LightTrans

EPIC Meeting on Photonics for AR/VR/MR:

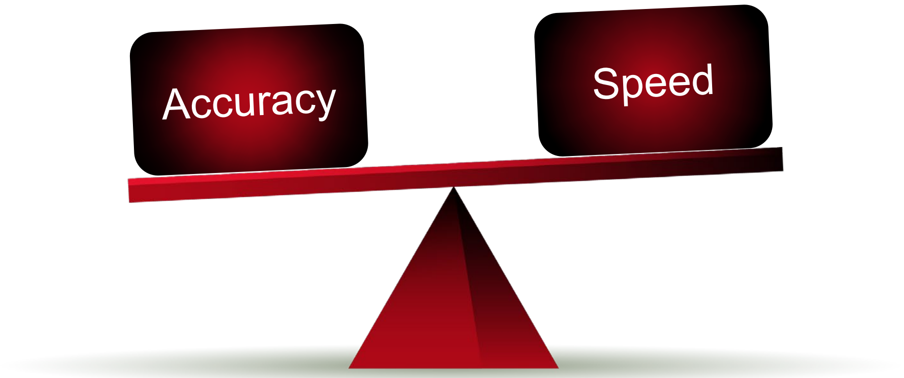
From Design to System Integration and Mass Production at Jabil Optics

Demands and Solutions for Modeling and Design Techniques of AR/VR Glasses

Frank Wyrowski, Christian Hellmann, Stefan Steiner

"It is all about accuracy and speed."

Developer of AR/VR glasses at Meta about modeling and design software.

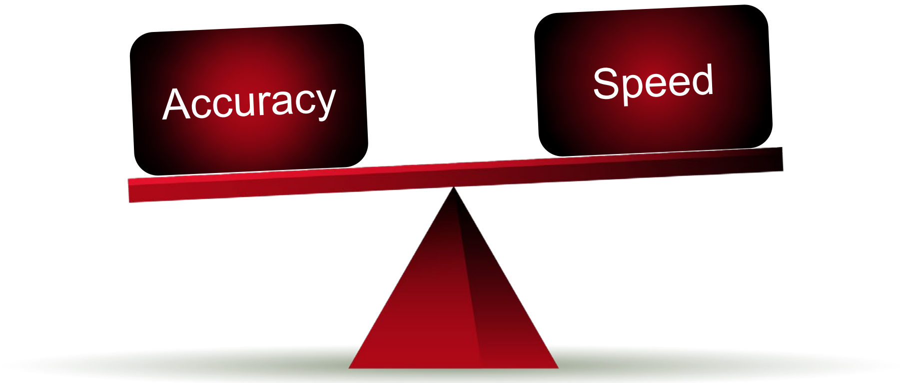


As accurate as needed.
As fast as possible.

Control of the accuracy-speed balance

Major trend in the usage and development of optics software

High speed means short time to results.



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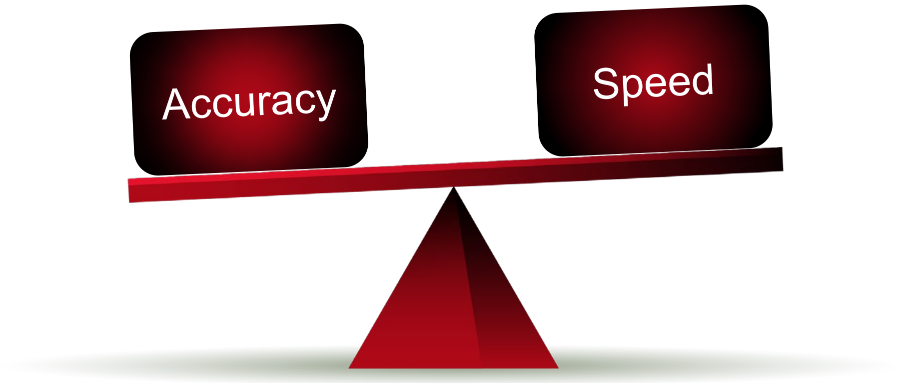
What means accuracy in optical modeling and design?



As accurate as needed.
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Major trend in the usage and development of optics software

Simulation Accuracy

The **simulation accuracy** depends on the algorithms used to model the reality.

Modeling of light sources, including, e.g., lasers, LEDs, LDs, VCSELs, thermal light sources, x-ray sources, and ultrashort pulses.

Modeling of components, including, e.g., lenses, freeform surfaces, Fresnel lenses, pancake lenses, GRIN lenses, metalenses, gratings, DOEs, crystals, apertures, prisms, fibers, scatterer, diffusers, micro lens arrays, and SLMs.

Modeling of detectors, including, e.g., aberrations, PSF/MTF, beam parameters, radiometry, photometry, colorimetry, and ultrashort pulse diagnostic.

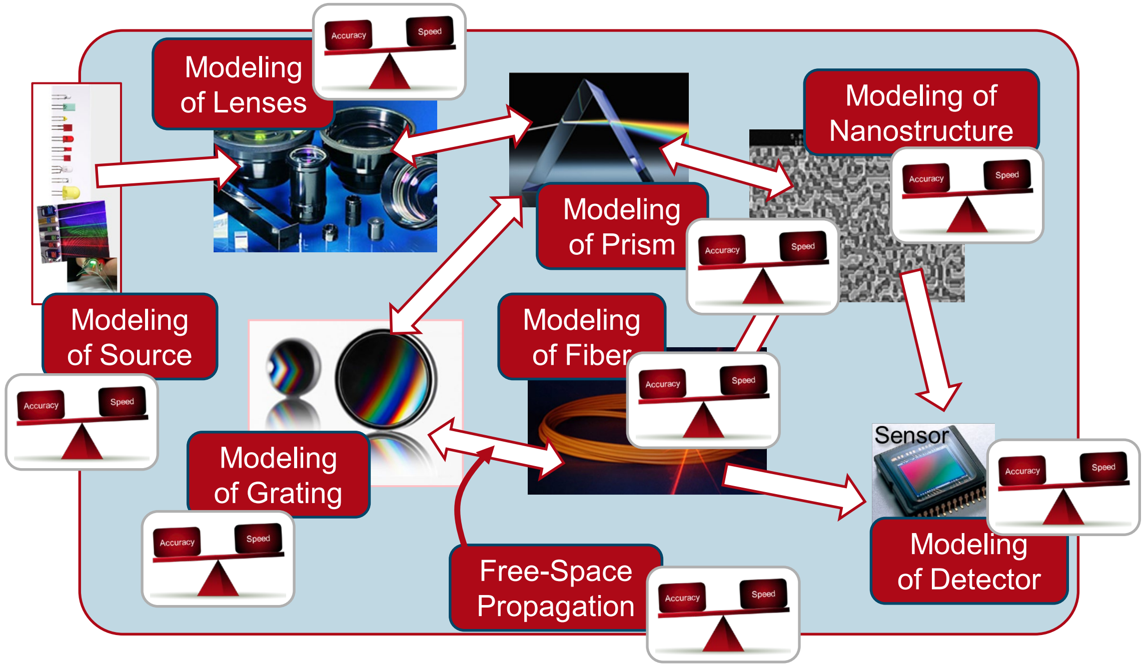
Modeling of optical effects, including, e.g., aberrations, energy redistribution, diffraction, scattering, interference, speckles, polarization, coherence, and spatiotemporal evolution.

Pool of Interoperable Modeling Techniques

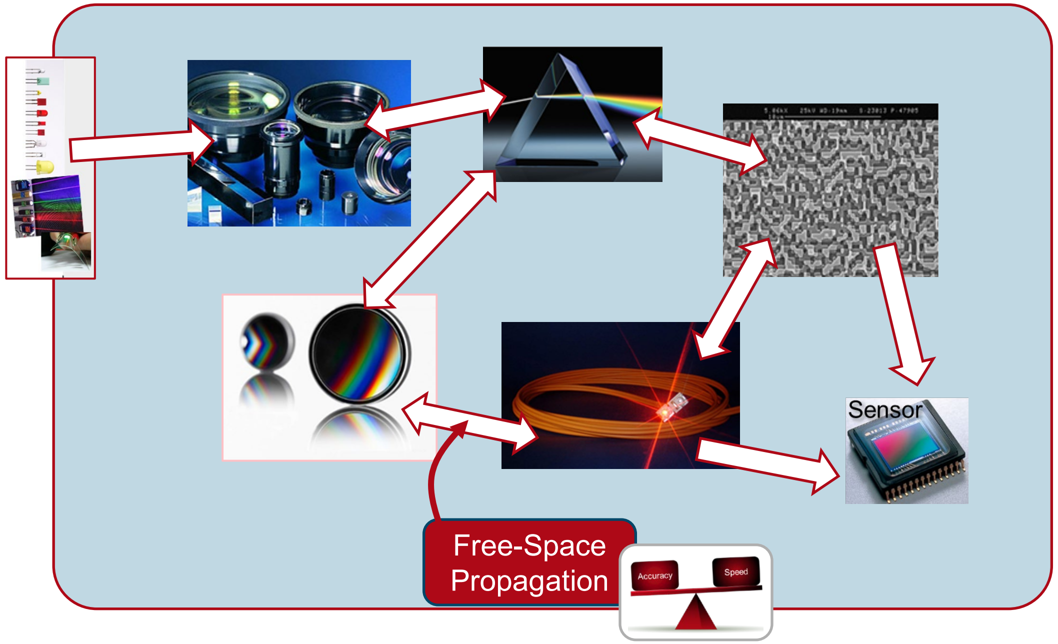
Each modeling and design task comes with a specific

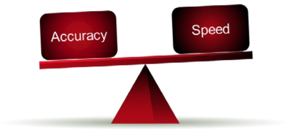
- selection of sources, components, and detectors, and
- preferences regarding the accuracy-speed balance.

Software must provide modeling techniques per source, component, and detector, with options for controlling the accuracy-speed balance.



Accuracy-Speed Balance of Free-Space Propagation Methods





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	

Easy Control of Free-Space Propagation in VirtualLab Fusion

Forward FFT	☑
Forward SFT	☑
Forward PFT	☐
Inverse FFT	☑
Inverse SFT	☑
Inverse PFT	☐

Fast
Rayleigh-Sommerfeld
integral

Forward FFT	☑
Forward SFT	☑
Forward PFT	☐
Inverse FFT	☐
Inverse SFT	☐
Inverse PFT	☑

Generalized
Far-Field integral

Research Article
Vol. 29, No. 2 / 18 January 2021 / *Optics Express* 1774
Optics EXPRESS

Generalized far-field integral

ZONGZHAO WANG,[1,2,*] OLGA BALADRON-ZORITA,[1,2] CHRISTIAN HELLMANN,[3] AND FRANK WYROWSKI[1]

[1] *Institute of Applied Physics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany*
[2] *LightTrans International UG, Kahlaische Strasse 4, 07745 Jena, Germany*
[3] *Wyrowski Photonics GmbH, Kahlaische Strasse 4, 07745 Jena, Germany*

Forward FFT	☐
Forward SFT	☐
Forward PFT	☑
Inverse FFT	☑
Inverse SFT	☑
Inverse PFT	☐

Generalized
Debye integral

Research Article
Vol. 28, No. 17 / 17 August 2020 / *Optics Express* 24459
Optics EXPRESS

Generalized Debye integral

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[*] *zongzhao.wang@uni-jena.de*

Forward FFT	☐
Forward SFT	☐
Forward PFT	☑
Inverse FFT	☐
Inverse SFT	☐
Inverse PFT	☑

Geometric propagation

Research Article
Vol. 36, No. 9 / September 2019 / *Journal of the Optical Society of America A* 1551
Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

Isolating the Gouy phase shift in a full physical-optics solution to the propagation problem

OLGA BALADRON-ZORITA,[1,2,*] ZONGZHAO WANG,[1,2] CHRISTIAN HELLMANN,[2,3] AND FRANK WYROWSKI[1]

[1] Applied Computational Optics Group, Institute of Applied Physics, Friedrich Schiller University Jena, Max-Wien-Platz 1, 07743 Jena, Germany
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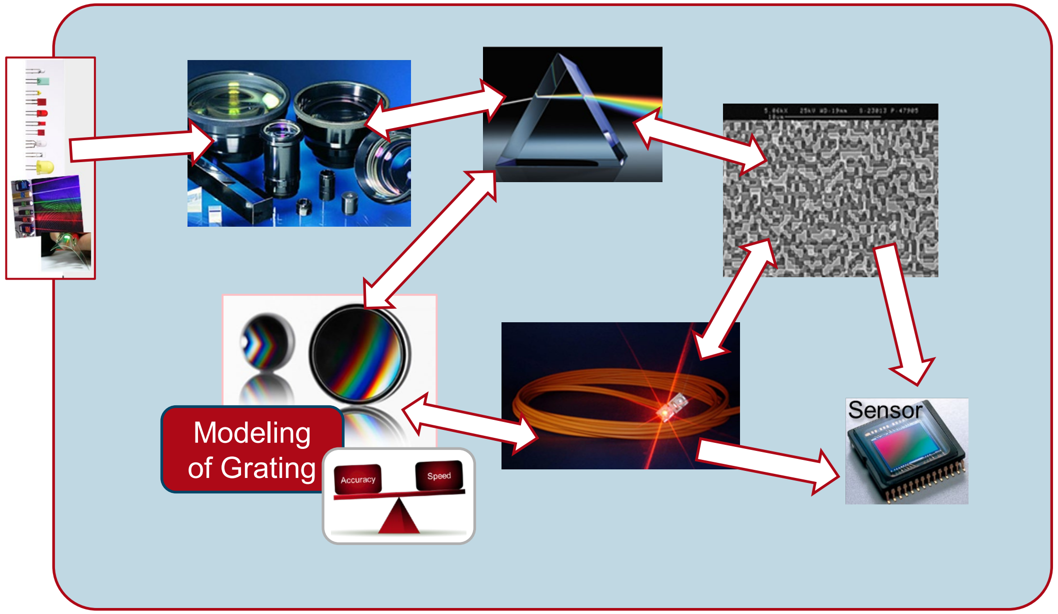
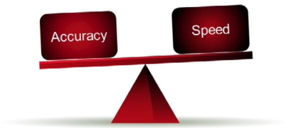
[*] Corresponding author: olga.baladron.zorita@uni-jena.de

Accuracy-Speed Balance of Grating Modeling Methods





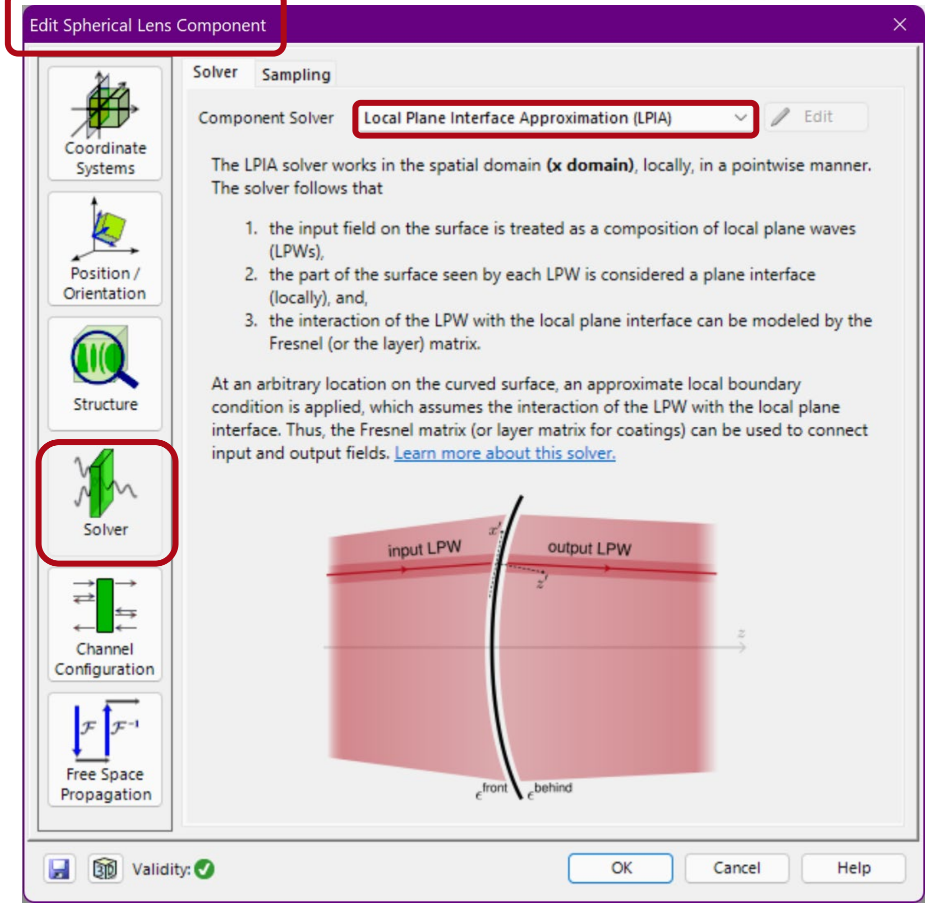
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Modal Method (FMM)	None	High	Low	Smaller periods lead to higher speed
Thin Grating Approximation	**Large periods & features, thin**	High	High	Thickness about wavelength; period & features larger than about ten wavelengths
	Otherwise	Low	High	
FMM 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	

Selected Components Come with Suitable Modeling Technique

Component Dialogue

Spherical Lens

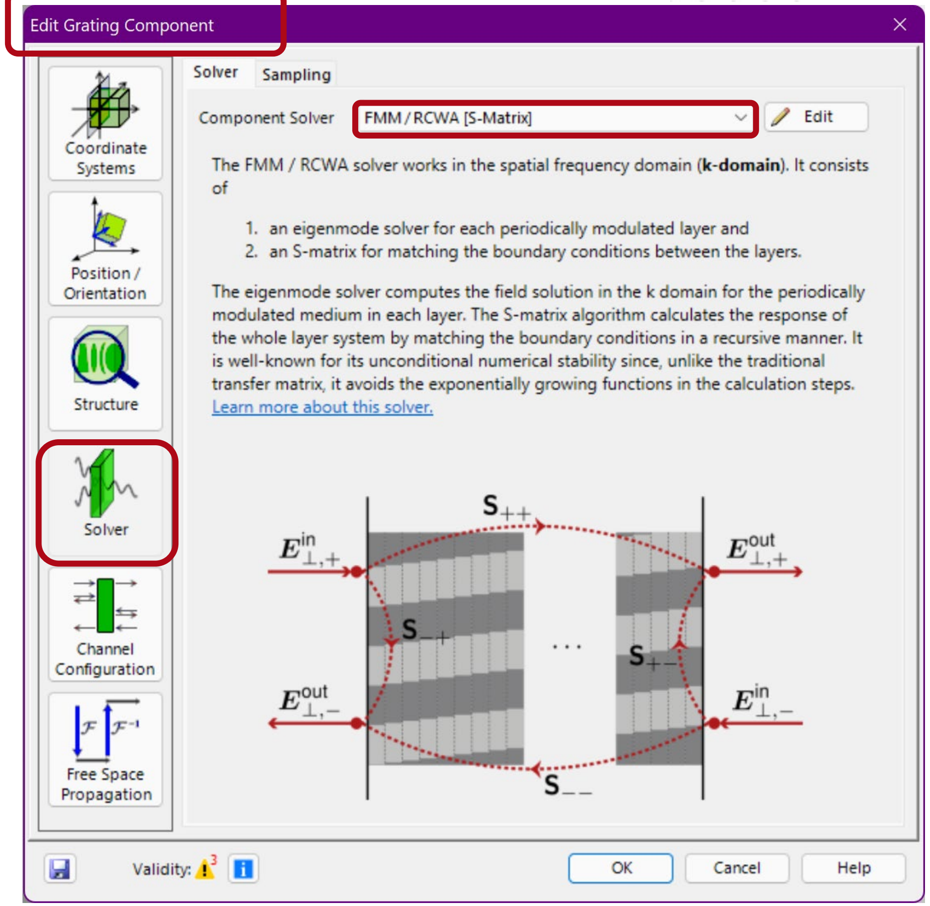
1



Component Dialogue

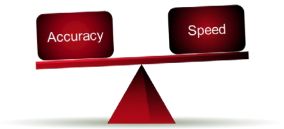
Grating

2



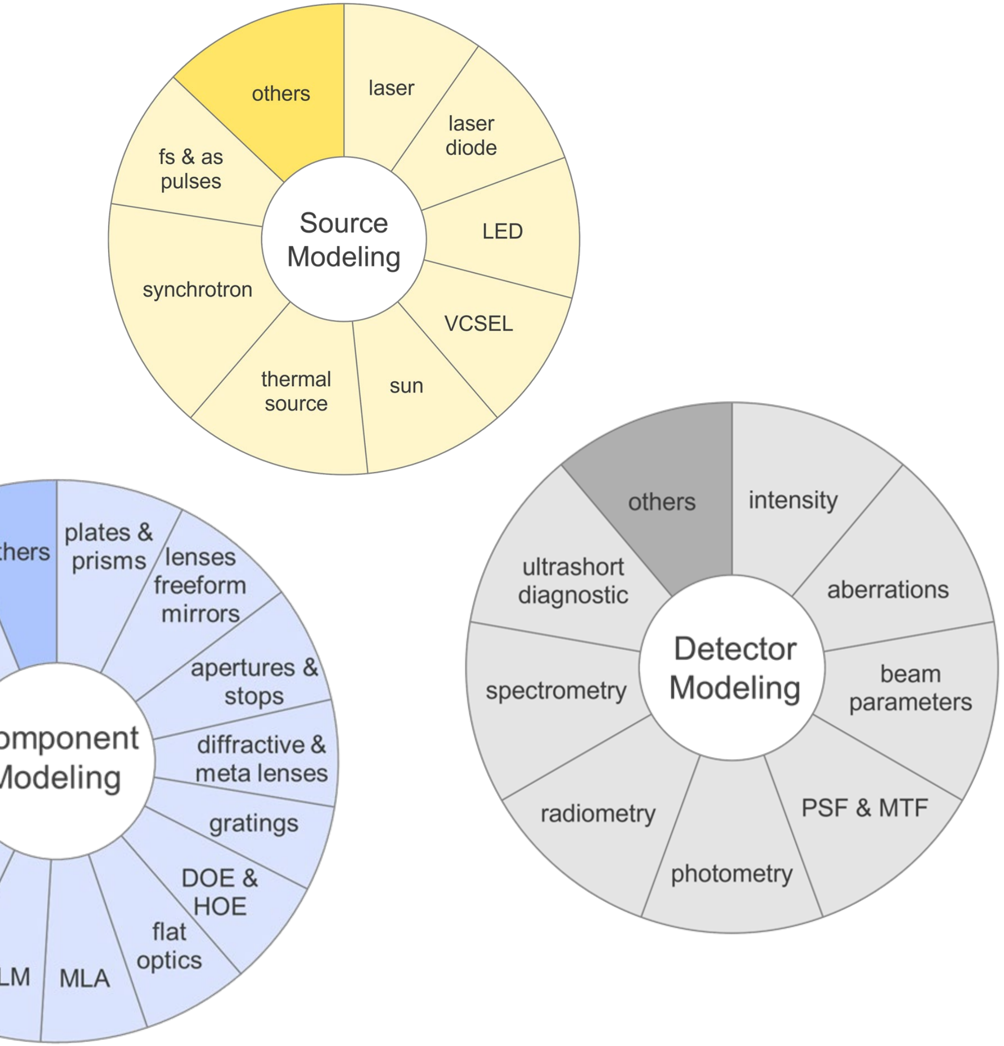
Pool of Interoperable Modeling Techniques

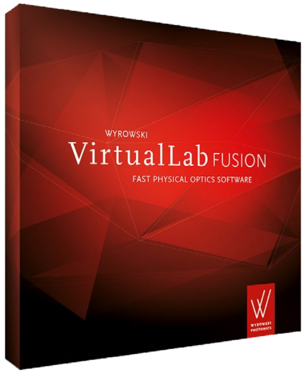
Control of accuracy-speed balance



Optics software should provide a

- Pool of many interoperable modeling techniques, and a
- Platform to connect them.



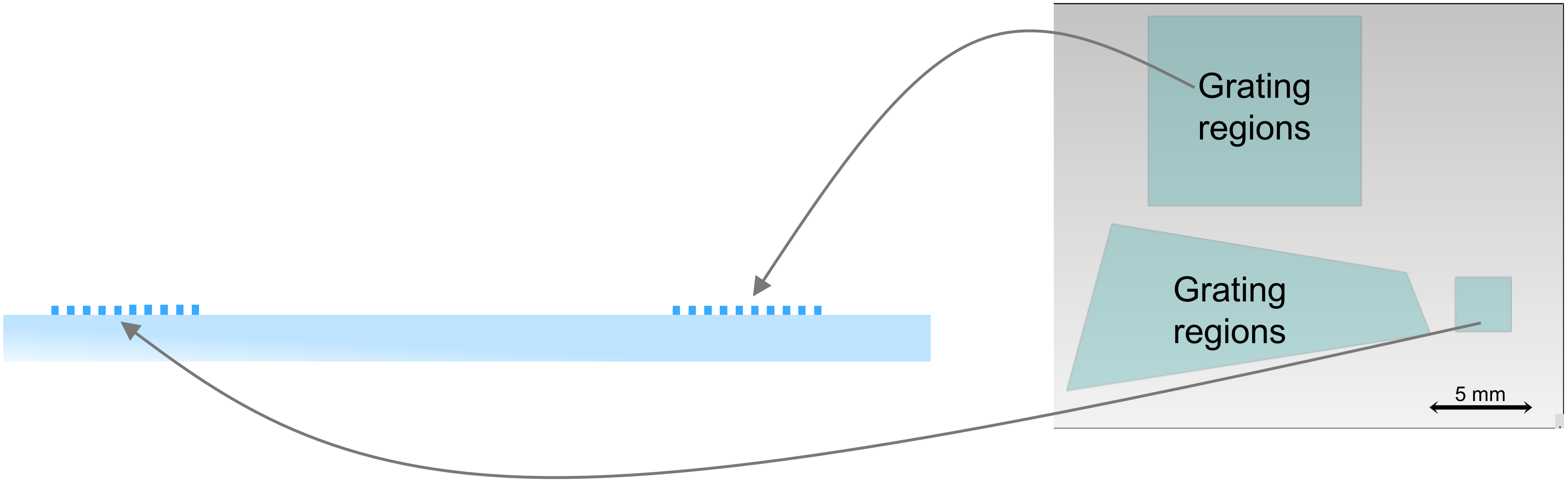


All simulations done with VirtualLab Fusion optics software

On the accuracy-speed balance in optical modeling and design of waveguide AR glasses

An application scenario

Application Scenario: HoloLens 1 – Type Layout



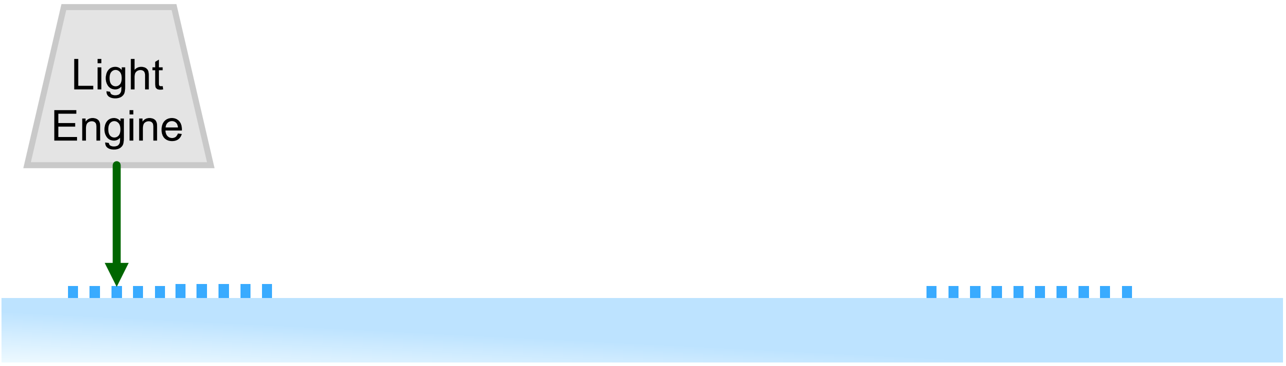
Connected Modeling Techniques: Source

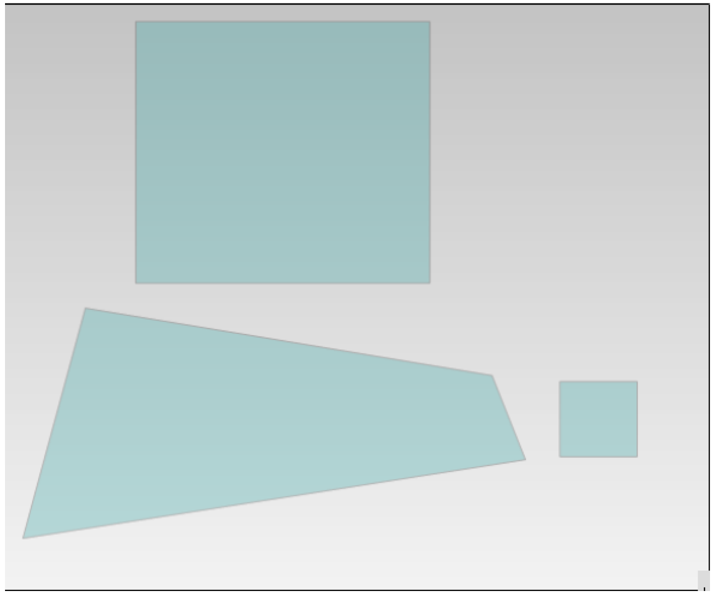
Light Engine Model

- Beam type: plane wave
- Beam radiusr $r = 1.5\,\mathrm{mm}$
- Polarization: Linearly polarized
- Wavelength: $\lambda = 530\,\mathrm{nm}$
- Bandwidth: $\Delta\lambda = 0\,\mathrm{nm}, 1\,\mathrm{nm}, 10\,\mathrm{nm}$

