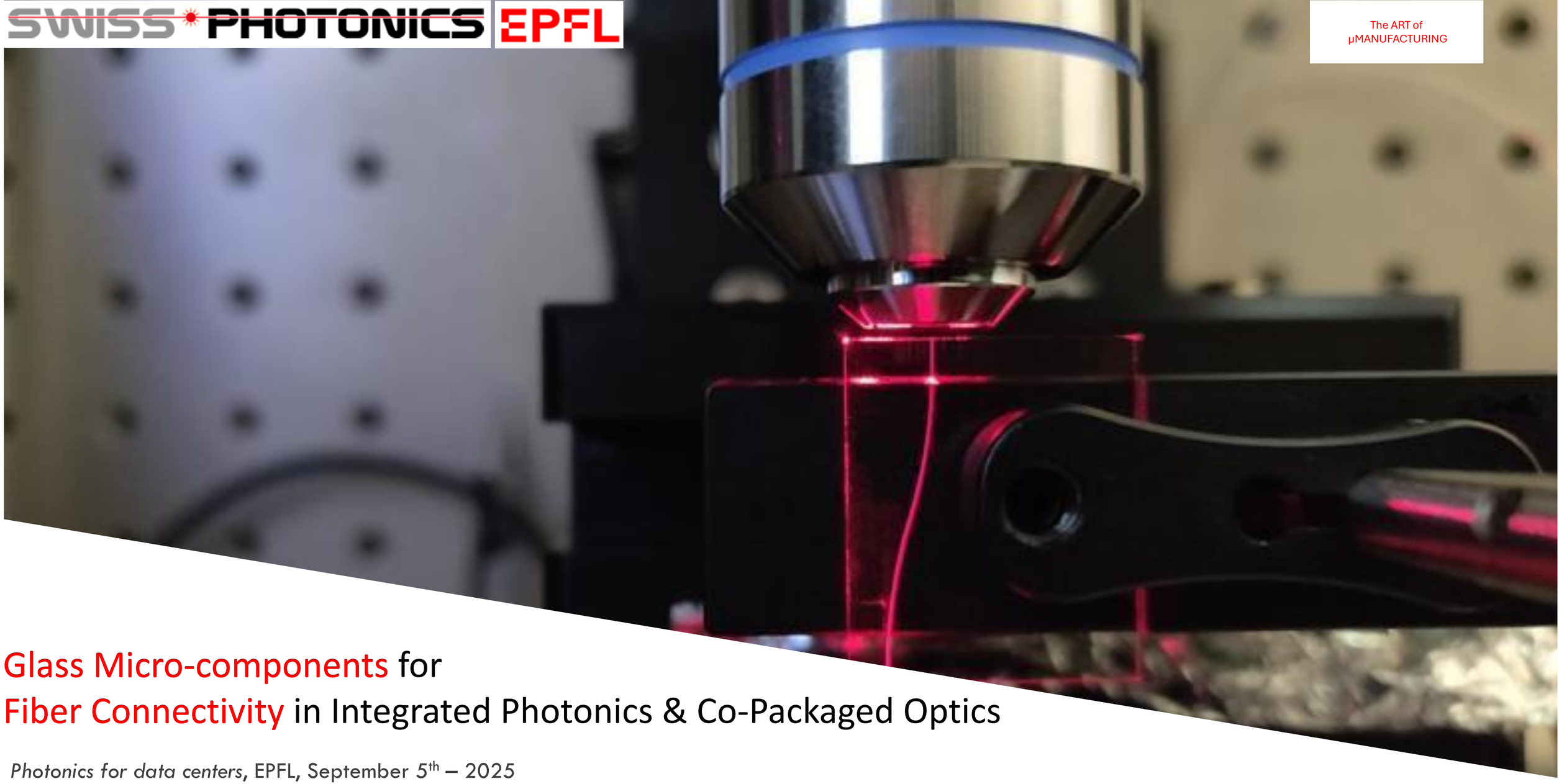
SWISS PHOTONICS EPFL

The ART of
µMANUFACTURING



Glass Micro-components for Fiber Connectivity in Integrated Photonics & Co-Packaged Optics

