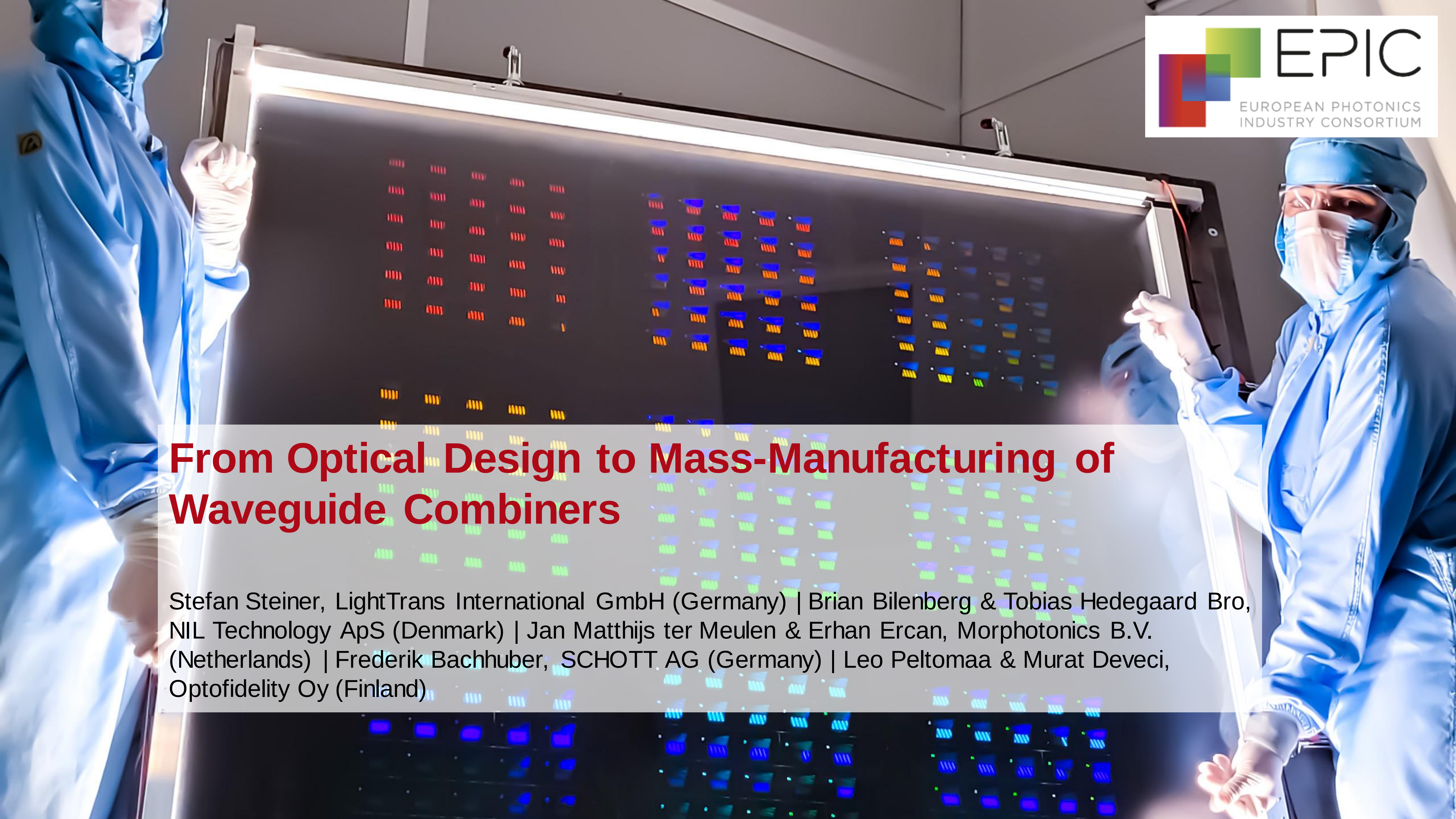


From Optical Design to Mass-Manufacturing of Waveguide Combiners

Stefan Steiner, LightTrans International GmbH (Germany) | Brian Bilenberg & Tobias Hedegaard Bro, NIL Technology ApS (Denmark) | Jan Matthijs ter Meulen & Erhan Ercan, Morphotonics B.V. (Netherlands) | Frederik Bachhuber, SCHOTT AG (Germany) | Leo Peltomaa & Murat Deveci, Optofidelity Oy (Finland)

High Quality Waveguides Beyond Wafer Scale

- Quality and costs are essential if AR glasses want to be the ‘next big thing’
- Starting in 2022, we presented a viable path beyond wafer-scale for AR waveguide optics mass manufacturing
- ‘basic’ proof-of-concept & entire value chain that can produce AR waveguide optics in high-volume via large scale nano-imprint, means low costs
- Since then, replication and image quality and performance are in the focus
- Goal: further establish the new approach towards high-volume and low-cost manufacturing of high-quality waveguides

Complete Value Chain of Pioneers

Fast Physical Optics Modeling & Design Software

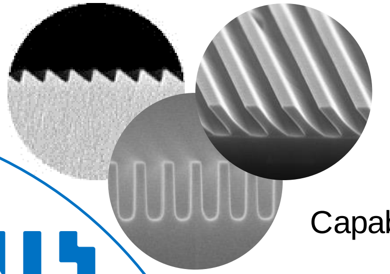
VirtualLab Fusion operates with a breakthrough technology for optical modeling & design based on physical optics

A powerful platform for innovative developments: LiDAR, AR/MR/VR Glasses, Laser Systems, Gratings, meta lenses, etc.

Pioneering – responsibly – together

Founder Otto Schott is considered the inventor of optical glass and became the pioneer of an entire industry.

Always opening up new markets and applications with a pioneering spirit and passion – for more than 130 years.



Large Area High-Precision Gratings

Accuracy in grating periodicity across large areas

Capable of designing & delivering non-periodic gratings

Leaders of Large-Area Nanoimprinting

World's largest-area, commercially available, fully integrated nanoimprinting machine

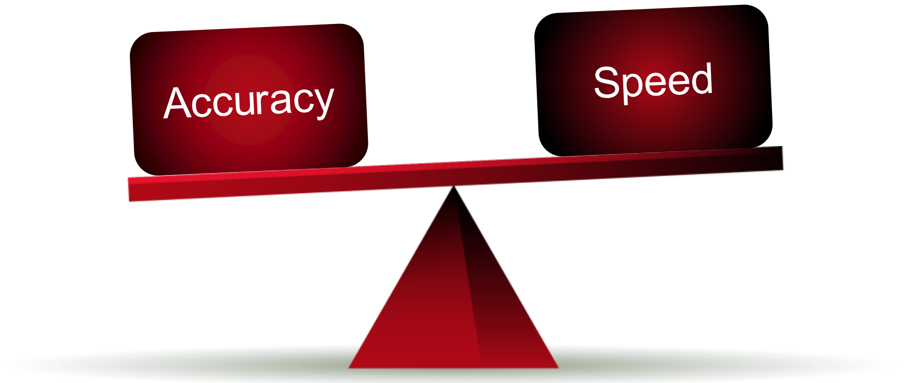
Cost-effective mass manufacturing of nano/micron structures via large-area nanoimprinting

Enabling Smarter Future

Global market leader in automated optical metrology & characterization solutions for AR waveguides and displays throughout the entire product life-cycle from R&D to high volume manufacturing

"It is all about accuracy and speed."

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

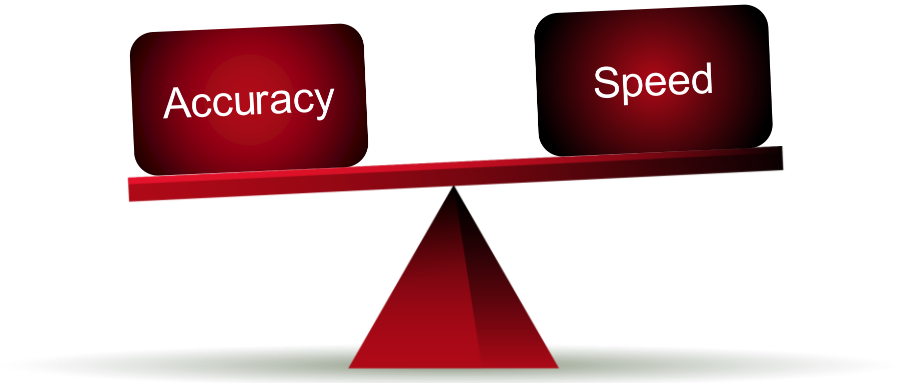


As accurate as needed.
As fast as possible.

Control of the accuracy-speed balance

Major trend in the usage and development of optics software

High speed means
short time to results.

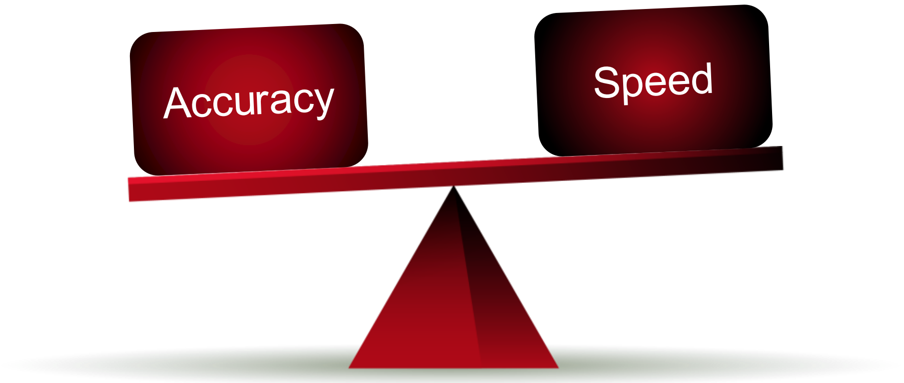


As accurate as needed.
As fast as possible.

Control of the accuracy-speed balance

Major trend in the usage and development of optics software

What means accuracy in optical modeling and design?



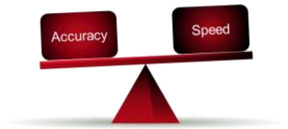
As accurate as needed.
As fast as possible.

Control of the accuracy-speed balance

Major trend in the usage and development of optics software

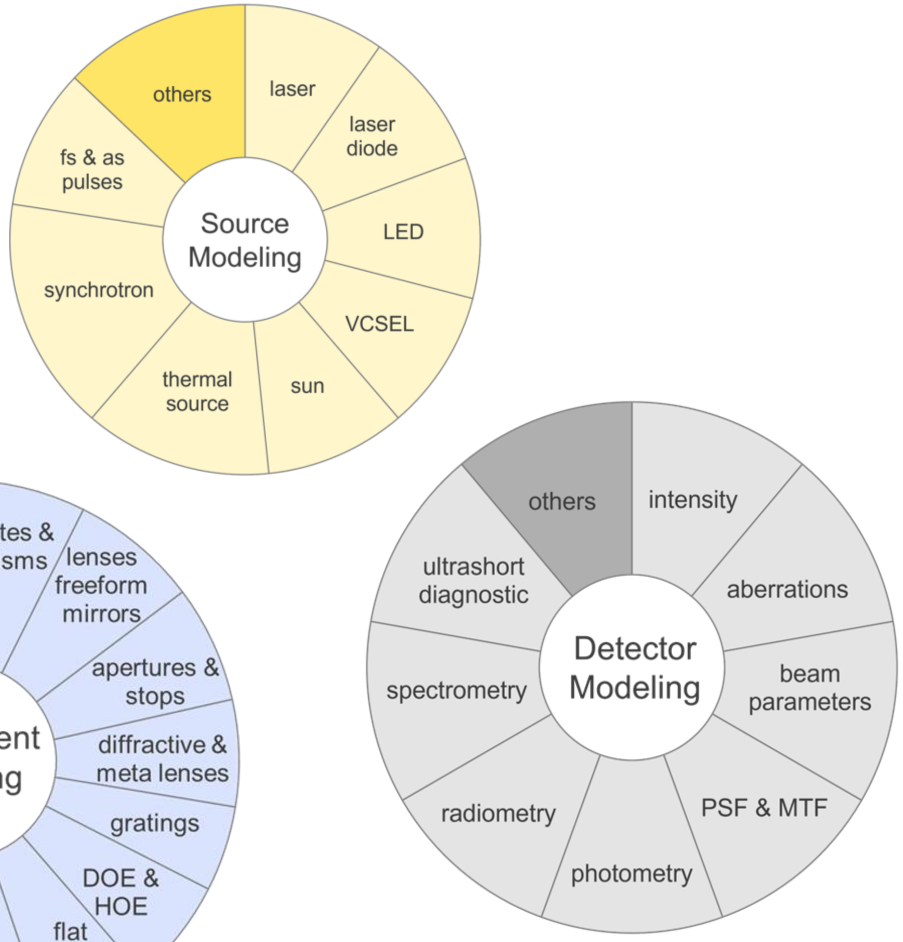
Pool of Interoperable Modeling Techniques