Bandwidth: $\Delta\lambda$

- Laser diode: some nanometers
- LED: some 10 nanometers





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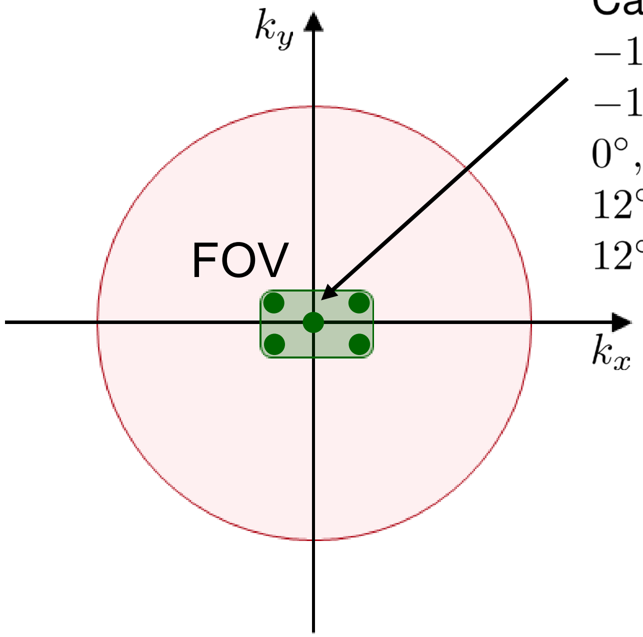
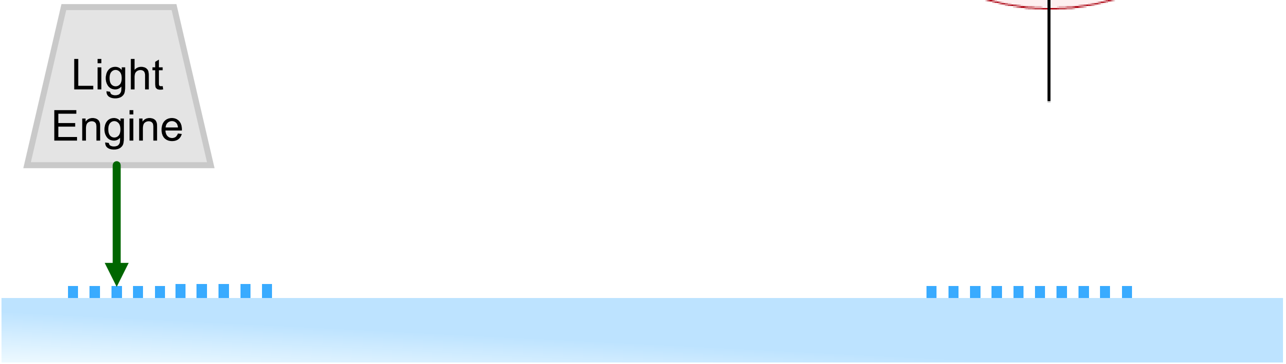
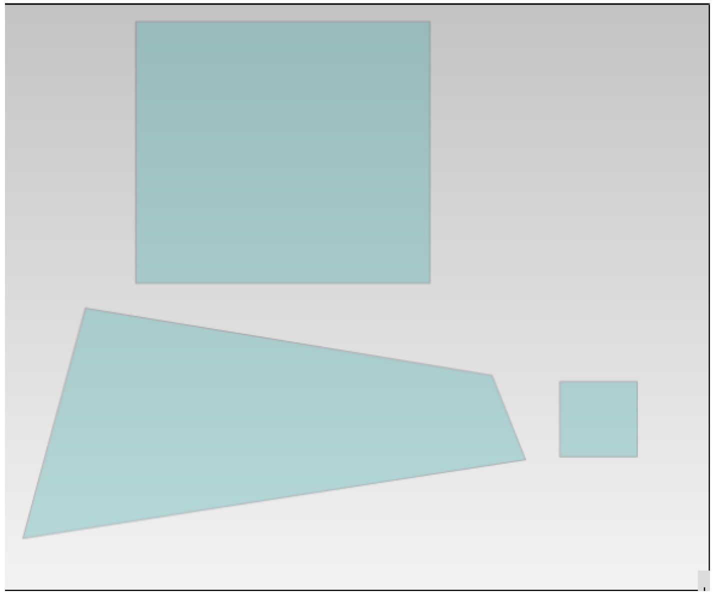


Cartesian angles (α, β)
$-12°, 7°$
$-12°, -7°$
$0°, 0°$
$12°, 7°$
$12°, -7°$





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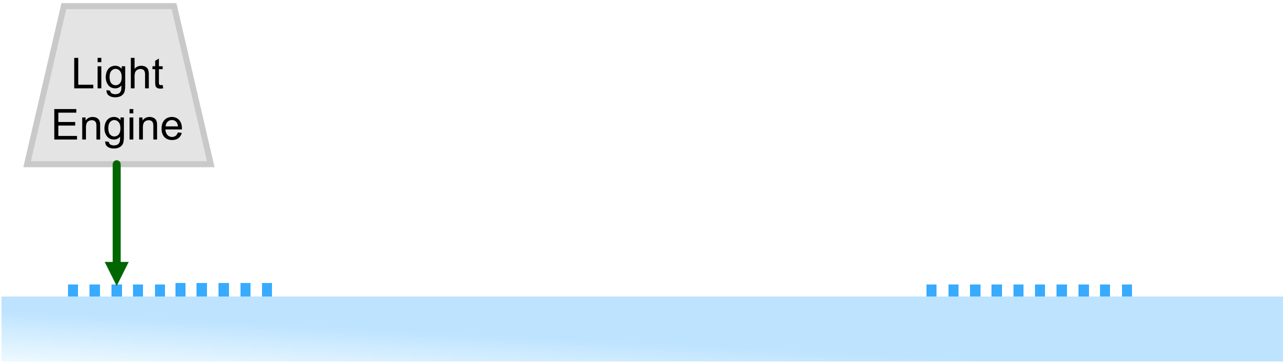
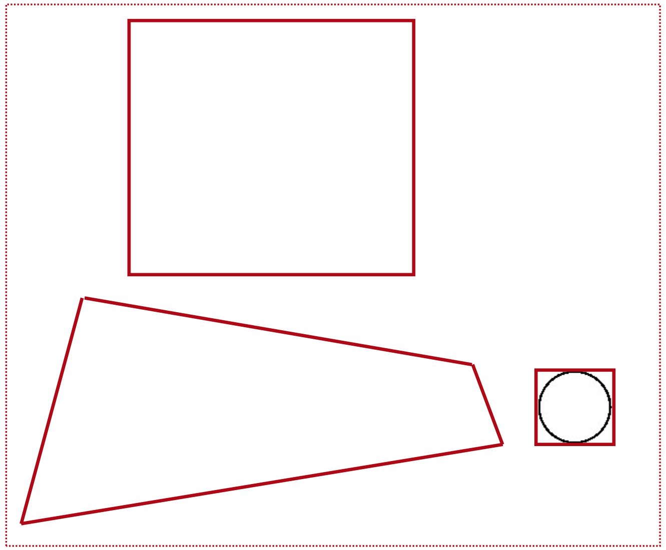
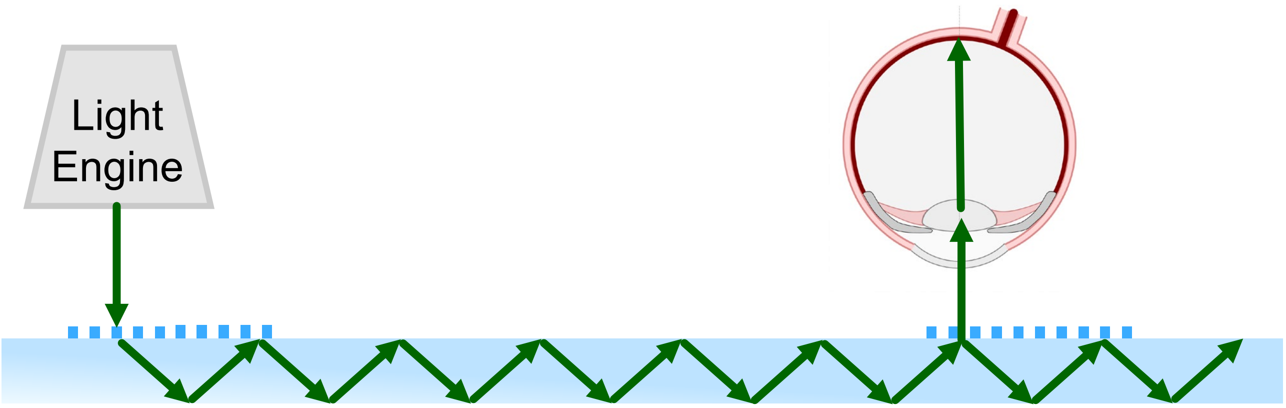


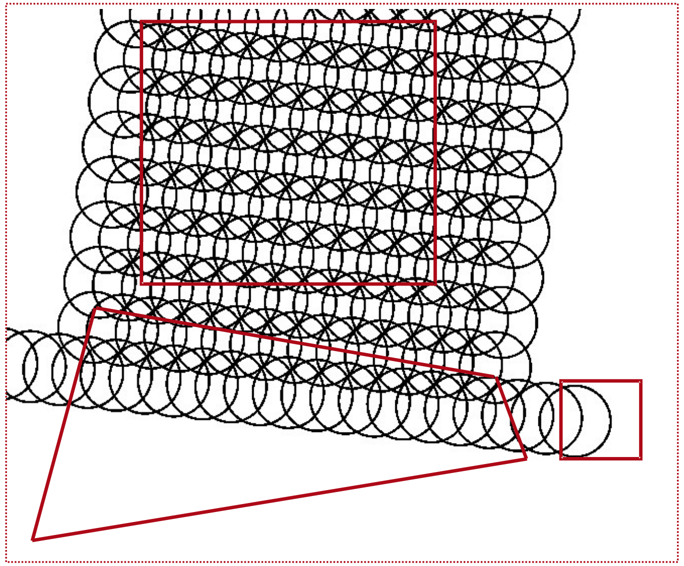


$D = 3\,\mathrm{mm}$

$(\alpha, \beta) = (12°, -7°)$

Connected Modeling Techniques: Beam Propagation





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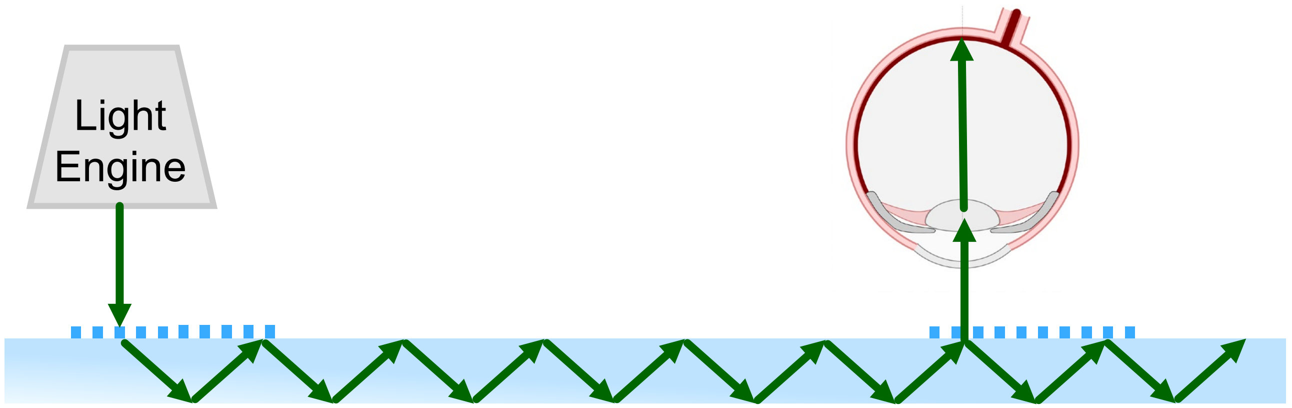
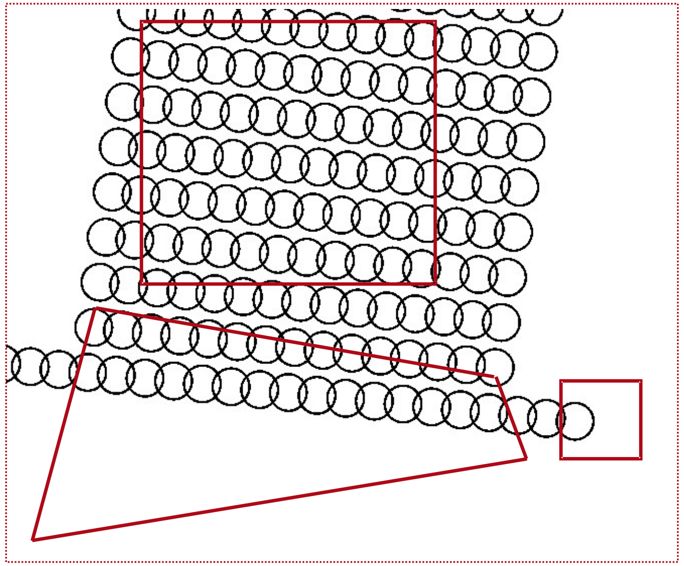
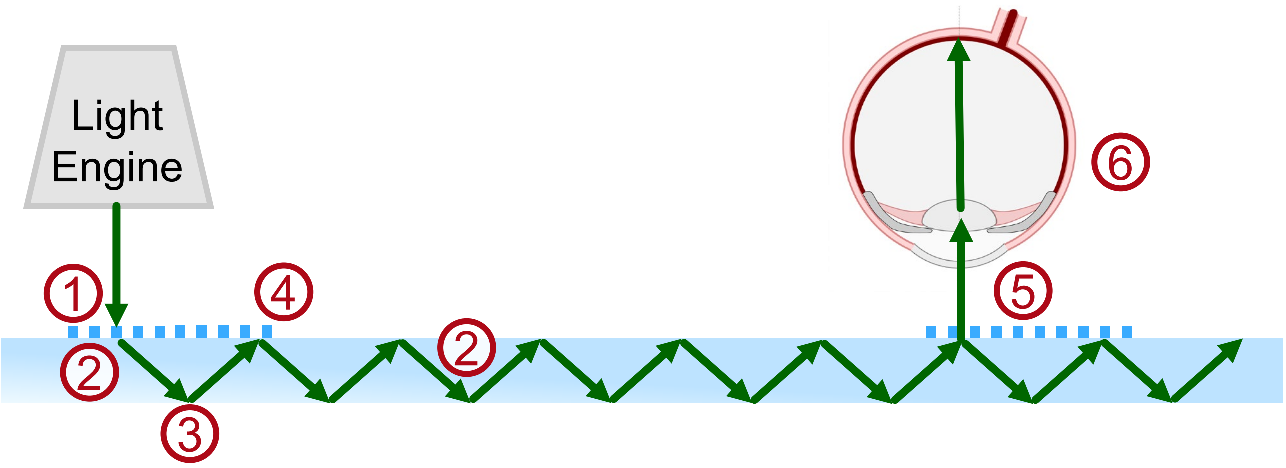
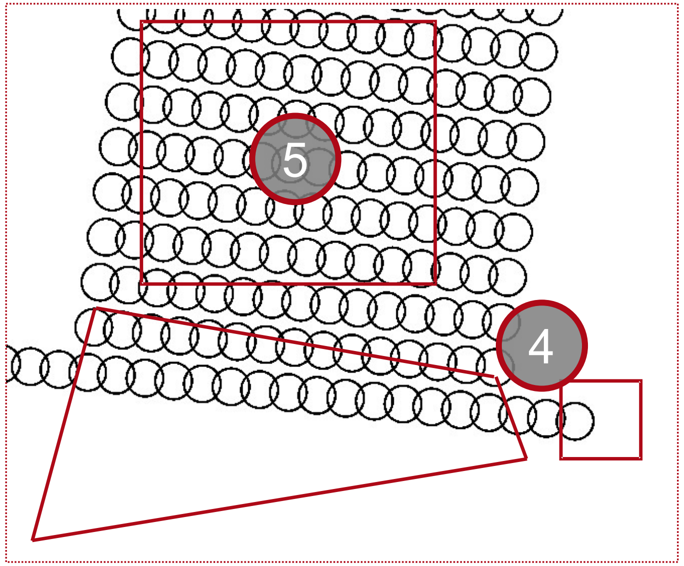




$$D = 1.6\,\text{mm}$$
$$(\alpha, \beta) = (12^\circ, -7^\circ)$$

Connected Modeling Techniques: Beam Propagation





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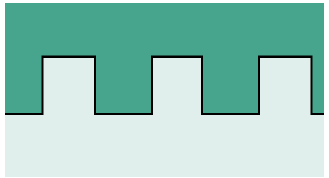
Connected Modeling Techniques: Grating

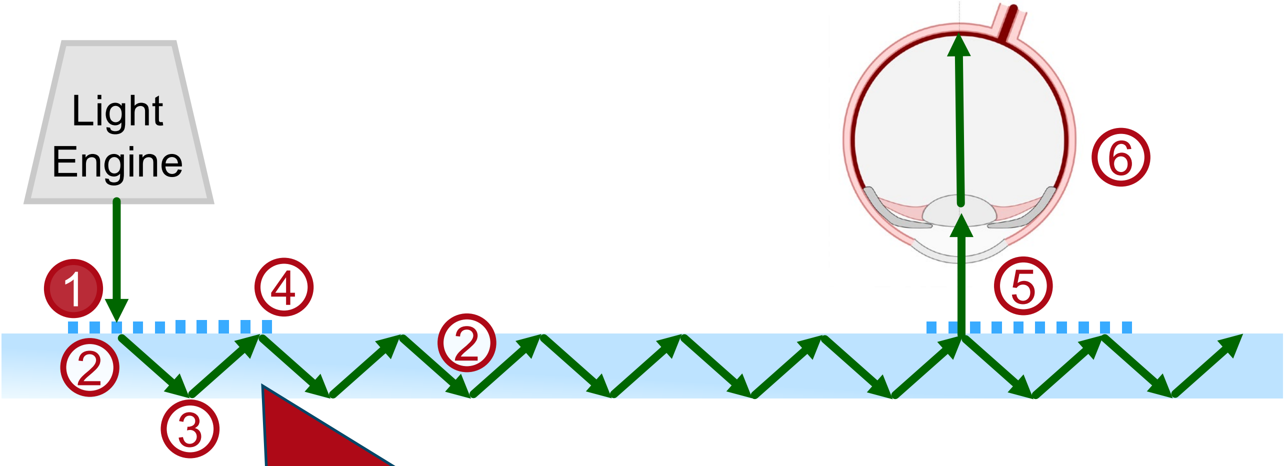
1 Grating model



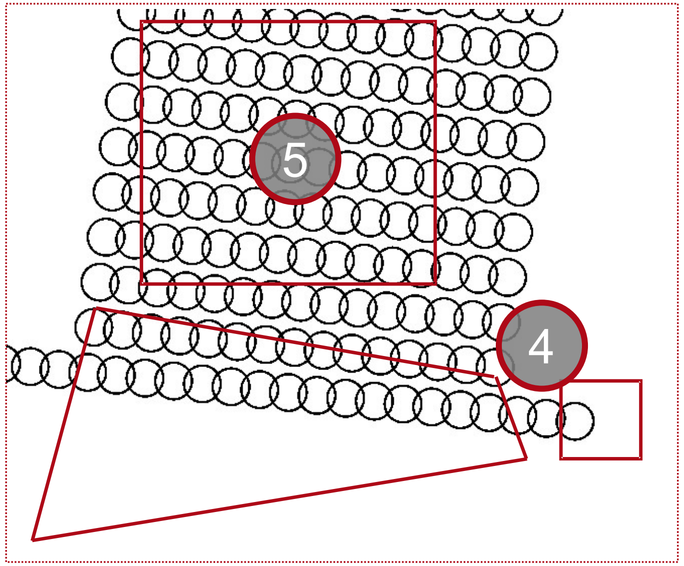
Grating types of interest:

- Binary
- Slanted
- Blazed
- Volume
- Anisotropic grating layers (liquid crystals)

Trend: increasing interest



Trend: higher index leads to anisotropic waveguides.



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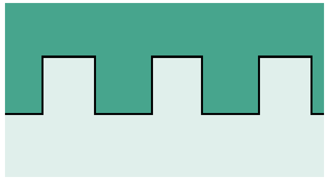
Connected Modeling Techniques: Grating

1 Grating model



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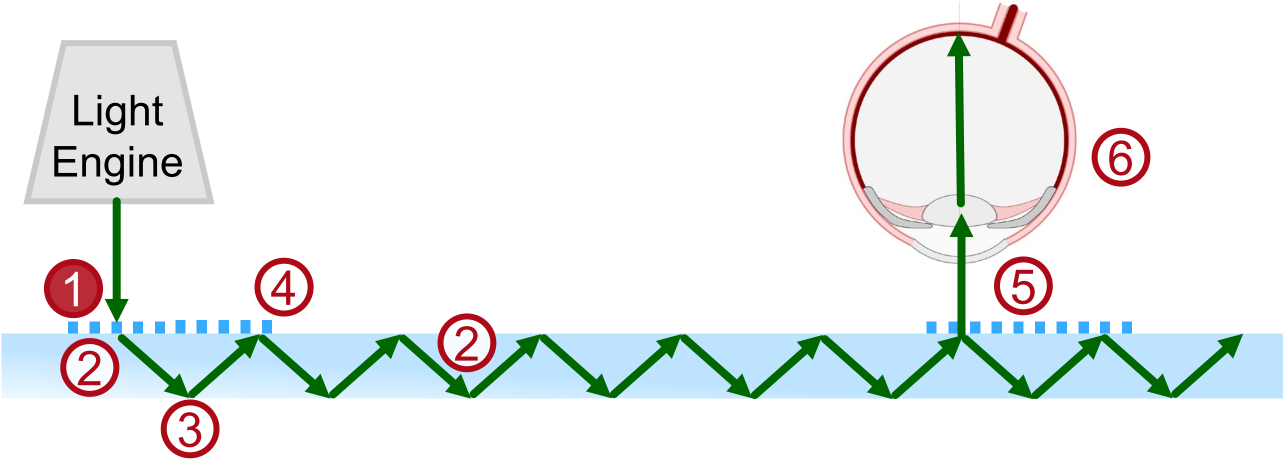

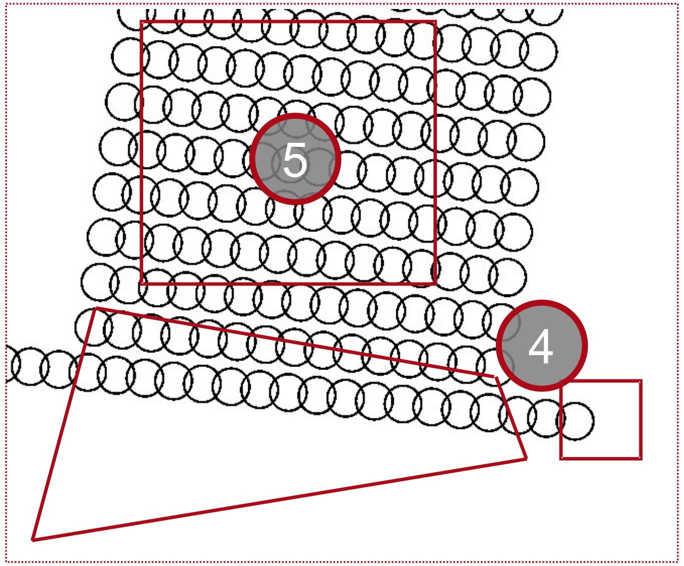

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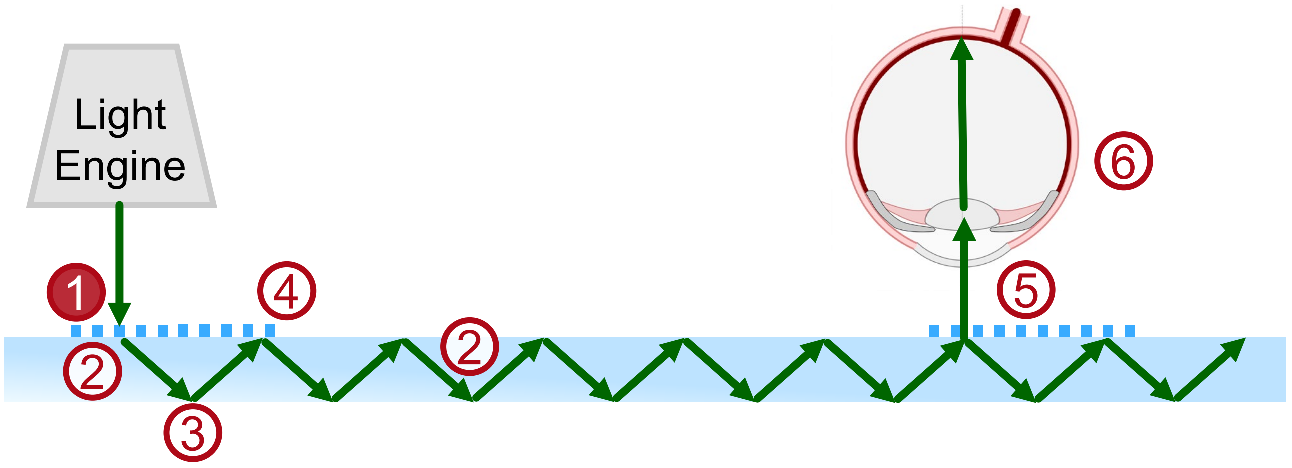
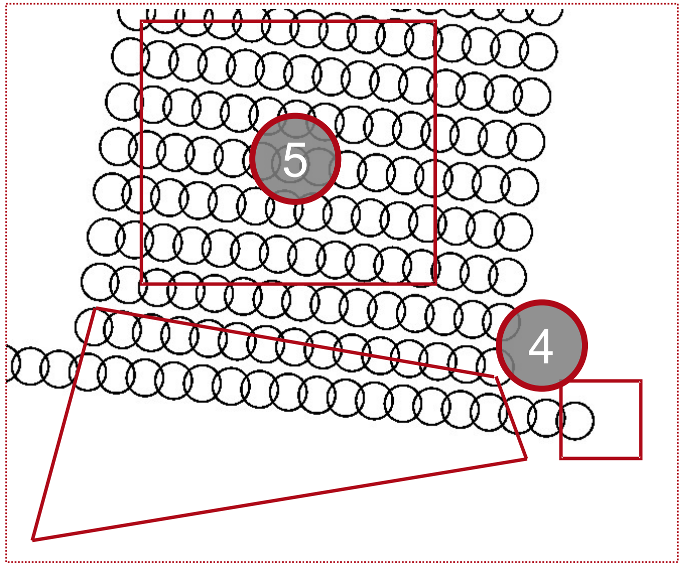
Connected Modeling Techniques: Grating