Photonics for data centers, EPFL, September 5th – 2025

Dr. Rolando Ferrini

FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

The Company

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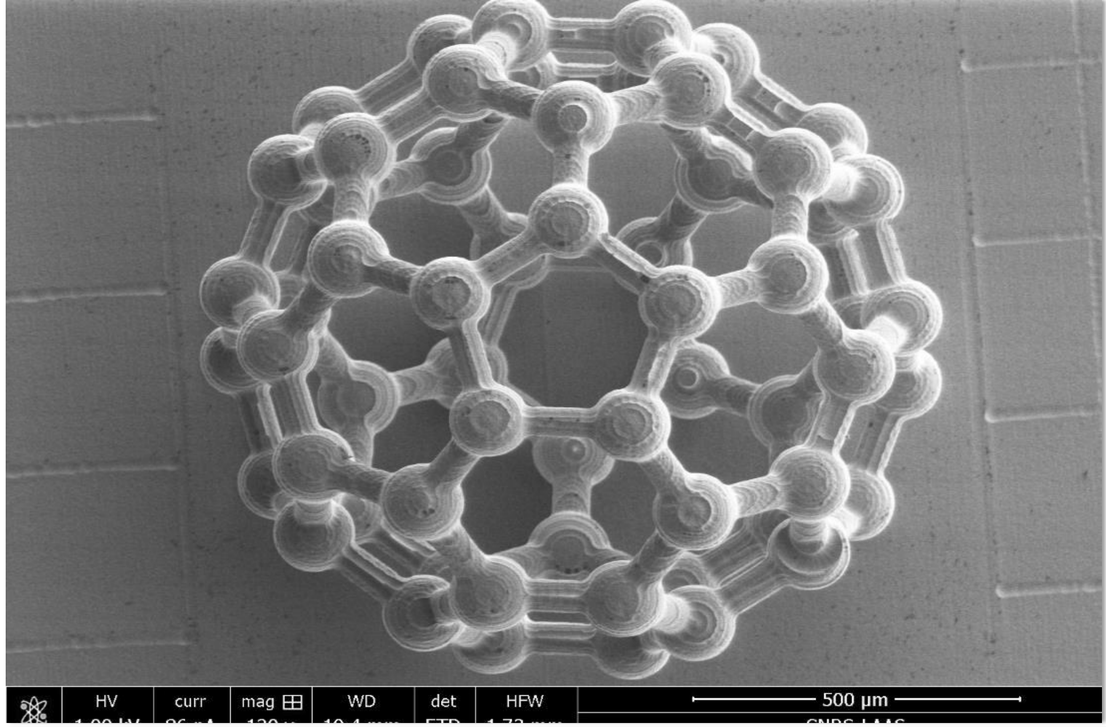
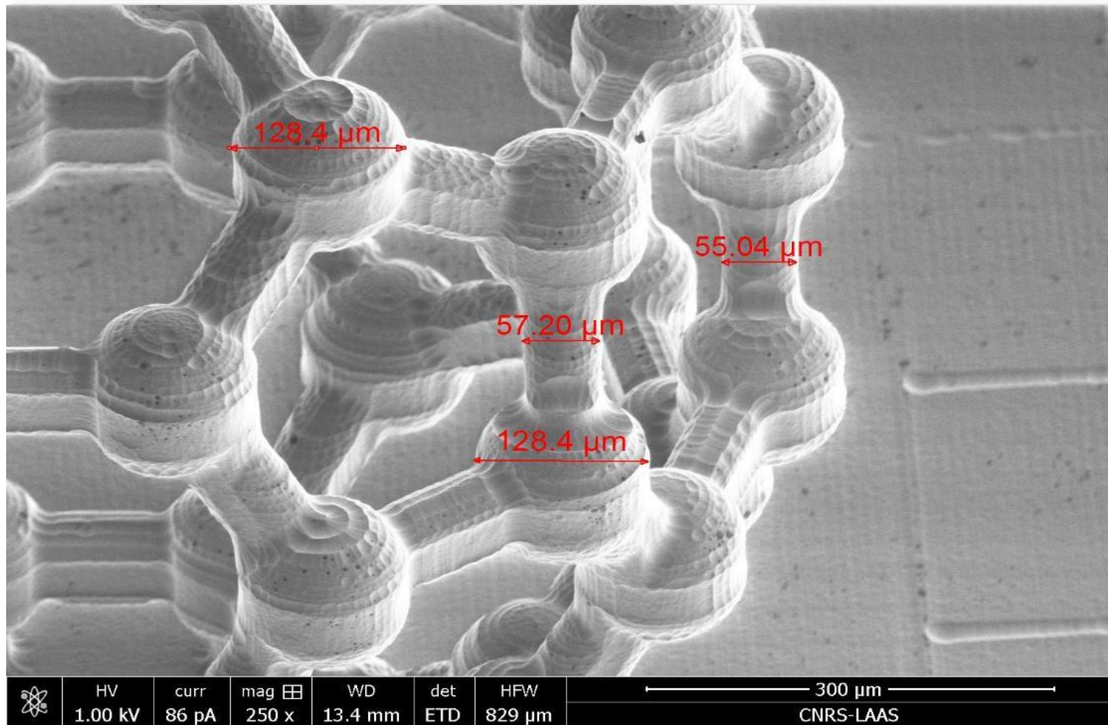
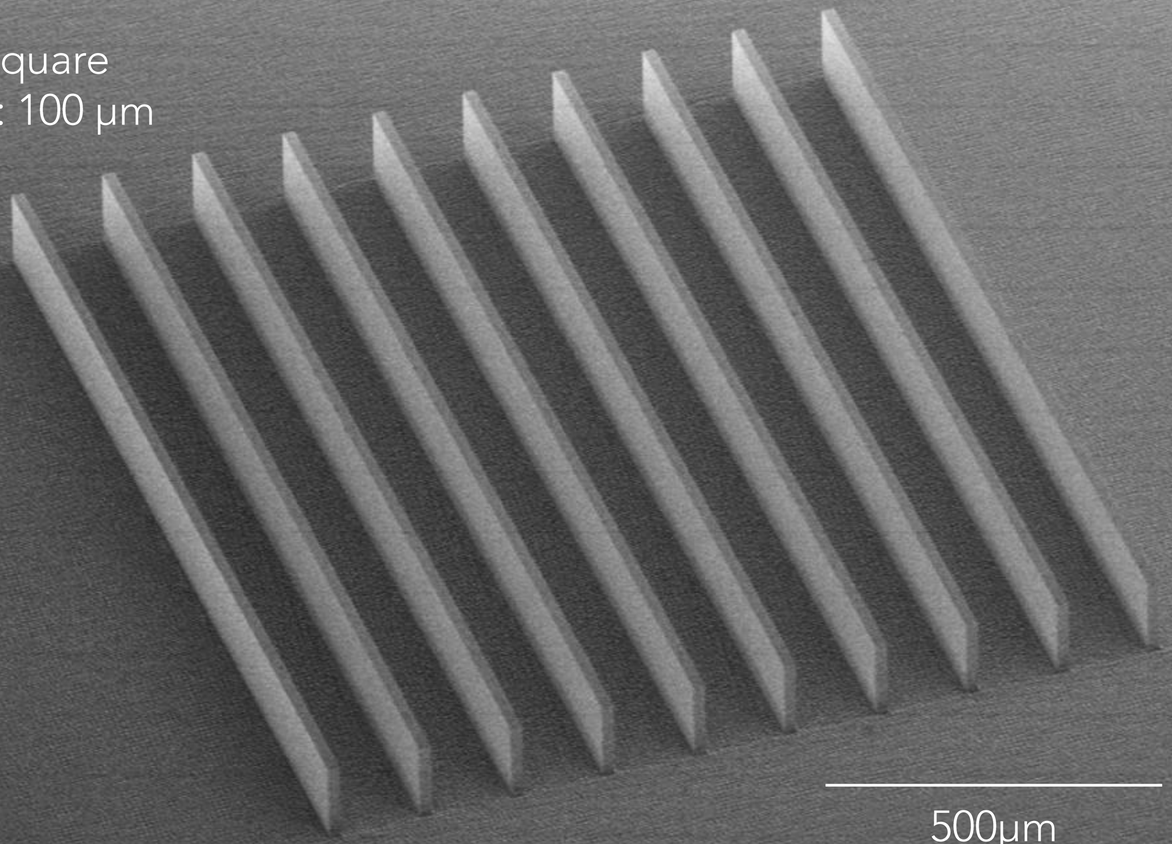
Performances in SiO_2
Resolution and tolerances

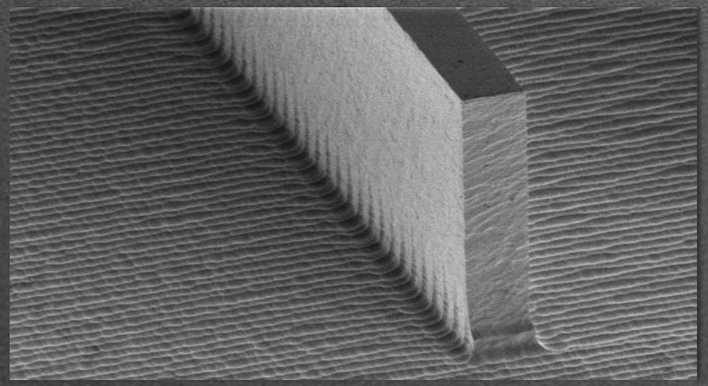
- Process resolution ~ 1 µm
- XY tolerances +/- 1 µm
- Z tolerance +/- 2 µm





