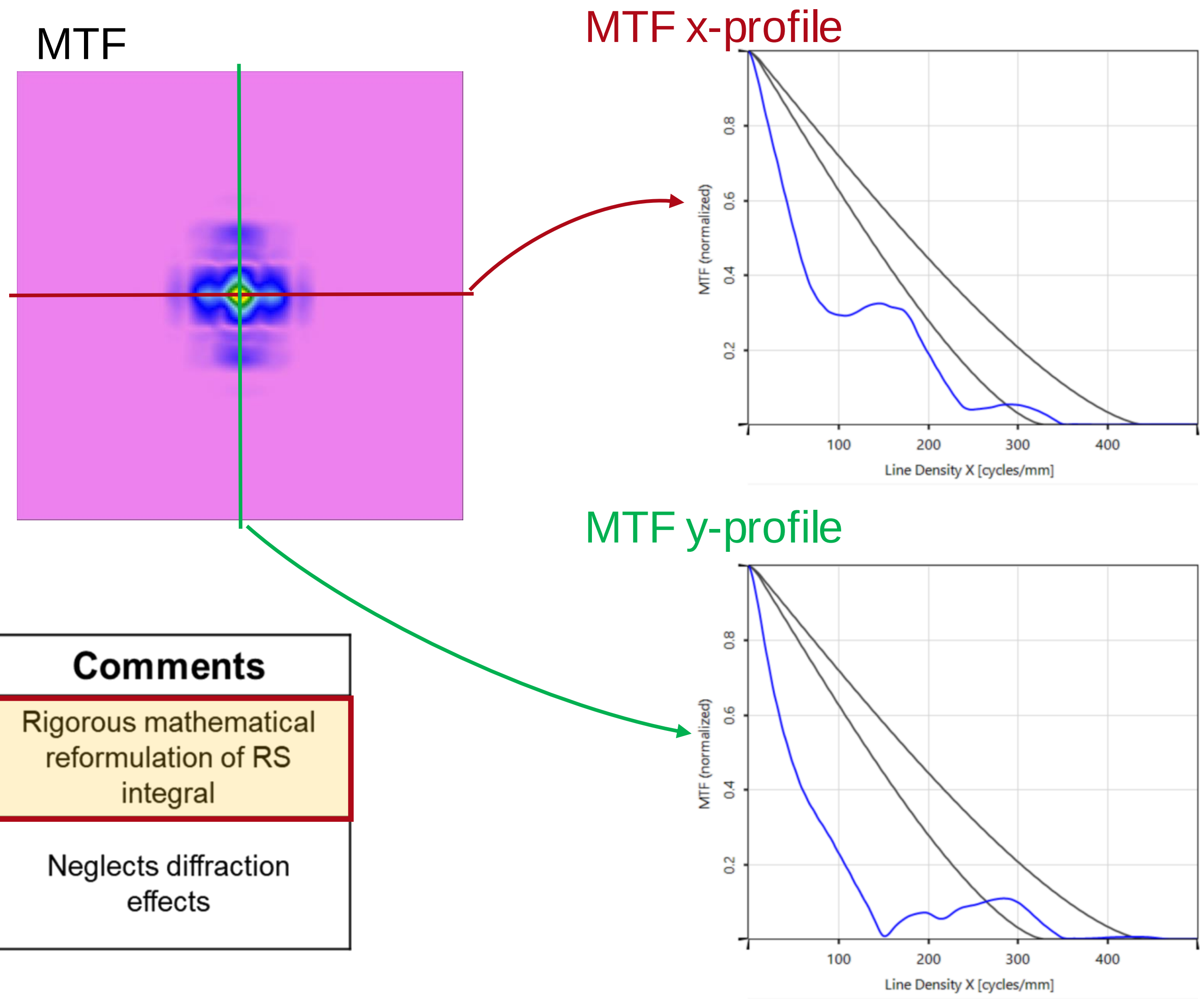
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	



sample file: "01c PSF&MTF w Diffraction.os"

PSF and MTF Calculation: with Diffraction in Waveguide

In contrast to the MTF of a uniformly filled aperture, the cross-sections along x and y show different profiles with some oscillations. Moreover, the resulting MTF is very different compared to the result without including diffraction effects.



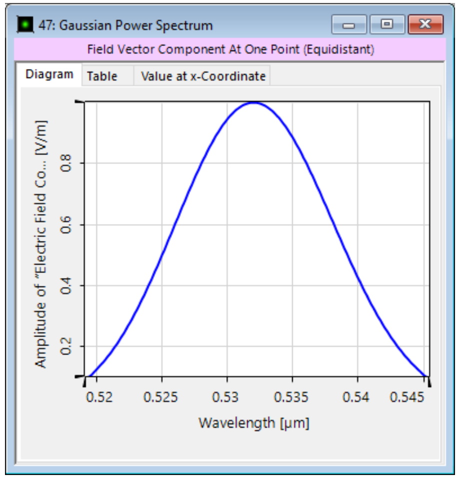
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

sample file: "01c PSF&MTF w Diffraction.os"