1

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	





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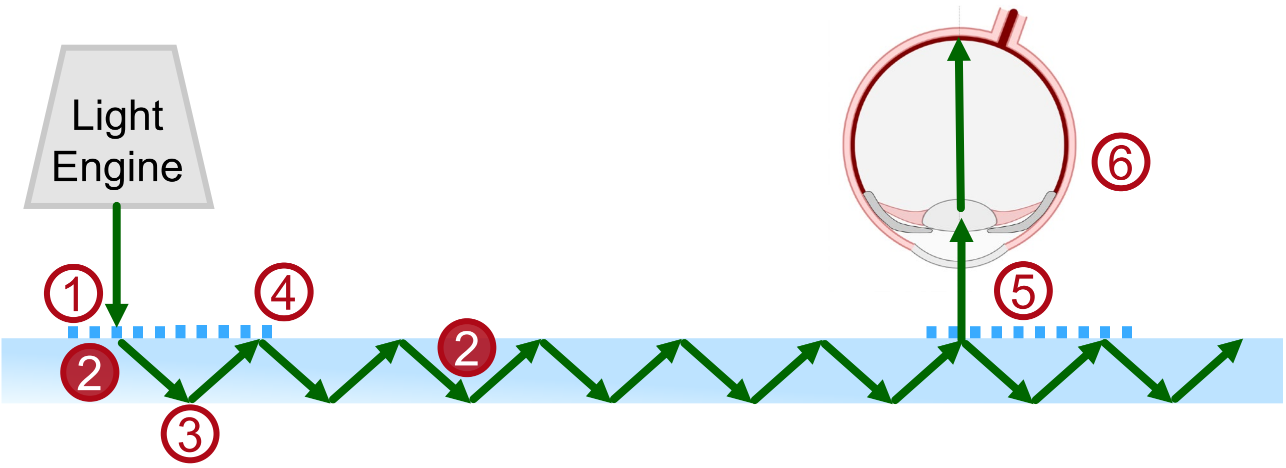
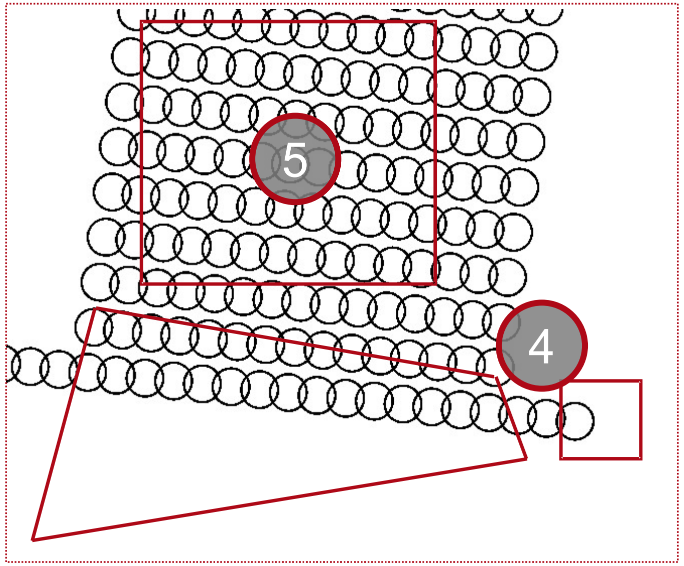
Connected Modeling Techniques: Inside Waveguide

2 Free-space propagation





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Connected Modeling Techniques: Inside Waveguide

2

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
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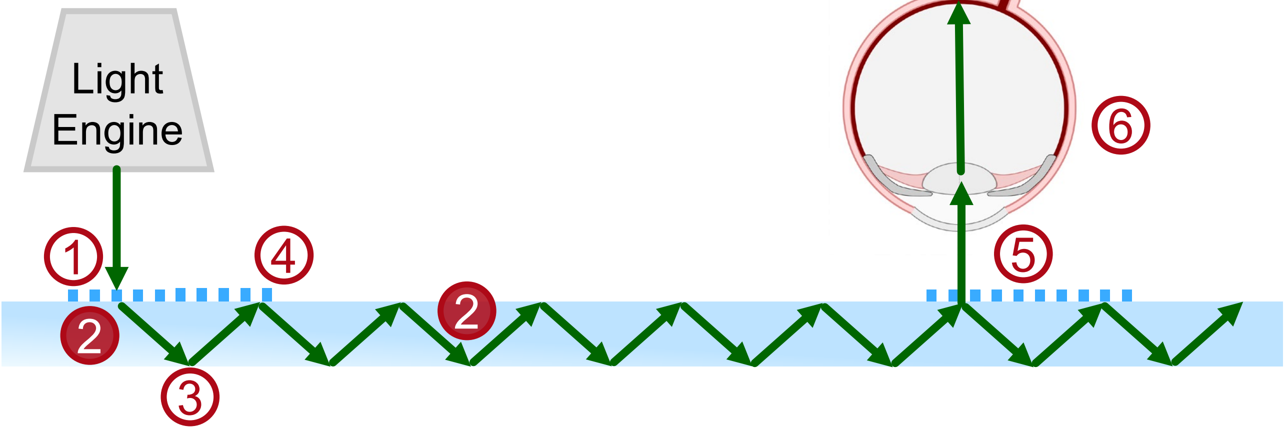

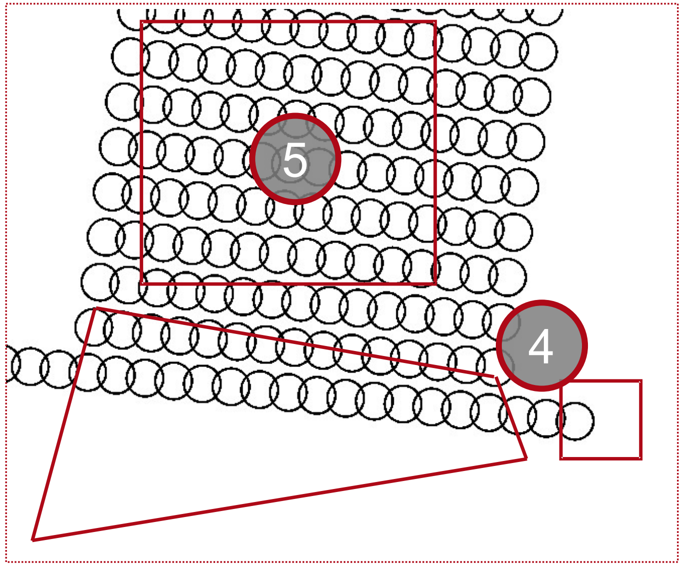

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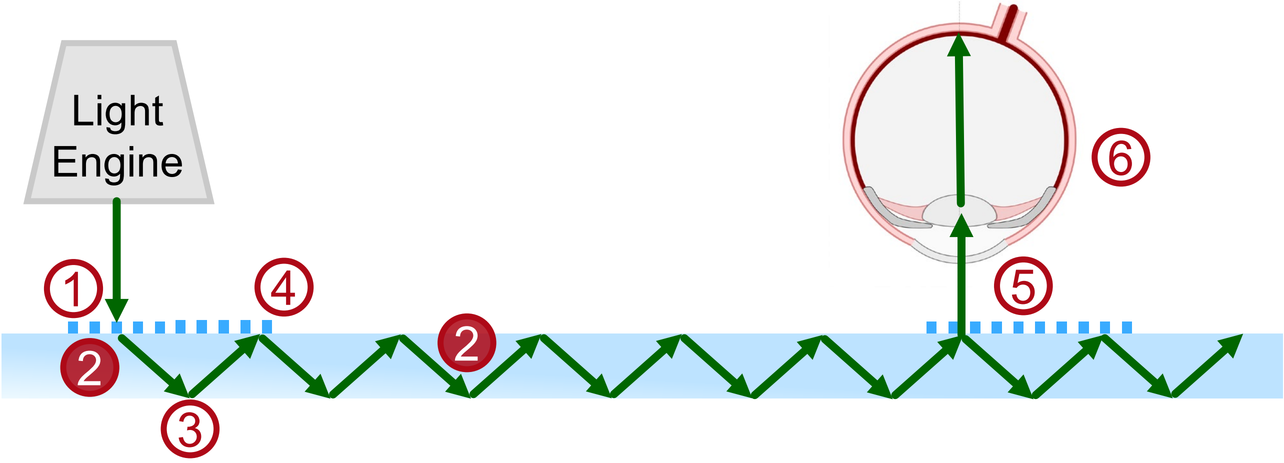

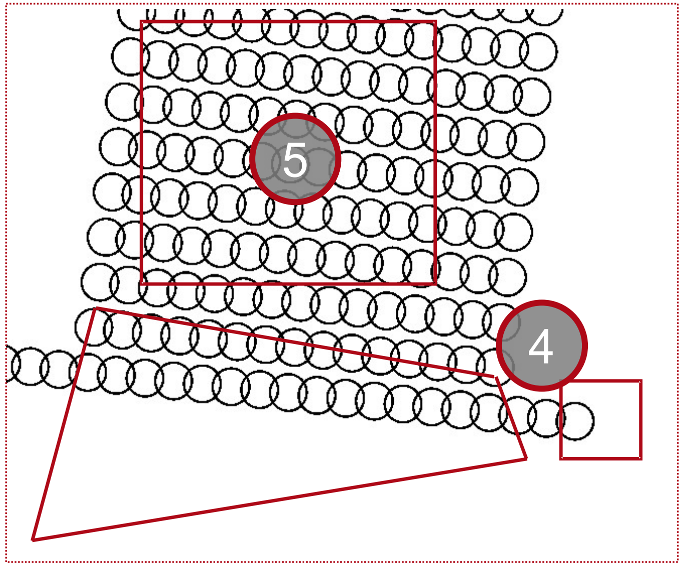

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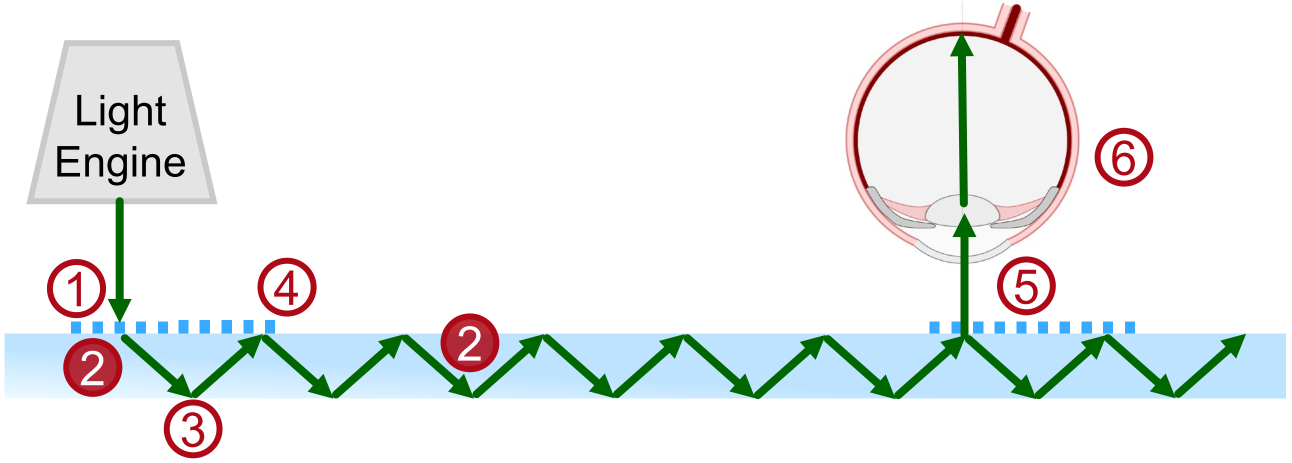
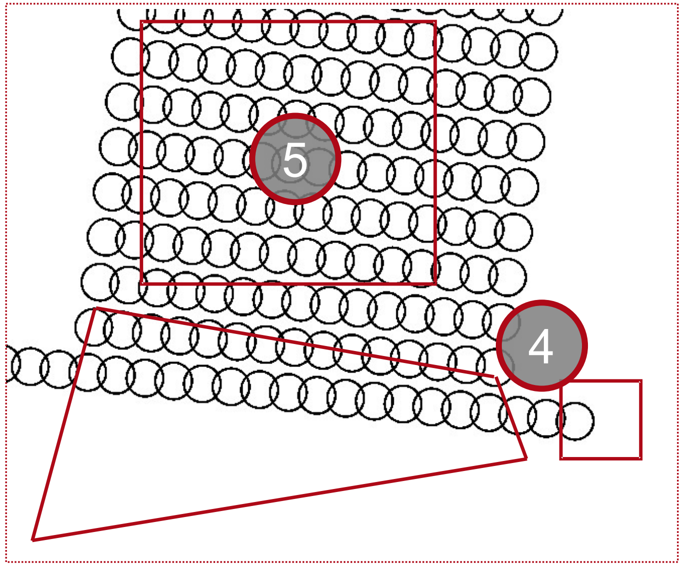
Selection of method must be decided with respect to modeling results!





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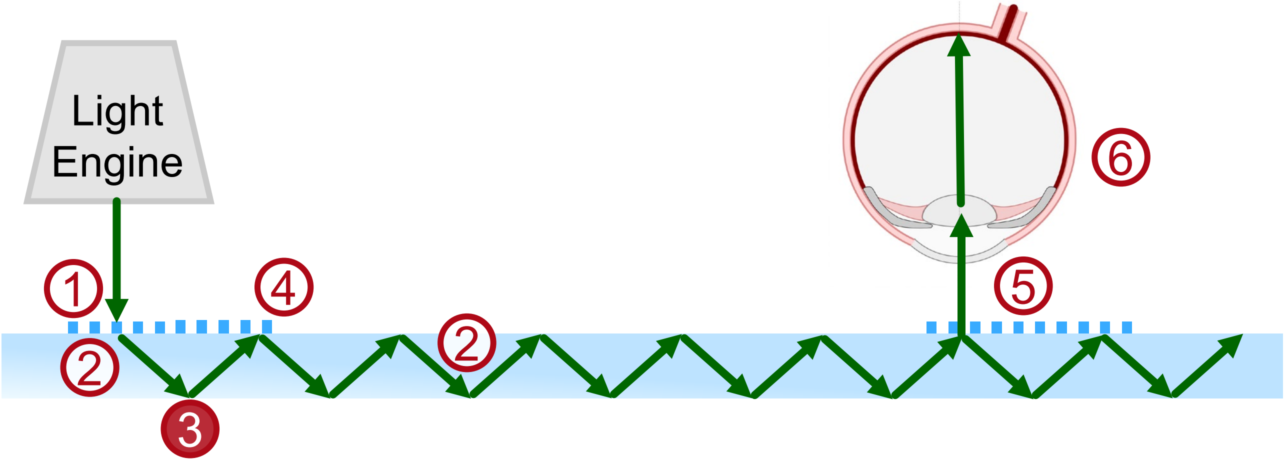
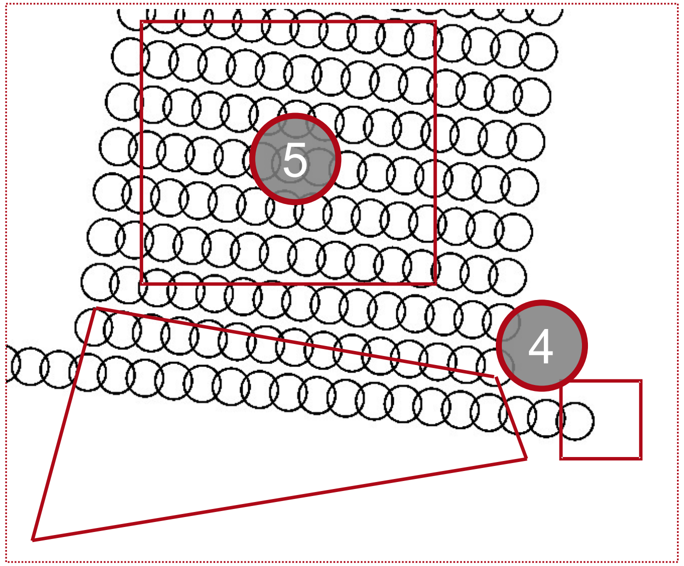
$(\alpha, \beta) = (12°, -7°)$

Connected Modeling Techniques: Waveguide Surfaces

3 Reflection at waveguide surfaces





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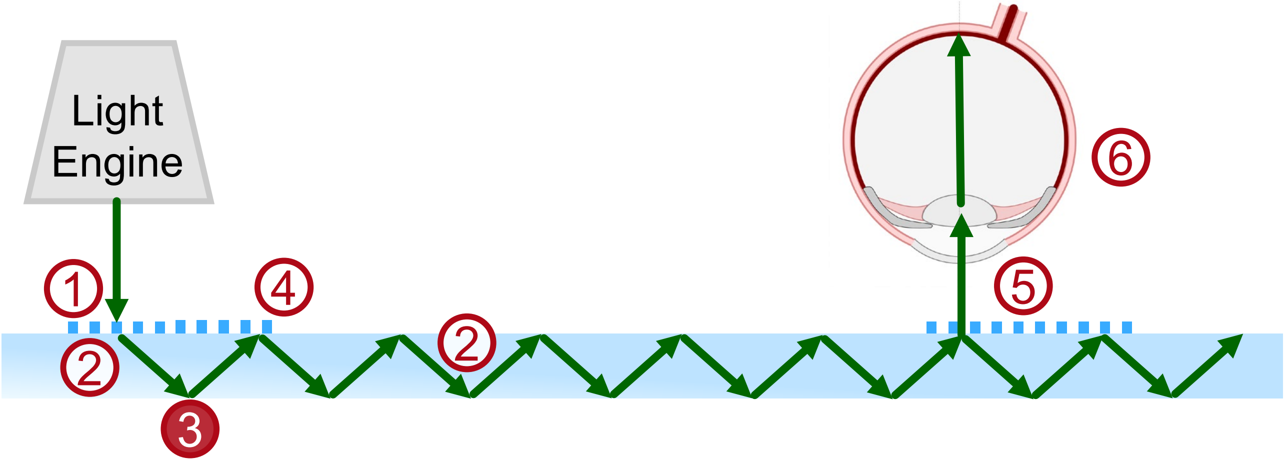
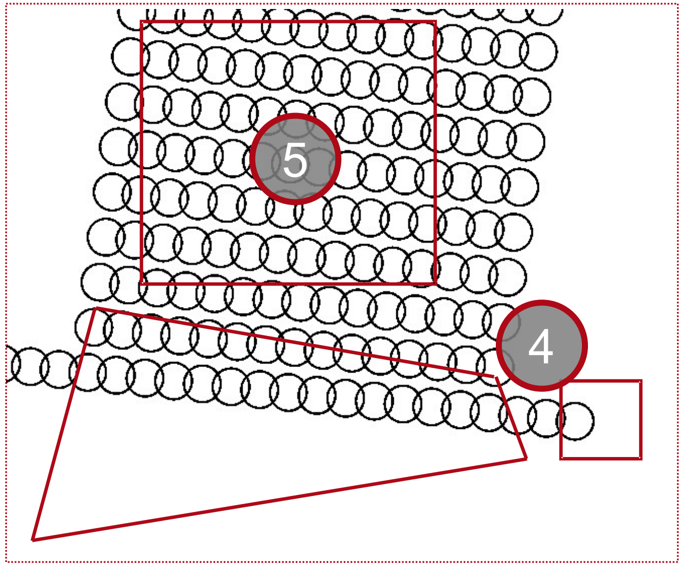
Connected Modeling Techniques: Waveguide Surfaces

3

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

Enables tolerancing



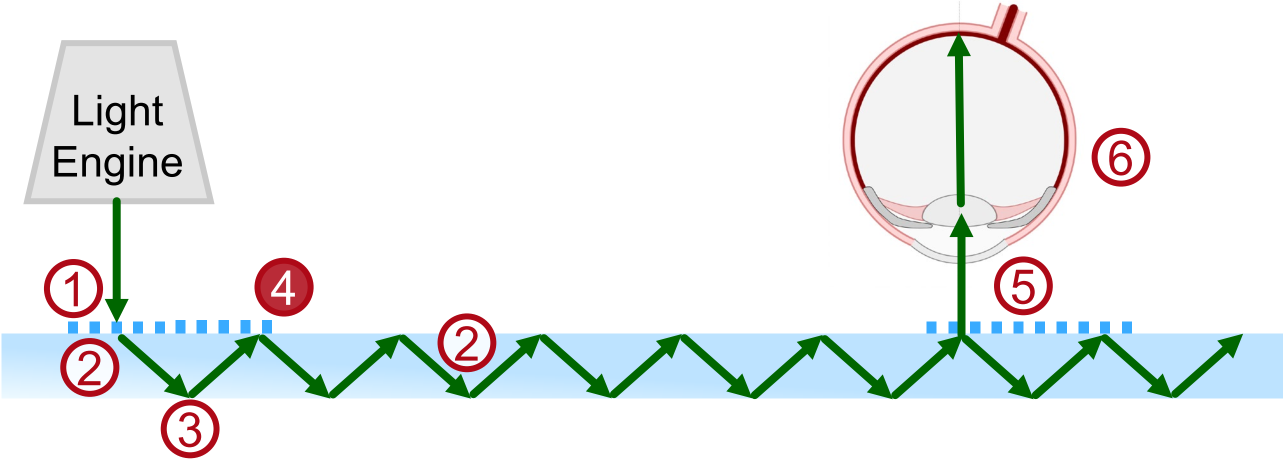


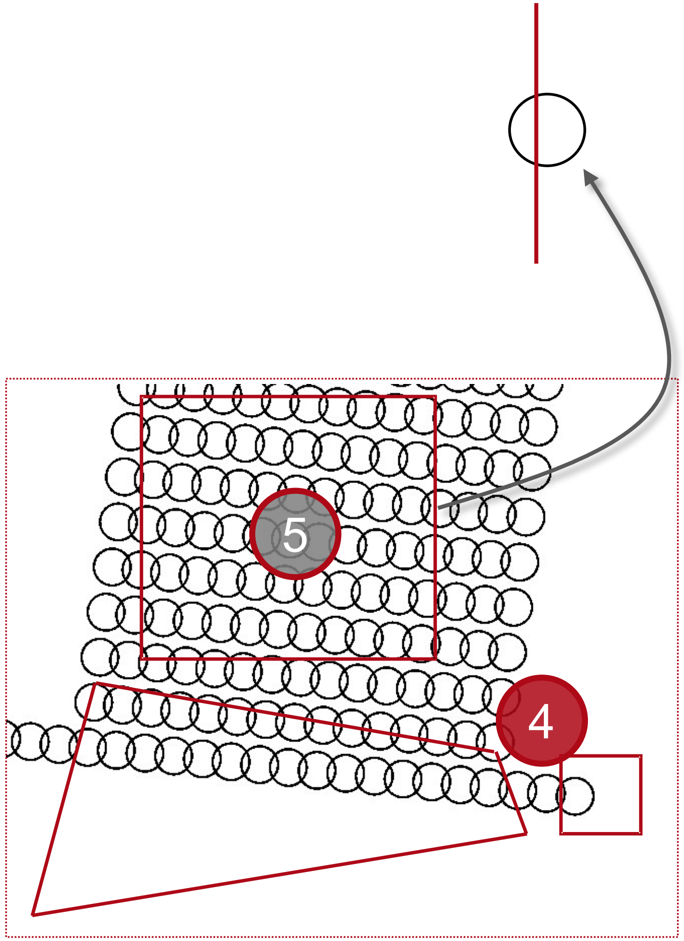
$D = 1.6\,\mathrm{mm}$

$(\alpha, \beta) = (12^\circ, -7^\circ)$

Connected Modeling Techniques: Region Boundaries

4 Region boundaries



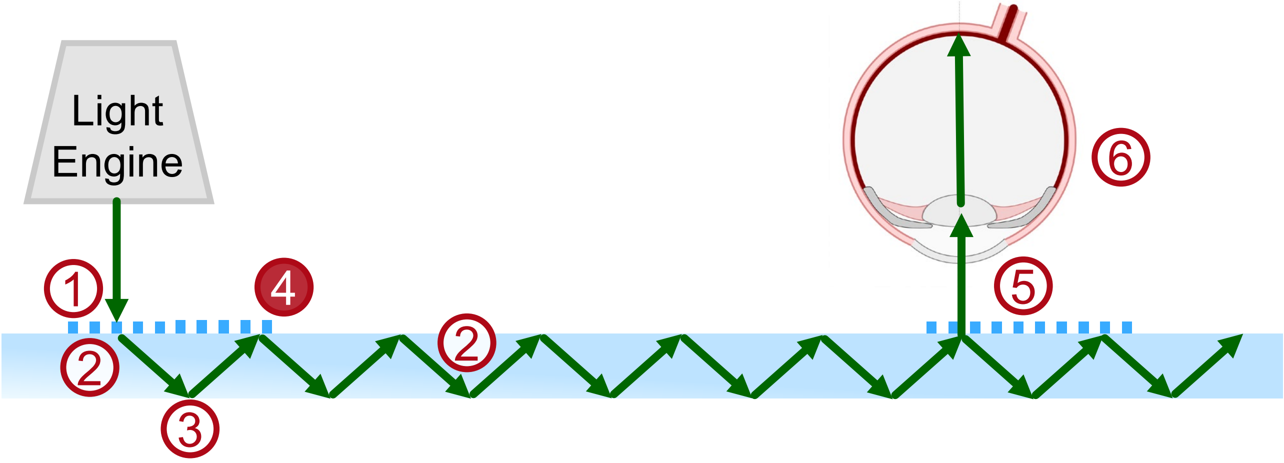


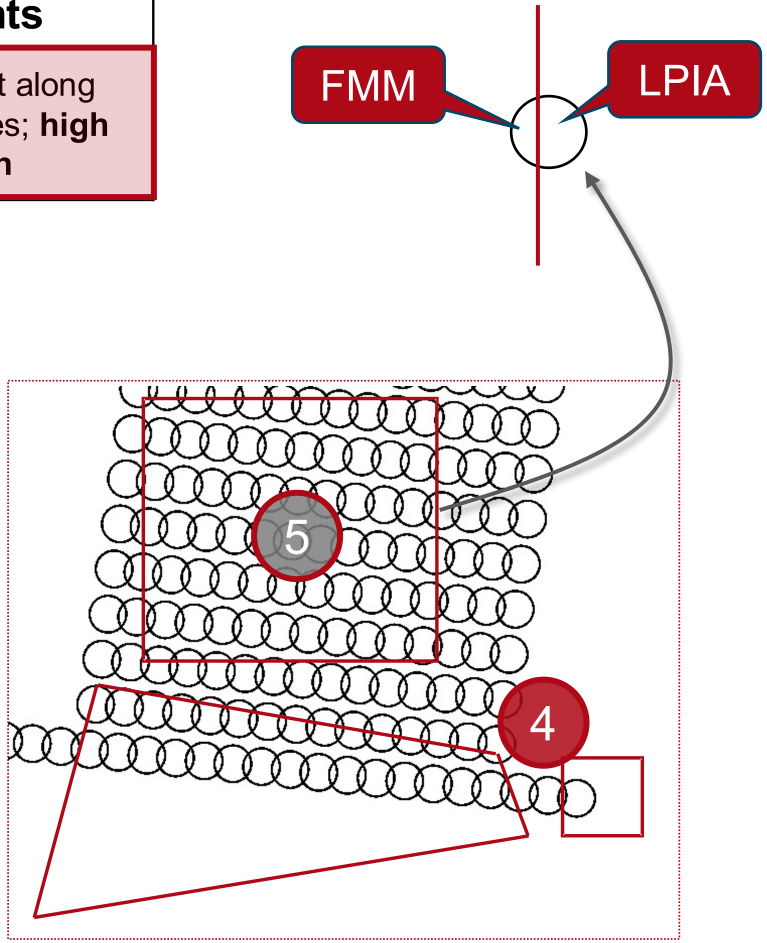
$D = 1.6\,\mathrm{mm}$
$(\alpha, \beta) = (12°, -7°)$