1 cm² square
Height: 100 µm



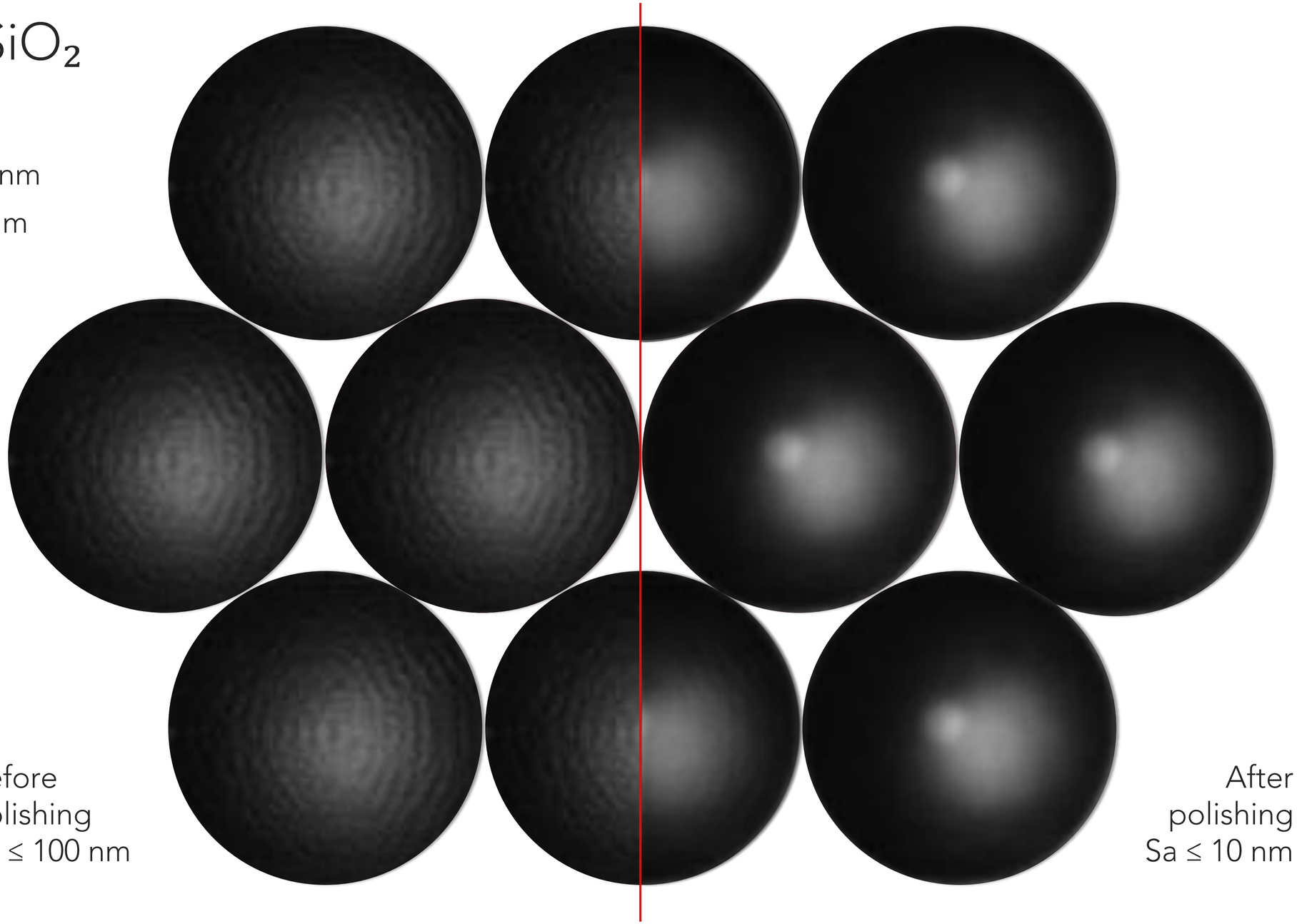


Performances in SiO_2 Aspect ratio

- Aspect ratio ≥ 1:500
- Sidewall deviation ≤ 0.1°
- Bulk height: up to 30 mm
- Working area up to 300 mm Ø