PSF & MTF Analysis – Part #2: Temporal Coherence

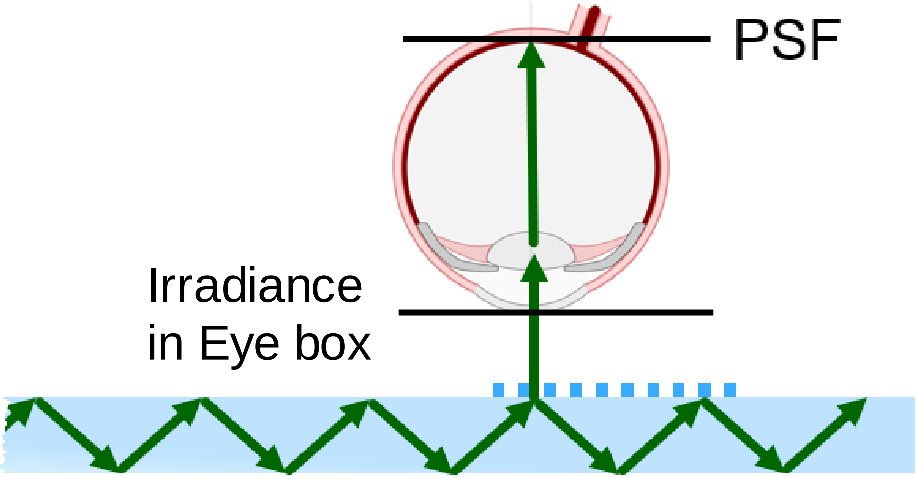
PSF and MTF Calculation: Frequency Model

In order to model the bandwidth of a source rigorously, the bandwidth must be sampled properly. The sampled frequencies (or wavelengths) then must be propagated through the system separately. This leads to a higher computational effort and calculation time.
For example, a source possessing a Gaussian spectrum (FWHM 10 nm) requires a sampling of 1 pm in this application. This leads to over 10000 simulations. Alternatively, its is sufficient to model a single spectral period of the system, where the irradiance pattern is repeating (please see next page).



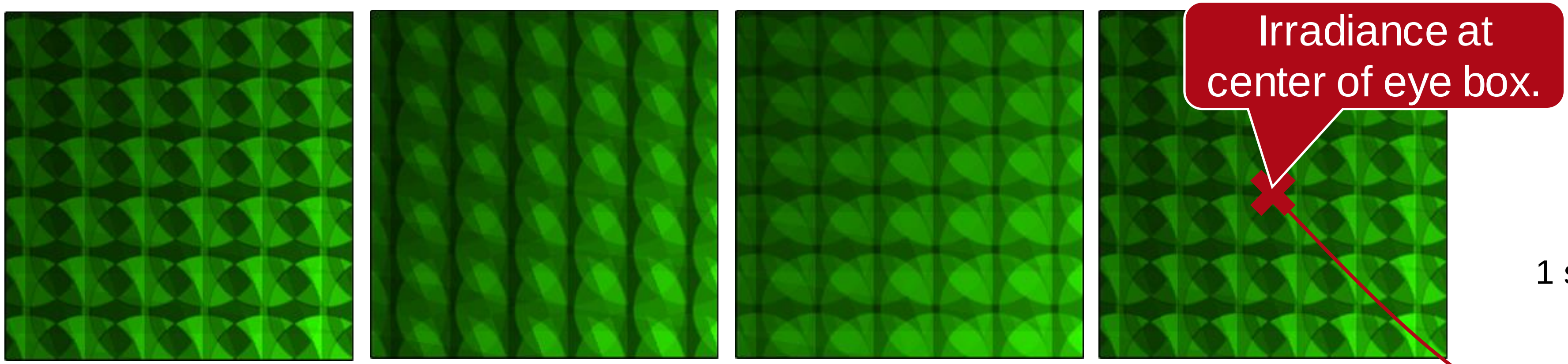
Gaussian spectrum (FWHM: 10 nm)

Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion & spectrum information not included	High	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector



PSF and MTF Calculation: Frequency Model

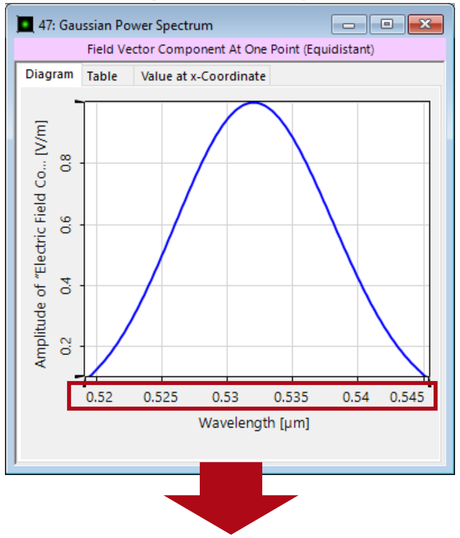
In order to model a complex waveguide system with a partially coherent light source more efficiently, periodic characteristics of the setup can be exploited. Typically, the resulting irradiance pattern in the eye box changes periodically as the wavelength is varied in the spectrum of the source:



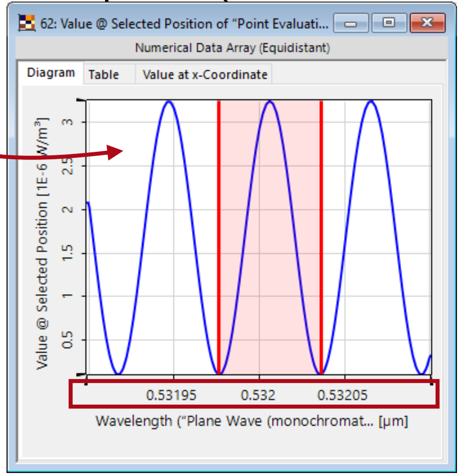
$\lambda = 531.98\ \mathrm{nm}$ | $\lambda = 532.00\ \mathrm{nm}$ | $\lambda = 532.02\ \mathrm{nm}$ | $\lambda = 532.04\ \mathrm{nm}$

The reason for this behavior is a repeating relative phase relationship between the modes. Thus, in this example waveguide it is sufficient to model just a single spectral period of 60 pm, where the irradiance pattern is repeating. Hence, instead of 10000 simulations (sampling 10 nm bandwidth with 1 pm distance), just the 60 pm (60 simulations, 1 pm distance) must be sampled to calculate the MTF.

full Gaussian spectrum (FWHM: 10 nm)



1 spectral period (bandwidth: 60 pm)



sample files: "02 Analysis of Spectral Period of Irradiance.os" & "02a Analysis of Spectral Period of Irradiance.run"

PSF and MTF Calculation: Frequency Model (w/o Diffraction)

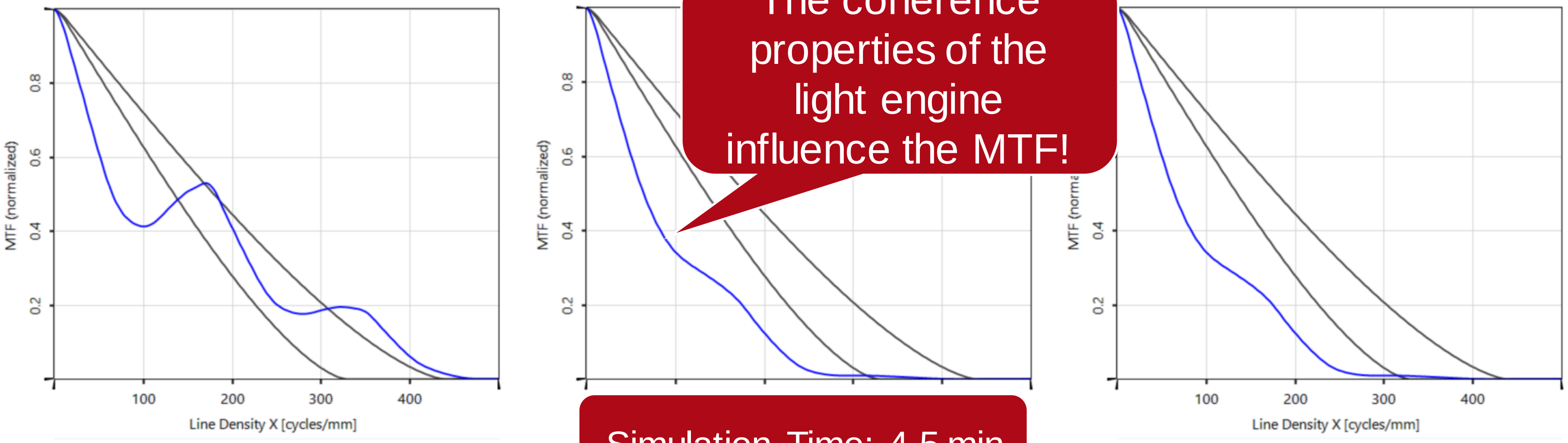
Results for Frequency Model:

$\Delta\lambda = 0$ nm | $\Delta\lambda = 1$ nm | $\Delta\lambda = 10$ nm

Irradiance in eye box

Dispersion leads to a smearing of the overlapping beams

cross-section of MTF (along x-direction)



The coherence properties of the light engine influence the MTF!