Connected Modeling Techniques: Region Boundaries

4

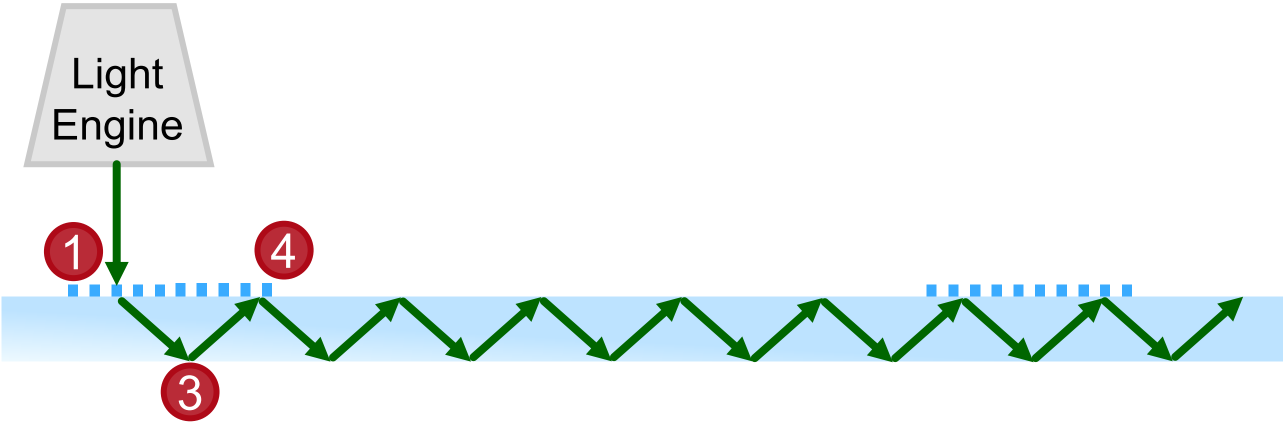
Methods	Preconditions	Accuracy	Speed	Comments
Local application of LPIA and FMM	Region extent not close to a few wavelengths	High	Very High	Beam profile cut along region boundaries; **high resolution**

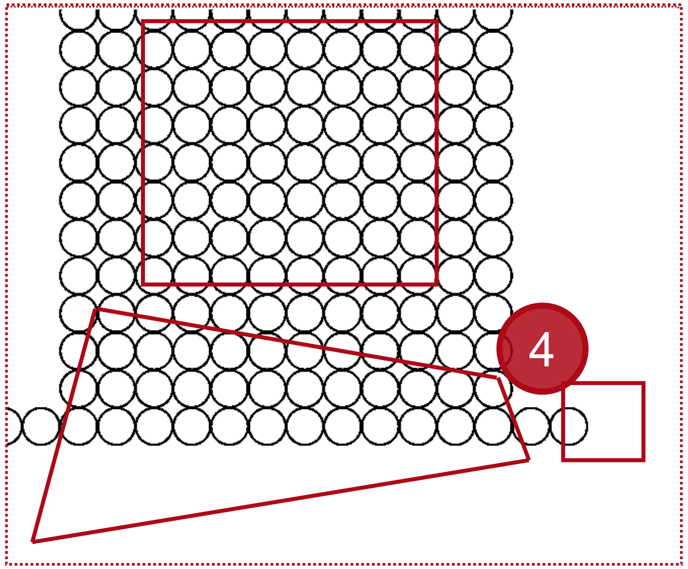




$D = 1.6\,\text{mm}$
$(\alpha, \beta) = (12°, -7°)$

Connected Modeling Techniques: Polarization Effect





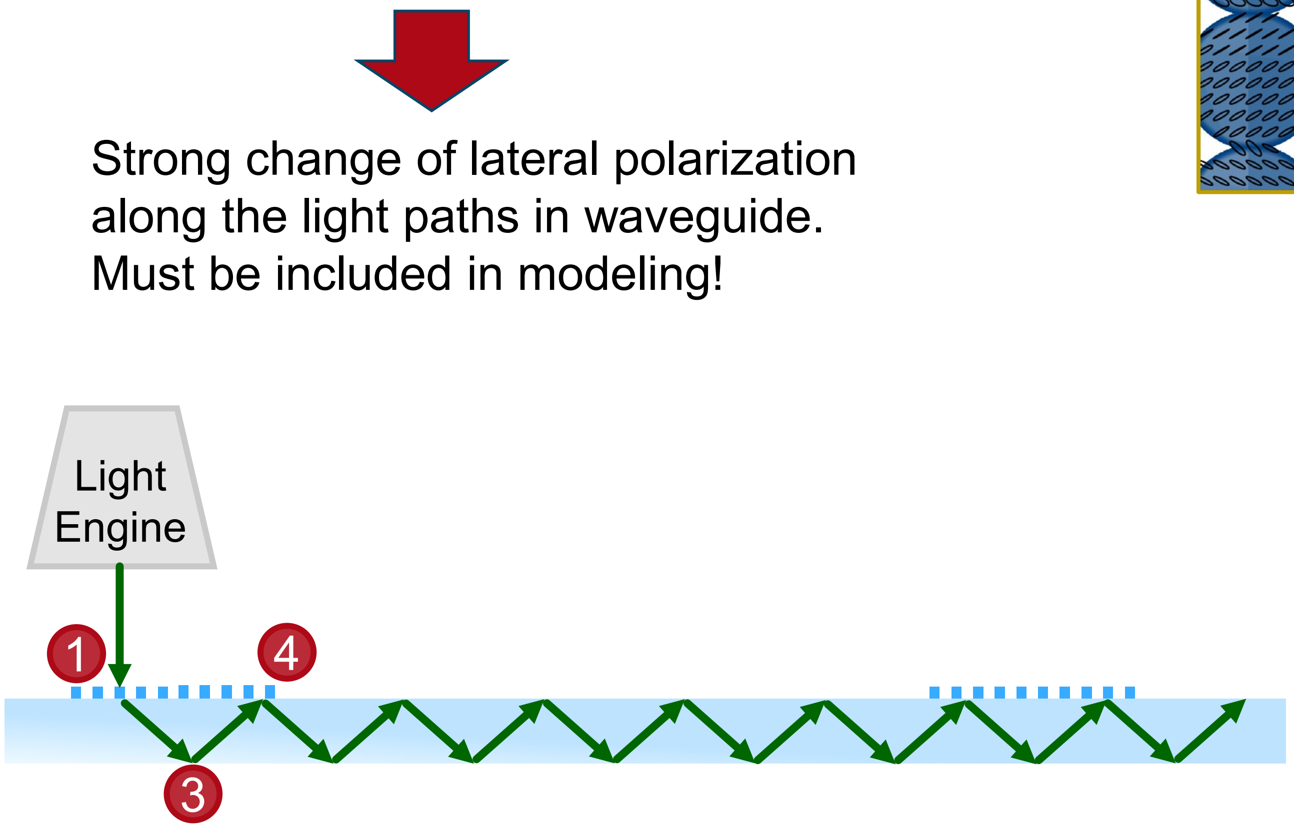
$D = 1.6\,\text{mm}$

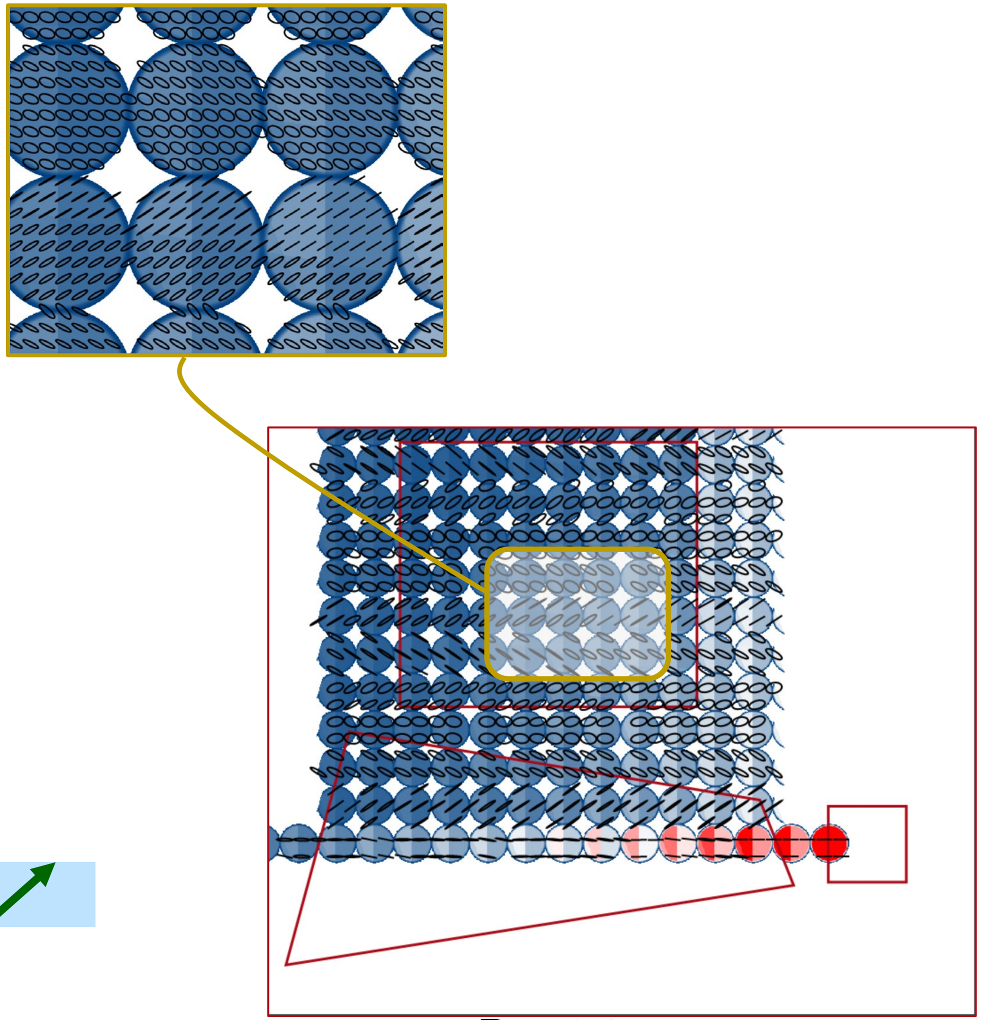
$(\alpha, \beta) = (0°, 0°)$

Connected Modeling Techniques: Polarization Effect

Modeling of gratings, TIR, and its regional separation per beam.

Strong change of lateral polarization along the light paths in waveguide. Must be included in modeling!





$D = 1.6\,\text{mm}$
$(\alpha, \beta) = (0°, 0°)$

Connected Modeling Techniques: Detector Eyebox

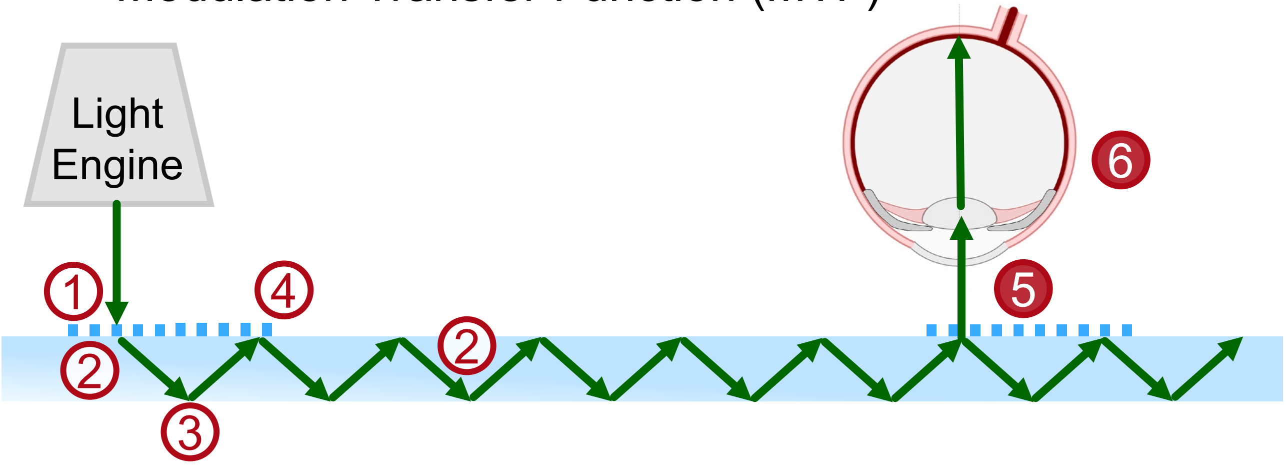
5 Full flexibility in detector modeling:
- Radiometry, e.g., irradiance per FOV or all FOVs, radiance
- Photometry, e.g., illuminance per FOV or all FOVs, luminance
- Uniformity measures

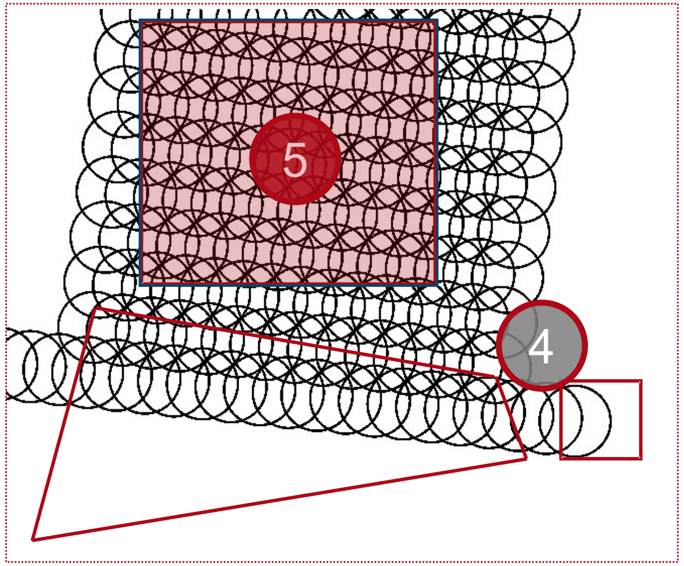
6 Eye model for
- Point spread function (PSF)
- Modulation Transfer Function (MTF)

Collaboration with

OPTOFIDELITY

Specify and provide detector models in software, which simulate measurements for characterization of waveguides.





$D = 3\,\text{mm}$

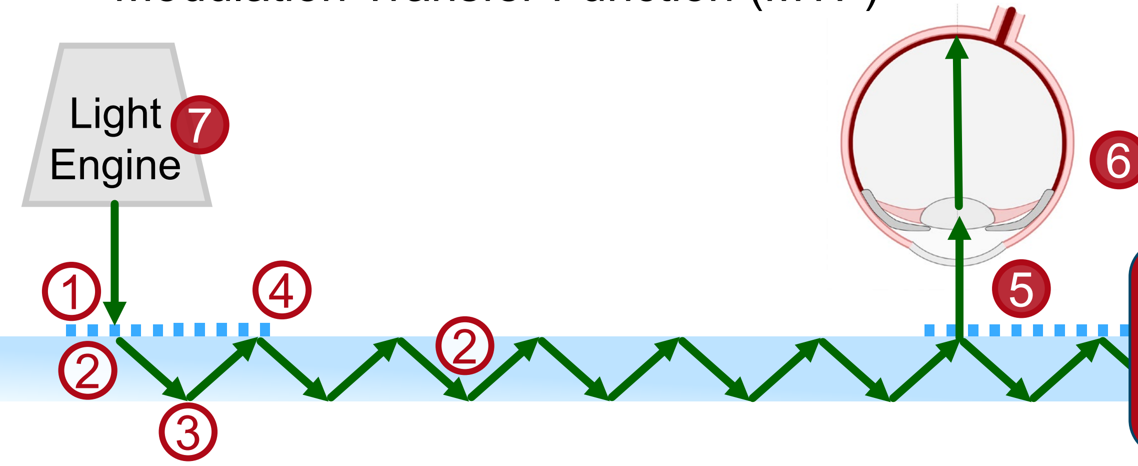
$(\alpha, \beta) = (12^\circ, -7^\circ)$

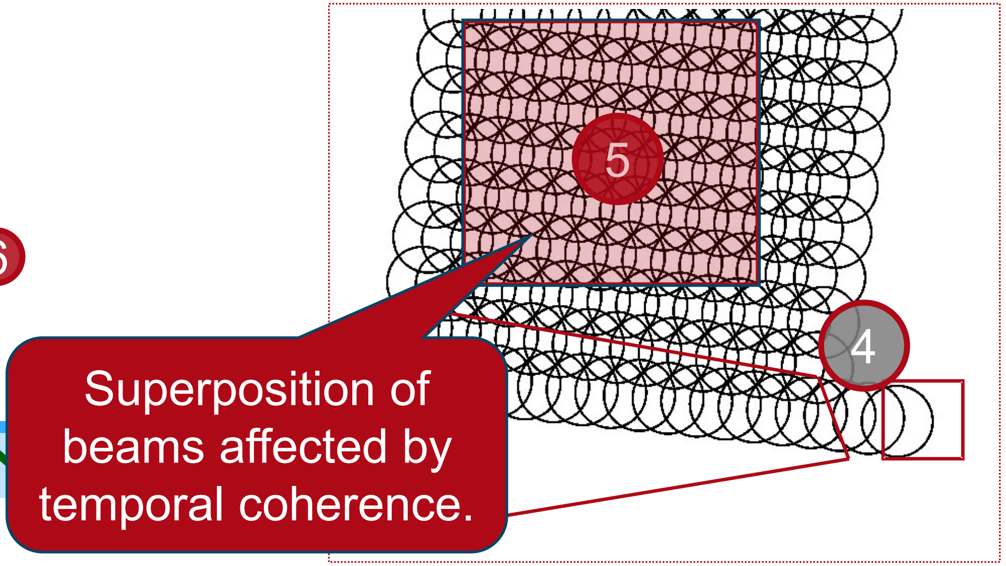
Connected Modeling Techniques: Detector Eyebox

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)

7 **Light Engine Model**
- Beam type: plane wave
- Beam diameter $D = 1.5\,\mathrm{mm}$
- Polarization: Linearly polarized
- Wavelength: $\lambda = 530\,\mathrm{nm}$
- Bandwidth: $\Delta\lambda = 0\,\mathrm{nm}, 1\,\mathrm{nm}, 10\,\mathrm{nm}$



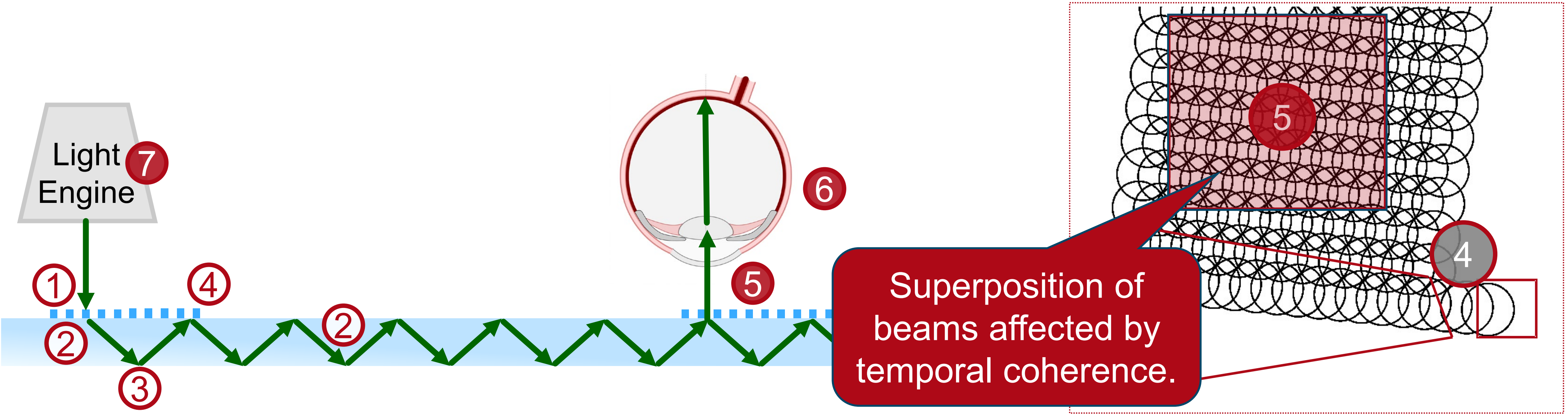


$D = 3\,\mathrm{mm}$
$(\alpha, \beta) = (12^\circ, -7^\circ)$

Connected Modeling Techniques: Temporal Coherence Model

7

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 not included	TBD	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector



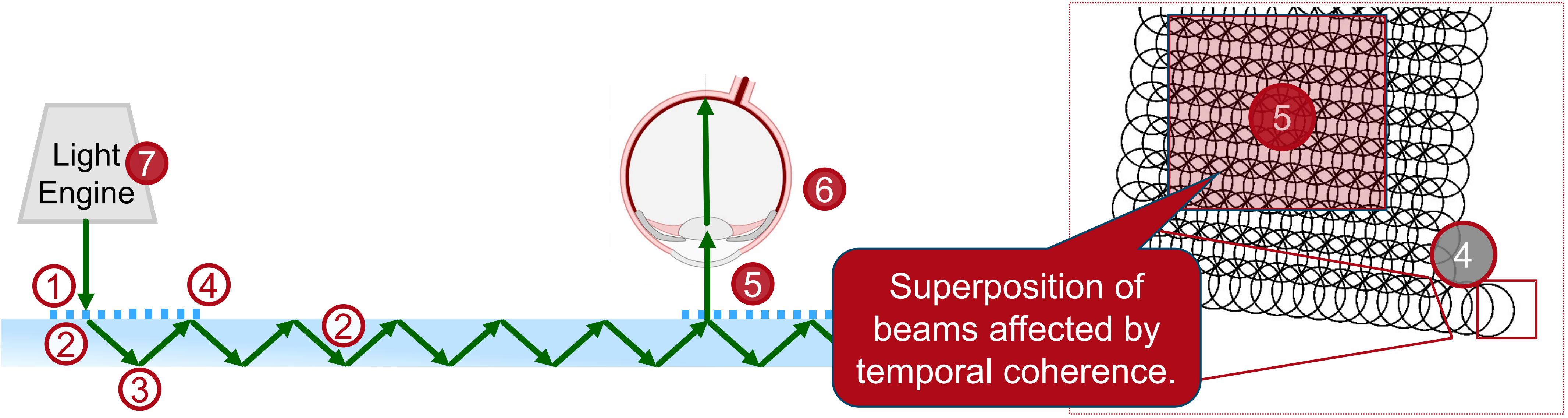
$D = 3\,\mathrm{mm}$

$(\alpha, \beta) = (12°, -7°)$

Connected Modeling Techniques: Temporal Coherence Model

7

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 not included	TBD	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector



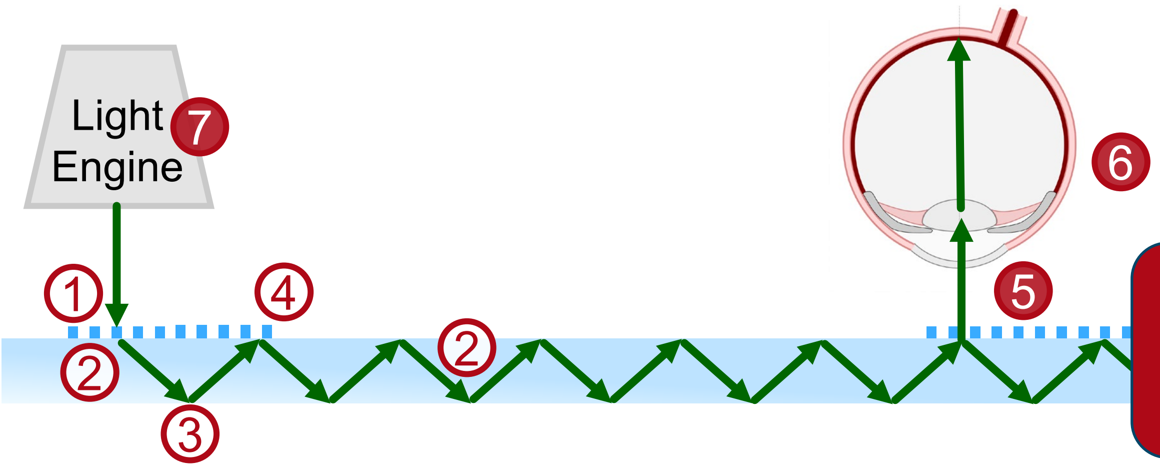
$D = 3\,\text{mm}$
$(\alpha, \beta) = (12^\circ, -7^\circ)$

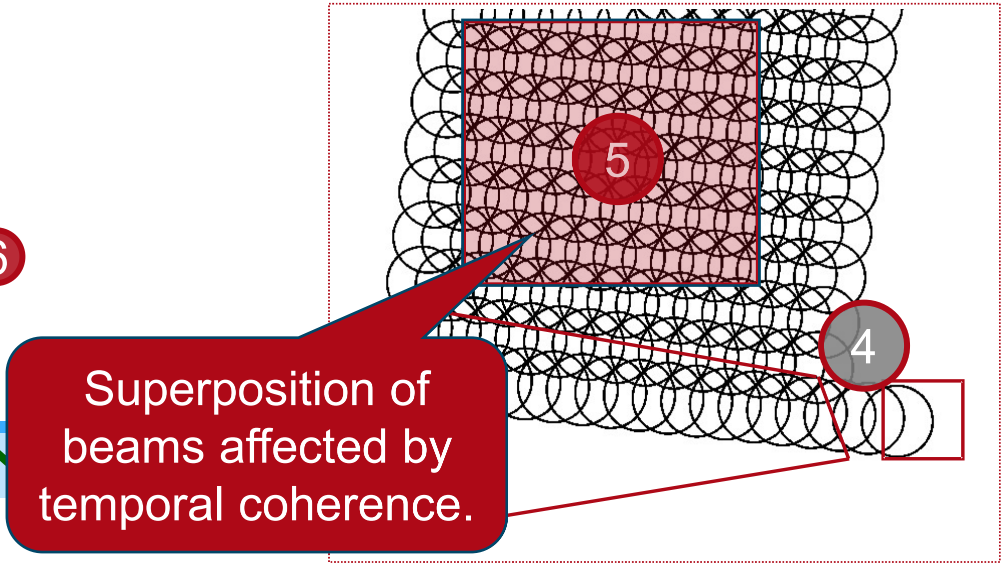
Connected Modeling Techniques: Temporal Coherence Model

7

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 not included	TBD	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

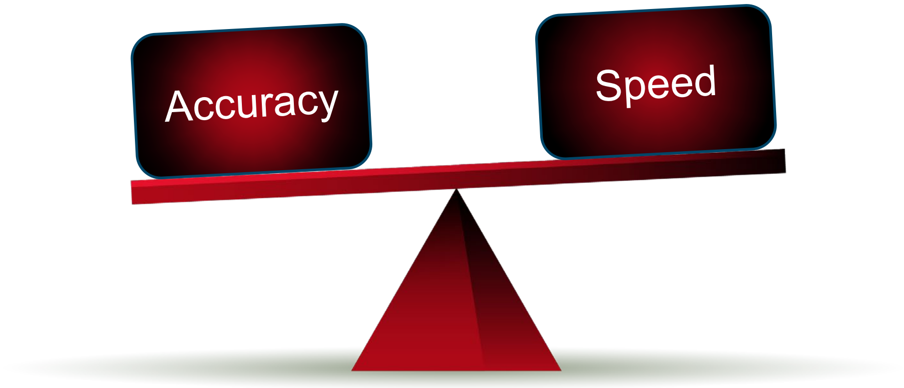
Selection of method must be decided with respect to modeling results!