Performances in SiO_2
Surface quality

- Patterned surface Sa ≤ 100 nm
- Surface treatment Sa ≤ 10 nm

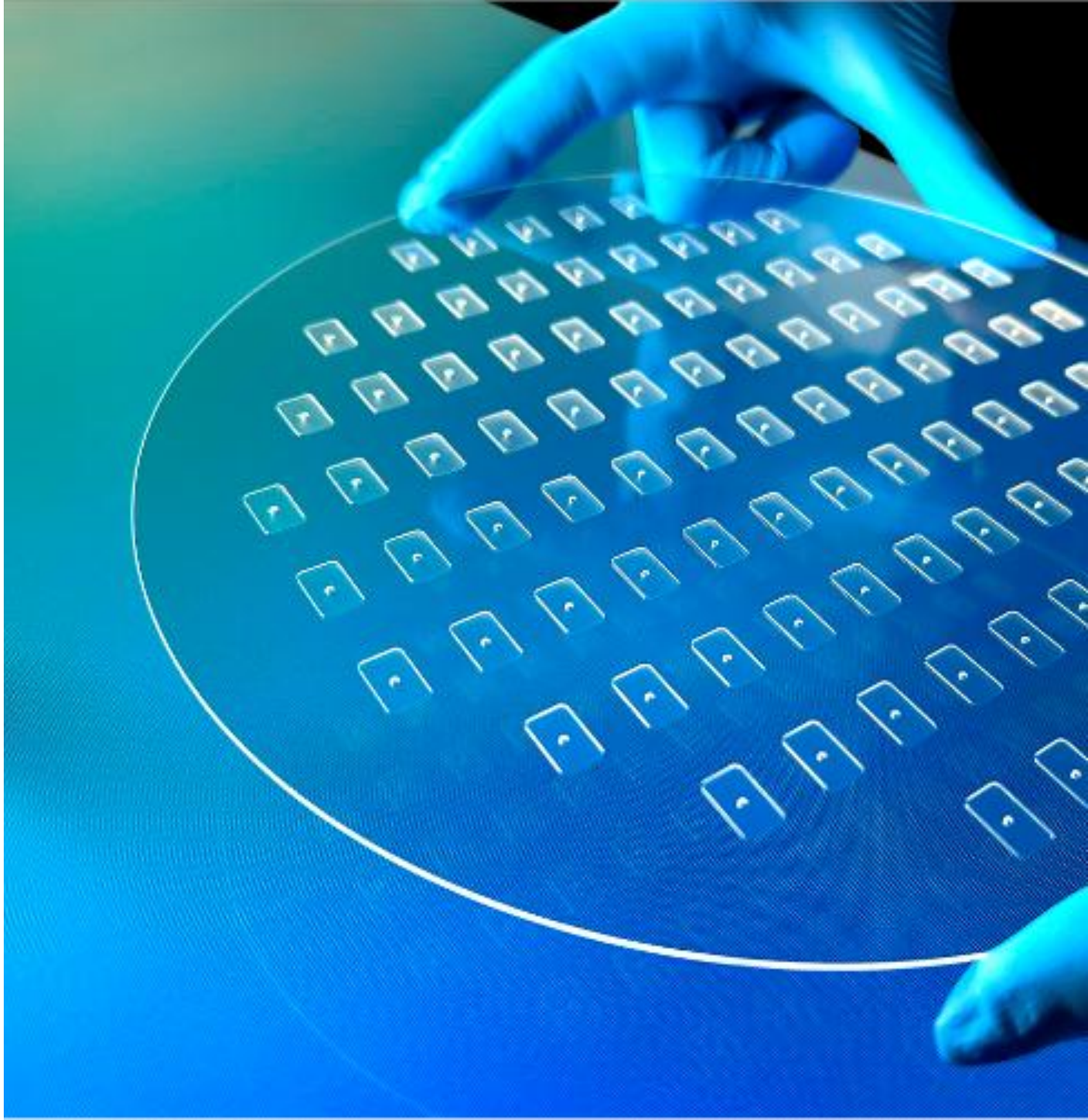


Before polishing
Sa ≤ 100 nm

After polishing
Sa ≤ 10 nm

Wafer-level fabrication

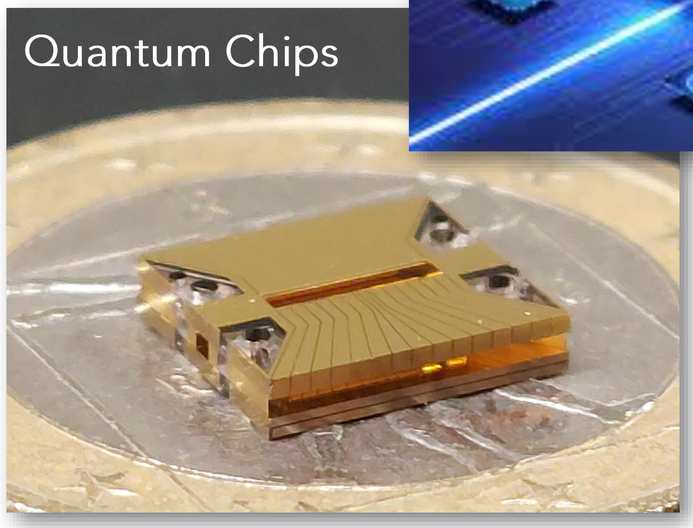
- **Unique** industrial laser processing, compatible with MEMS foundry protocols
- **High-throughput:** capacity for several thousand wafers/product/year
- **Scalability** can be easily enhanced due to proprietary, parallelized processes and production systems