Simulation Time: 4.5 min

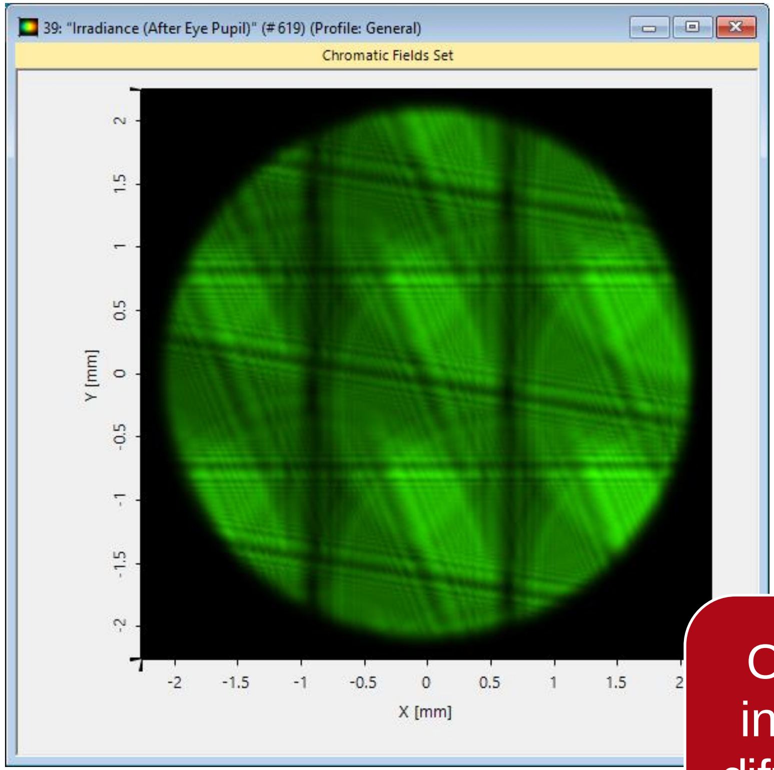
files: "02b Irradiance in Eyebox Frequency Model wo Diffraction.os" & "02c MTF Frequency Model wo Diffraction (1 SP).os"

PSF and MTF Calculation: Frequency Model (with Diffraction)

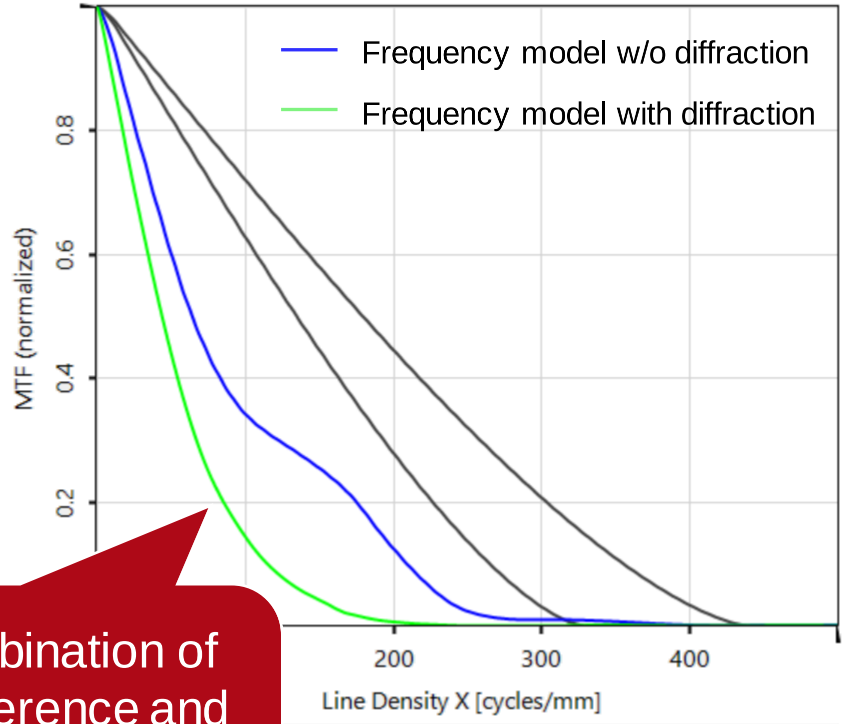
Results for Frequency Model:

$\Delta\lambda = 10\ \text{nm}$

irradiance in eye box



cross-section of MTF (along x-direction)



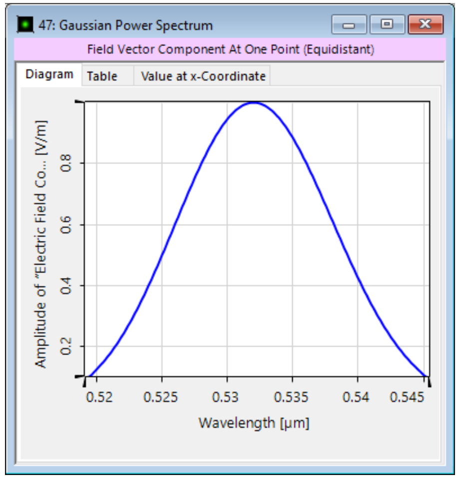
Only the combination of including coherence and diffraction effects provides an accurate result!