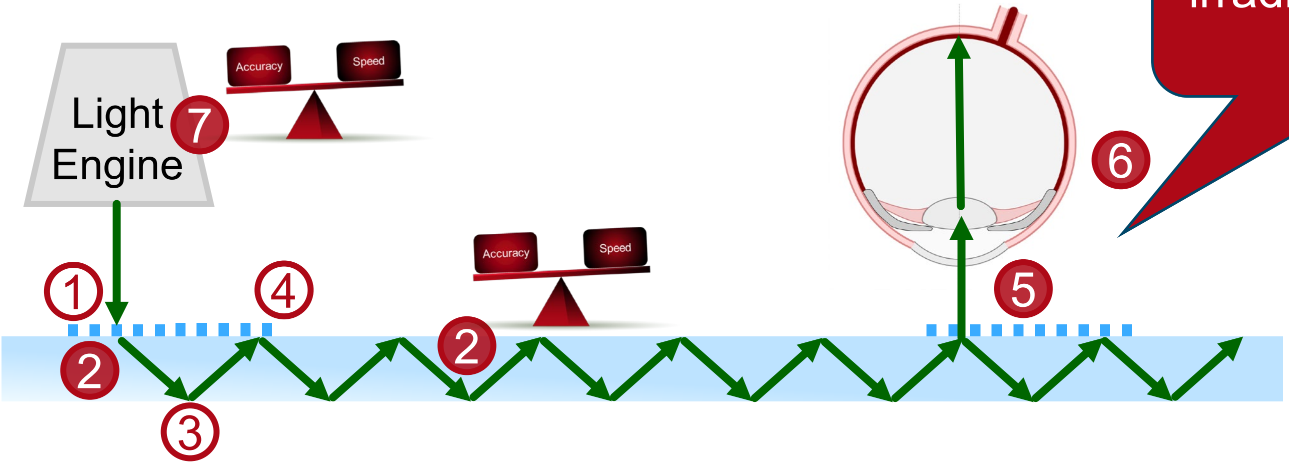
$D = 3\,\text{mm}$
$(\alpha, \beta) = (12°, -7°)$

Control of Accuracy–Speed Balance

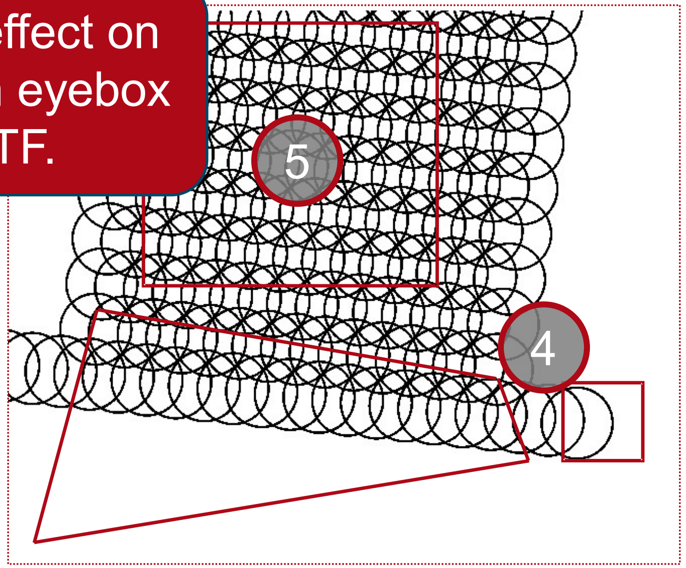


Accuracy-speed balance to be investigated:

- Inclusion of diffraction 2
- Inclusion and modeling temporal coherence 7



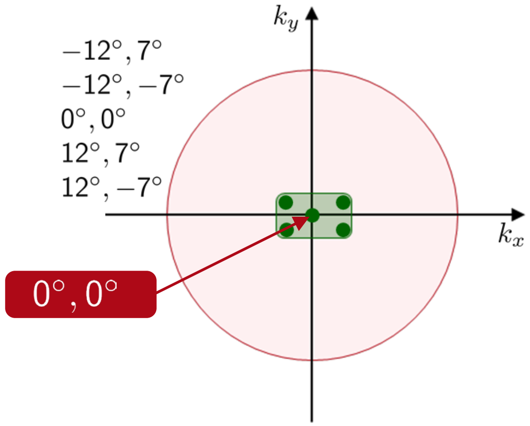
Accuracy: effect on irradiance in eyebox and MTF.



$D = 3\,\mathrm{mm}$

$(\alpha, \beta) = (12^\circ, -7^\circ)$

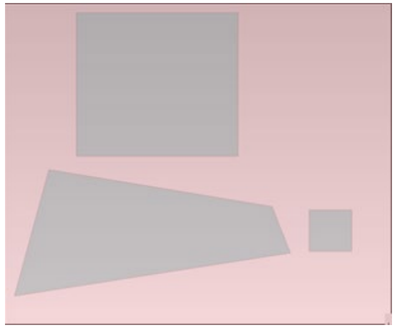
Irradiance Detector: Inside View and Output View

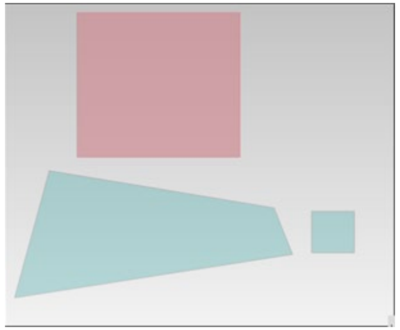


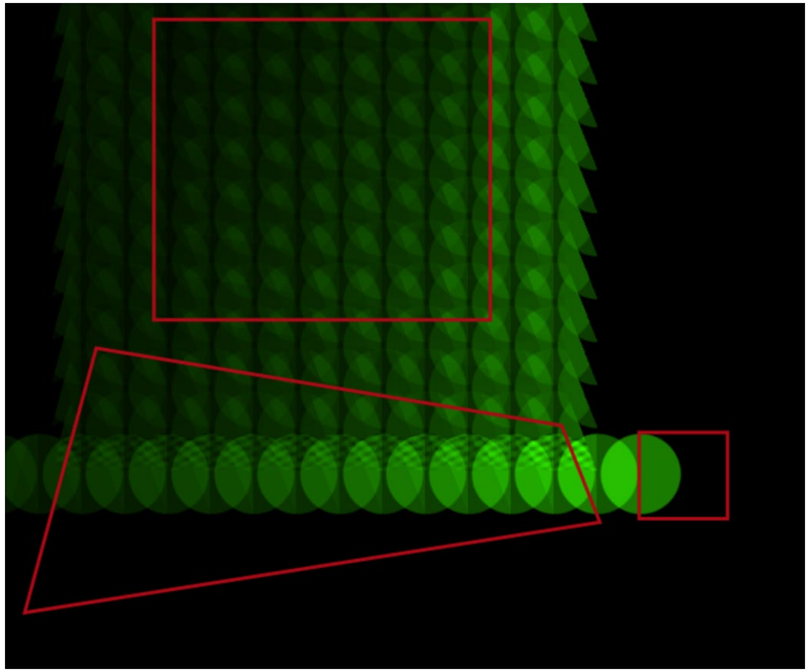
$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$

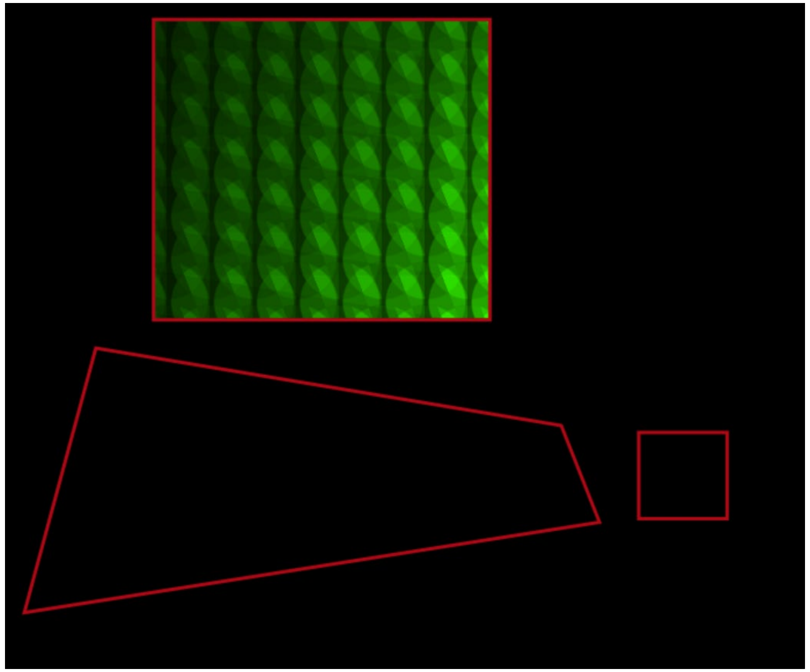
$\lambda = 530\,\text{nm}$

$r = 1.5\,\text{mm}$

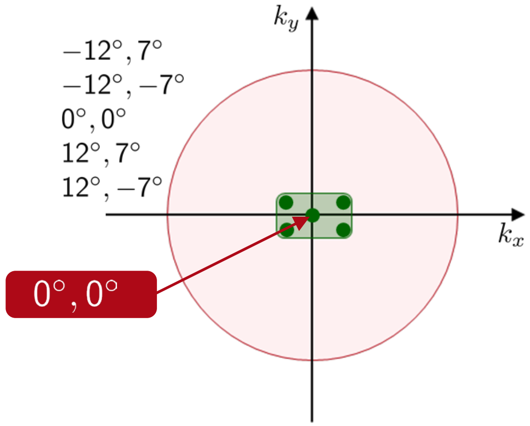




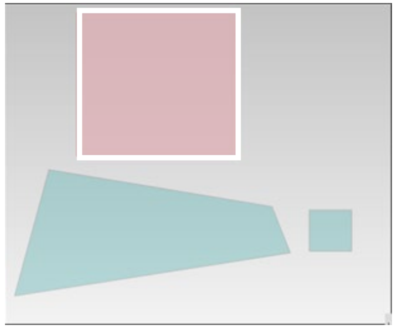


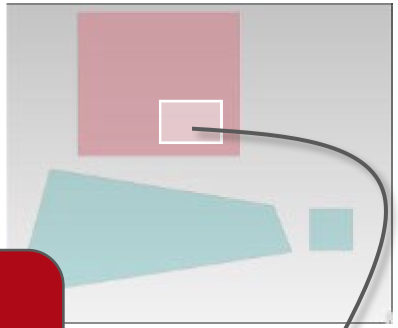


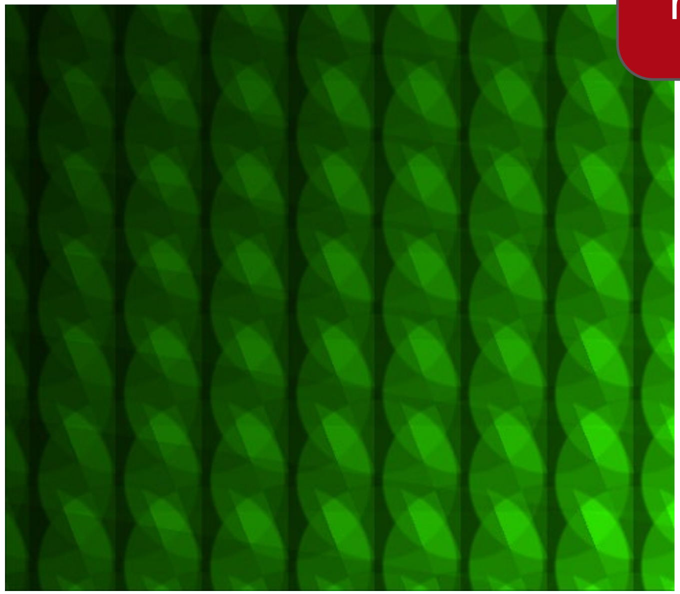
Irradiance Detector: Output View



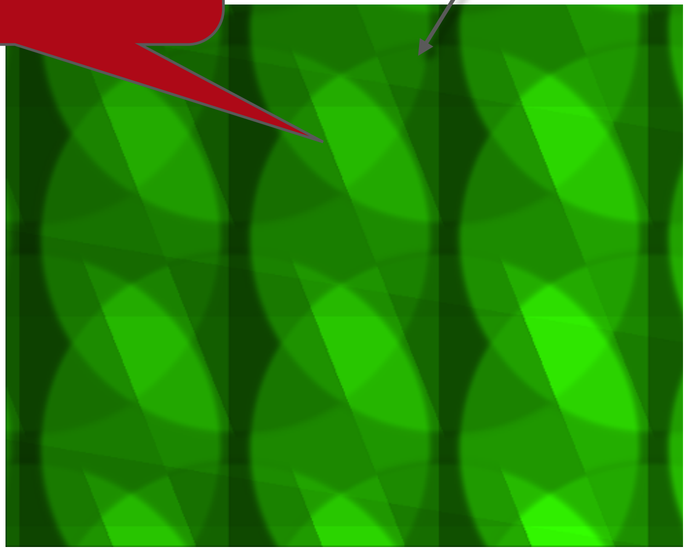
$E_x^{\text{in}} = 1, E_y^{\text{in}} = 0$
$\lambda = 530$ nm
$r = 1.5$ mm





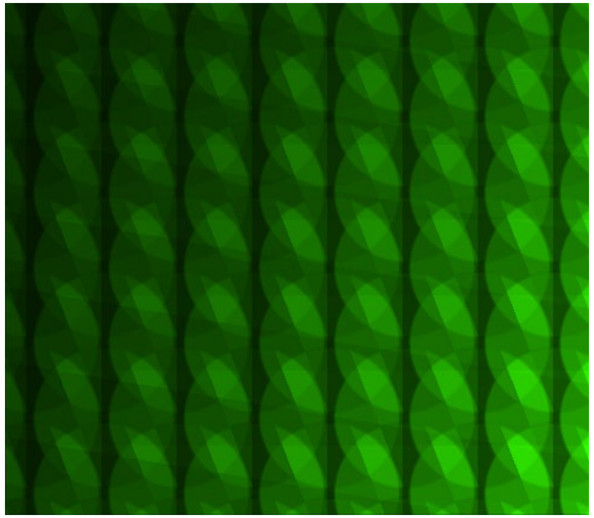


Highly resolved region boundaries.



Diffraction Inside Waveguide: Irradiance Eyebox

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	



without diffraction in waveguide

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
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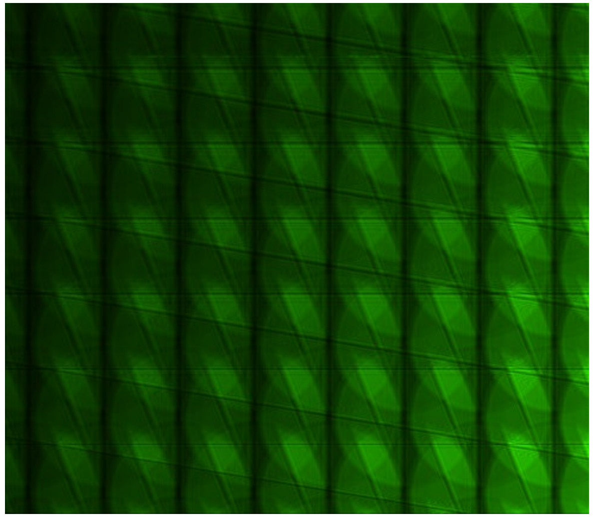
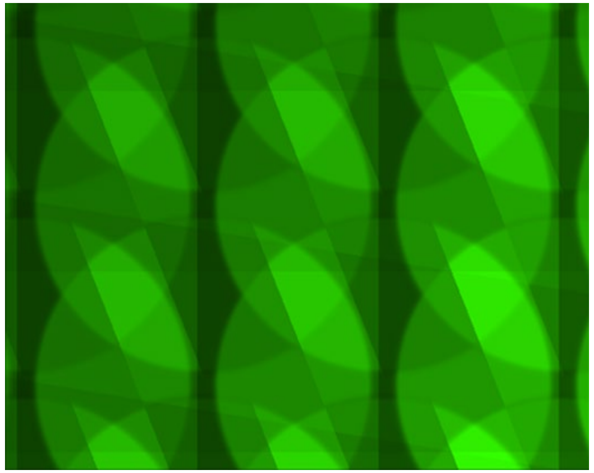


with diffraction in waveguide

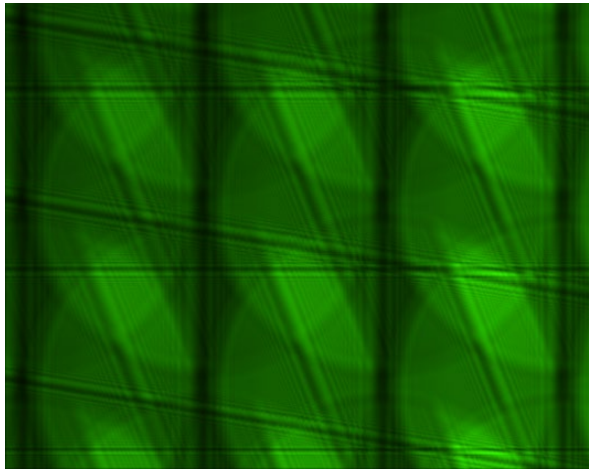
Diffraction Inside Waveguide: Irradiance Eyebox (Zoom In)

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	



without diffraction in waveguide

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	



with diffraction in waveguide

Diffraction Inside Waveguide: Irradiance Eyebox (Zoom In)

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
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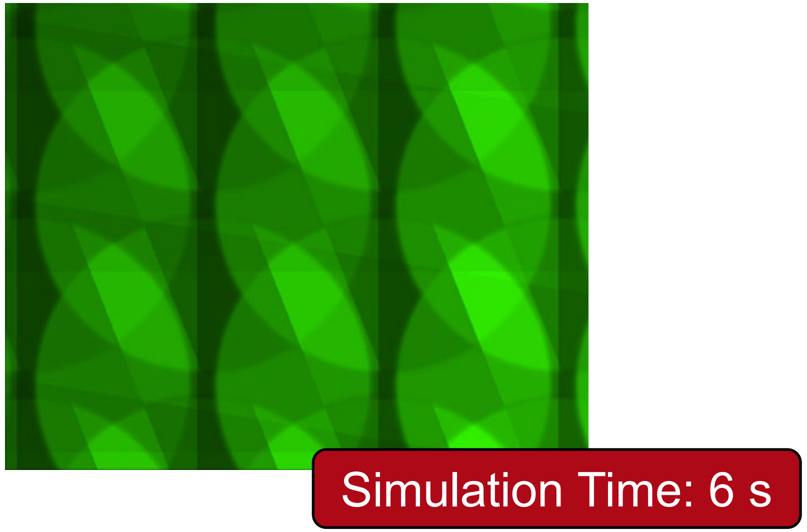

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Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
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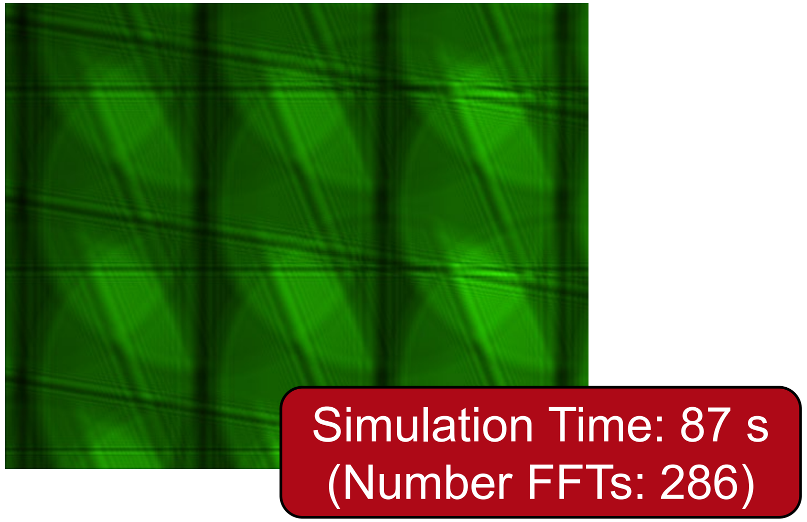
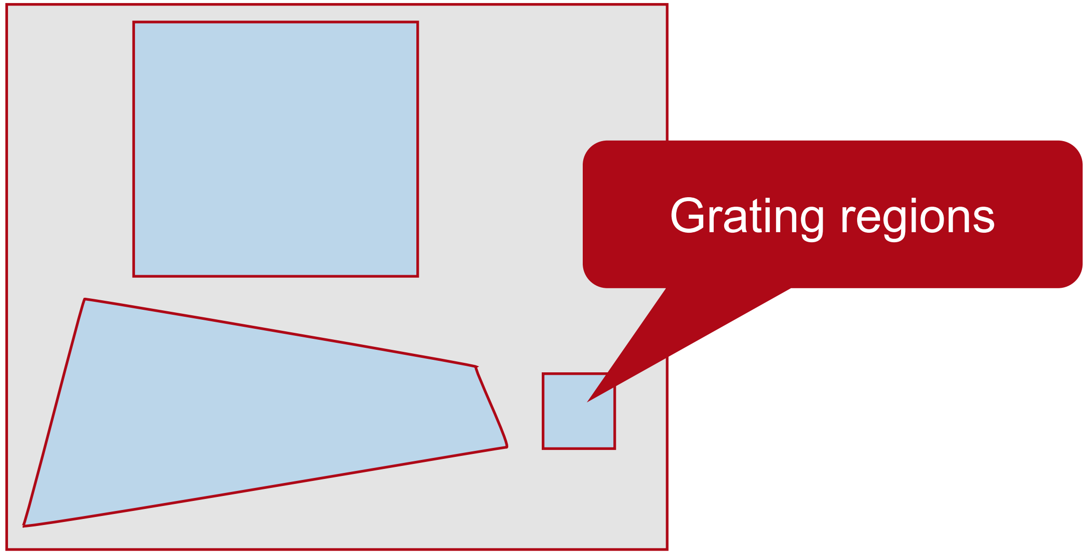
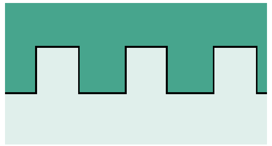


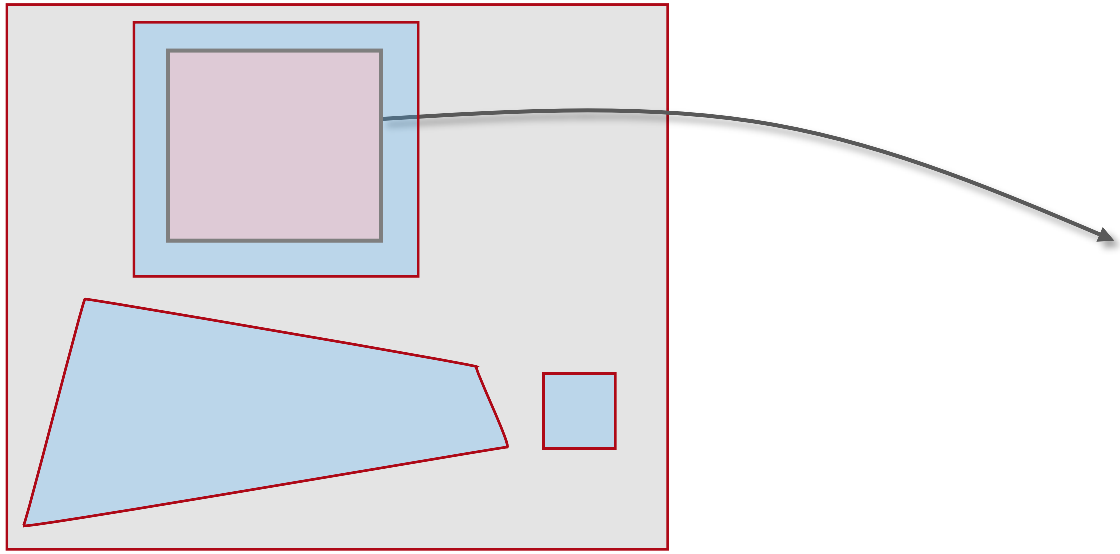
Grating Optimization: Uniformity in Eyebox

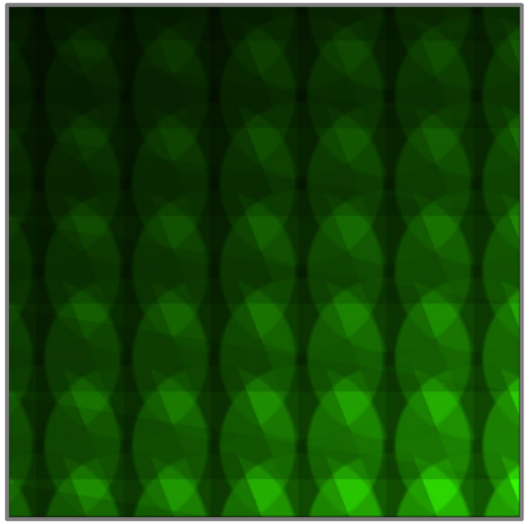


Grating type: Binary



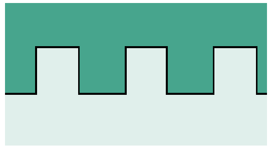
Grating Optimization: Uniformity in Eyebox





Before Optimization

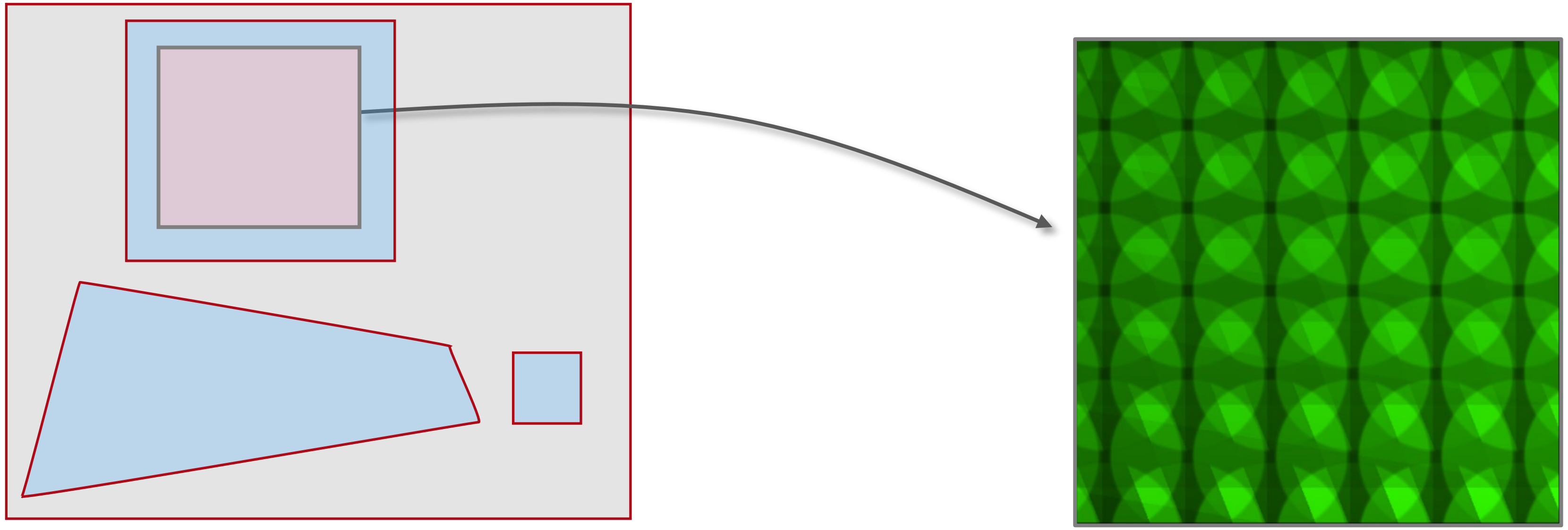
Grating type: Binary



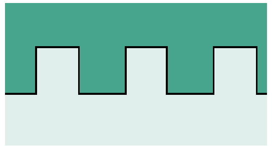
Optimize lateral modulation of grating parameters:

- Height
- Width of ridge

Grating Optimization: Uniformity in Eyebox



Grating type: Binary



After Optimization

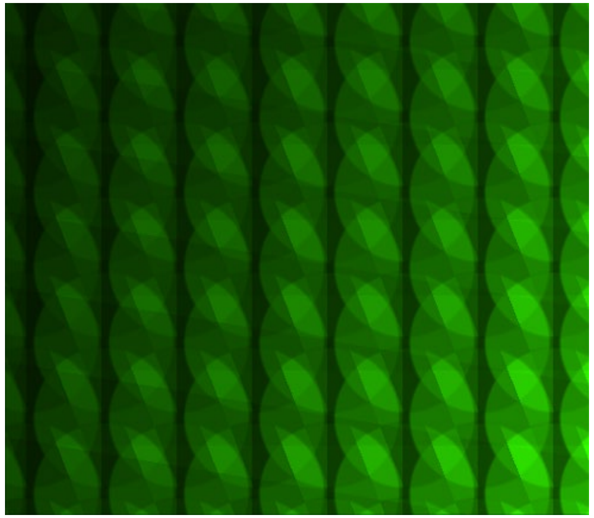
Optimize lateral modulation of grating parameters:

- Height
- Width of ridge

Diffraction Inside Waveguide: Effect on Irradiance and PSF/MTF

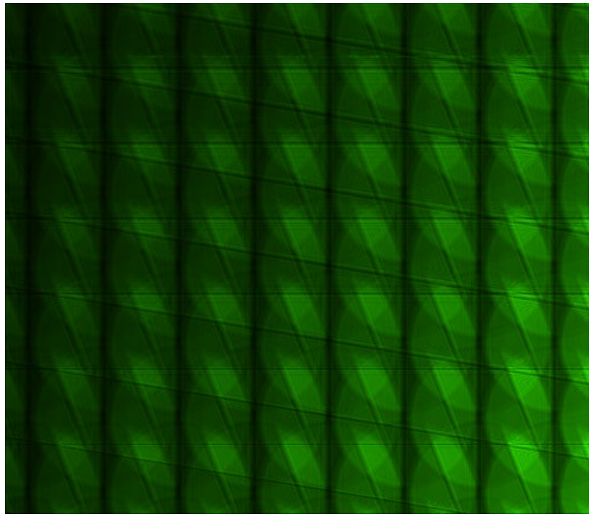
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Simulation Time: 6 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	