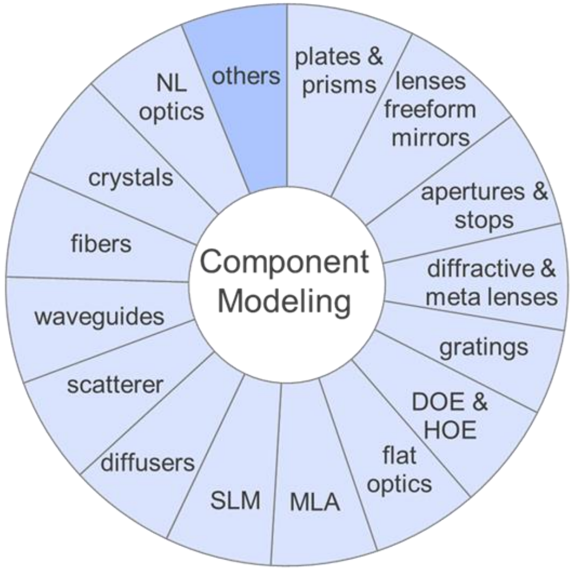
Control of accuracy-speed balance



Optics software should provide a

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



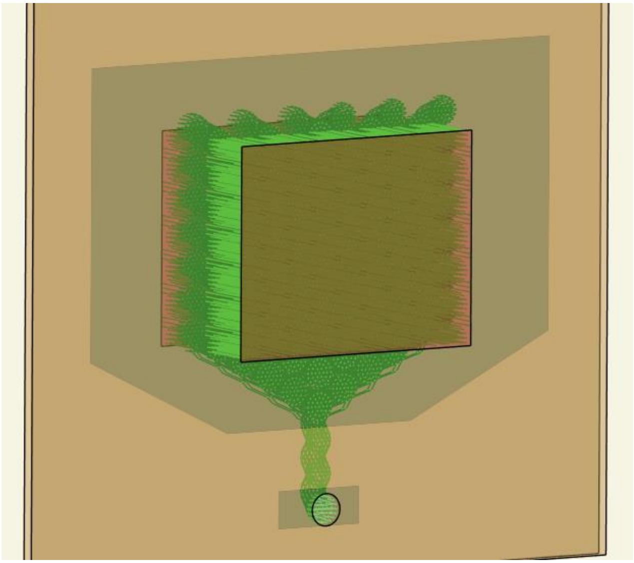


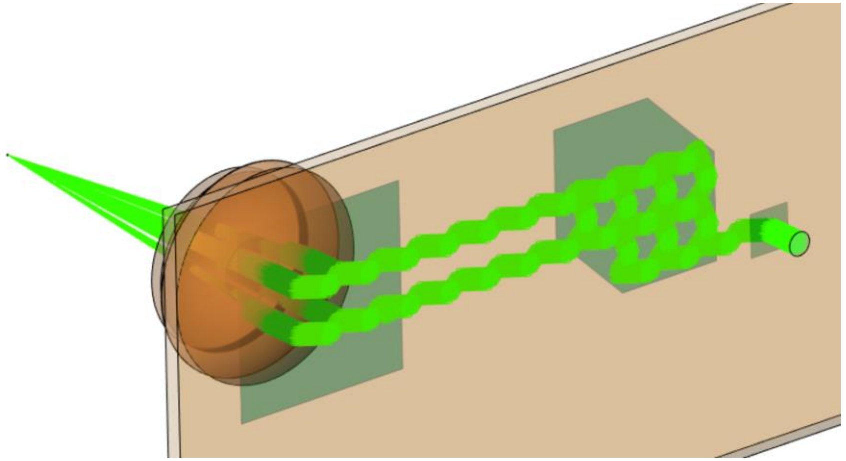
Overview Workflow for Design of Waveguides

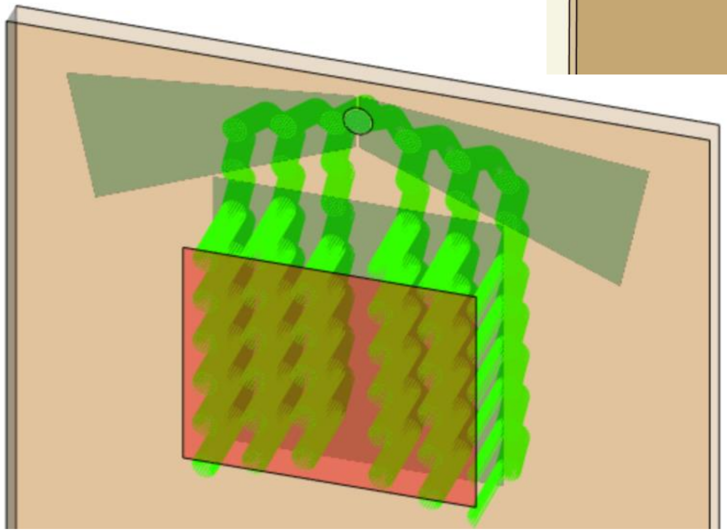
1. Configuration of basic optical lightguide setup with grating regions

2. Definition of grating types, shapes and parameters.

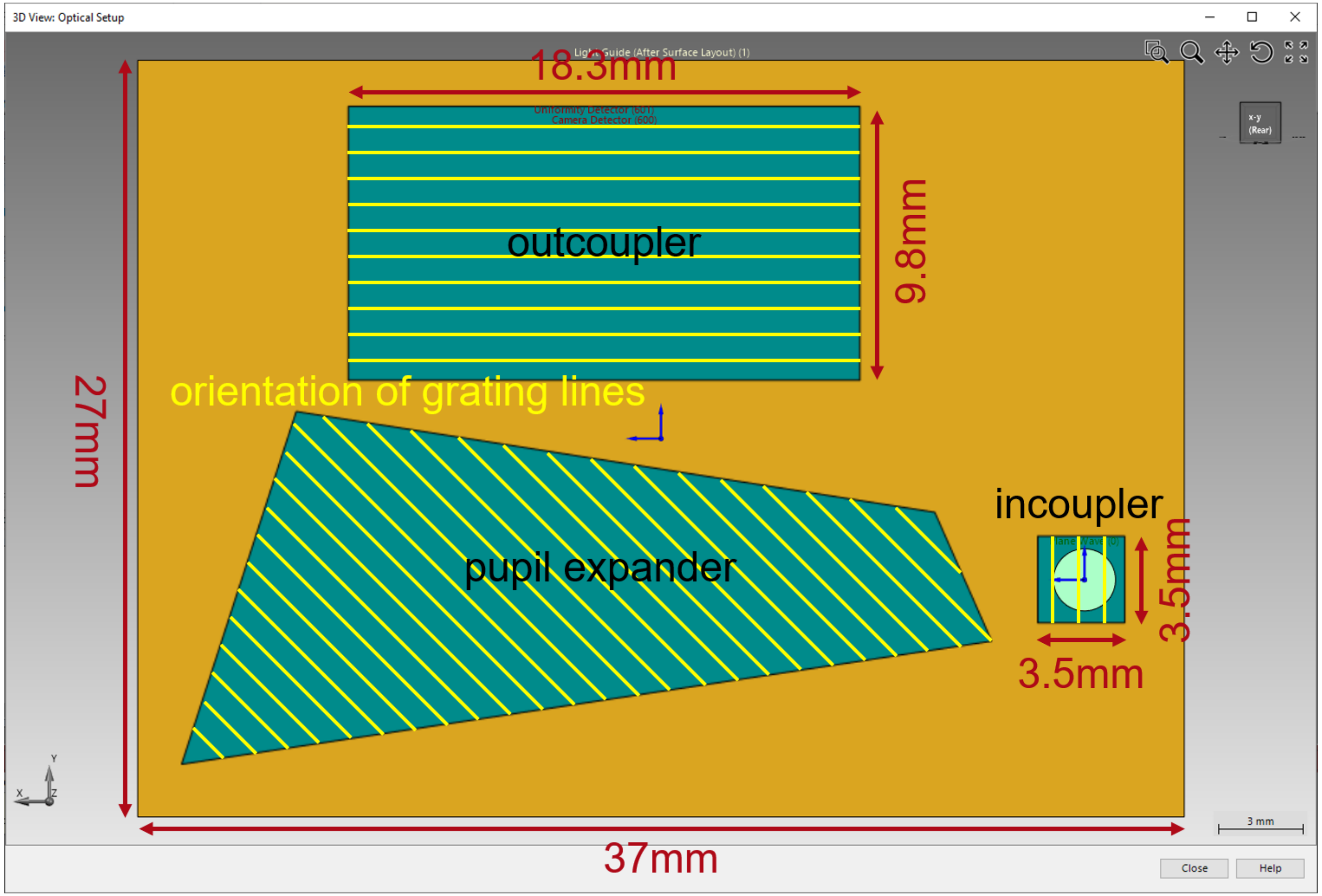
3. Select variables and define merit functions to optimize the modulated grating parameters.







Design of Waveguide – Lateral Layout



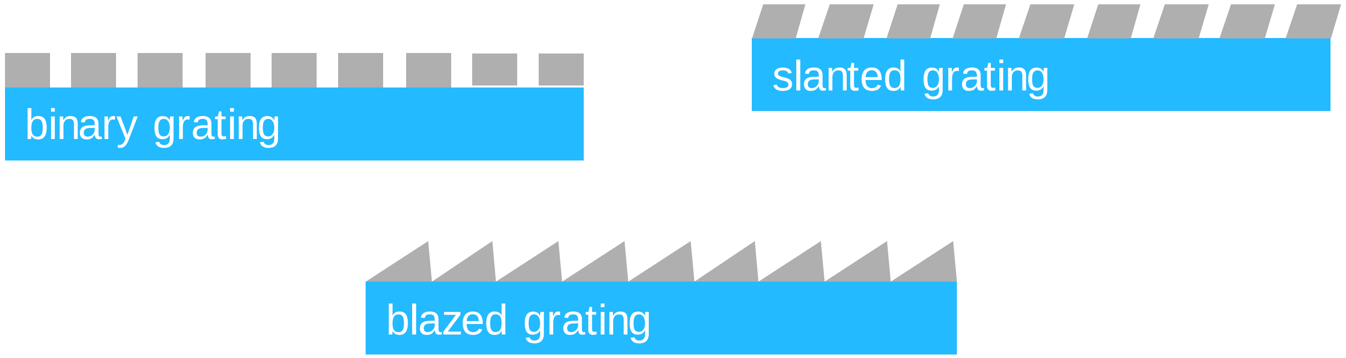
Specifications:

- 1D-1D pupil expansion
- FOV: 32°×18°
- eye-box: 15 mm × 8 mm
- eye-relief: 5 mm

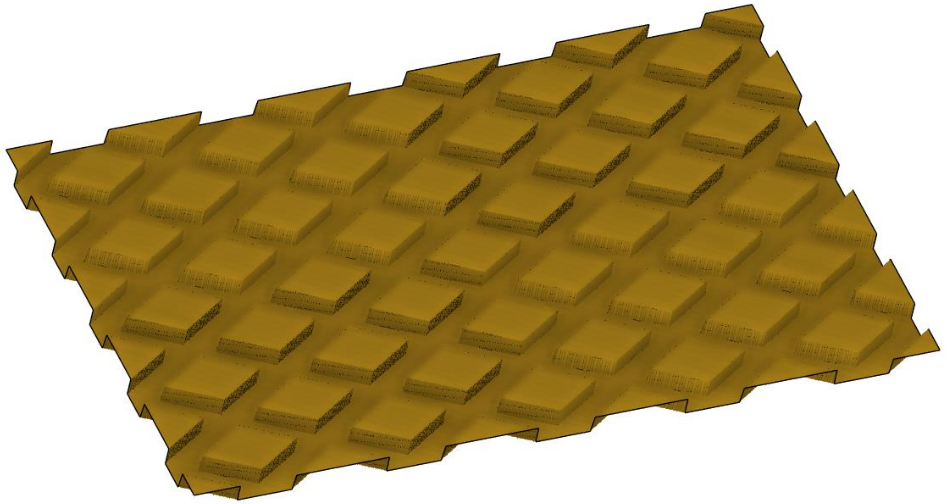
- substrate: Schott Realview 2.0
- 1D-periodic gratings
- index of grating material: 1.88