Fiber-to-chip connectivity for integrated & quantum photonics

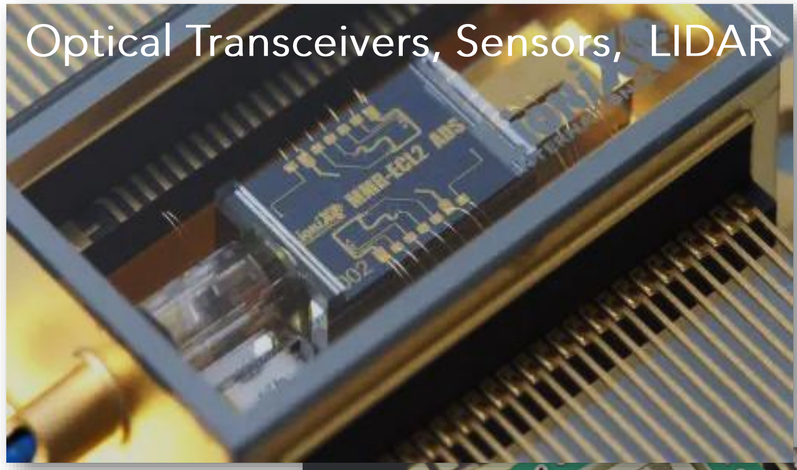
… TO PRODUCTS

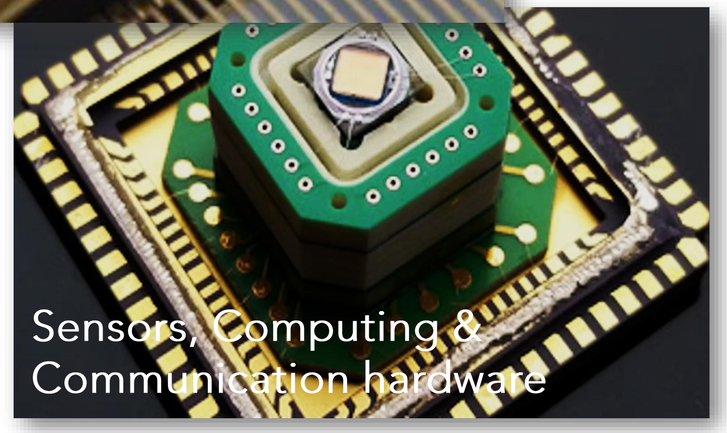
FROM DEVICES …



PACKAGING

ASSEMBLY



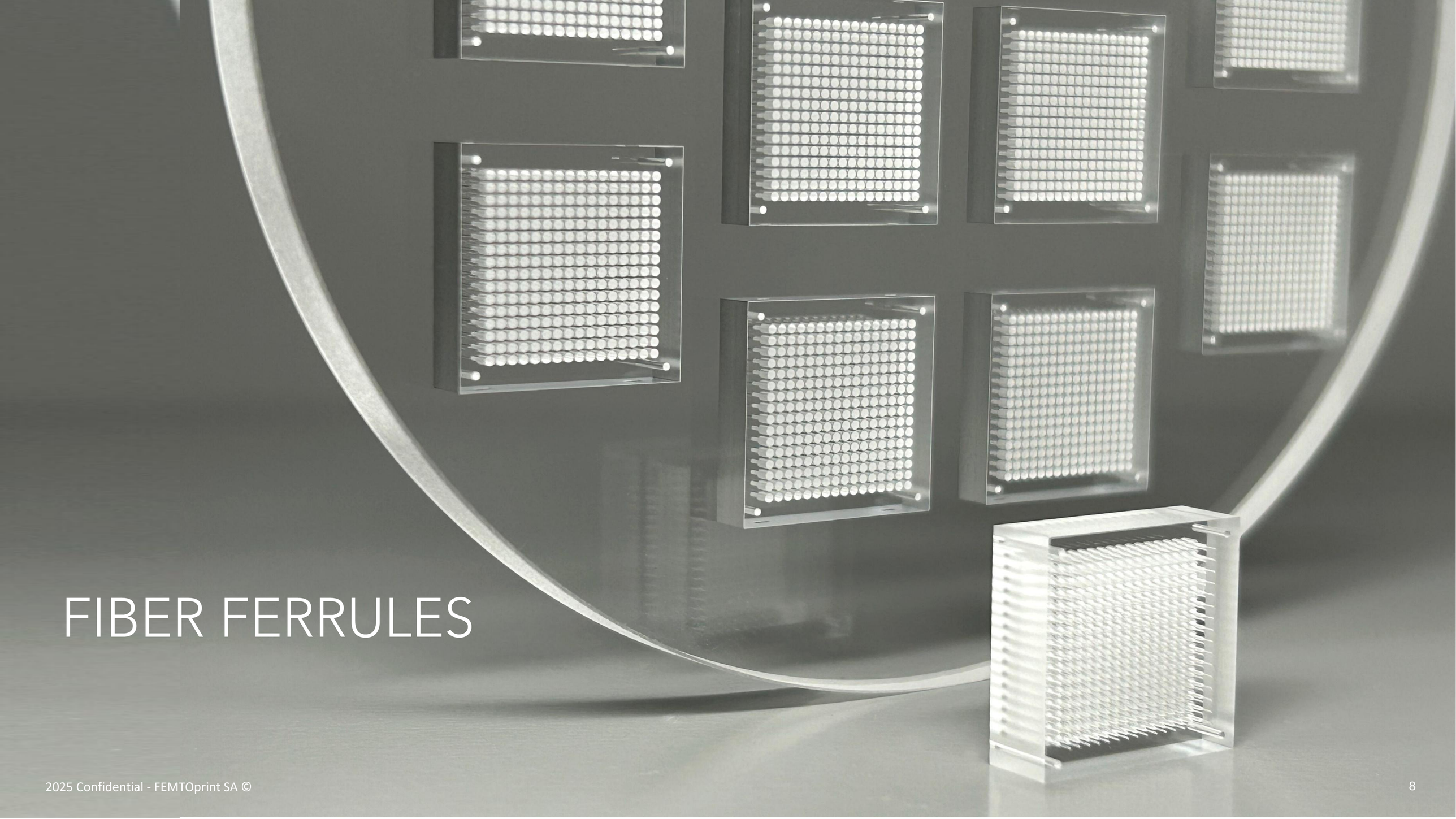


FIBER-TO-CHIP CONNECTIVITY

V-GROOVES
1D & 2D HOLE ARRAYS

WAVEGUIDES
SSCs, F-IN/-OUT, DCs

MINIATURIZED OPTICS
MICRO-OPTICS

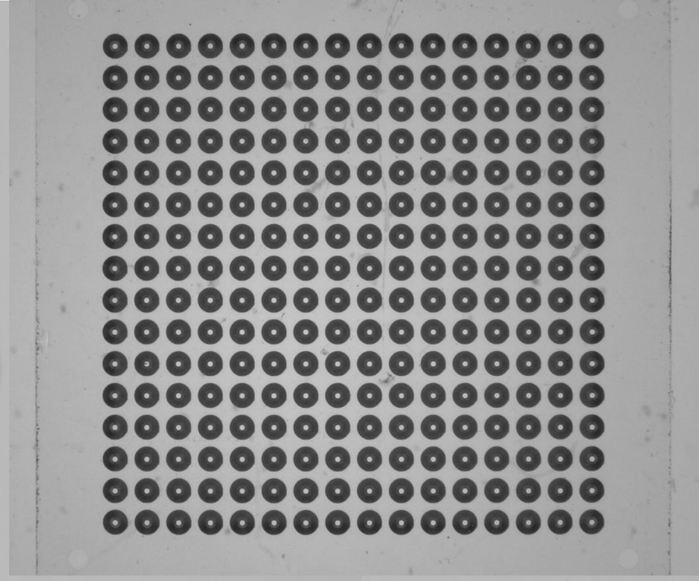


FIBER FERRULES

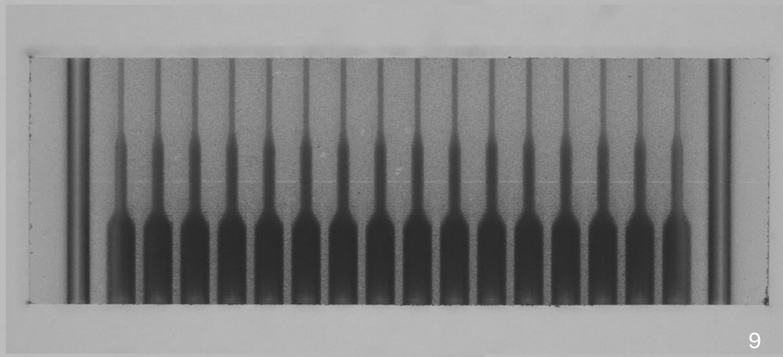
16x16 ARRAY

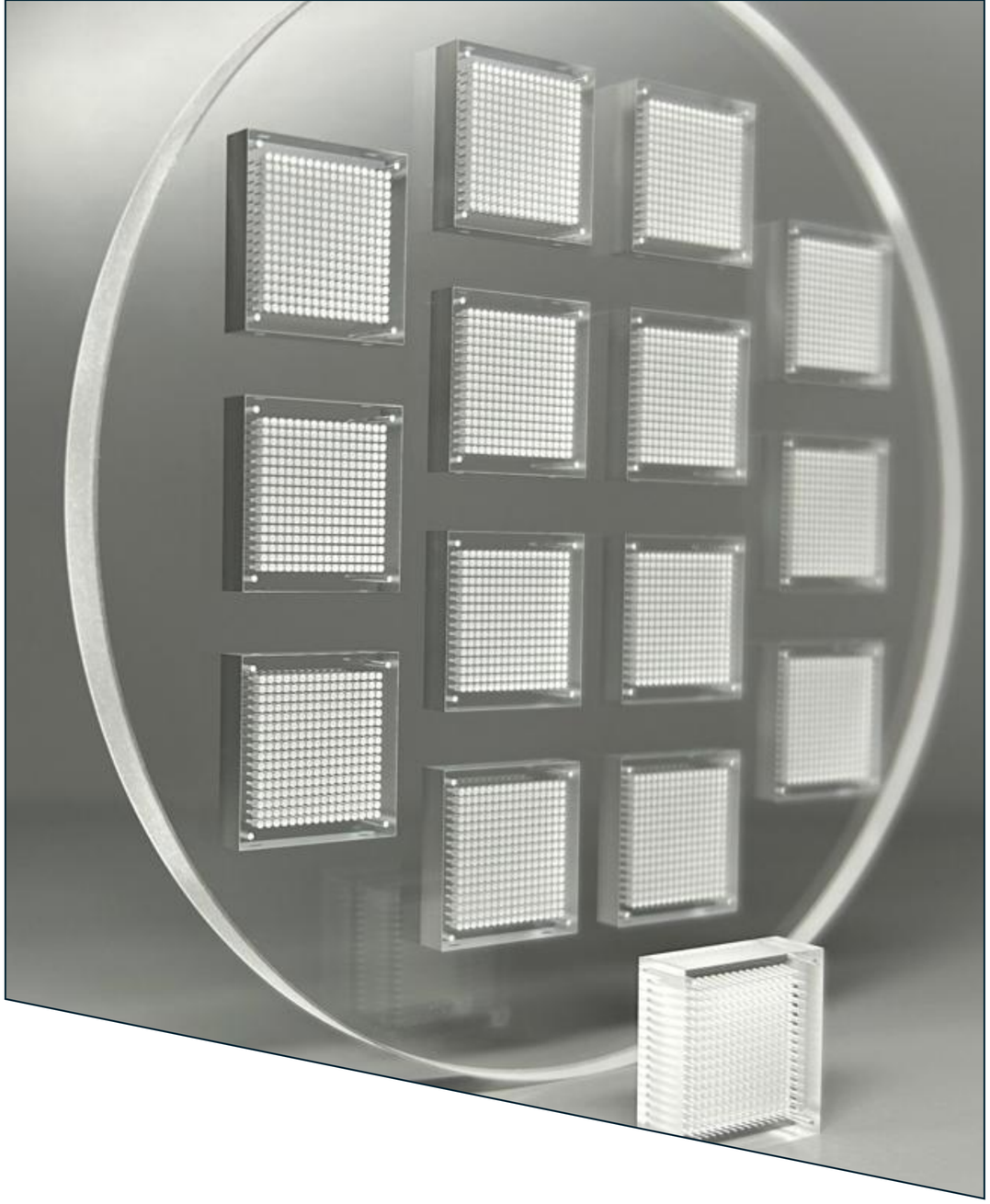
Fused silica

Thickness = 5 mm
Pitch = 0.75 mm
Target diameter = 0.1255 mm



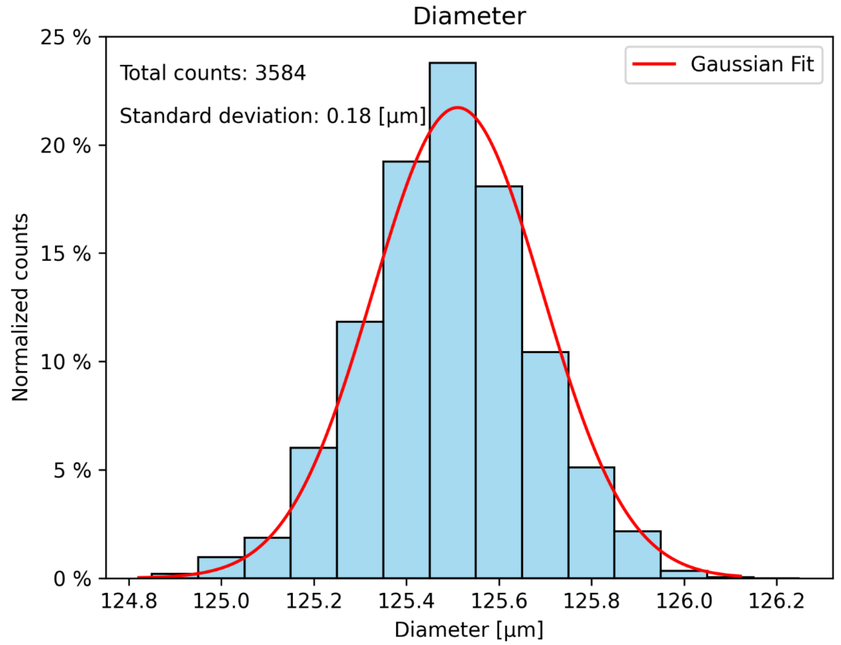
HOLE DIAMETER & POSITION

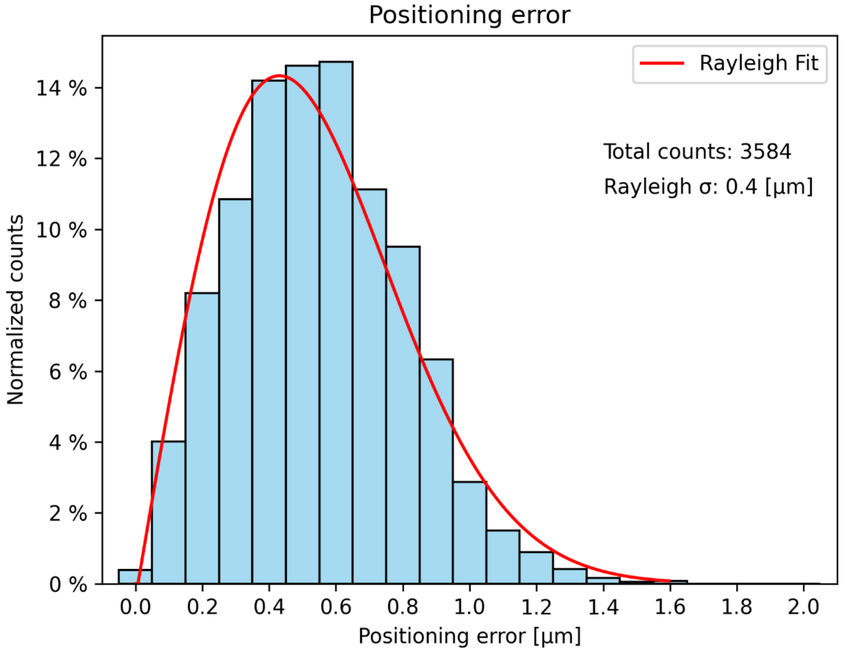