Simulation Time: 87 s
(Number FFTs: 286)



Diffraction Inside Waveguide: Effect on Irradiance

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	

Simulation Time: 6 s

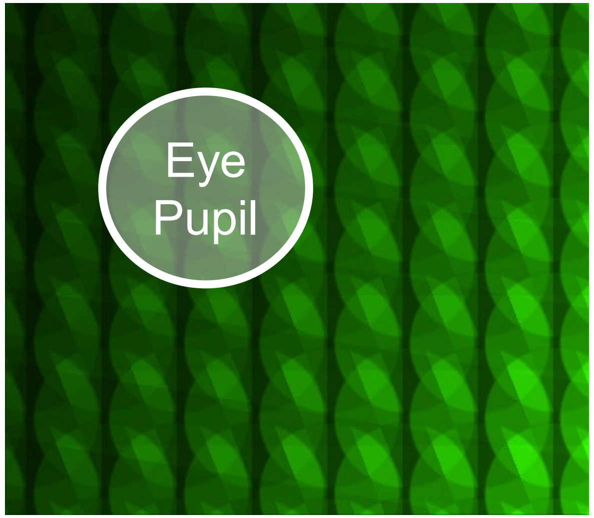
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Simulation Time: 87 s
(Number FFTs: 286)

Accuracy-speed balance:
Optimization of gratings for uniformity in eyebox: w/o diffraction inside waveguide

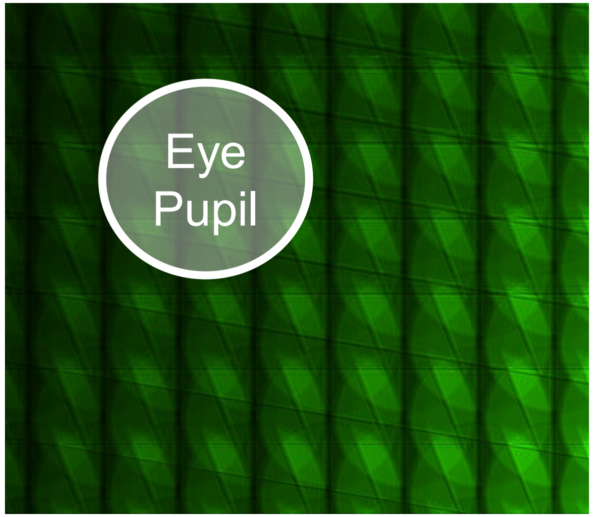
Diffraction Inside Waveguide: Effect on PSF/MTF

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	



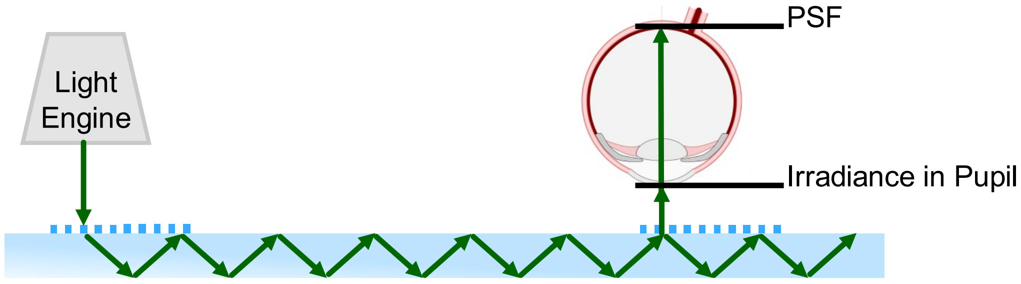
Eye pupil: 4 mm

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	



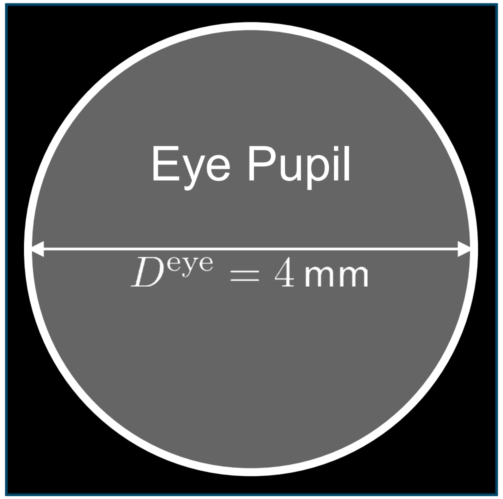
Eye pupil: 4 mm

PSF and MTF Calculation: Eye Model

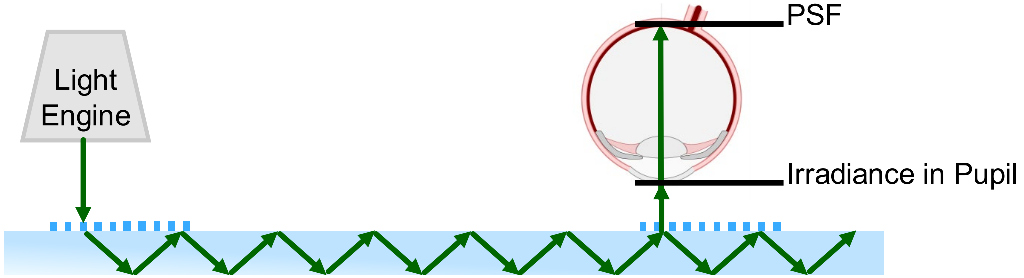


Eye model:

- Pupil diameter: $D^{\mathrm{eye}} = 4\,\mathrm{mm}$
- Ideal lens: $f^{\mathrm{eye}} = 16.452\,\mathrm{mm}$

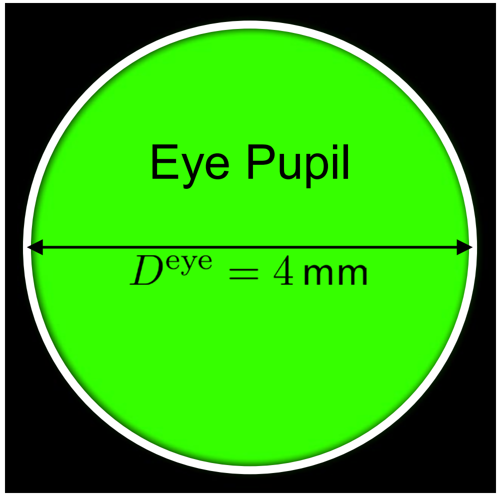


PSF and MTF Calculation: Pupil Filled

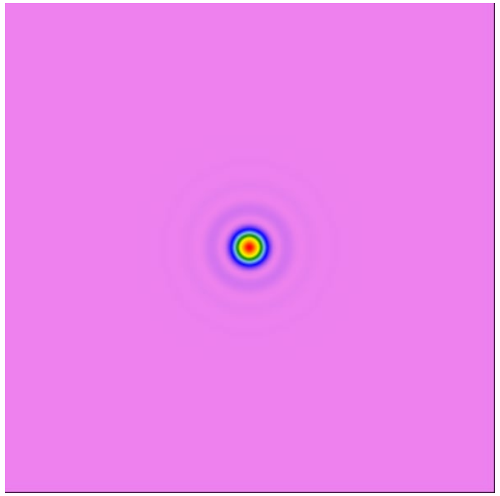


Eye model:
- Pupil diameter: $D^{\mathrm{eye}} = 4\,\mathrm{mm}$
- Ideal lens: $f^{\mathrm{eye}} = 16.452\,\mathrm{mm}$

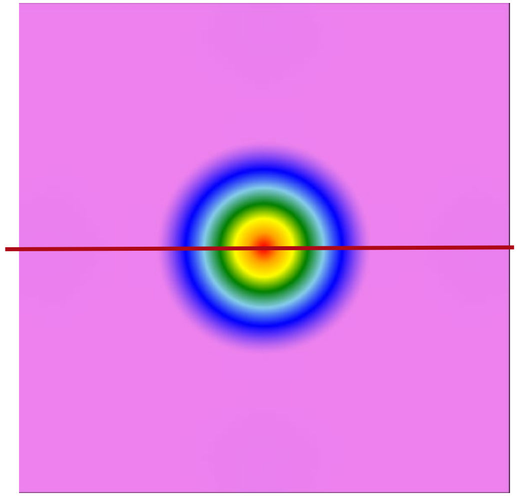
Irradiance in Pupil



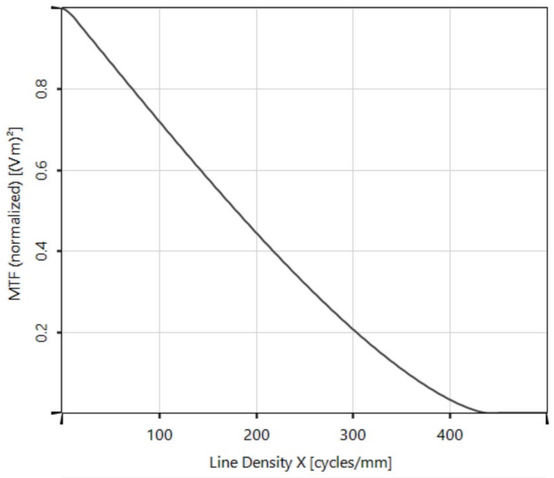
PSF



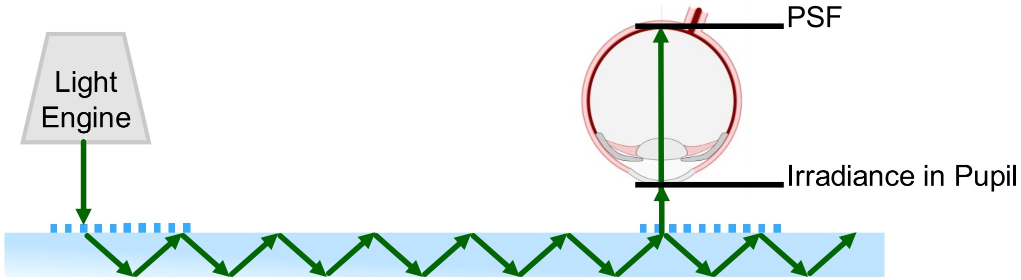
MTF



MTF x-profile



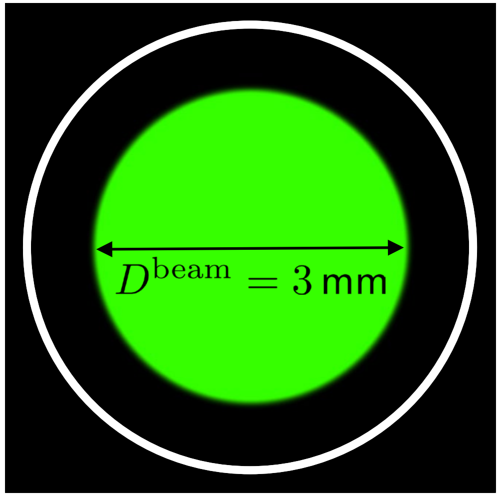
PSF and MTF Calculation: One Beam in Pupil



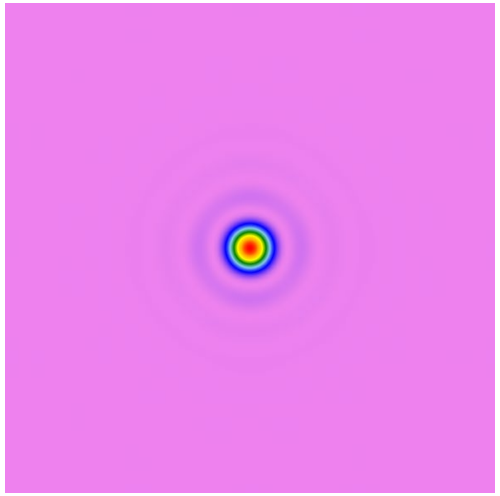
Eye model:

- Pupil diameter: $D^{\text{eye}} = 4\,\text{mm}$
- Ideal lens: $f^{\text{eye}} = 16.452\,\text{mm}$

Irradiance in Pupil



PSF



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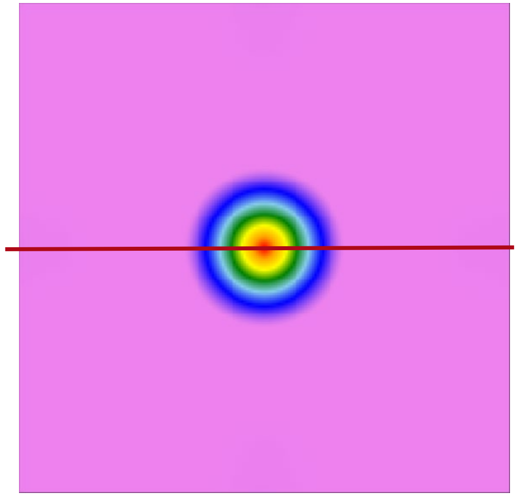
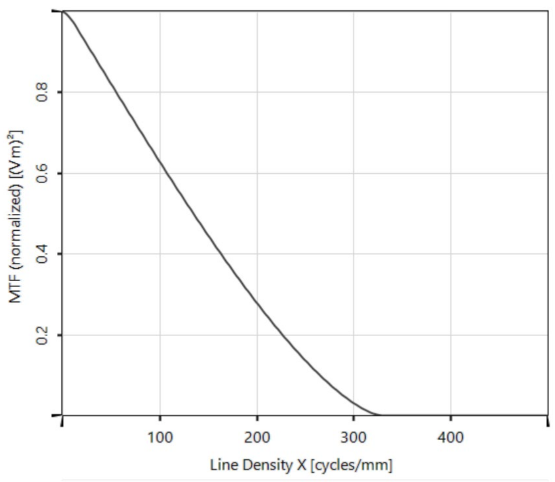
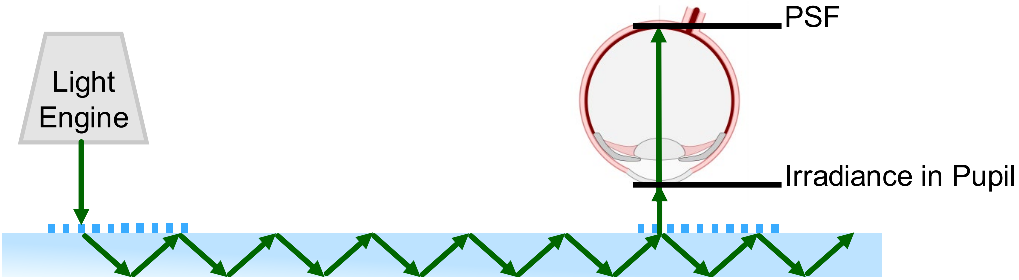


MTF x-profile



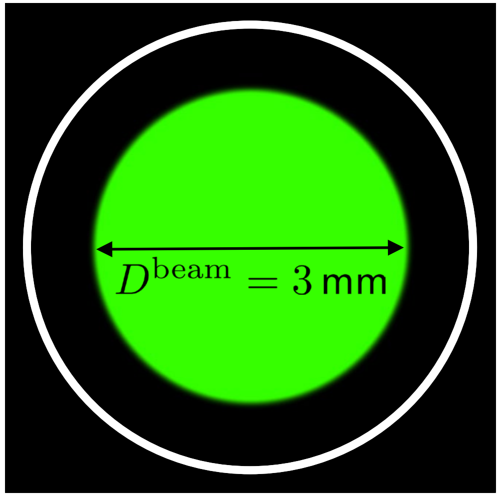
PSF and MTF Calculation: One Beam in Pupil



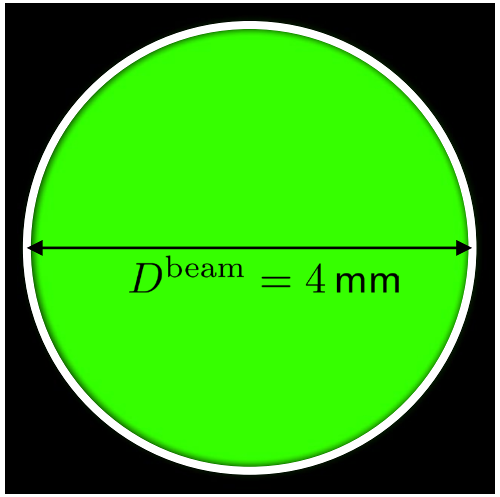
Eye model:

- Pupil diameter: $D^{\text{eye}} = 4\,\text{mm}$
- Ideal lens: $f^{\text{eye}} = 16.452\,\text{mm}$

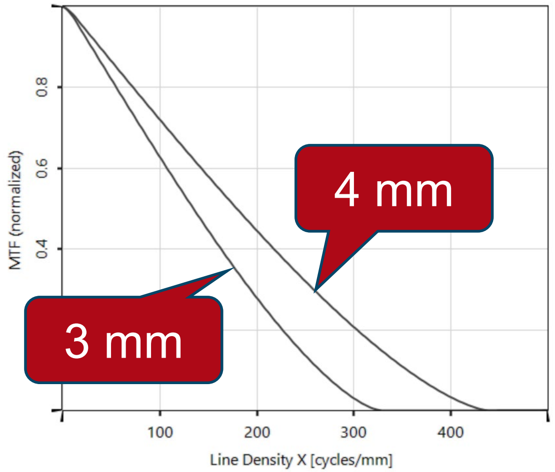
Irradiance in Pupil



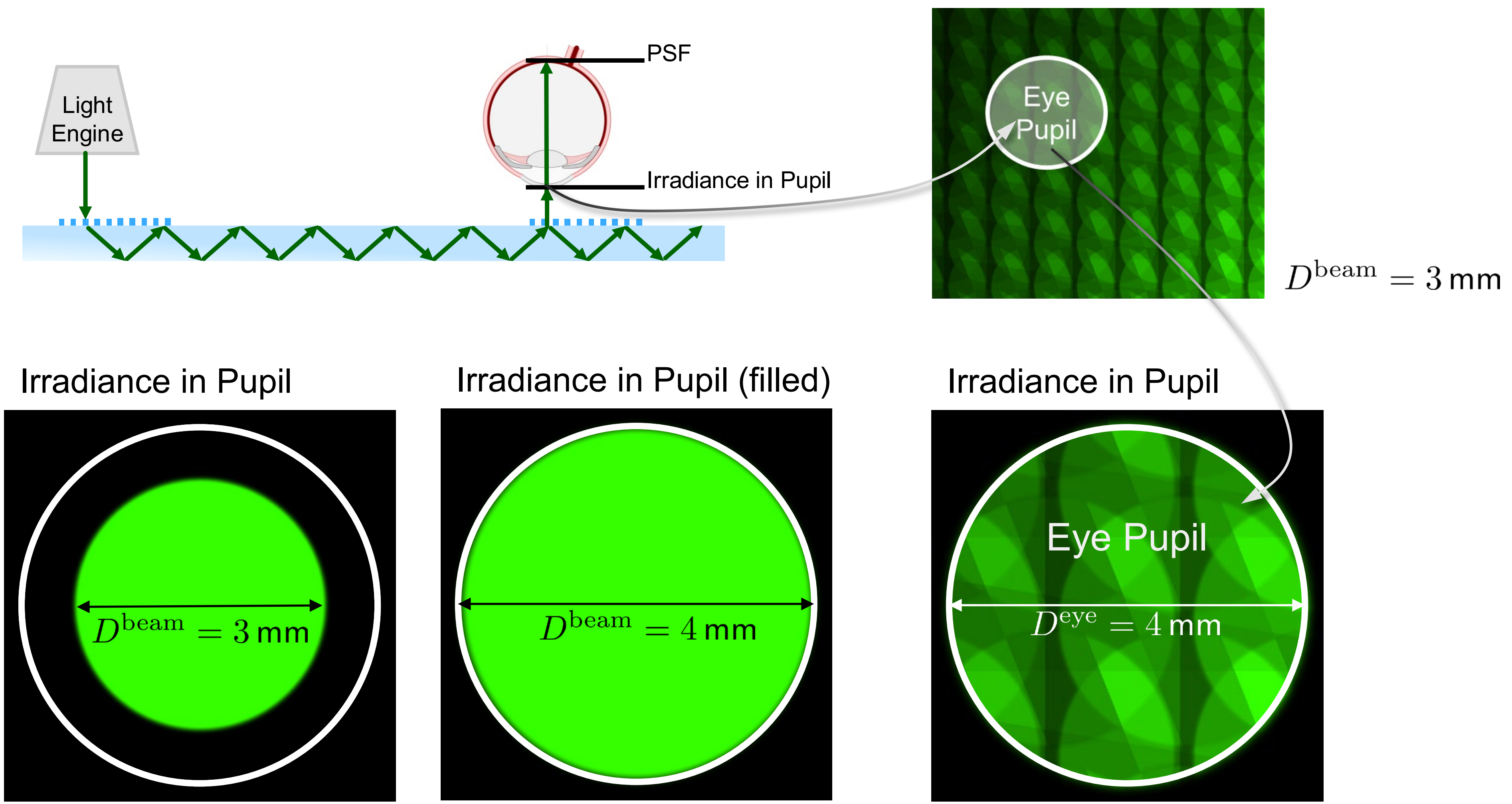
Irradiance in Pupil (filled)



MTF x-profile

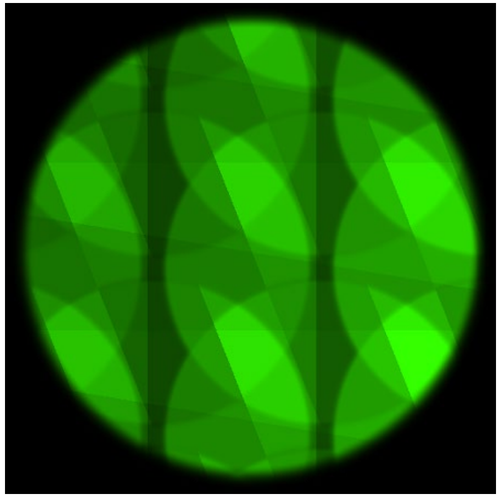


PSF and MTF Calculation: Beams in Eyebox

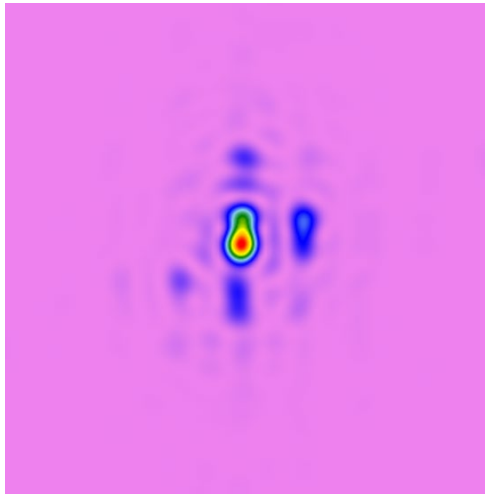


PSF and MTF Calculation: w/o Diffraction in Waveguide

Irradiance in Pupil



PSF



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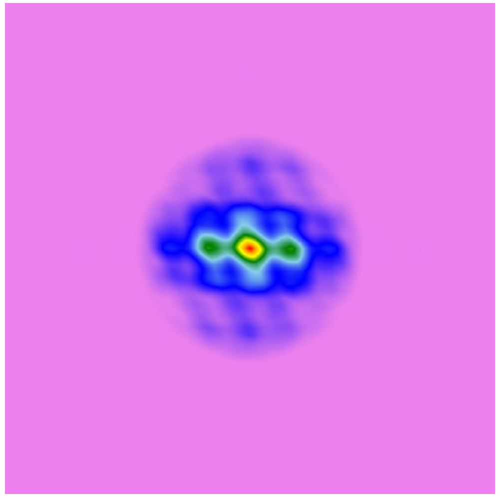
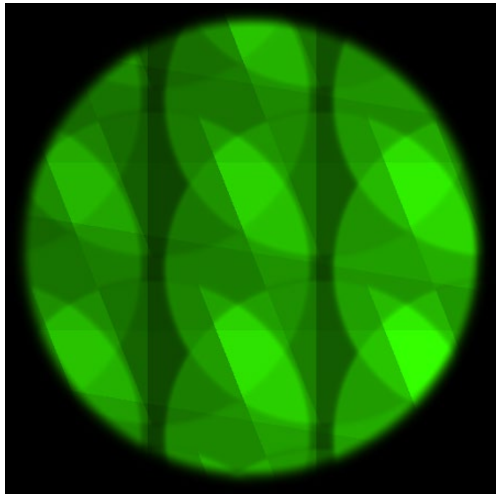


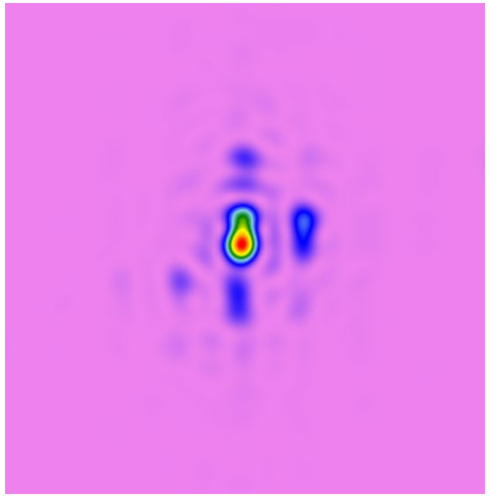
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

PSF and MTF Calculation: w/o Diffraction in Waveguide

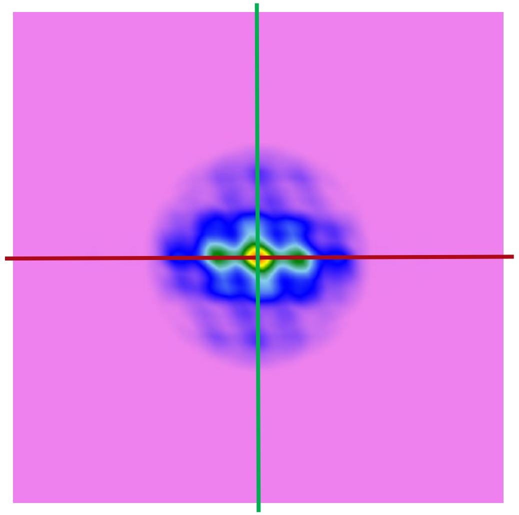
Irradiance in Pupil



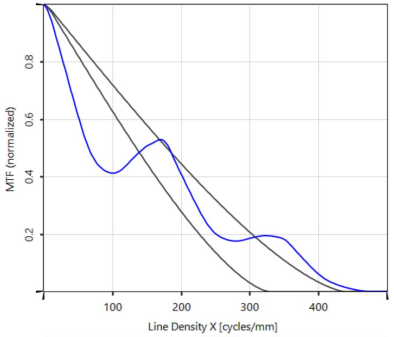
PSF



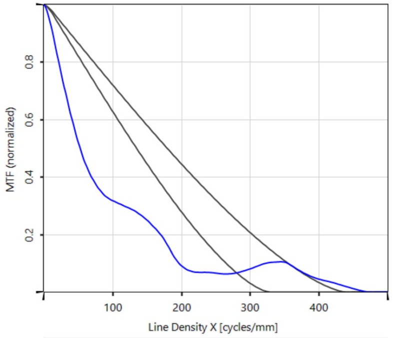
MTF



MTF x-profile



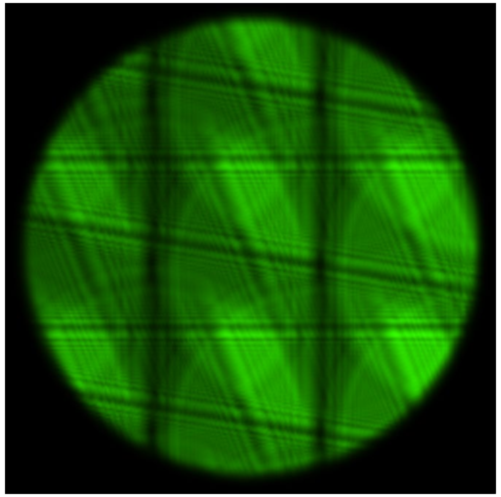
MTF y-profile



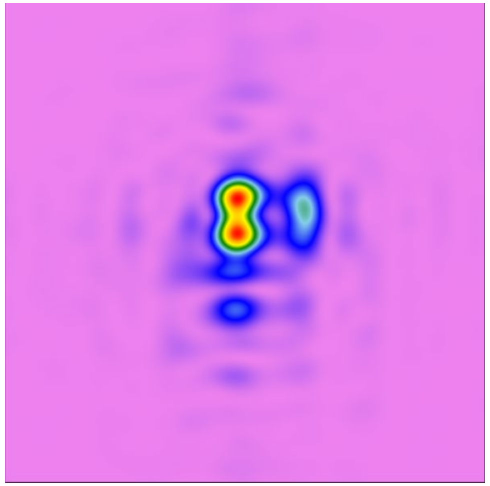
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