Overview Workflow for Design of Waveguides

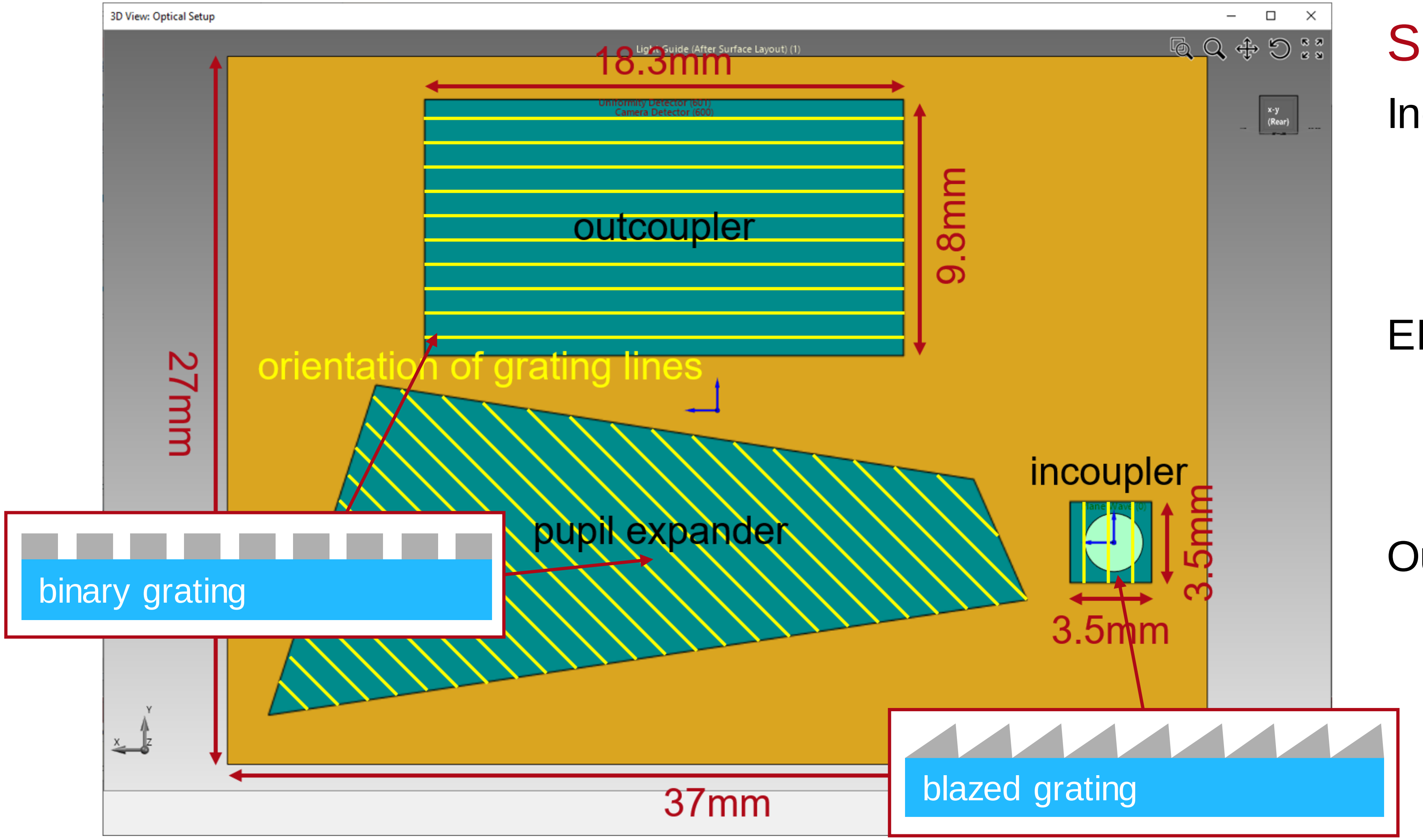
1. Configuration of basic optical lightguide setup with grating regions
2. Definition of grating types, shapes and parameters.
3. Select variables and define merit functions to optimize the modulated grating parameters.



1D-periodic structures


complex 2D-periodic structures

Design of Waveguide – Grating Definitions



Specifications:

Incoupler:

- period: 415 nm
- blazed grating (2024: slanted)

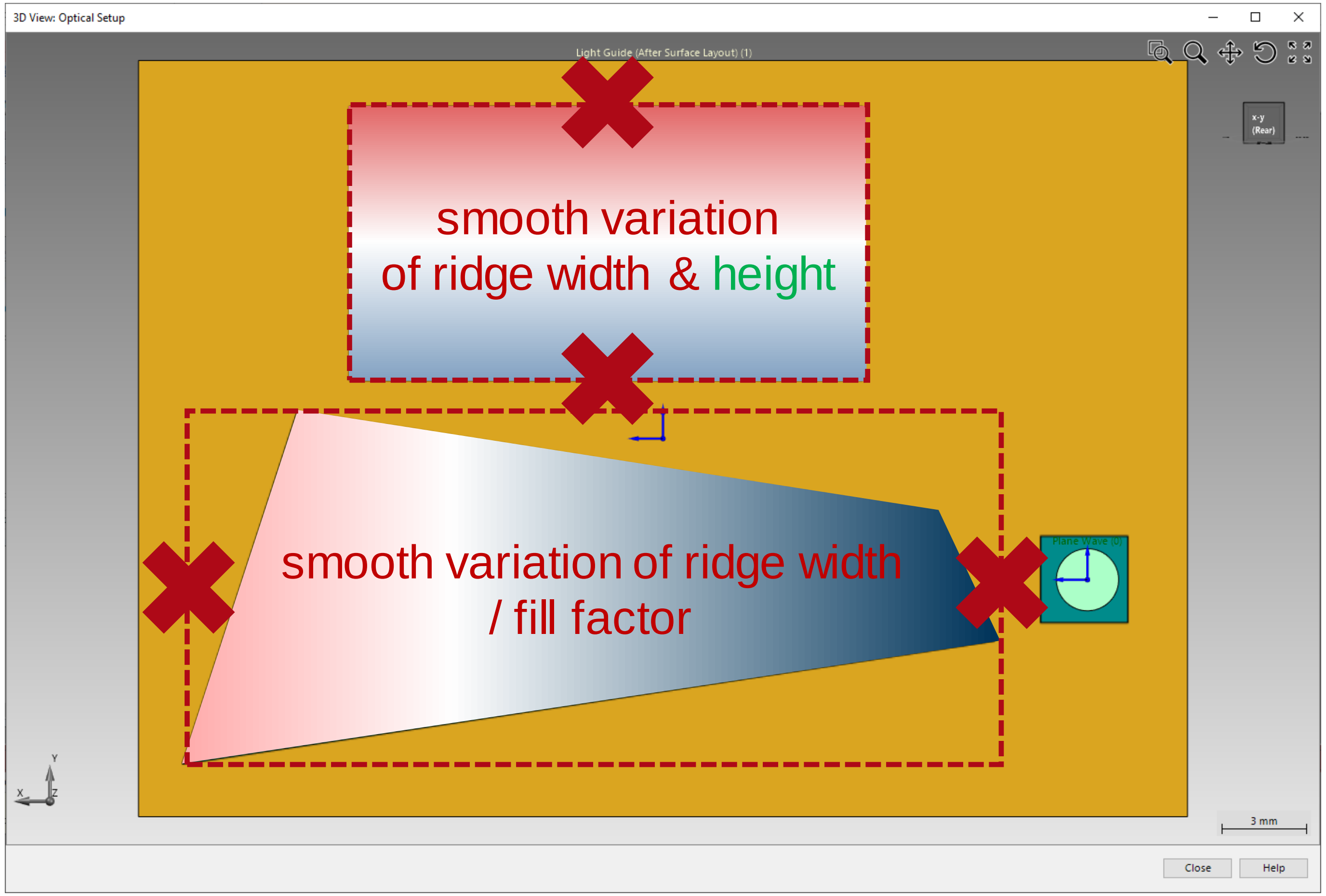
EPE:

- period: 293.45 nm
- binary grating

Outcoupler:

- period: 415 nm
- binary grating (2024: slanted)

Design of Waveguide – Grating Definitions Part #2



- continuously modulated grating parameters with pre-calculated LUTs
- modulation type can be adapted (e.g. linear or exponential)
- tremendous reduction of parameters during the optimization by just defining the parameters at 2 points

Parameters to be Optimized	**Ranges**
blaze angle of incoupler	10° – 50°
fill factor of EPE	10% – 90%
fill factor of outcouple grating	10% – 90%
height of outcouple grating	50 nm – 400 nm

Overview Workflow for Design of Waveguides

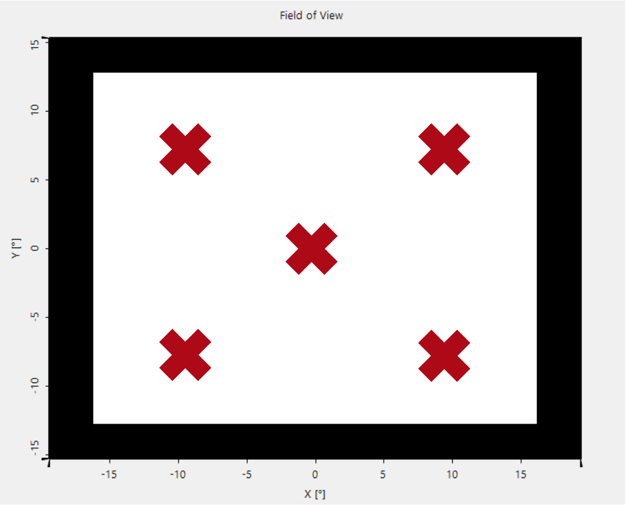
1. Configuration of basic optical lightguide setup with grating regions
2. Definition of grating types, shapes and parameters.
3. Select variables and define merit functions to optimize the modulated grating parameters.

Merits (per FoV angle or mode):

merit function	**aim**
Uniformity Error	lower means better
Arithmetic Mean	higher means better

+

Consideration of FoV



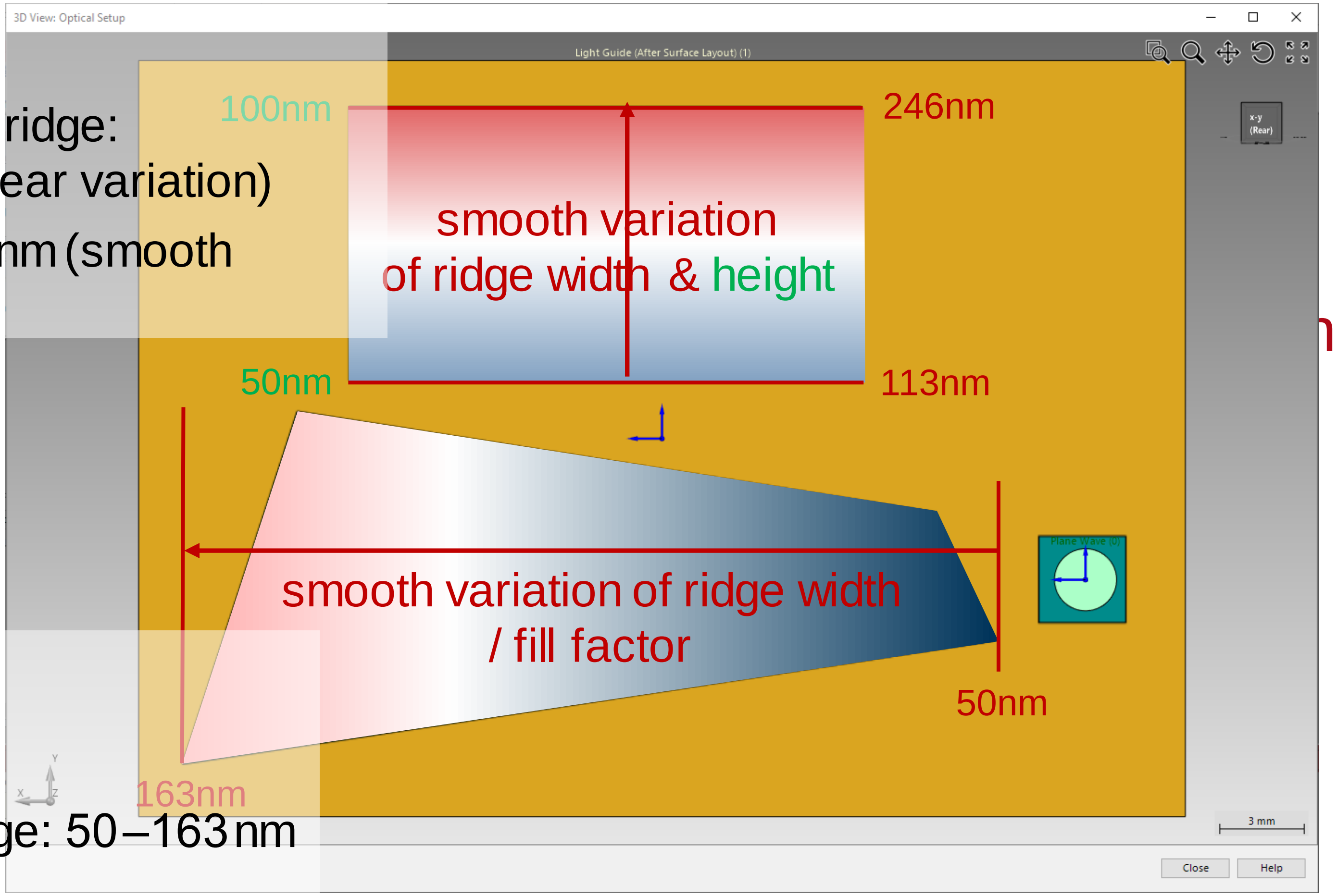
result of central FoV mode
+
1 mode/angle per quadrant
=
5 modes total

Optimization method: Evolutionary algorithm with proper weights (parallelizable via distributed computing)

Design of Waveguide – Grating Parameters

Outcoupler:

- period: 415 nm
- width of grating ridge: 113–246 nm (linear variation)
- height: 50–100 nm (smooth variation)