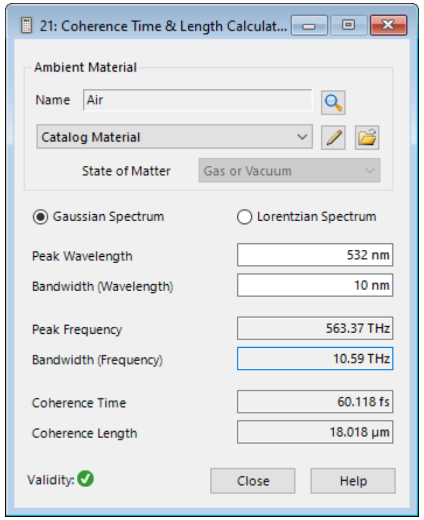
Simulation Time: 50 min

sample file: "02d Irradiance in Eyebox w Diffraction (1 SP).os & 02e MTF Frequency Model w Diffraction (1 SP).os"

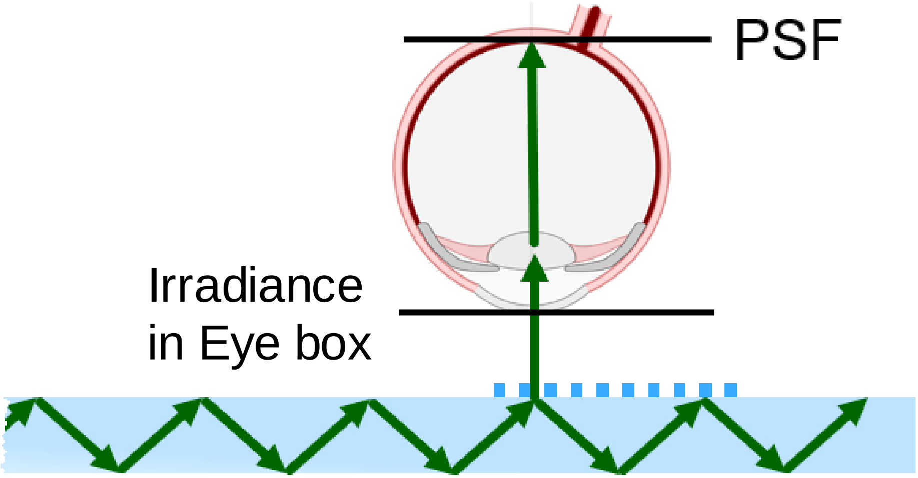
PSF and MTF Calculation: Time Model

An alternative modeling technique is the analysis of the travel time of a single wavelength (e.g. peak wavelength of the spectrum). The comparison of the travel time and the coherence time (or length) allows us to distinguish whether the light must be treated coherently or incoherently. For example, a bandwidth of 10 nm (FHWM) leads to a coherence time of 60.1 fs and 18.0 µm coherence length.





Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion & spectrum information not included	High	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

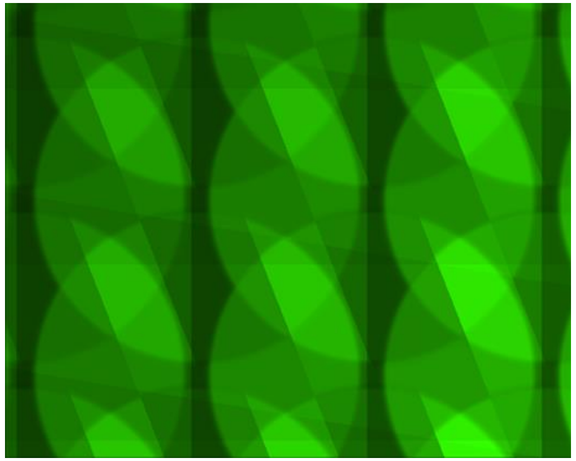


PSF and MTF Calculation: Time Model (w/o Diffraction)

Results for Time Model:

Irradiance in eye box

$\Delta\lambda = 0$ nm

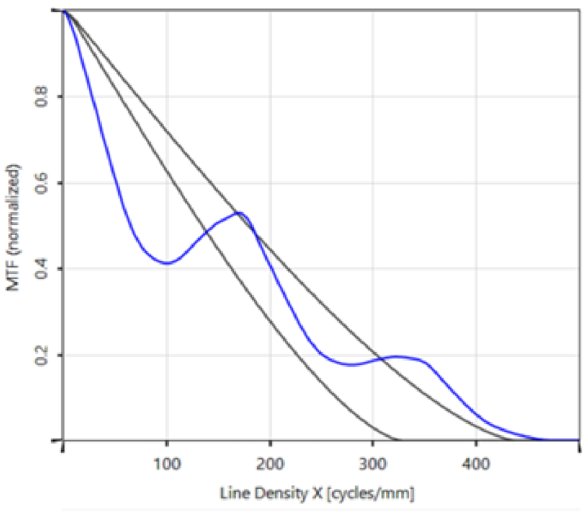


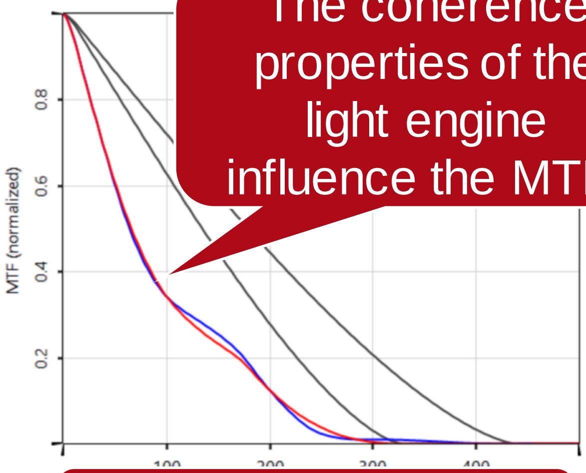
$\Delta\lambda = 1$ nm

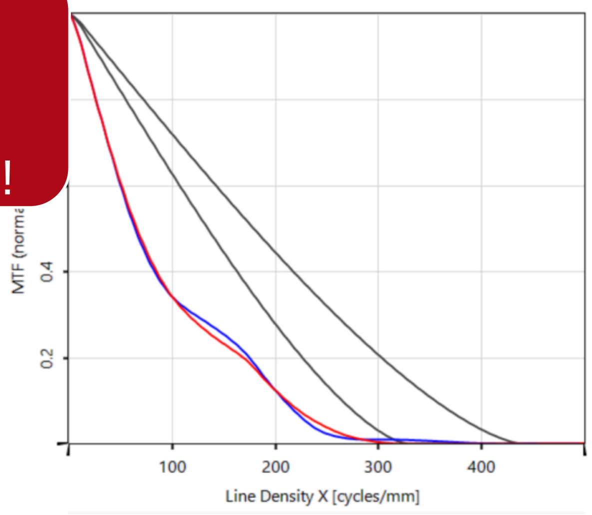
$\Delta\lambda = 10$ nm

Dispersion effect not included!

cross-section of MTF (along x-direction)







The coherence properties of the light engine influence the MTF!

Simulation Time: 7 sec

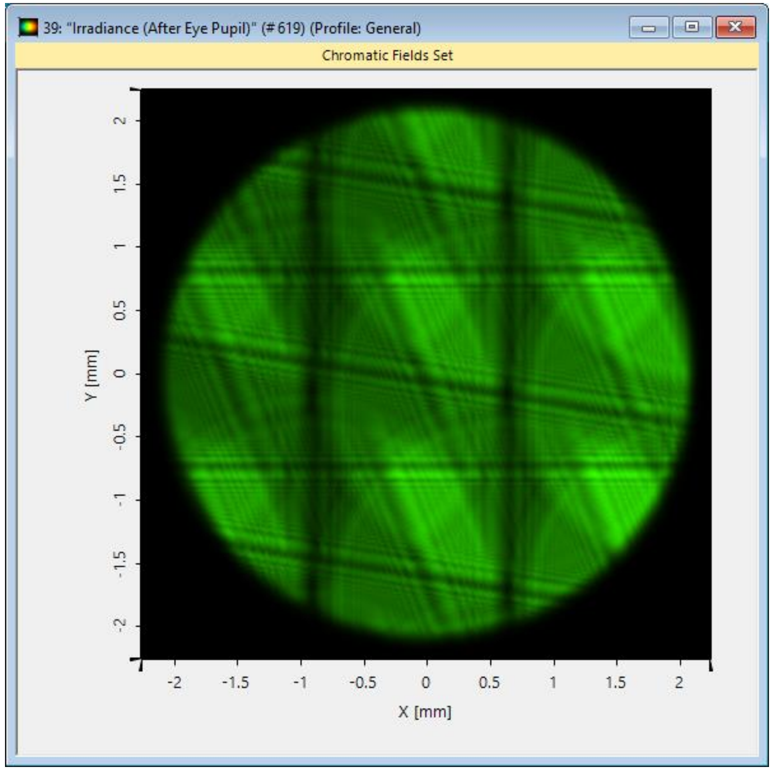
sample file: "03 Irradiance & MTF Time Model wo Diffraction.os"

PSF and MTF Calculation: Time Model (with Diffraction)

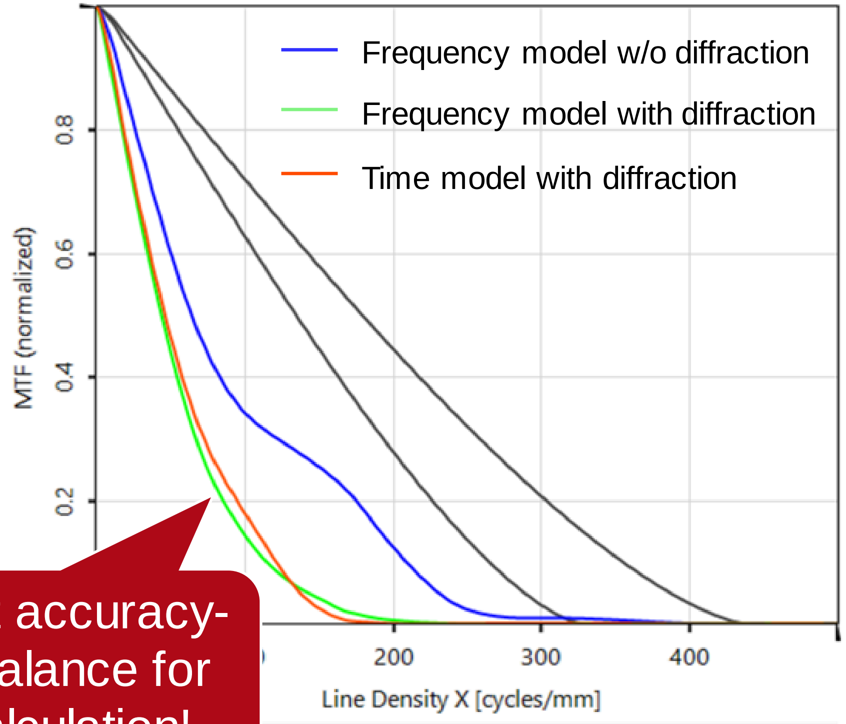
Results for Frequency Model:

$\Delta\lambda = 10$ nm

irradiance in eye box



cross-section of MTF (along x-direction)



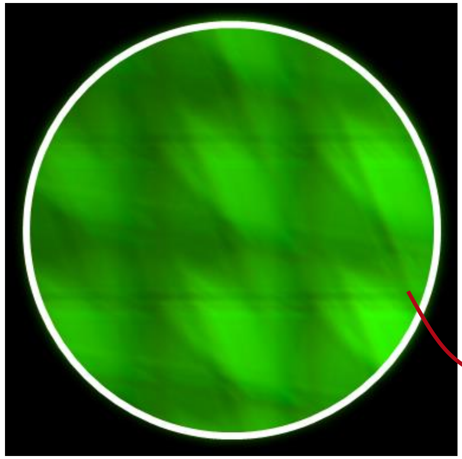
Excellent accuracy-speed balance for MTF calculation!

Simulation Time: 2.5 min

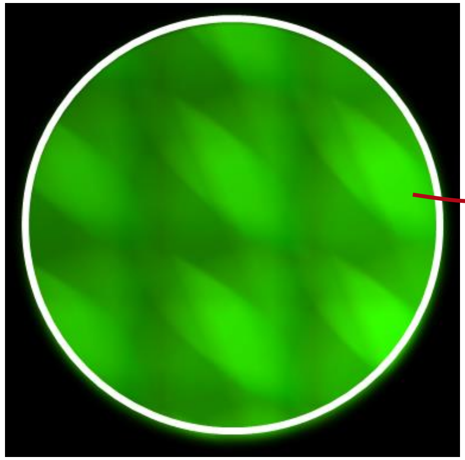
sample file: "03a Irradiance & MTF Time Model w Diffraction.os"