Hole diameter & position

Sub-µm control





2D hole arrays for high-precision fiber ferrules

- Available on various substrates

  Fused silica (FS)
  - thermal match with silica fibers

  Borofloat 33 (BF33)
  - thermal match with SiPh

- Available with a large range of thicknesses

  typically 3 - 7mm
  - enhanced mechanical robustness

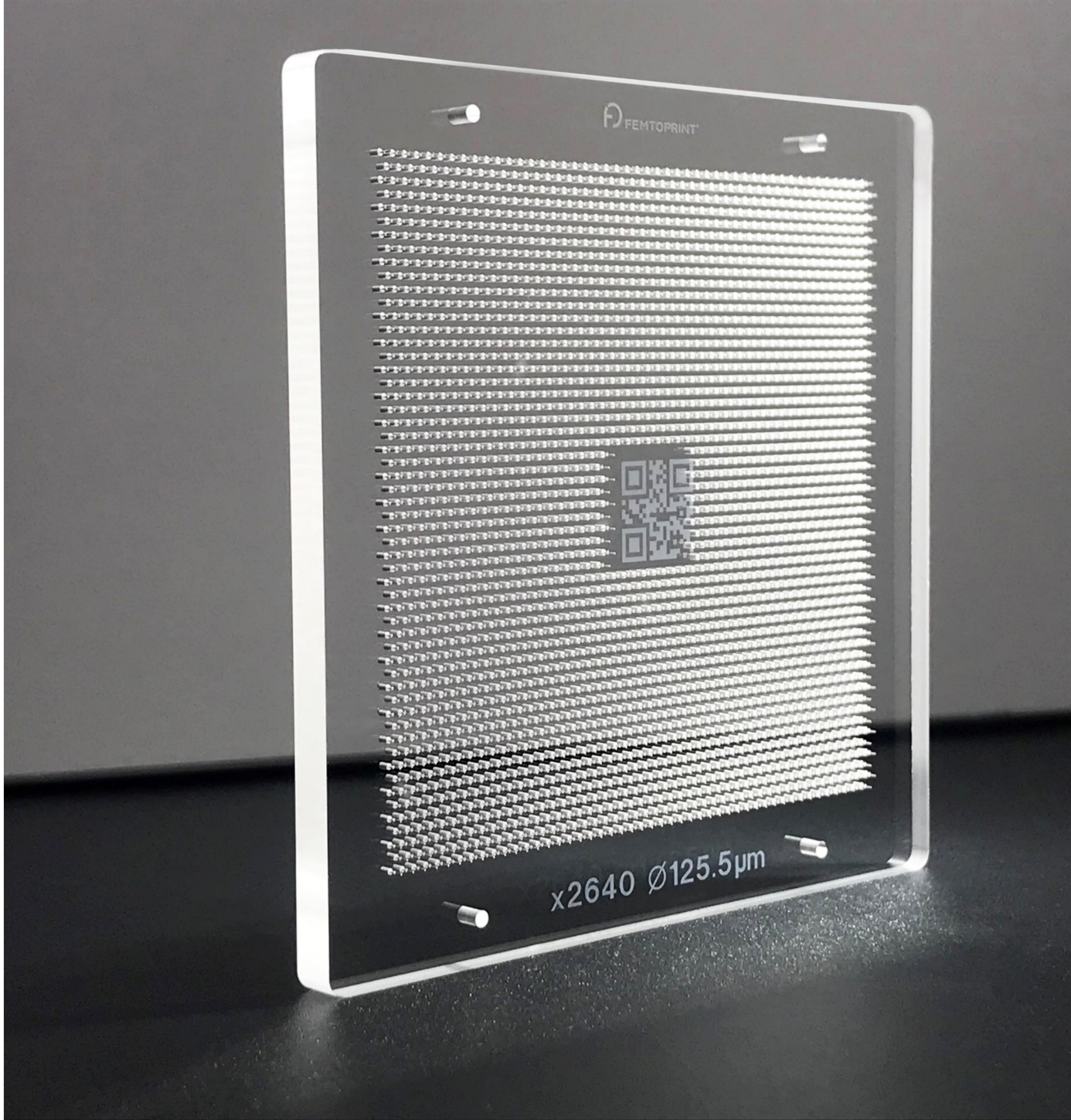
- Tailored hole shapes with multiple sections

  e.g. core-cladding, coating, jacket
  - enhanced stability

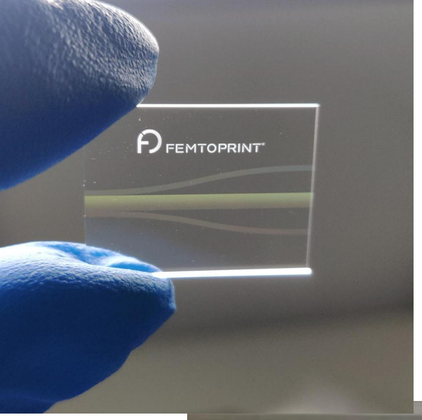
- Tilted holes

  - reduced Fresnel losses

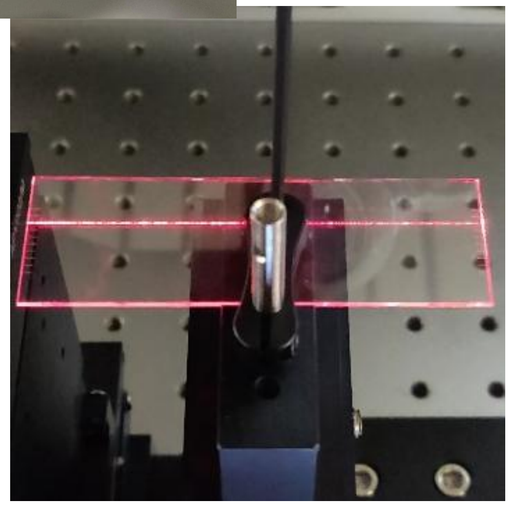
  - improved grating in-coupling

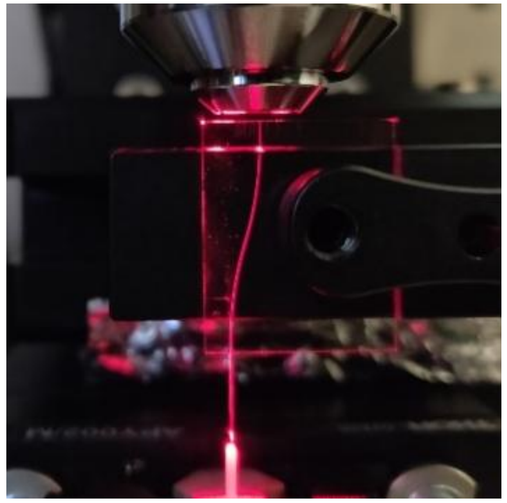