Incoupler:

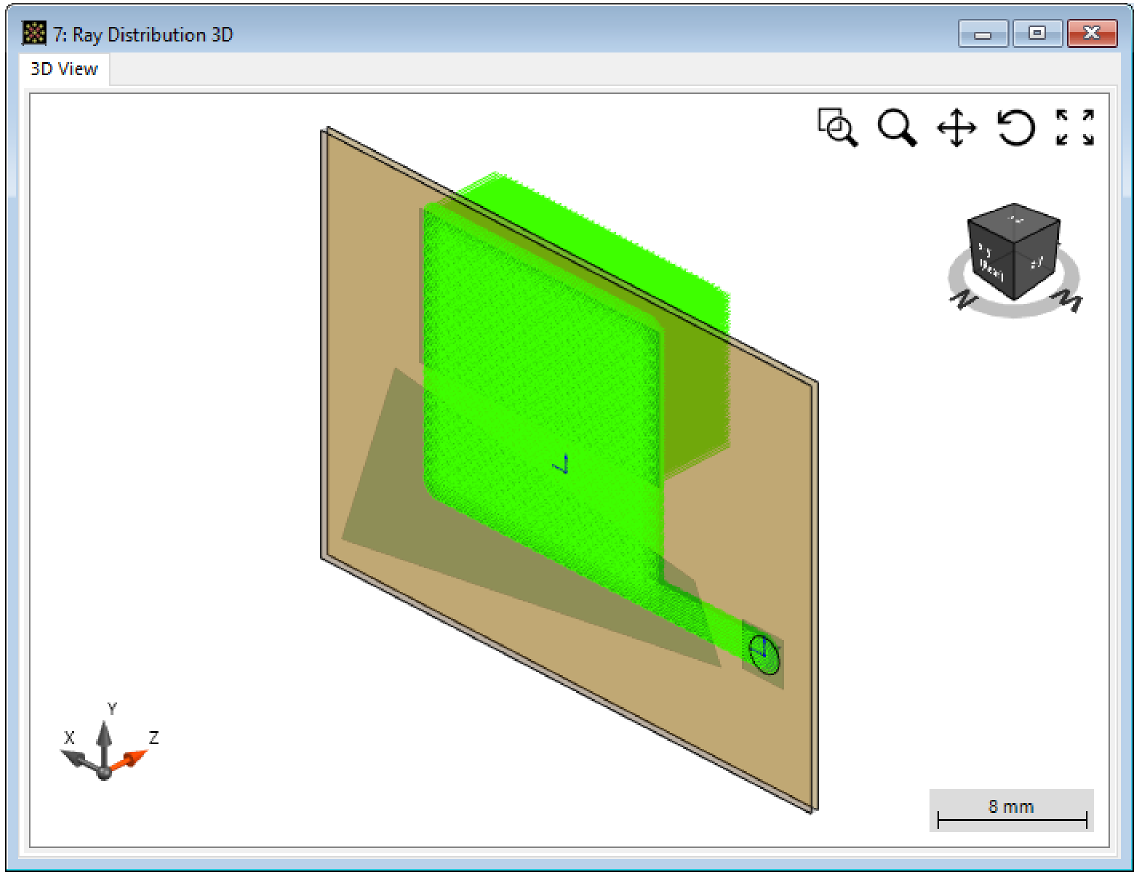
- period: 415 nm
- blaze angle: 29.9°

Pupil Expander:

- period: 293.45 nm
- width of grating ridge: 50–163 nm (linear variation)
- height: 50 nm (constant)

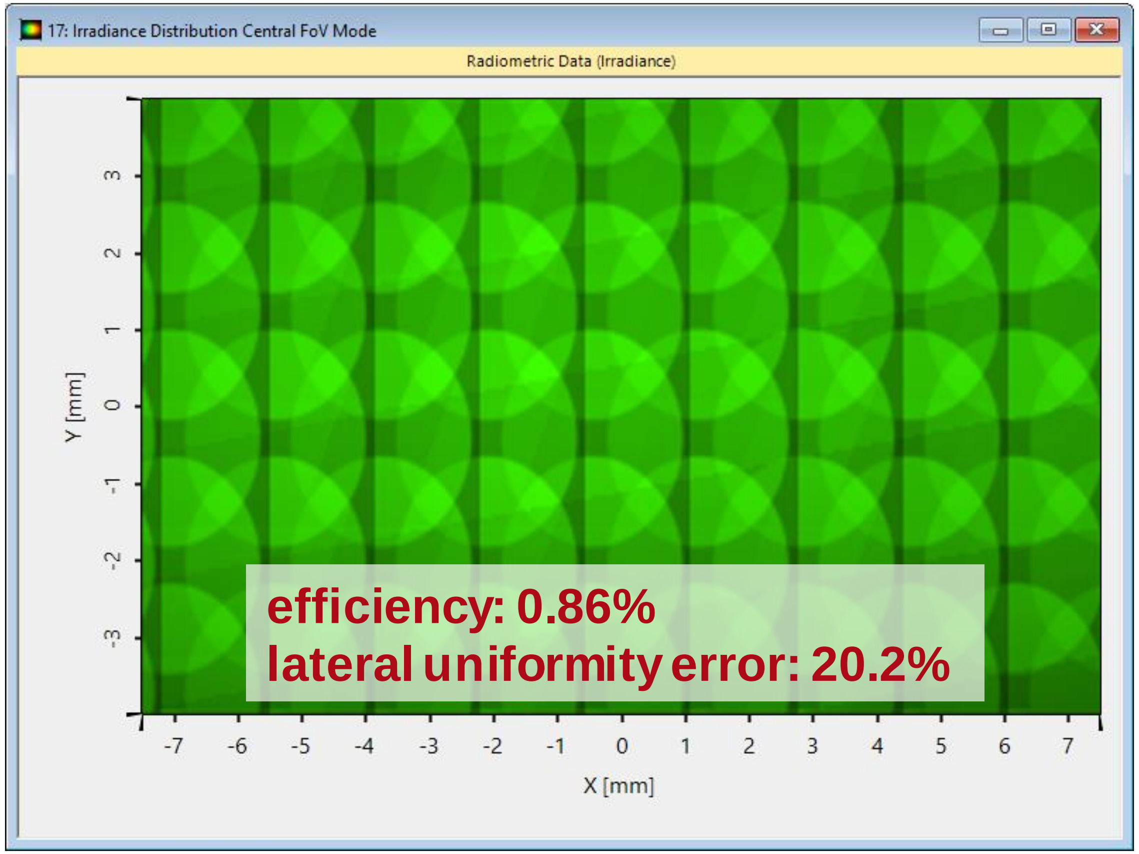
Simulation Results of Optimized Device

racing result for central direction of the FOV



(for illustration just light hitting the eyebox is shown)

calculated irradiance in eye-box for central direction



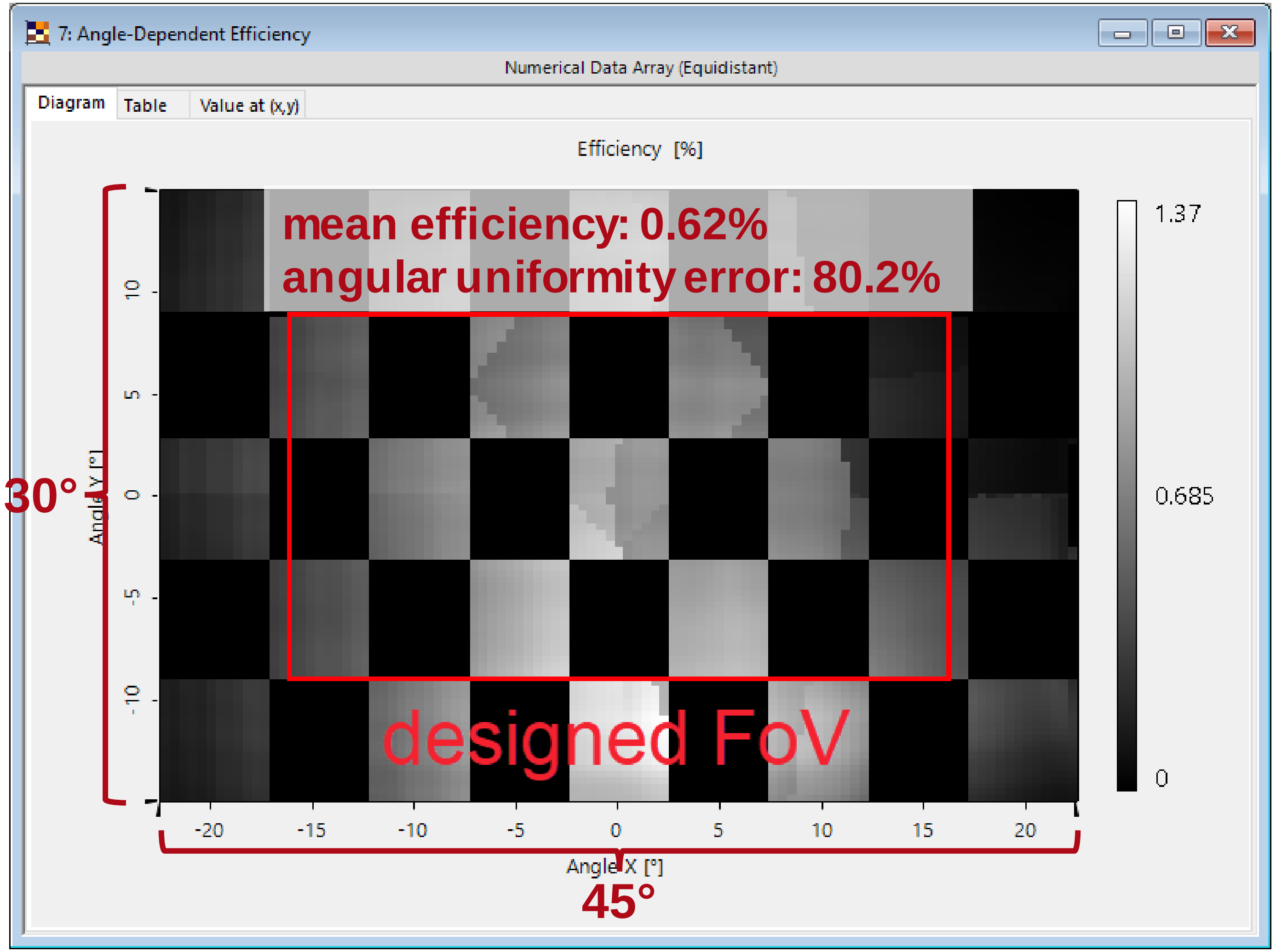
(including polarization effects & rigorously calculated grating responses)

Simulation Results of Optimized Device

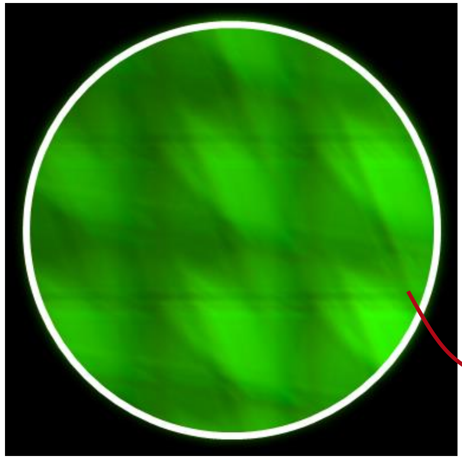
analysis by using angular checkerboard:

one box: 5°× 6°

whole range: 45°× 30°

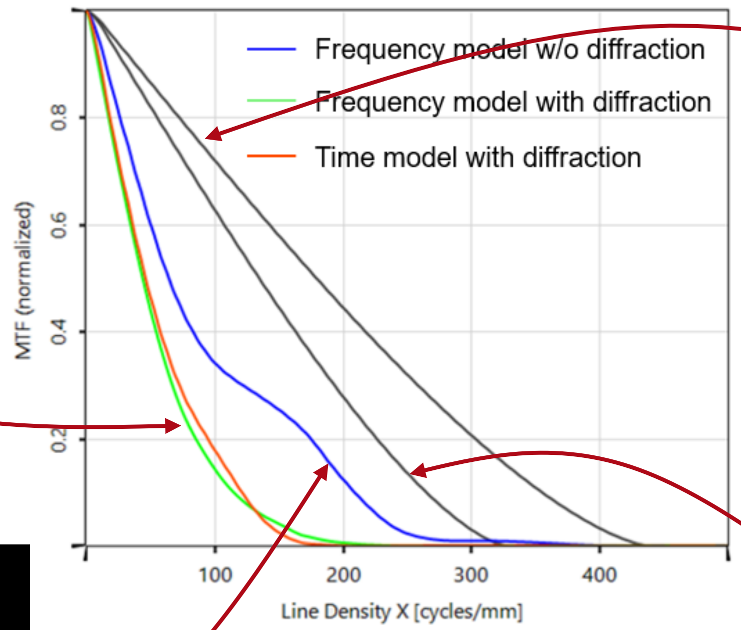


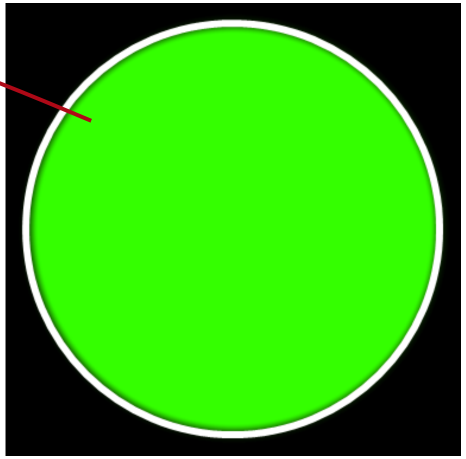
Analysis of MTF



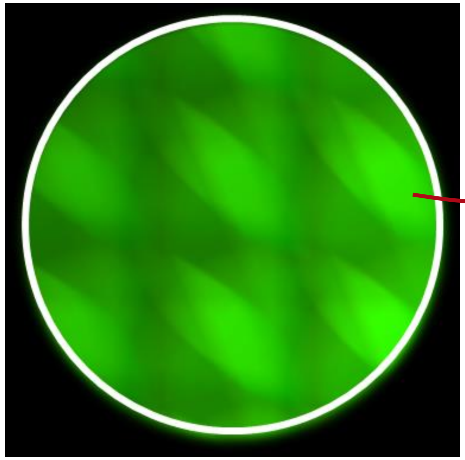
Partially coherent, with diffraction

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

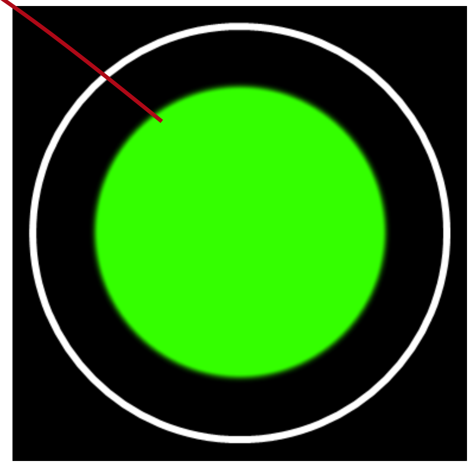




Coherent, uniform, 4 mm



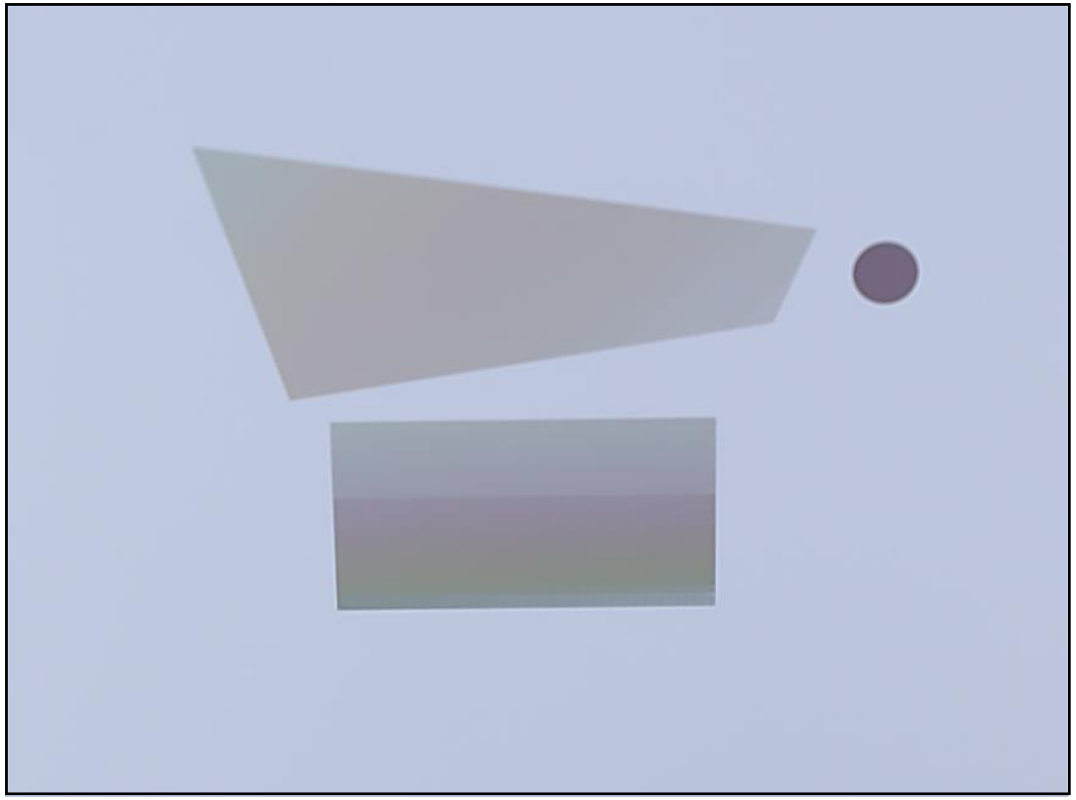
Partially coherent, without diffraction



Coherent, uniform, 3 mm

Waveguide Optics Mastering

NIL TECHNOLOGY

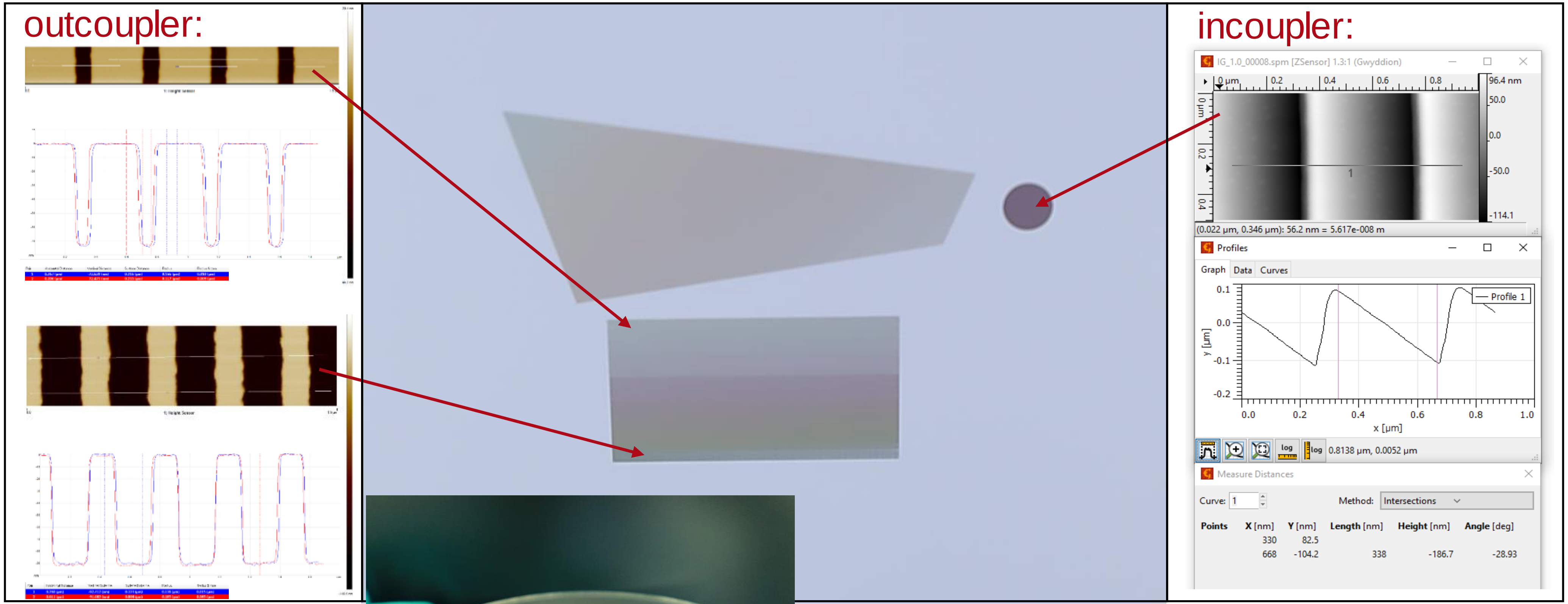


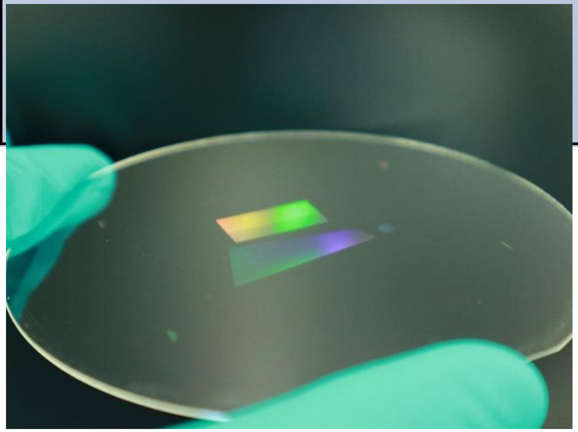
Complete AR master with:

- blazed input grating
- fill factor modulated expander grating
- depth and fill factor modulated output grating

Waveguide Optics Mastering

NIL TECHNOLOGY

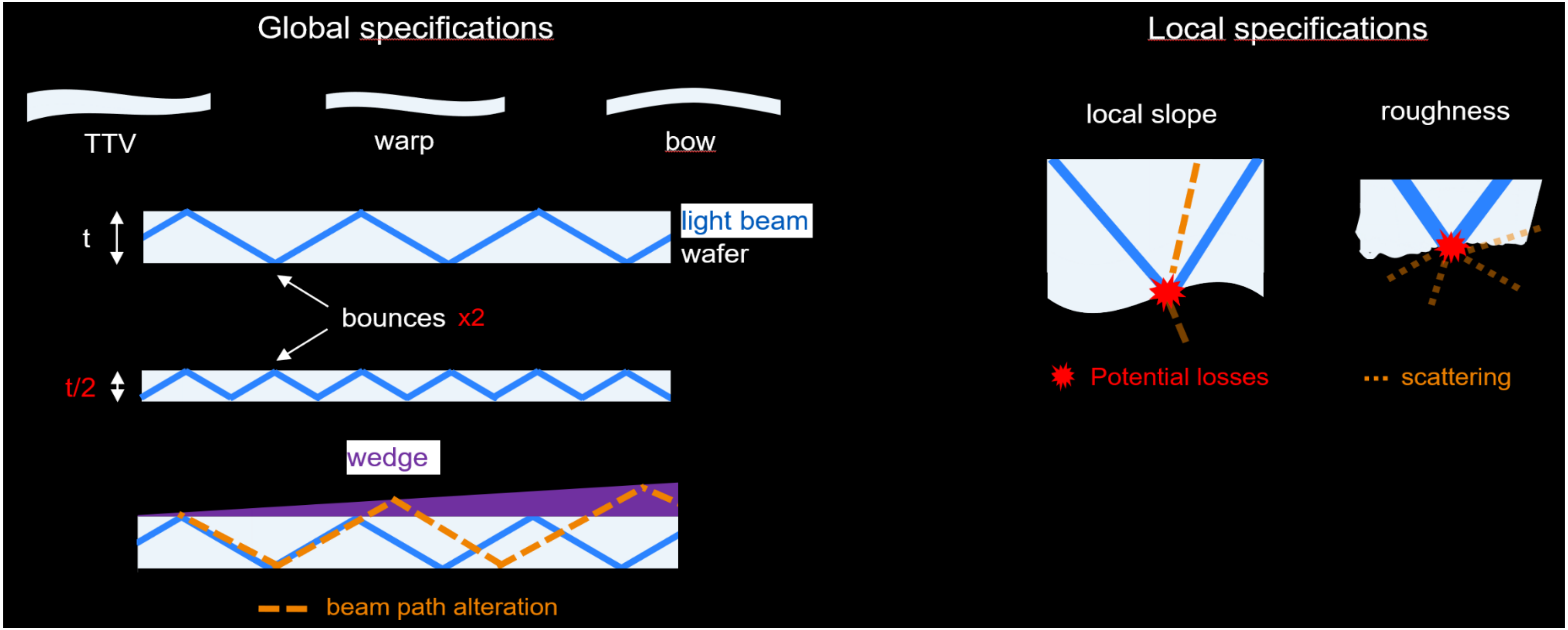




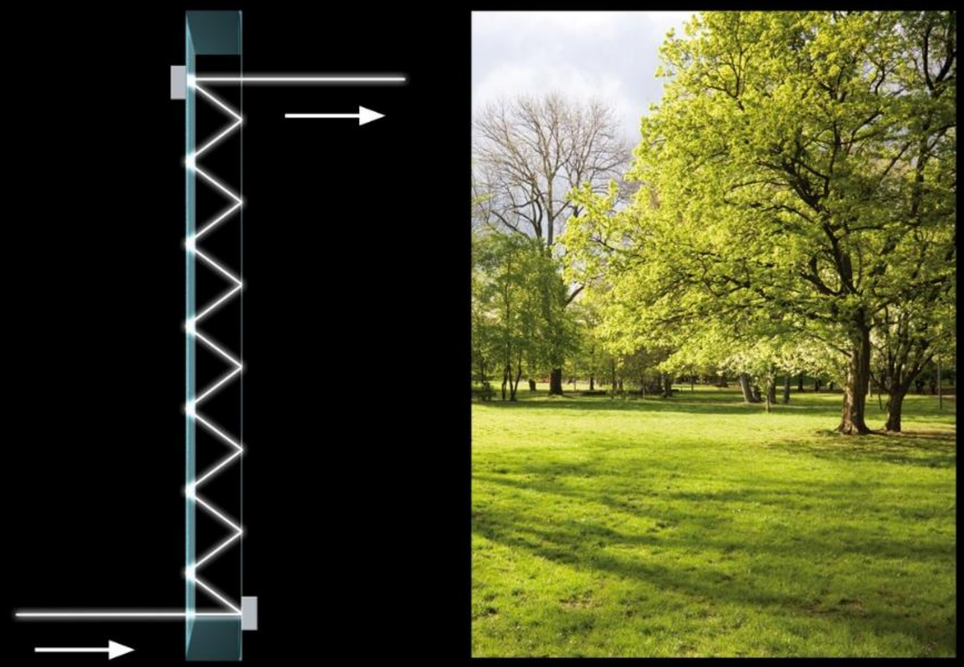
- fill factor modulation from 17% (top) to 56% (bottom)
- depth modulation from 72 nm (top) to 92 nm (bottom).