PSF and MTF Calculation: With Diffraction in Waveguide

Irradiance in Pupil



PSF



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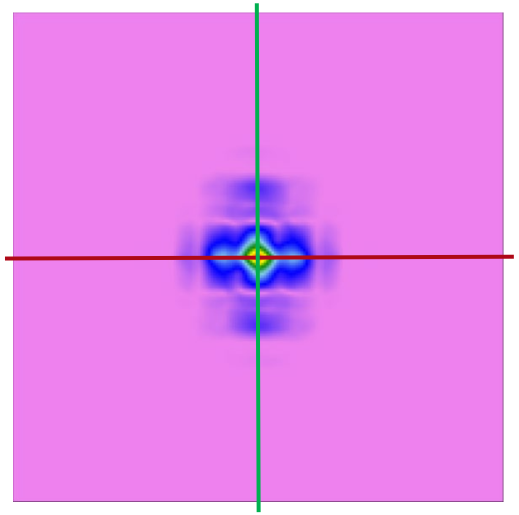
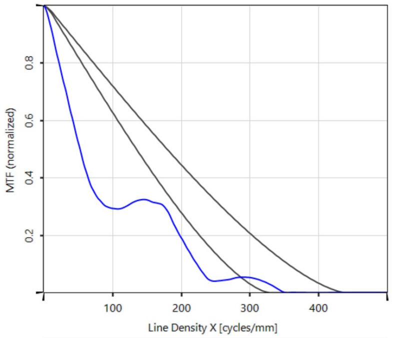
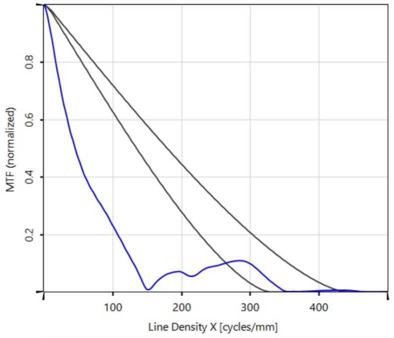


MTF x-profile



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	

Diffraction Inside Waveguide: Effect on MTF

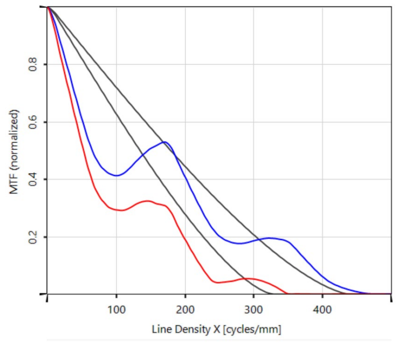
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Simulation Time: 11 s

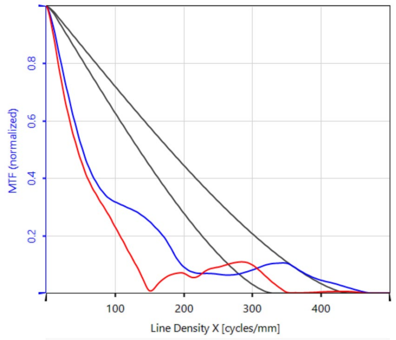
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Simulation Time: 95 s
(Number FFTs: 304)

MTF x-profile



MTF y-profile



w/o diffraction
w/ diffraction

Diffraction Inside Waveguide: Effect on Irradiance and MTF

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	

Simulation Time: 11 s

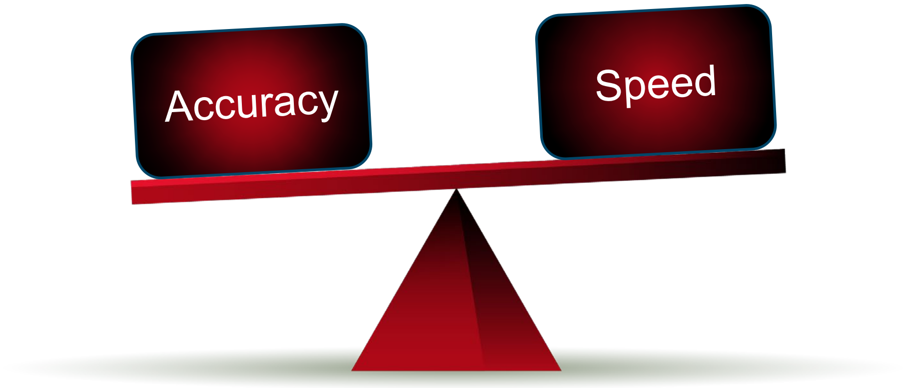
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Simulation Time: 95 s
(Number FFTs: 304)

Accuracy-speed balance:

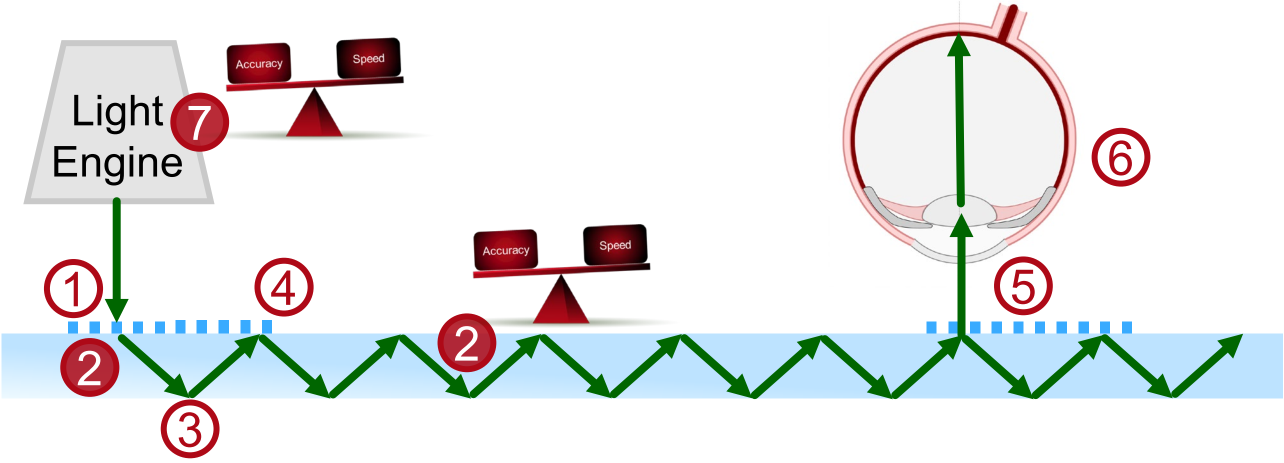
- Final evaluation of MTF performance of waveguide glasses: w/ diffraction inside waveguide

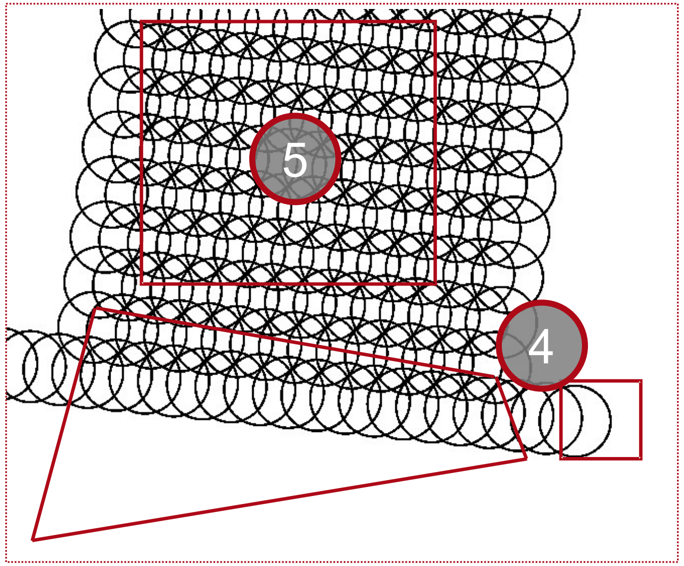
Control of Accuracy–Speed Balance



Accuracy-speed balance to be investigated:

- Inclusion of diffraction ② ✓
- Inclusion and modeling temporal coherence ⑦ ?





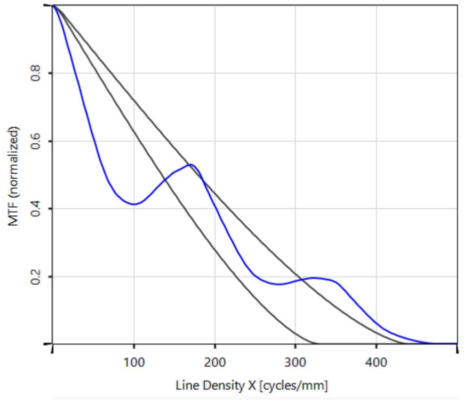
$D = 3\,\text{mm}$
$(\alpha, \beta) = (12°, -7°)$

Temporal Coherence Modeling: MTF Detectors (x Profile)

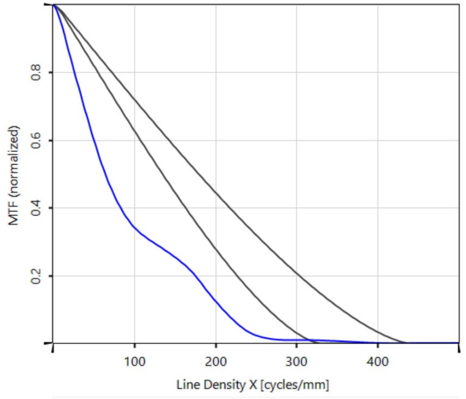
Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion not included	TBD	Very High	One frequency only; use of different travel time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

Frequency model

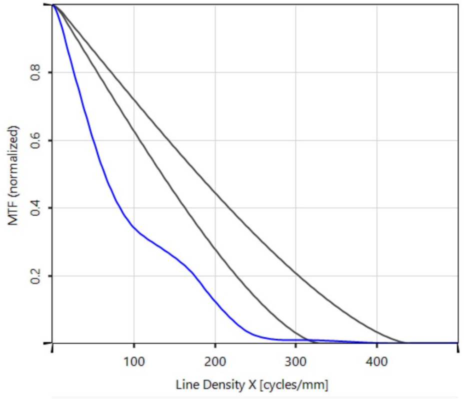
Time model



$\Delta\lambda = 0\,\mathrm{nm}$



$\Delta\lambda = 1\,\mathrm{nm}$



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

Temporal Coherence Modeling: MTF Detectors (x Profile)

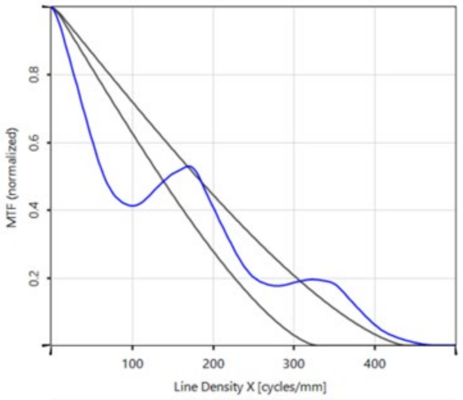
Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion not included	TBD	Very High	One frequency only; use of different travel time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

Frequency model

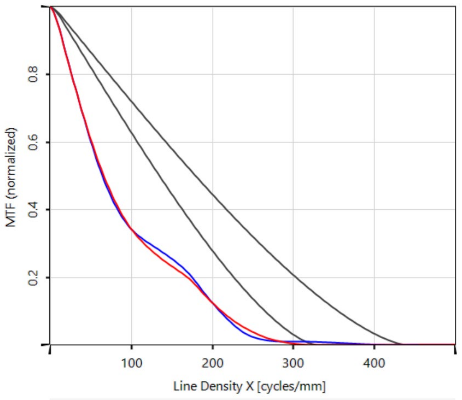
CPU Time: 9.5 min

Time model

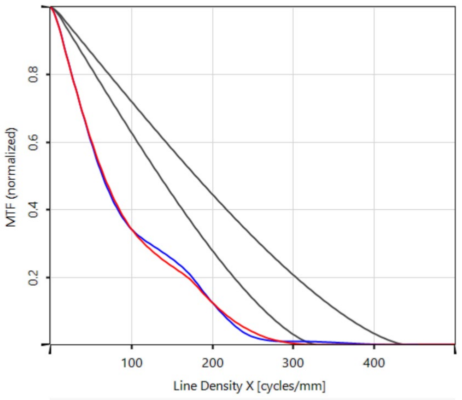
CPU Time: 11 s



$\Delta\lambda = 0\,\text{nm}$



$\Delta\lambda = 1\,\text{nm}$



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

Temporal Coherence Modeling: MTF Detectors (x Profile)

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 not included	TBD	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

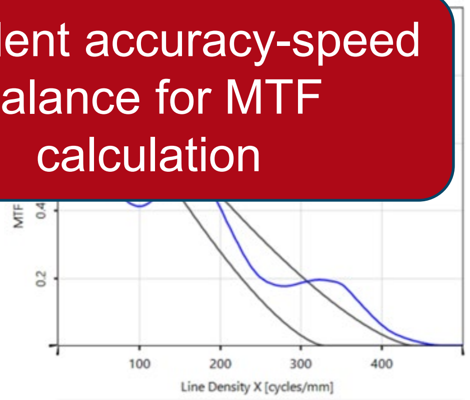
Frequency model

CPU Time: 9.5 min

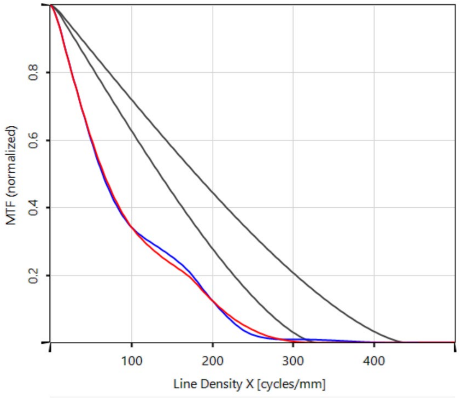
Time model

CPU Time: 11 s

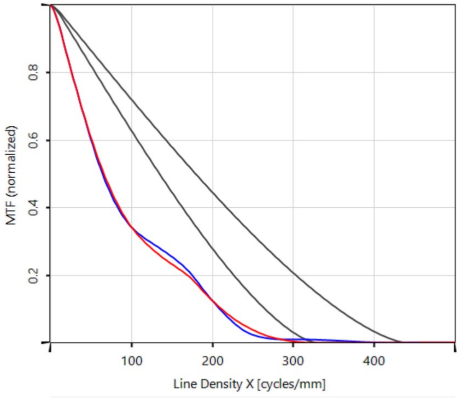
Excellent accuracy-speed balance for MTF calculation



$\Delta\lambda = 0\,\mathrm{nm}$

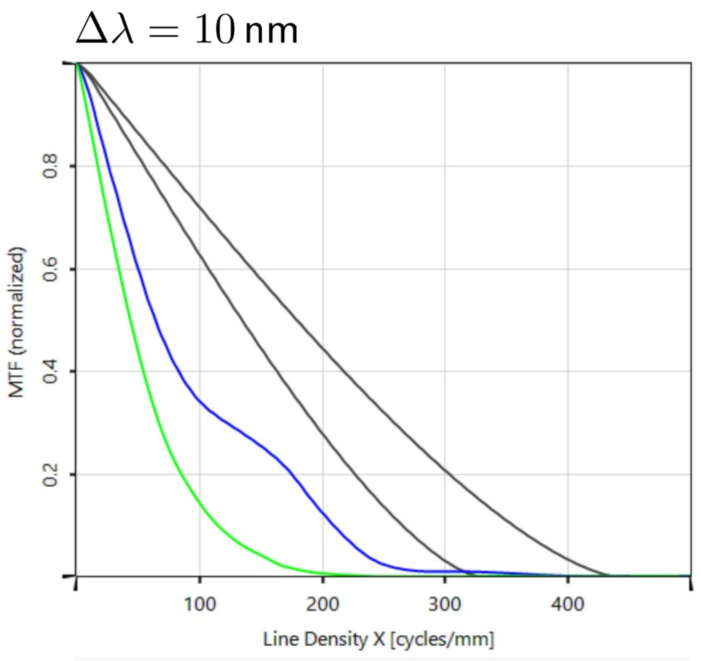


$\Delta\lambda = 1\,\mathrm{nm}$



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

Temporal Coherence & Diffraction Modeling: MTF Detectors



Frequency model & w/o diffraction

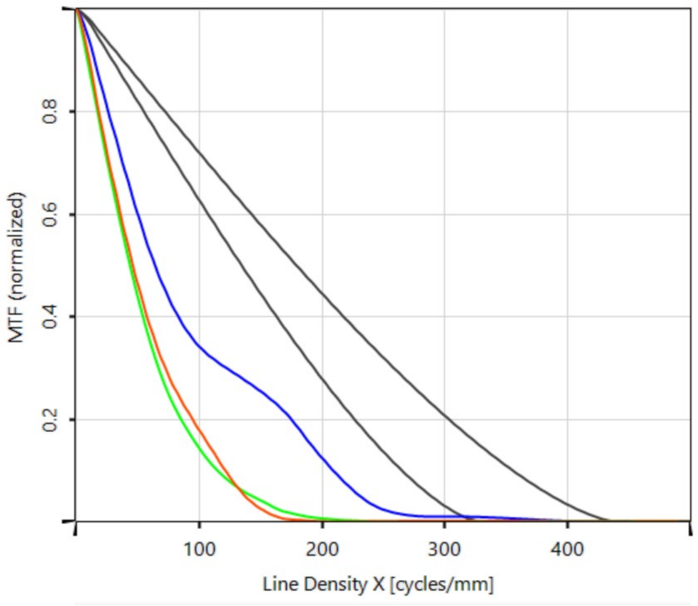
CPU Time: 9.5 min

Frequency model & w/ diffraction

CPU Time: 80 min

Temporal Coherence & Diffraction Modeling: MTF Detectors

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



Frequency model & w/o diffraction — CPU Time: 9.5 min

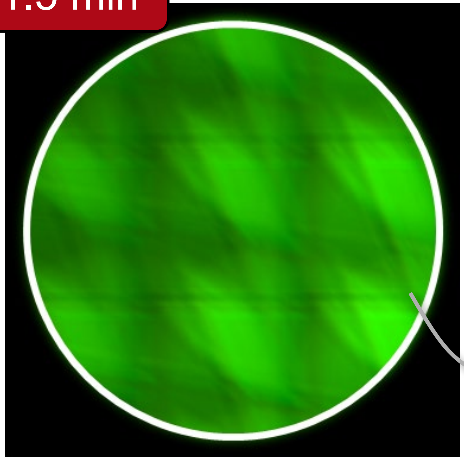
Frequency model & w/ diffraction — CPU Time: 80 min

Time model & w/ diffraction — CPU Time: 1.5 min

Excellent accuracy-speed balance for MTF calculation

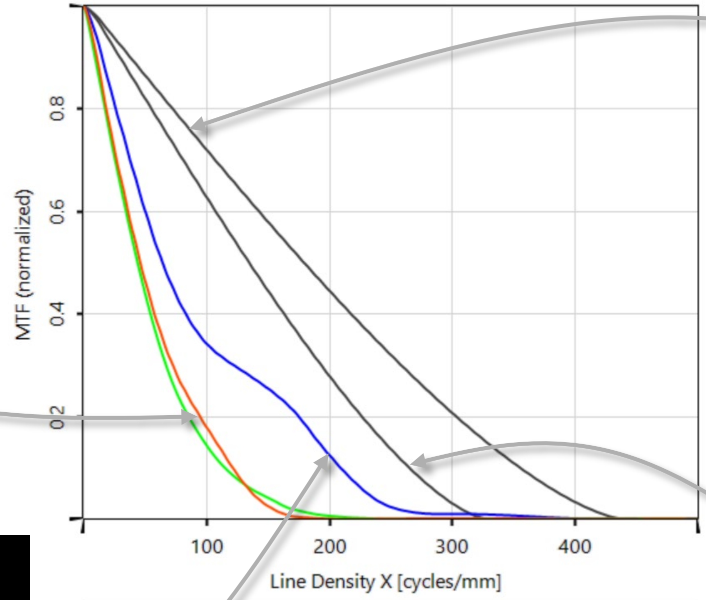
Irradiances in Pupil and MTFs

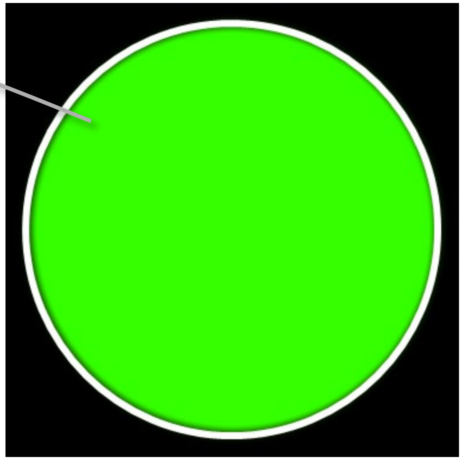
CPU Time: 1.5 min



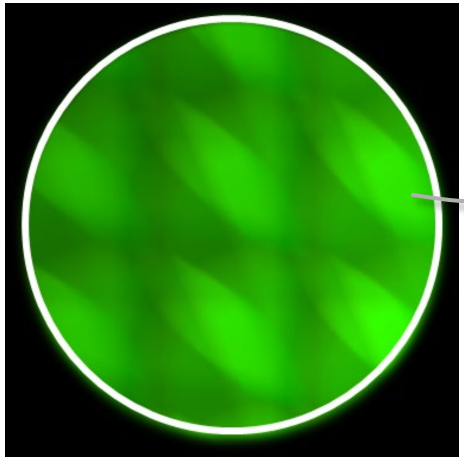
Partially coherent, w/ diffraction

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

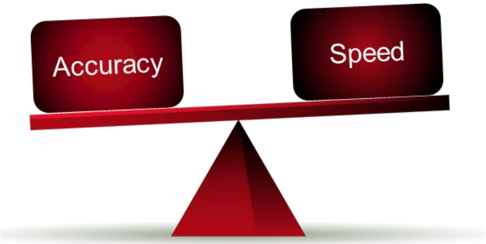


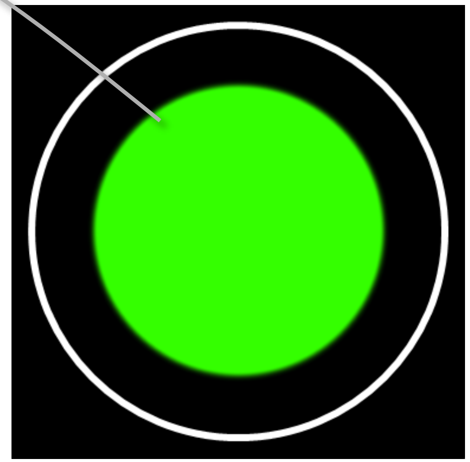


Coherent, uniform, $4\,\mathrm{mm}$



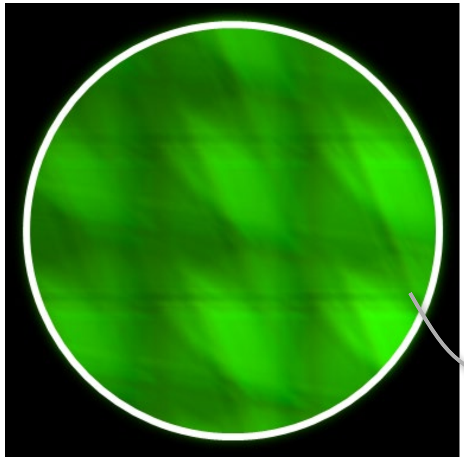
Partially coherent, w/o diffraction





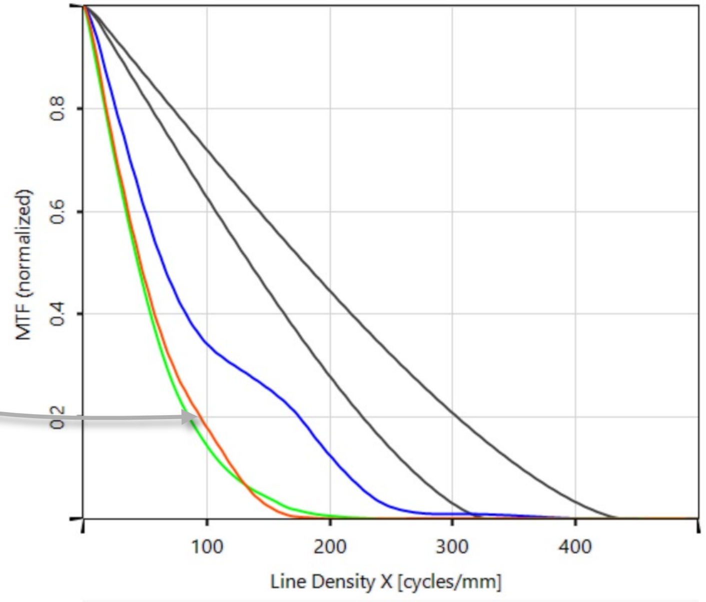
Coherent, uniform, $3\,\mathrm{mm}$

Irradiances in Pupil and MTF: Simulation and Measurement

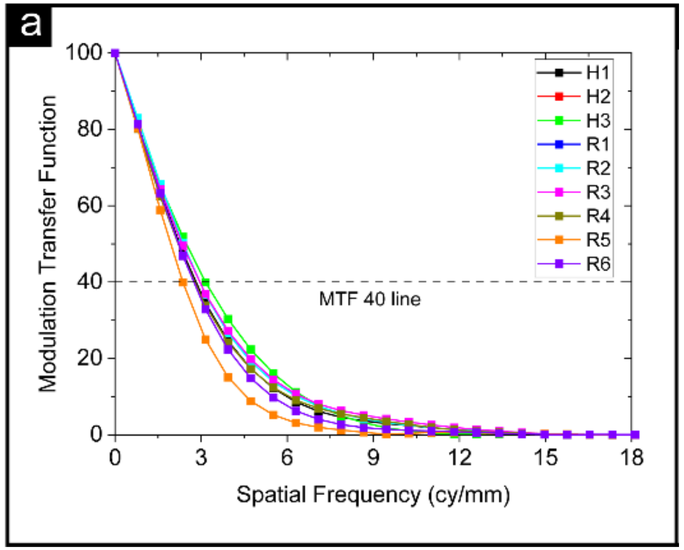


Partially coherent, w/ diffraction

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



Measurements (different layout)



Time model & w/ diffraction

CPU Time: 1.5 min

Temporal Coherence & Diffraction: MTF Simulation

Temporal Coherence Model

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	High	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

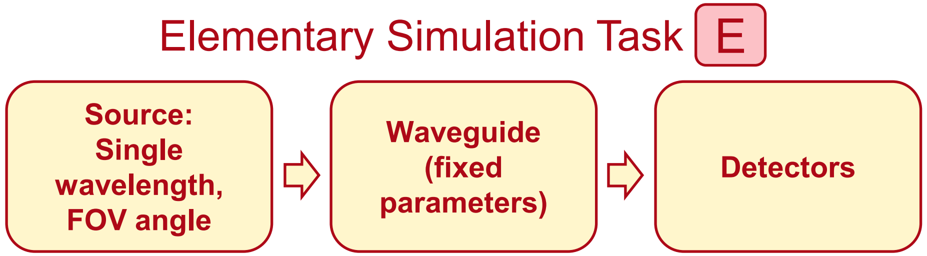
Free-space Propagation Model

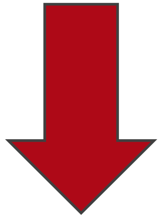
Methods	Preconditions	Accuracy	Speed	Comments
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

Accuracy-speed balance:

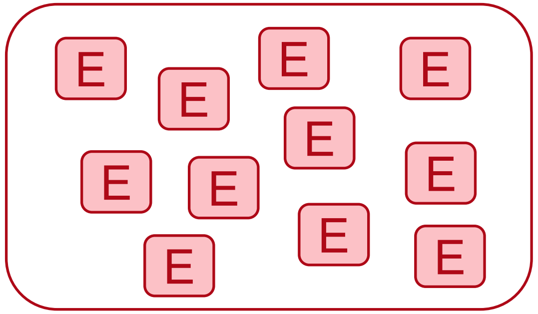
- Accurate evaluation of MTF demands inclusion of temporal coherence and diffraction inside waveguide.
- Simulation time: about a minute per FOV