WAVEGUIDES



3D Glass Waveguides

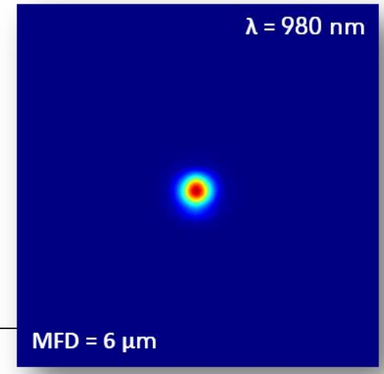


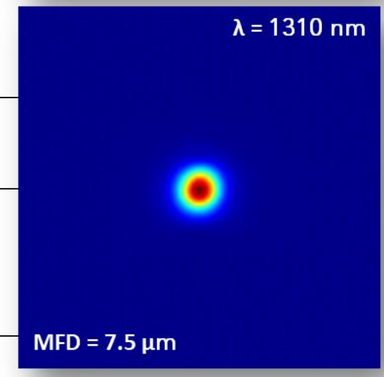


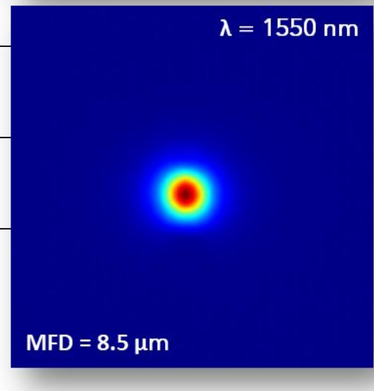
- Single mode & Multi-mode waveguides
- 3D waveguides with bending in XYZ
- In-bulk termination and tapering
- Alignment markers for assembly & packaging
- Facet polishing for rapid prototyping & characterization

Materials	Fused Silica (FS) Borofloat (BF33) Eagle (EXG)
Machining area	200 x 200 x 3 mm Whatever shape
Wavelength λ [nm]	980, 1310, 1550
MFD for SM [µm]	Tunable between 6 and 12 µm Circularity > 95%
Relative positioning	< ± 1 µm
Min. Bending Radius	≤ 20 mm
Propagation Loss	≤ 0.2 - 0.3 dB/cm
Δn	10^{-2} - 10^{-3}