Summary & Conclusion

Irradiances in Pupil and MTFs

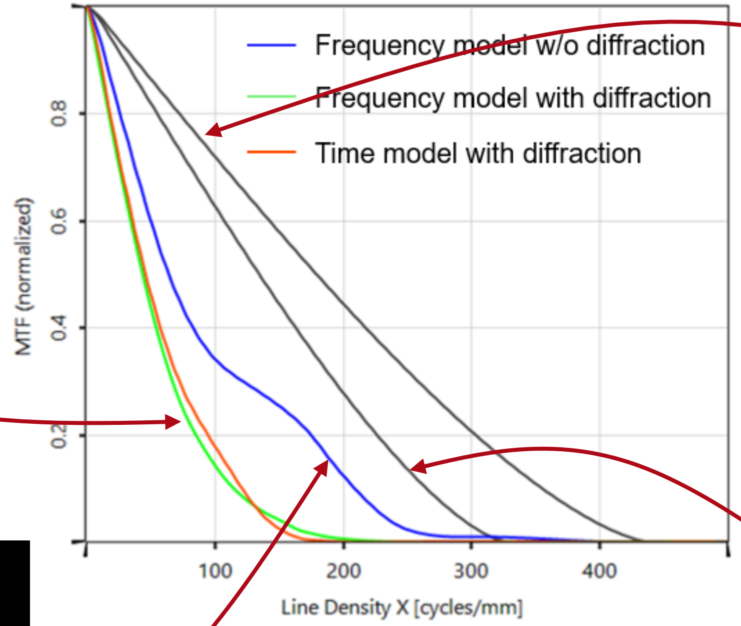


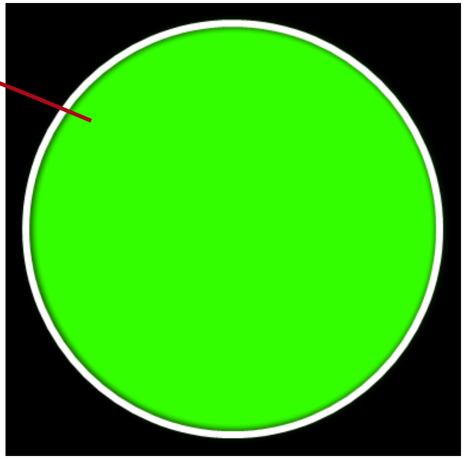
Partially coherent, with diffraction



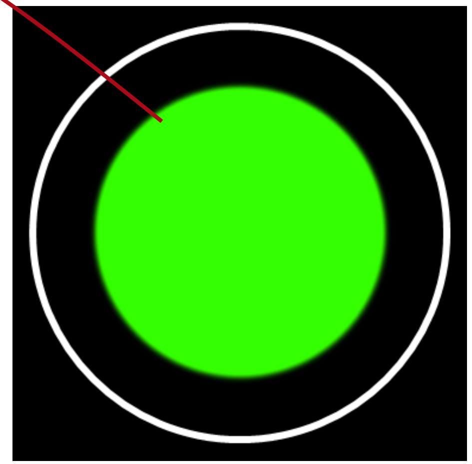
Partially coherent, without diffraction

$\Delta\lambda = 10\ \text{nm}$



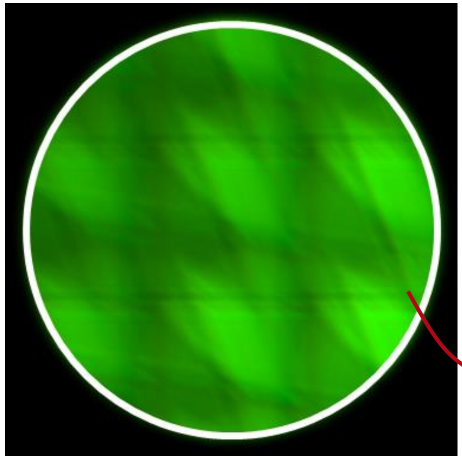


Coherent, uniform, 4 mm



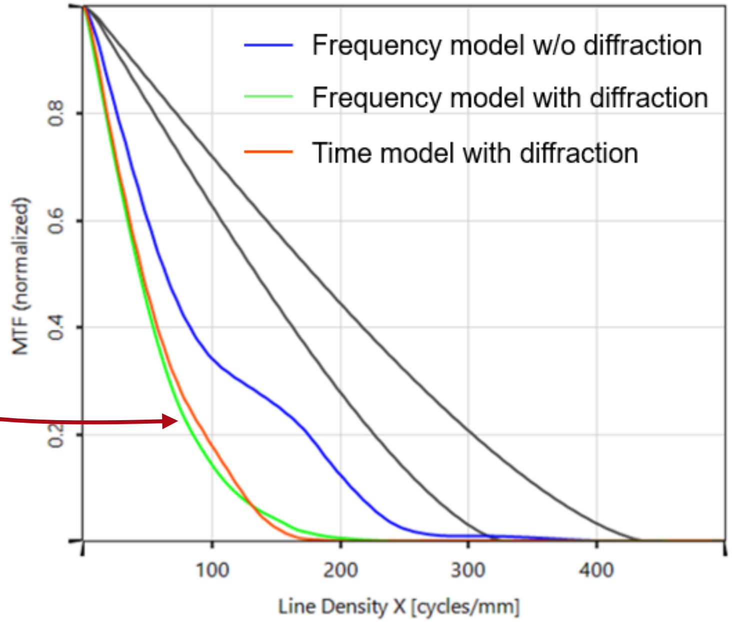
Coherent, uniform, 3 mm

Irradiances in Pupil and MTF: Simulation and Measurement



Partially coherent, with diffraction

$\Delta\lambda = 10\ \mathrm{nm}$



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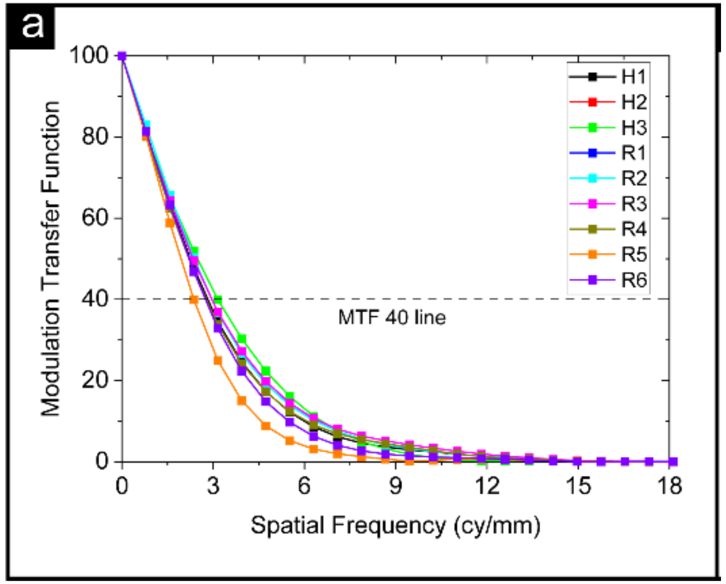
Measurements (different layout)



Conclusion:
For the adequate modeling of the optical performance, such as PSF and MTF, of grating-based waveguides, diffraction and coherence effects must be considered! In order to be able to model complex optical systems accurately and fast, highly interoperable modeling techniques on a single platform are a necessity. This also allows for a detailed control of the accuracy and speed balance.

Document Information

title	MTF Analysis in Complex Waveguide Devices
document code	LIG.0018
document version	2.1
software version	2023.2 (Build 1.146)
software edition	• VirtualLab Fusion Advanced • Light Guide Toolbox Gold Edition
category	Application Use Case
further reading	• Grating Analysis and Smoothly Modulated Grating Parameters on Lightguides • Uniformity Detector for Lightguide Systems • Light Guide Layout Design Tool • Flexible Region Configuration • How to Set Up a Lightguide with Real Grating Structures