Elementary Simulation Tasks



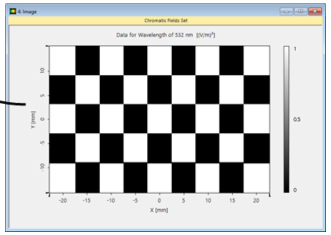


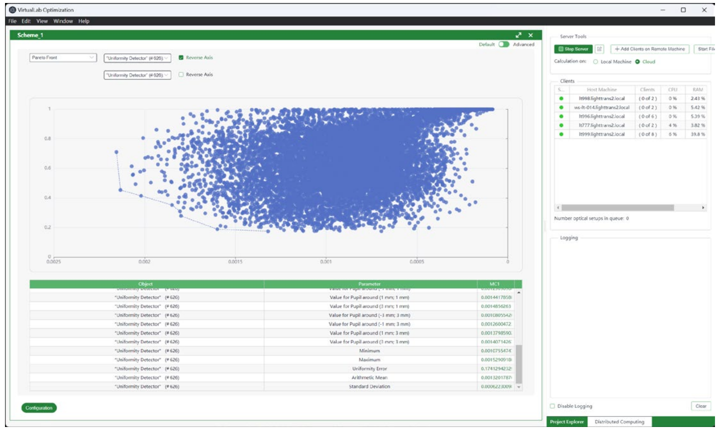
- Model of full FOV
- Optimization, e.g., with evolution algorithm
- Tolerancing



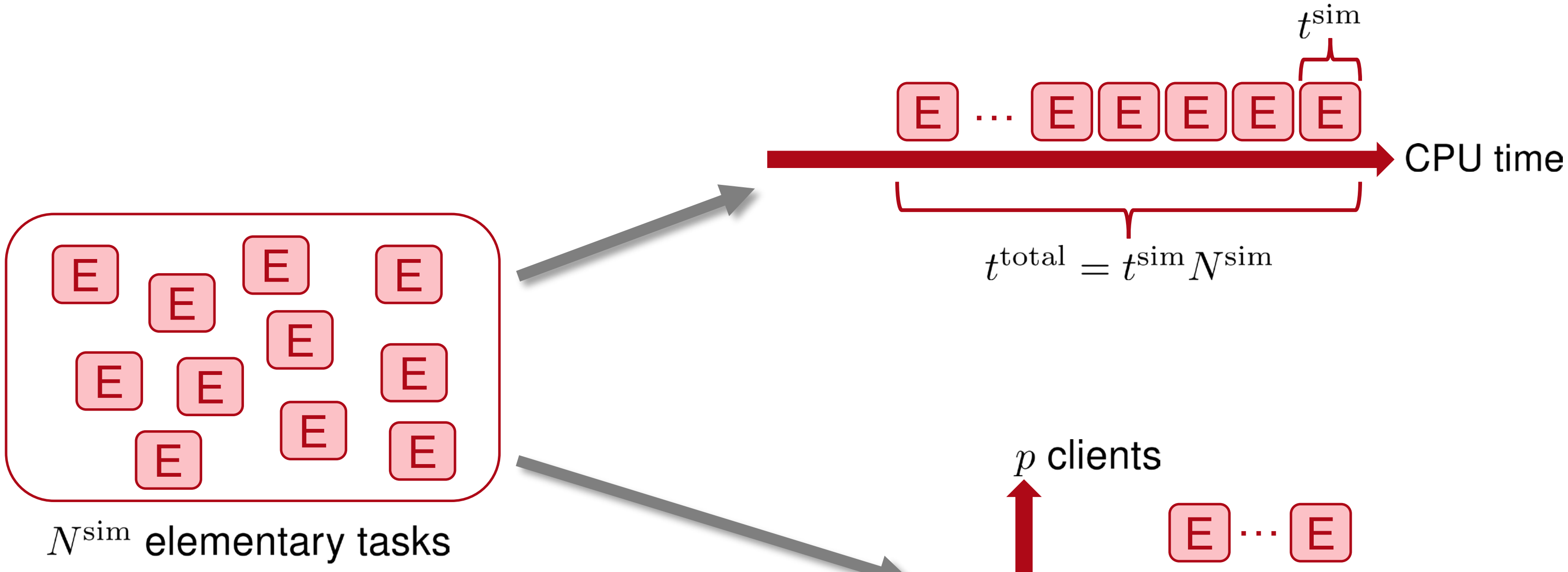
Collection of elementary simulation tasks

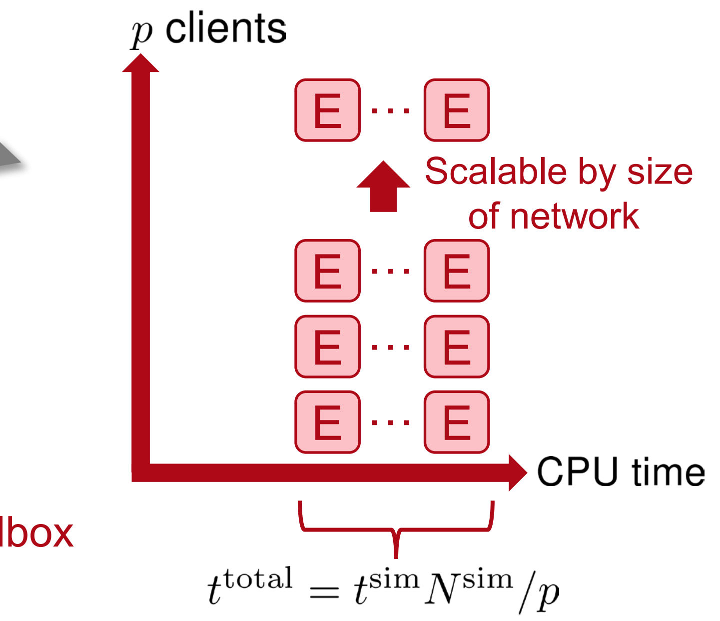
varying parameter: 101 x 101 different FOV – angles, weighted by checkerboard pattern

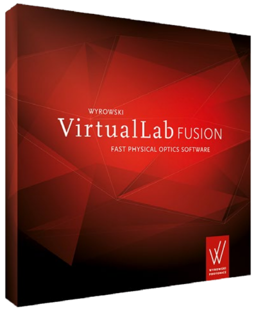




Distributed Computing







Distributed Computing Toolbox

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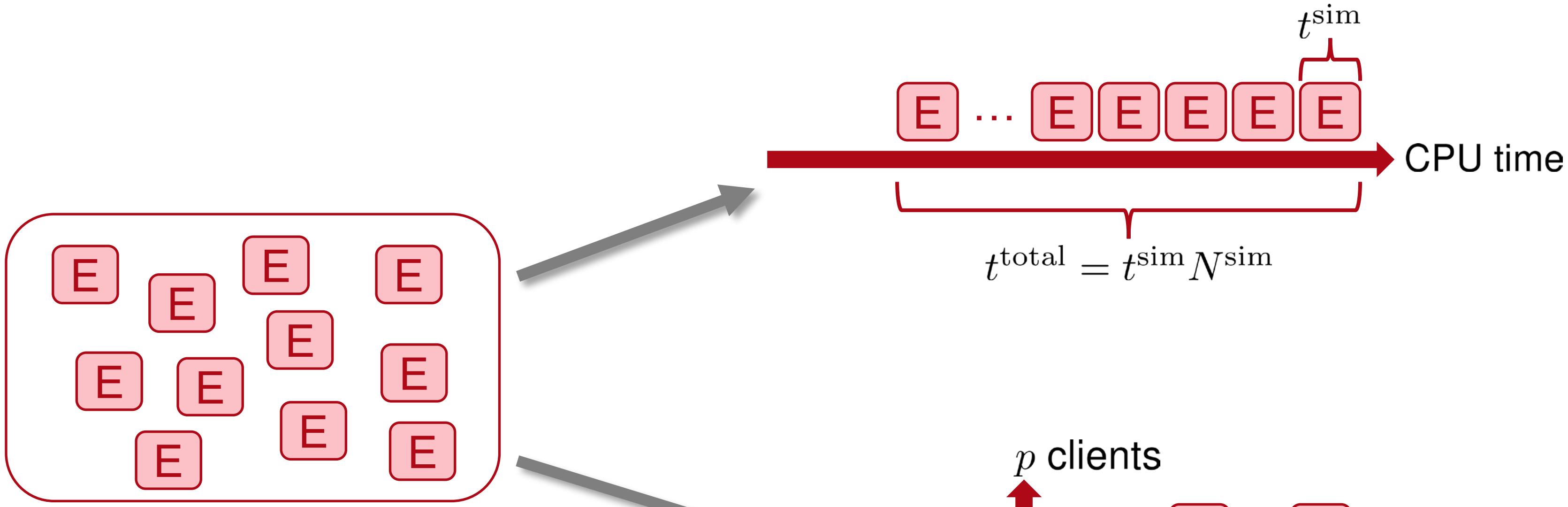
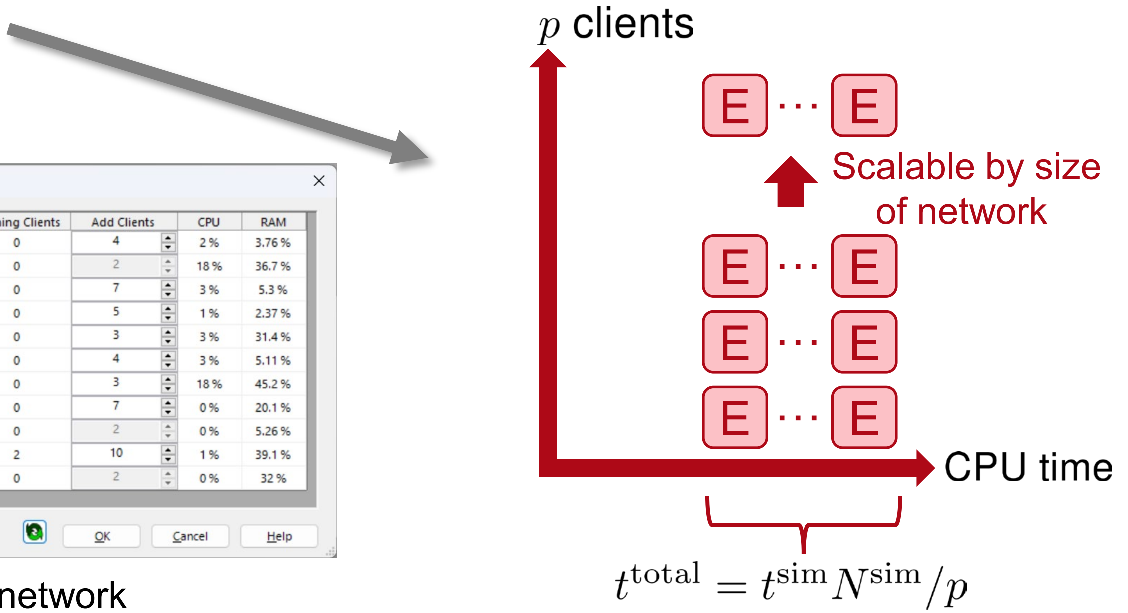
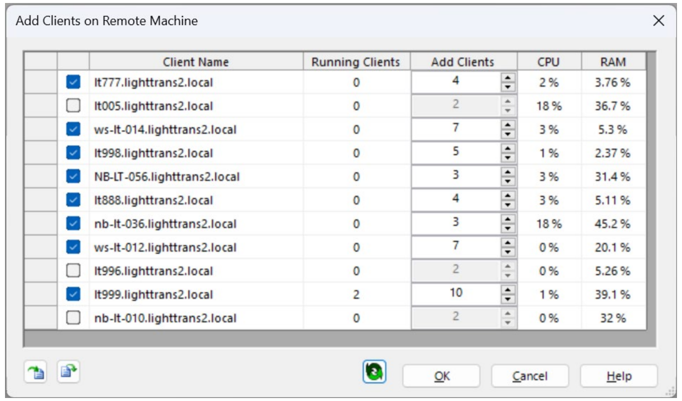
Distributed Computing



N^{sim} elementary tasks

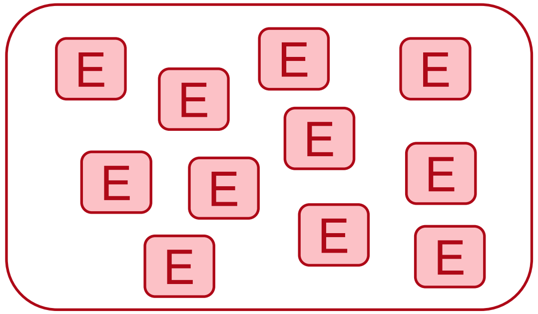




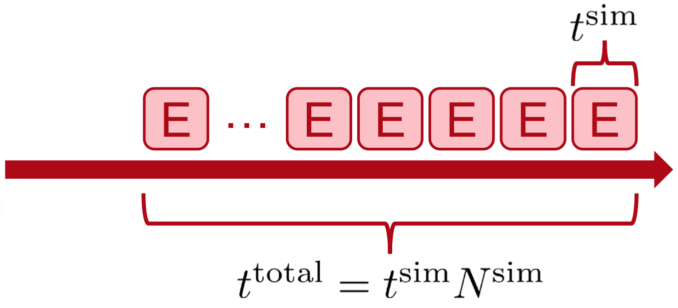
	Client Name	Running Clients	Add Clients	CPU	RAM
☑	lt777.lighttrans2.local	0	4	2 %	3.76 %
☐	lt005.lighttrans2.local	0	2	18 %	36.7 %
☑	ws-lt-014.lighttrans2.local	0	7	3 %	5.3 %
☑	lt998.lighttrans2.local	0	5	1 %	2.37 %
☑	NB-LT-056.lighttrans2.local	0	3	3 %	31.4 %
☑	lt888.lighttrans2.local	0	4	3 %	5.11 %
☑	nb-lt-036.lighttrans2.local	0	3	18 %	45.2 %
☑	ws-lt-012.lighttrans2.local	0	7	0 %	20.1 %
☐	lt996.lighttrans2.local	0	2	0 %	5.26 %
☑	lt999.lighttrans2.local	2	10	1 %	39.1 %
☐	nb-lt-010.lighttrans2.local	0	2	0 %	32 %

Configure client network

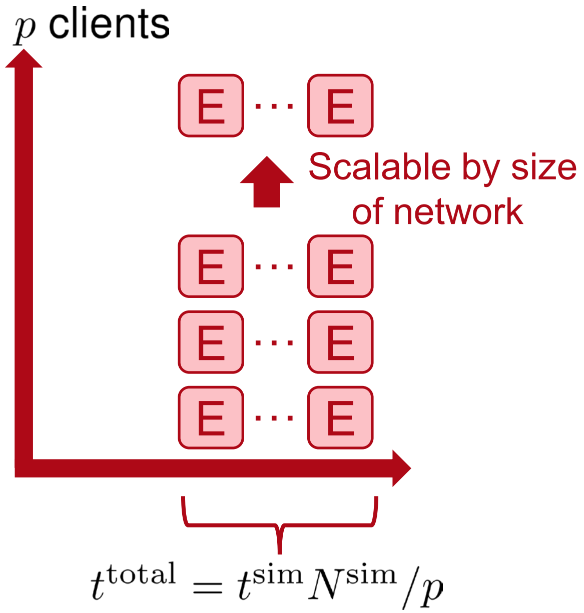
Distributed Computing: Example MTF vs. FOV

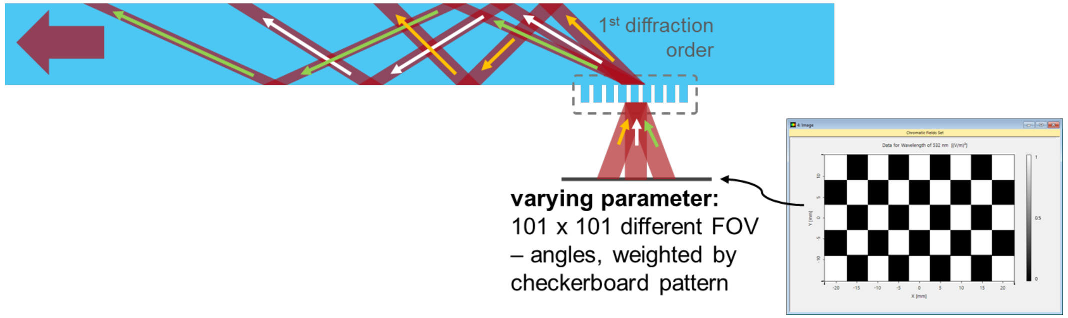


$N^{\mathrm{sim}} = 10201$ tasks



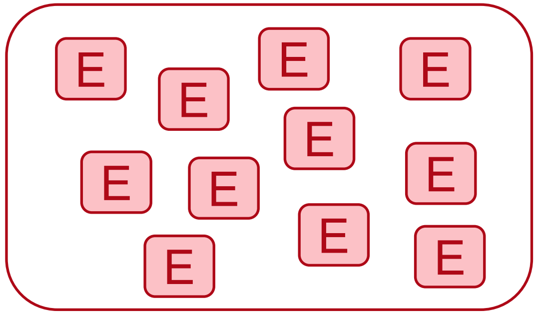
- Elementary simulation: $t^{\mathrm{sim}} \approx 90\,\mathrm{s}$
- Total simulation time: $t^{\mathrm{total}} \approx 250\,\mathrm{h}$



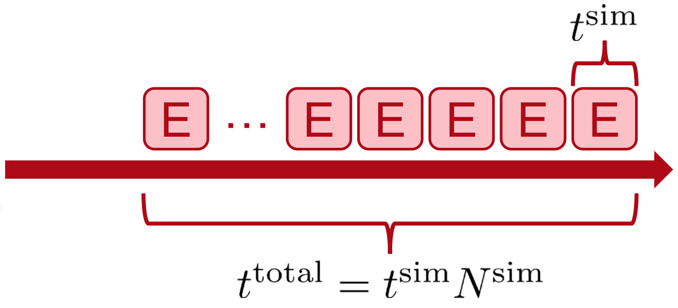


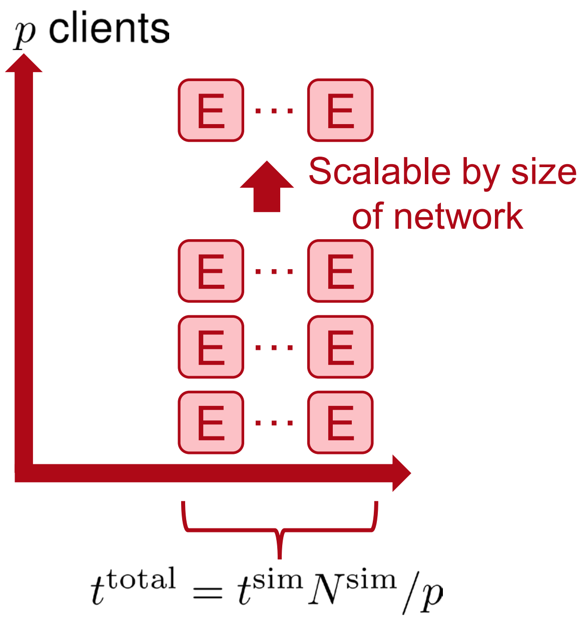
- Number of clients in network: $p = 25$
- Elementary simulation: $t^{\mathrm{sim}} \approx 90\,\mathrm{s}$
- Total simulation time: $t^{\mathrm{total}} \approx 12\,\mathrm{h}$

Distributed Computing: Example Optimization of Uniformity

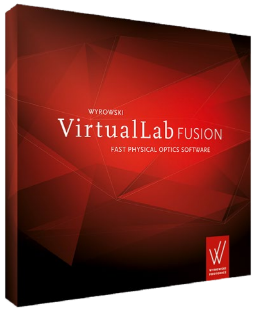


$N^{\mathrm{sim}} = 12000$ simulations





Evolution algorithm



Optimization Toolbox
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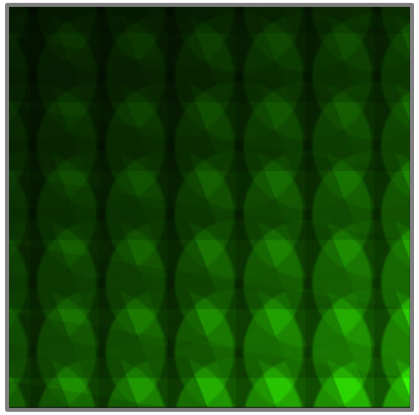
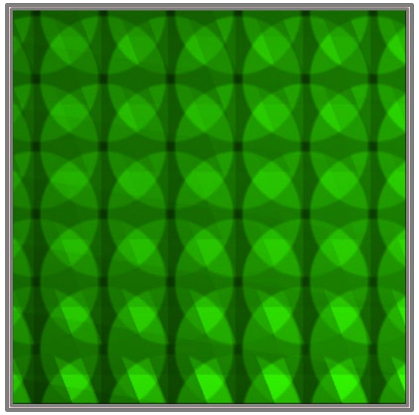
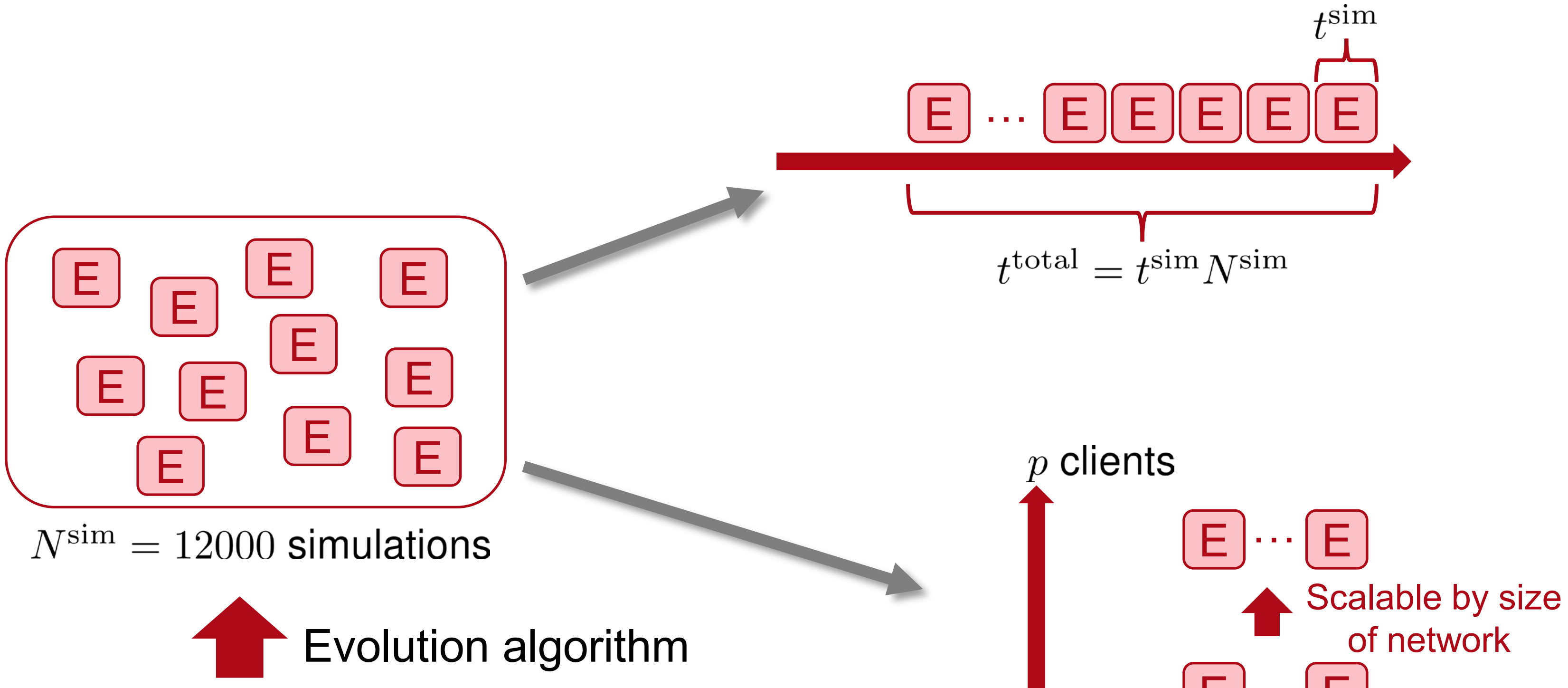


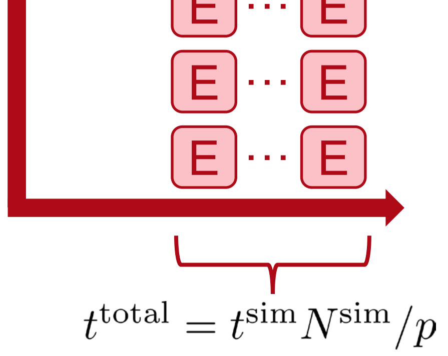
Before Optimization

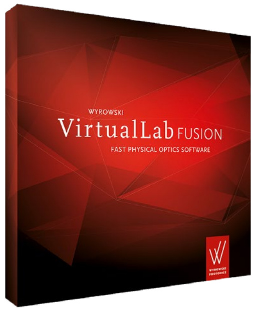


After Optimization

Distributed Computing: Example Optimization of Uniformity







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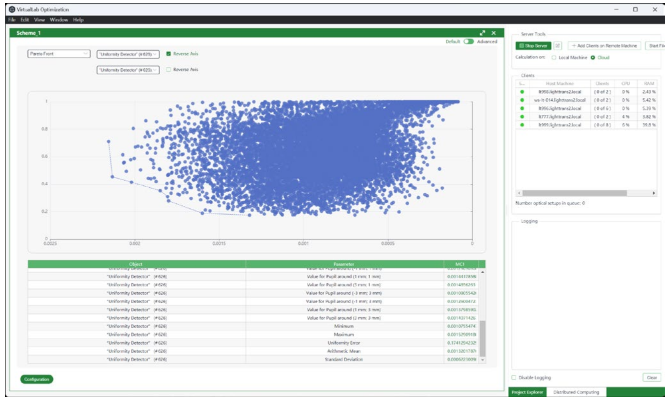
- Elementary simulation: $t^{\text{sim}} \approx 7\,\text{s}$
- Total simulation time: $t^{\text{total}} \approx 23\,\text{h}$

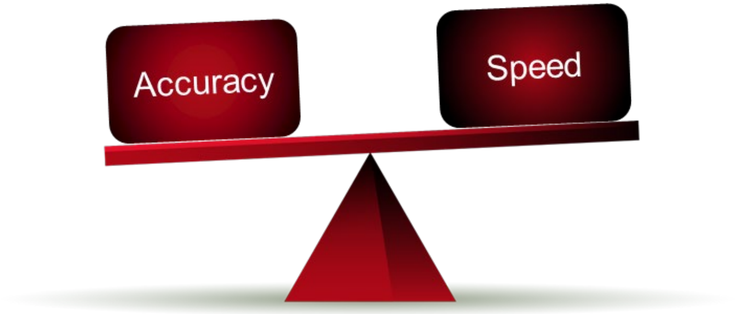


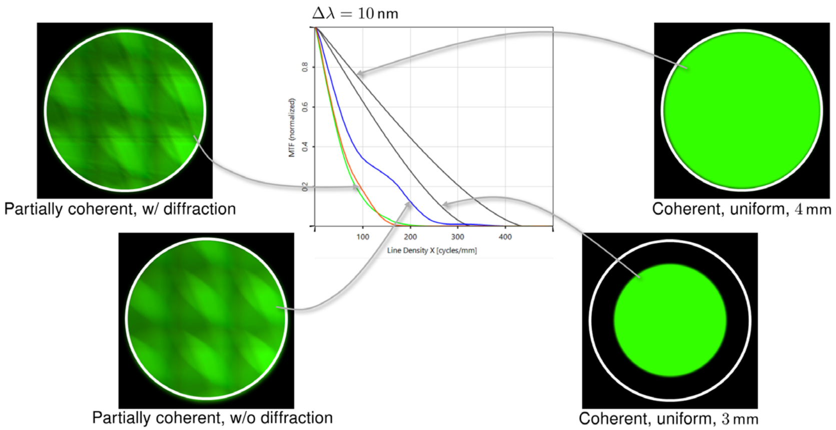
- Number of clients in network: $p = 20$
- Elementary simulation: $t^{\text{sim}} \approx 90\,\text{s}$
- Total simulation time: $t^{\text{total}} \approx 1.5\,\text{h}$

Conclusion

The control of the accuracy-speed balance is of utmost importance in the modeling and design of waveguide AR glasses.

Optics software should provide a
- Pool of many interoperable modeling techniques, and a
- Platform to connect them.





All simulations done with VirtualLab Fusion optics software.

As accurate as needed.
As fast as possible.

Distributed Computing Toolbox
Optimization Toolbox
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