AFM scan of blazed input grating showing the sharp profile with 29 degrees blaze angle.

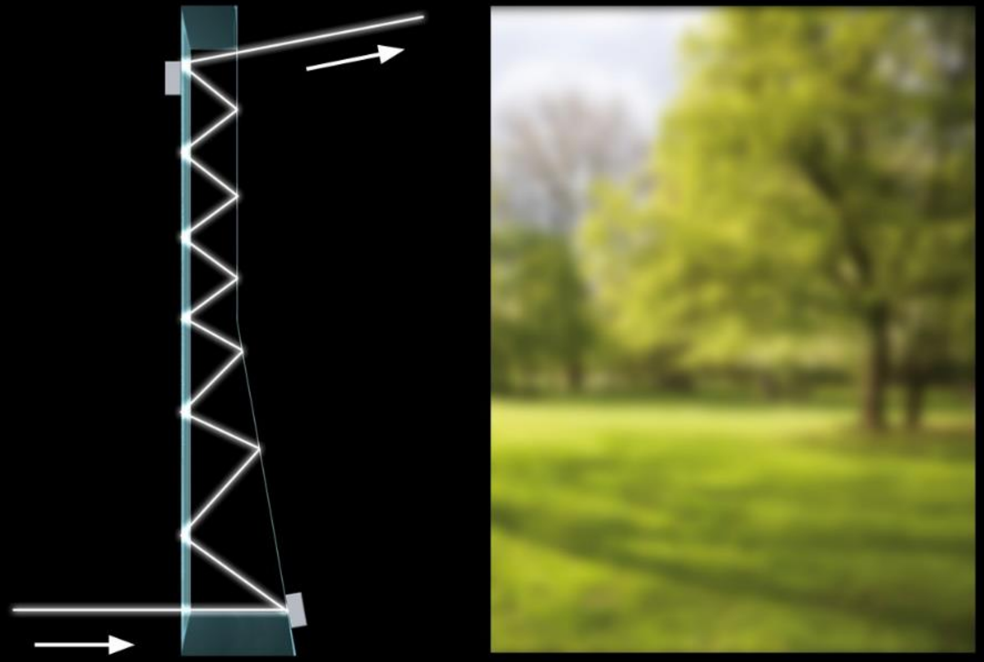
Surface topology impacts waveguide performance!



Impact of (local) Wedge



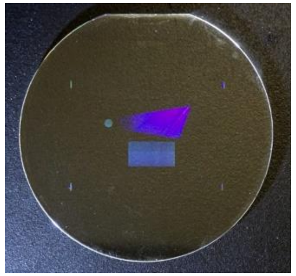
No (local) wedge MTF unchanged

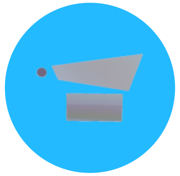


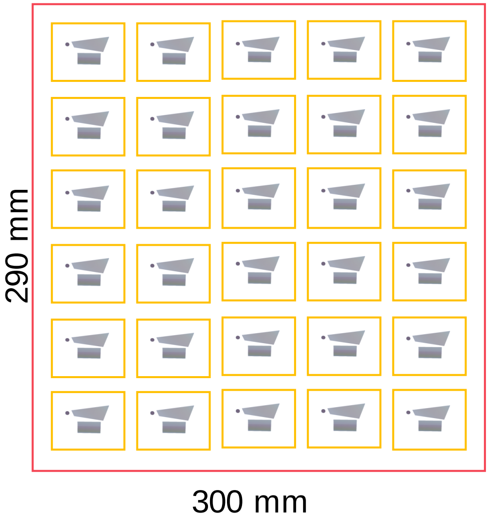
Large (local) wedge MTF decreased

Manufacturing scaling advantage

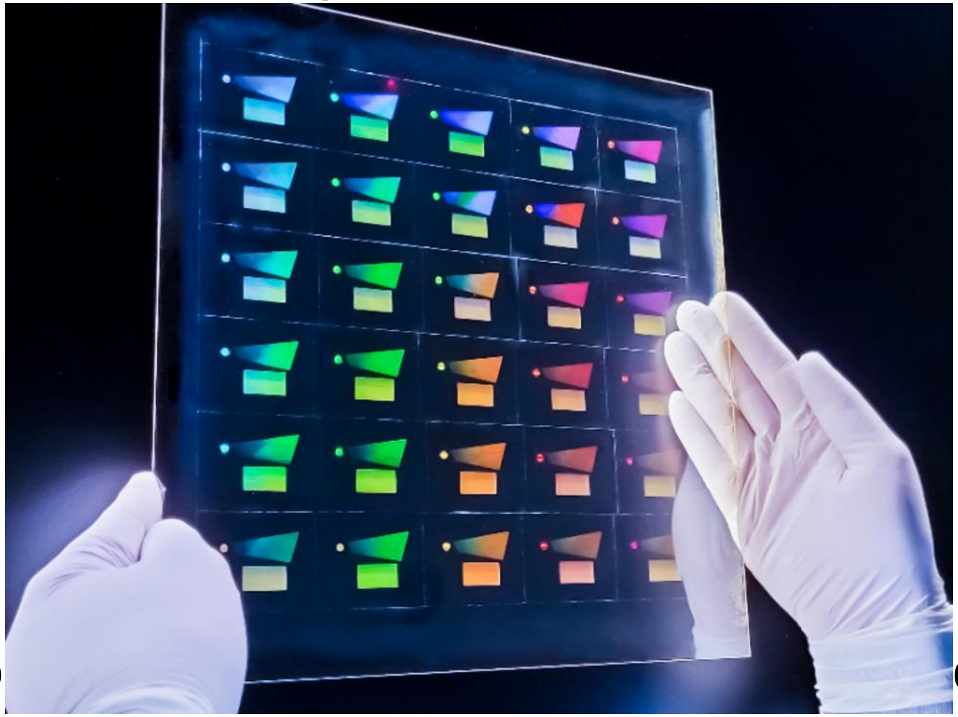
Single eyepiece Master → **Master Upscaling (Morphotonics proprietary)**







Upscaled Submaster

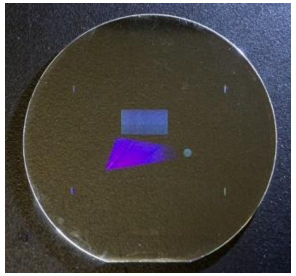


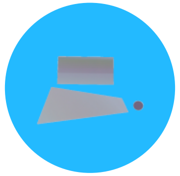
- Masters can be tedious & complex to originate, o … de in wafer format
- Upscaling of masters is essential to increase throughput

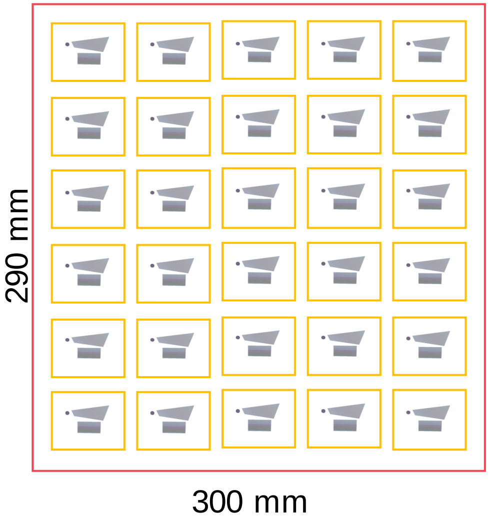
30 waveguides

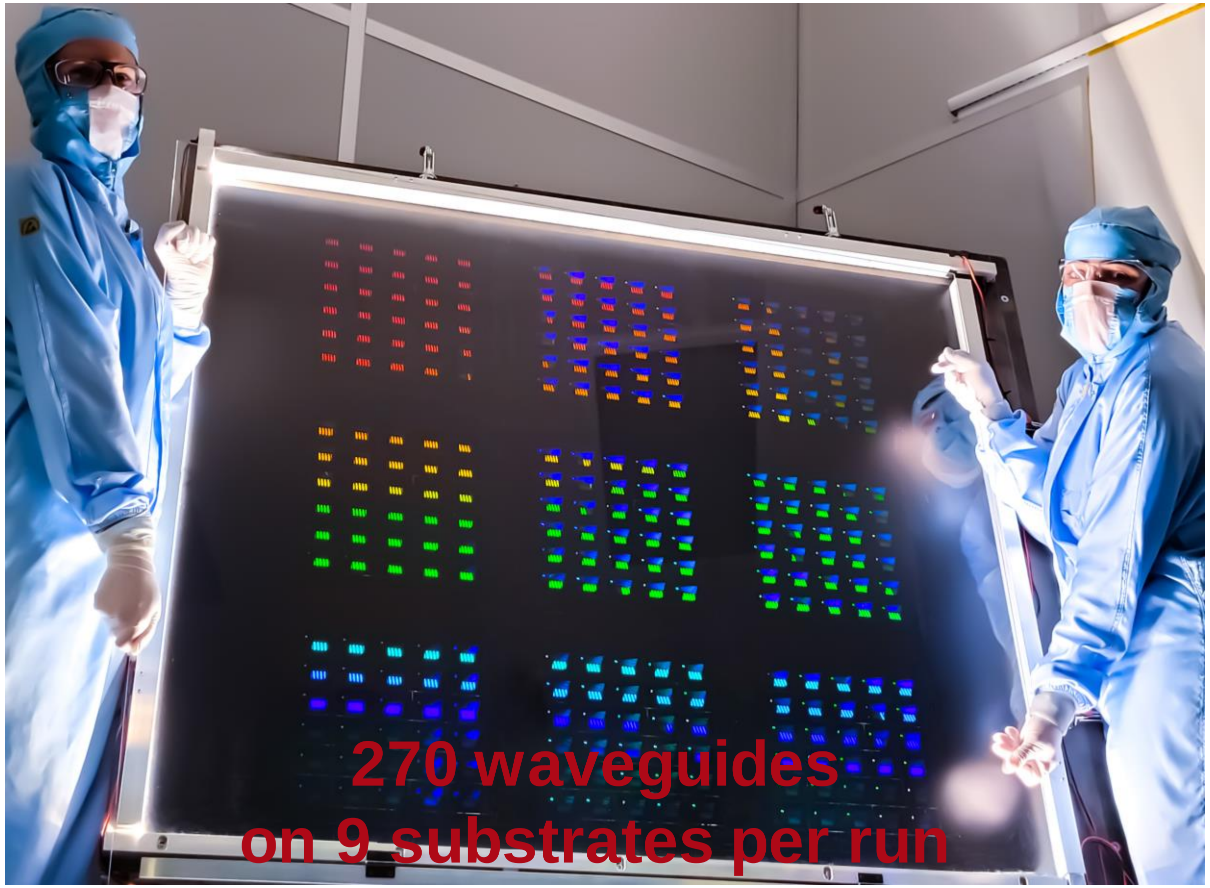
Manufacturing scaling advantage

Single eyepiece Master → **Master Upscaling (Morphotonics proprietary)** → **R2P Imprint**







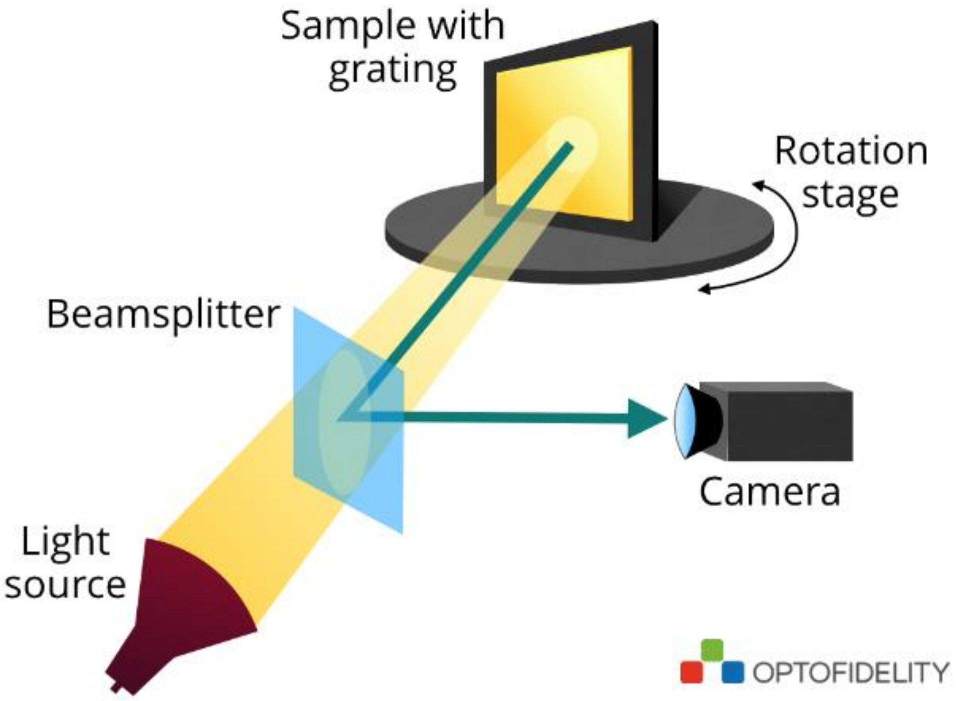


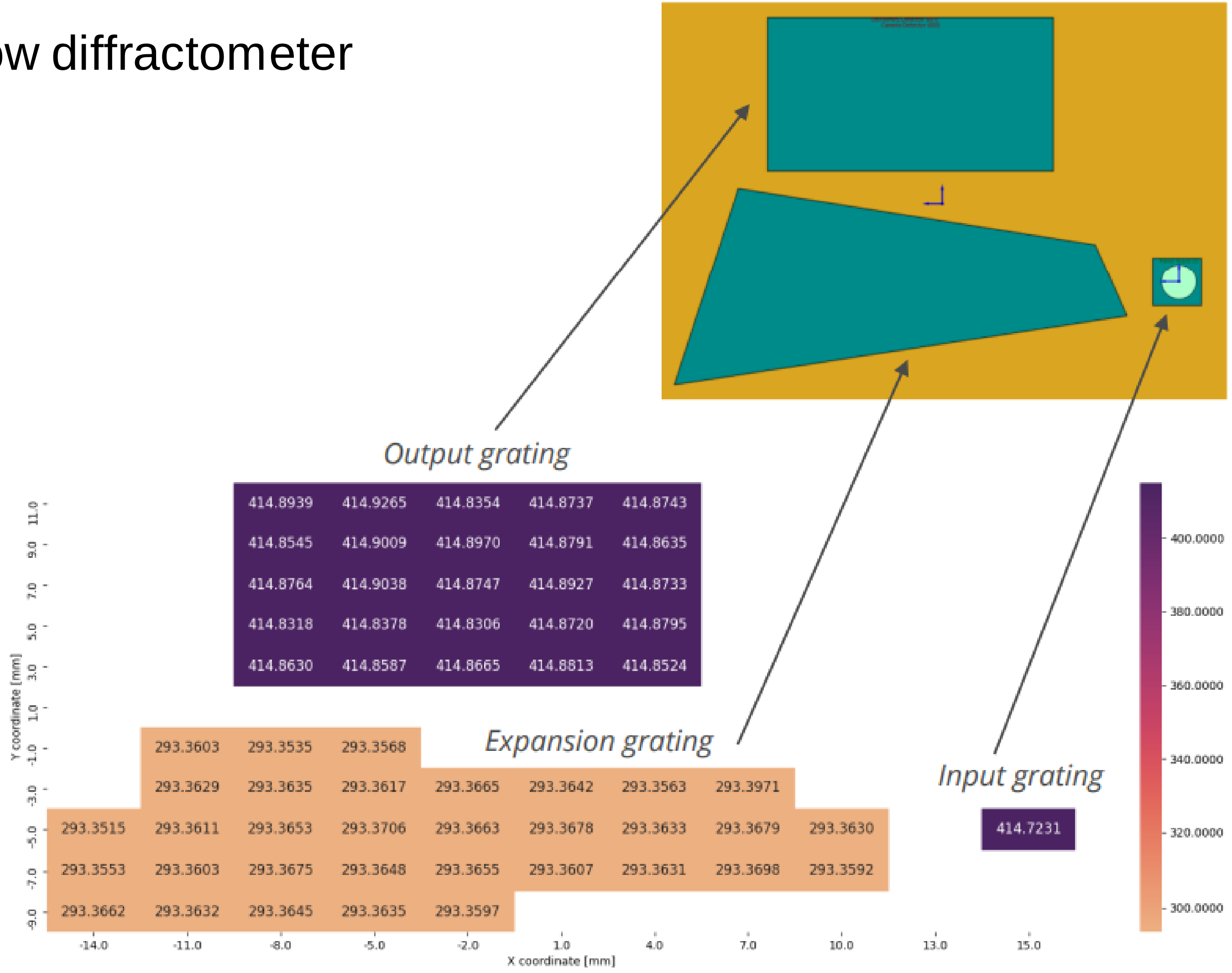
- Masters can be tedious & complex to originate, o
  format
- Upscaling of masters is needed to increase throu
- Roll-to-Plate (R2P) NIL can replicate multiple sca
  grouped together

Characterization of Imprinted Waveguides

Grating period determined by high-end Littrow diffractometer

1) single waveguide





Homogeneity of Imprinted Waveguides

OPTOFIDELITY

Grating period determined by high-end Littrow diffractometer

1) single waveguide
2) wafer (30 waveguides)

	Design	Master	Imprint sample 1 Upper right corner	Imprint sample 2 Lower left corner (same sample) 200×200 mm apart
Incoupler	415 nm	414.97 nm	414.8 nm	414.98 nm
Expander	293.45 nm	293.43 nm ± 2 pm (standard deviation)	293.35 nm ± 9 pm (standard deviation)	Not measured
Outcoupler	415 nm	415.01 nm ± 7 pm (standard deviation)	414.88 nm ± 47 pm (standard deviation)	414.88 nm ± 21 pm (standard deviation)

Homogeneity of Imprinted Waveguides

OPTOFIDELITY

Grating period determined by high-end

1) single waveguide
2) wafer (30 waveguides)
3) R2P imprint (270 waveguides)

	Design	Master	H1	H2	H3	R1	R2	R3	R4	R5	R6
Incoupler	415	414.97	414.98	414.97	414.96	414.97	414.98	414.95	414.96	414.96	414.91
Expander	293.45	293.43 ± 2 pm	293.47 ± 9 pm	293.46 ± 9 pm	293.44 ± 7 pm	293.44 ± 7 pm	293.44 ± 6 pm	293.44 ± 6 pm	293.44 ± 6 pm	293.45 ± 6 pm	293.46 ± 9 pm
Outcoupler	415	415.01 ± 7 pm	415.00 ± 17 pm	415.00 ± 15 pm	415.02 ± 20 pm	414.99 ± 16 pm	414.98 ± 26 pm	414.99 ± 19 pm	414.99 ± 20 pm	414.99 ± 18 pm	415.00 ± 24 pm

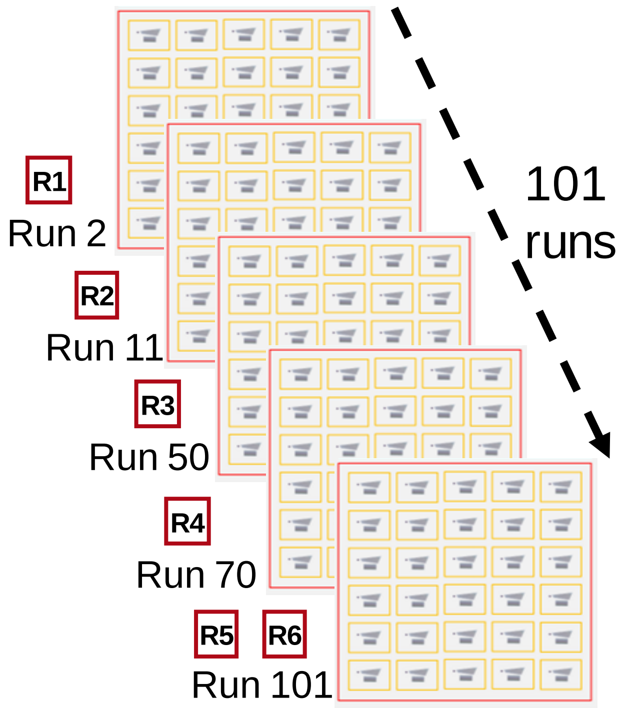
(all values in nm unless denoted differently)

Repetition Quality of Imprinted Waveguides

OPTOFIDELITY

Grating period determined by high-end

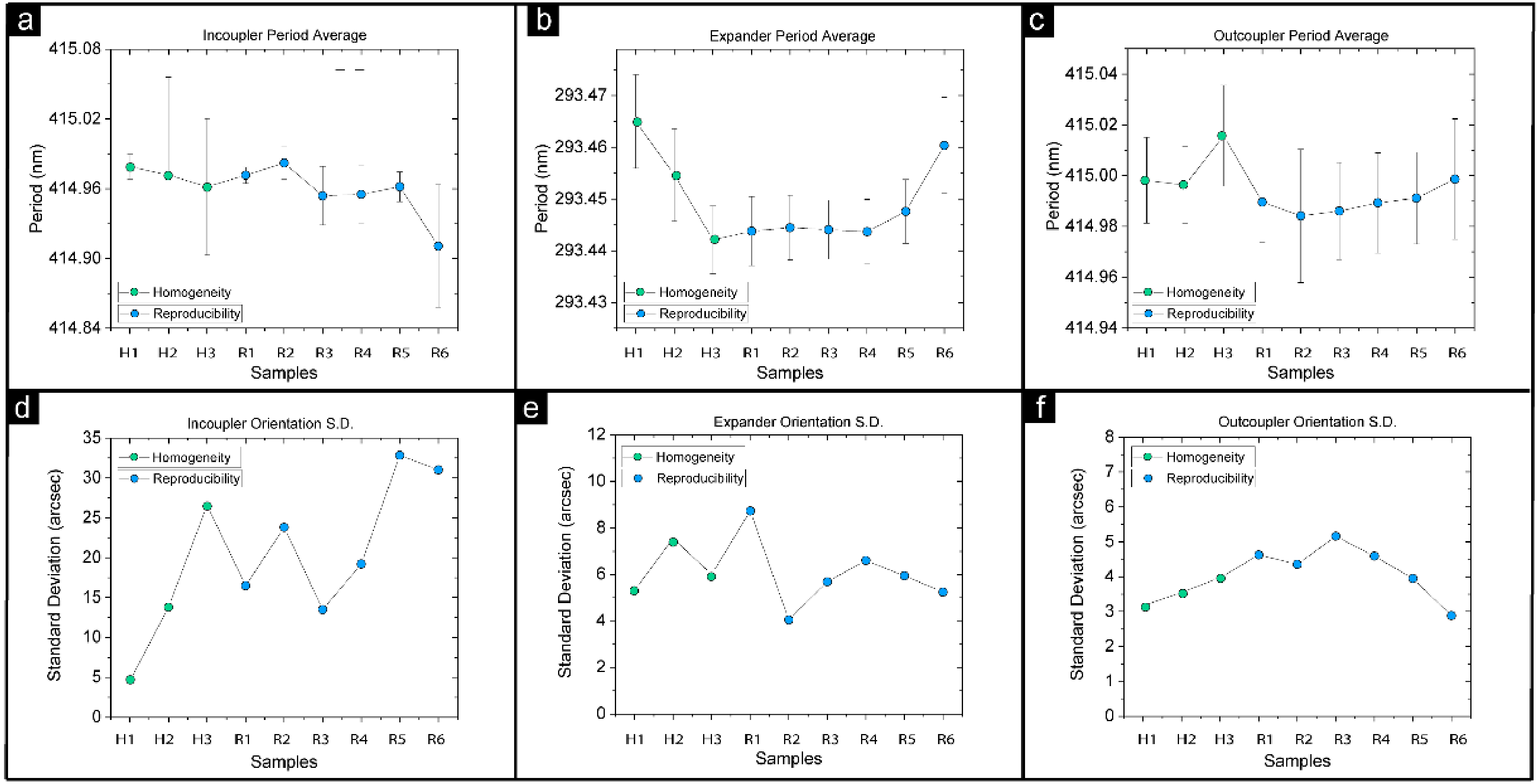
1) single waveguide
2) wafer (30 waveguides)
3) R2P imprint (270 waveguides)
4) 101 repetitions



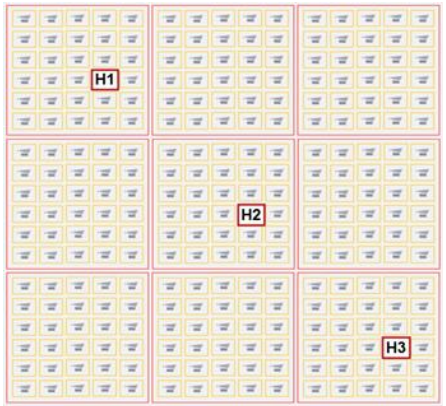
	Design	Master	H1	H2	H3	R1	R2	R3	R4	R5	R6
Incoupler	415	414.97	414.98	414.97	414.96	414.97	414.98	414.95	414.96	414.96	414.91
Expander	293.45	293.43 ± 2 pm	293.47 ± 9 pm	293.46 ± 9 pm	293.44 ± 7 pm	293.44 ± 7 pm	293.44 ± 6 pm	293.44 ± 6 pm	293.44 ± 6 pm	293.45 ± 6 pm	293.46 ± 9 pm
Outcoupler	415	415.01 ± 7 pm	415.00 ± 17 pm	415.00 ± 15 pm	415.02 ± 20 pm	414.99 ± 16 pm	414.98 ± 26 pm	414.99 ± 19 pm	414.99 ± 20 pm	414.99 ± 18 pm	415.00 ± 24 pm

(all values in nm unless denoted differently)

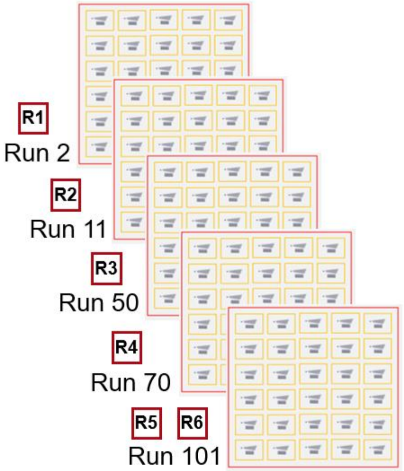
Homogeneity and Reproducibility of Waveguides



green:



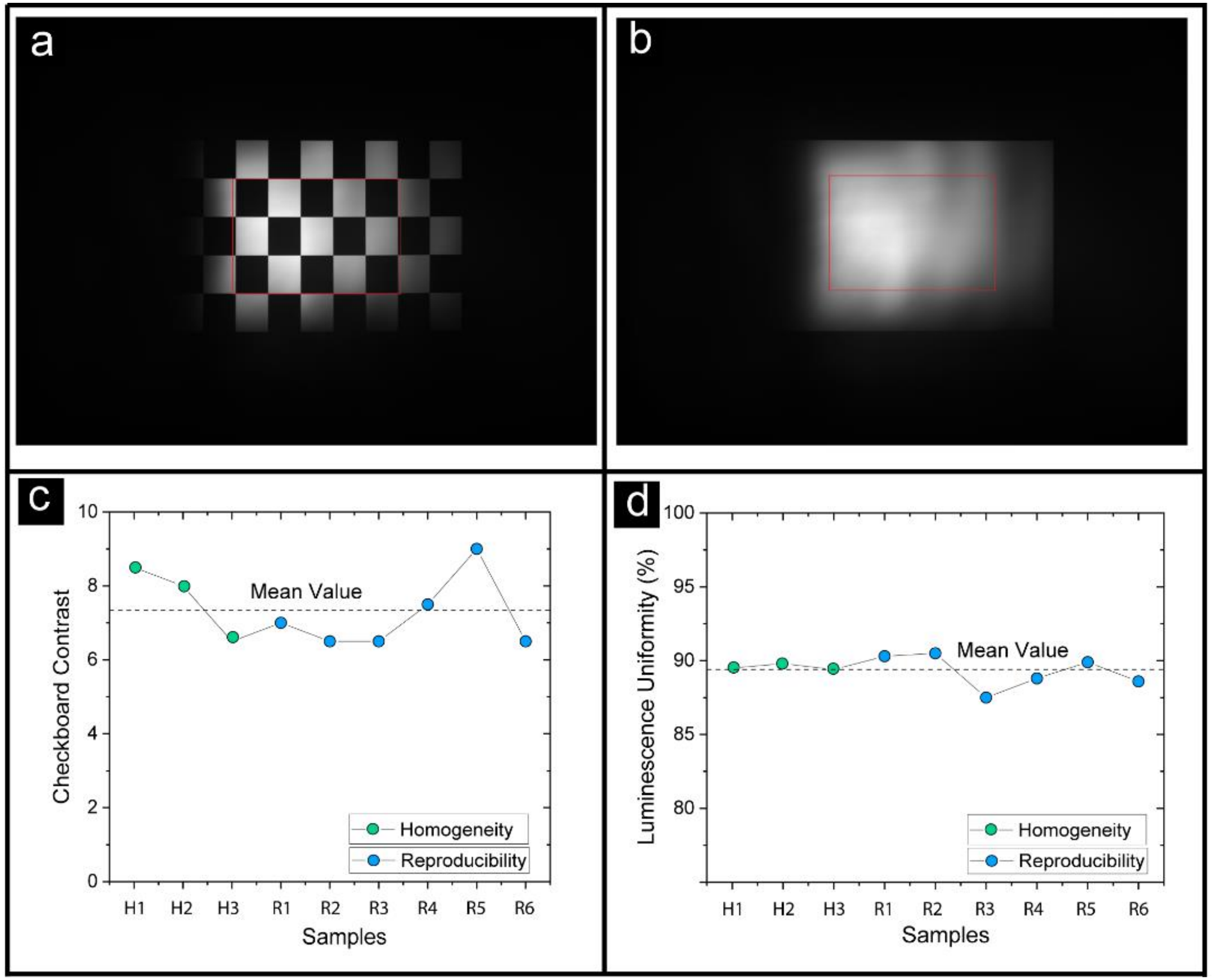
blue:



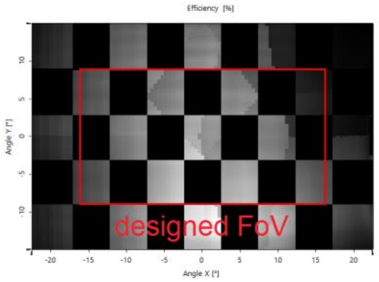
Angular Uniformity Measurements

OPTOFIDELITY

checkerboard contrast and luminance uniformity measured on IEC63145 standard with OptoProjector:

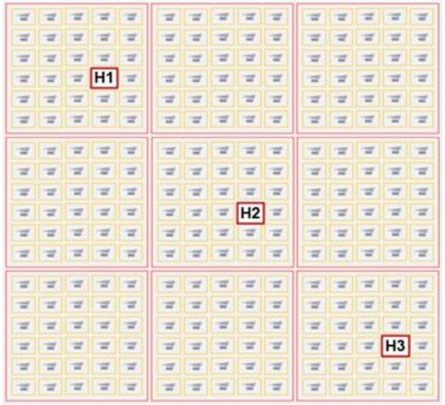


simulation result:

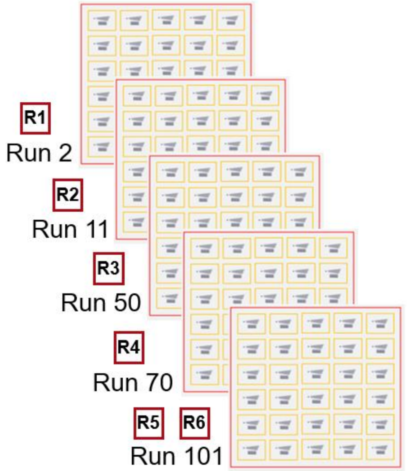


- very high homogeneity and reproducibility
- just negligible fluctuations
- good agreement with simulation result

green:

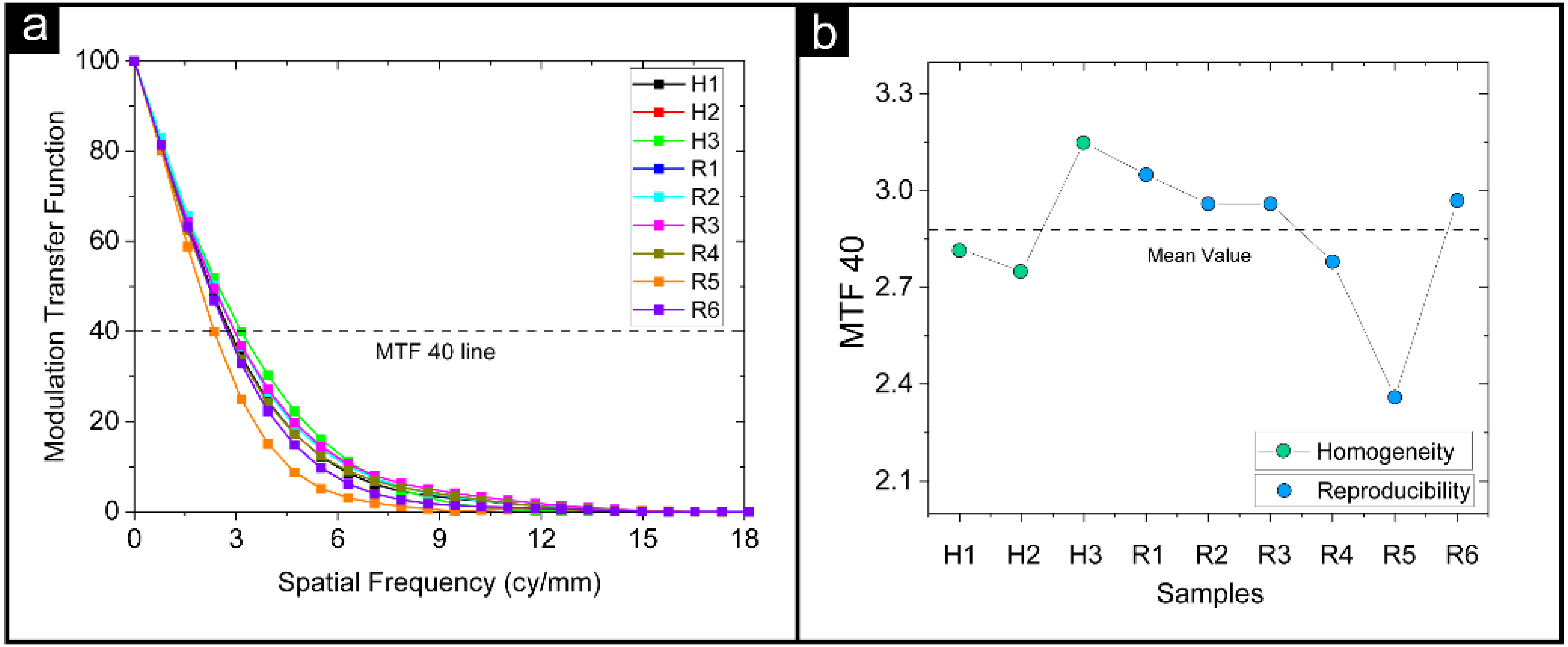


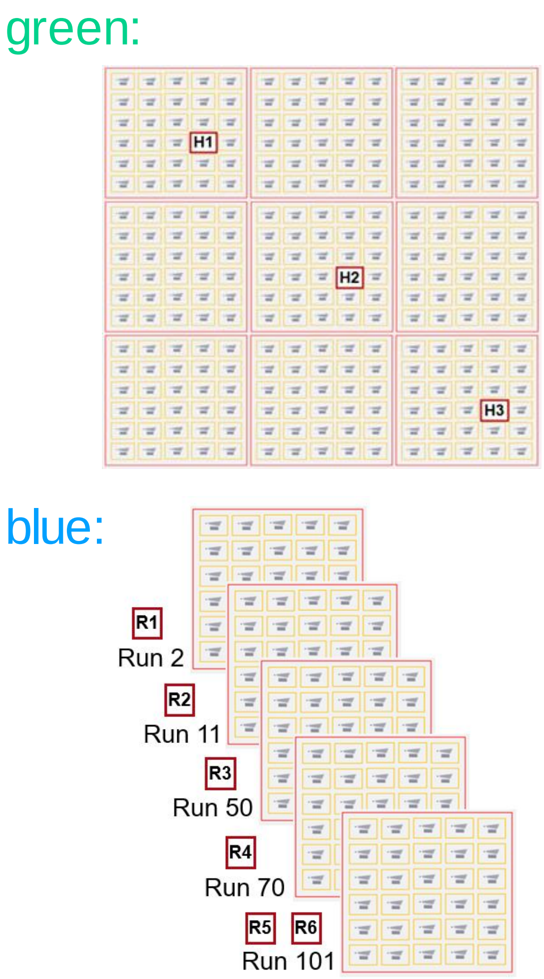
blue:



Measured MTF

MTF measured with camera and telescope objective:





imprinted waveguide exhibit a comparable MTF (a) and a decent MTF 40 value (b)

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Summary

We have shown a viable path from Optical Design to Mass Manufacturing of Waveguide Combiners!

- successful transition to high-volume manufacturing or AR waveguides, display-oriented, high-quality focused
- high-index squared glass enable the increase the production volume
- together with complex design, high-end mastering and in-depth quality inspection, large area nanoimprint proves that mass production is feasible
- end-to-end supply chain and cooperation of experts in different disciplines is key