LIGHT GUIDING

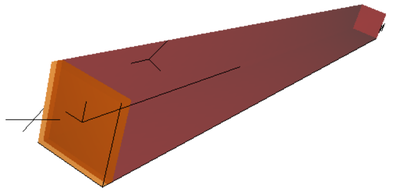




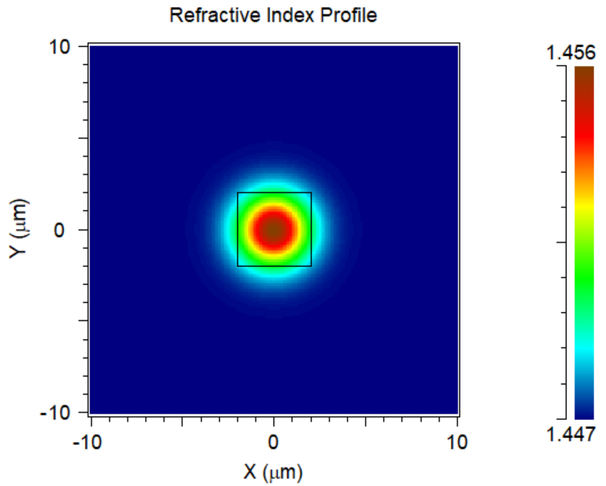


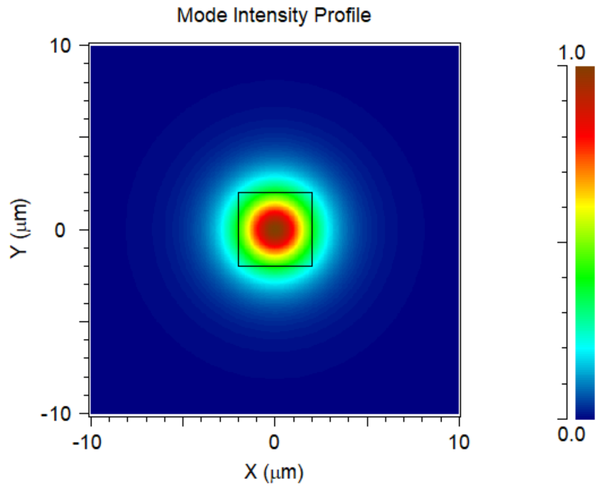
Mode Field Diameter (MFD)
Guided propagation

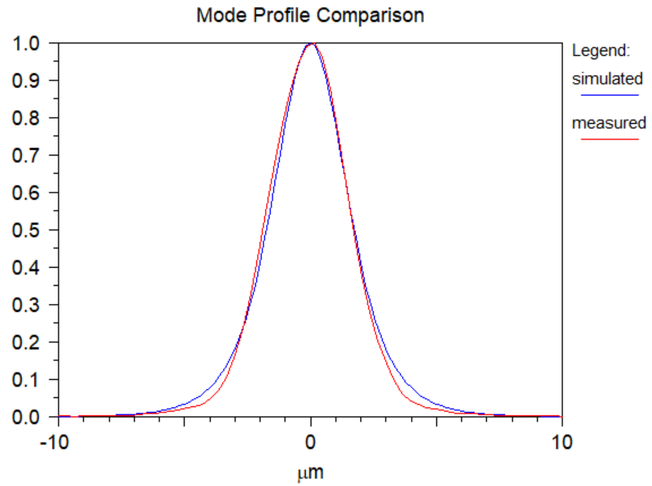
Simulation input
- Δn: 0.0093
- Profile: Gaussian
- Dimensions: 4 µm x 4 µm



MFD – Simulation vs. Measurement
- Simulated: 7.65 µm x 7.65 µm
- Measured: 7 – 8 µm







Mode Field Diameter (MFD)

Free-space propagation

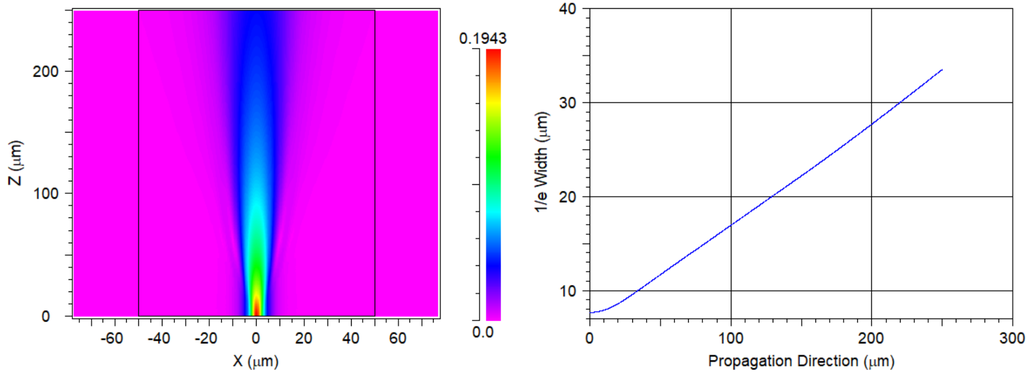
Simulation input

WG

- Δn: 0.0093
- Profile: Gaussian
- Dimensions: 4 µm x 4 µm

Free propagation in SiO_2

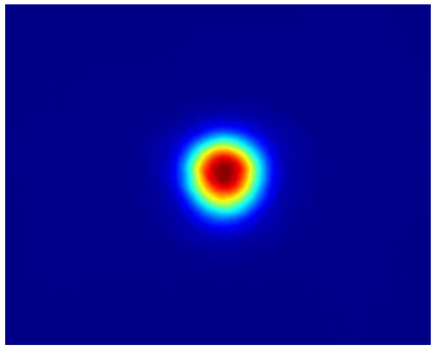
- n: 1.4468
- Profile: Uniform
- Dimensions: 50 µm x 250 µm

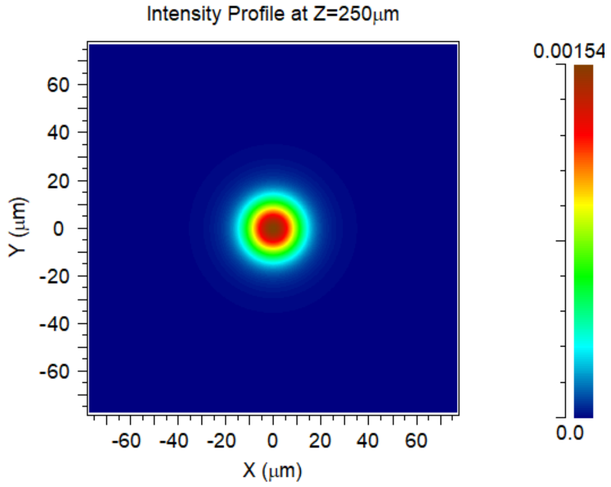


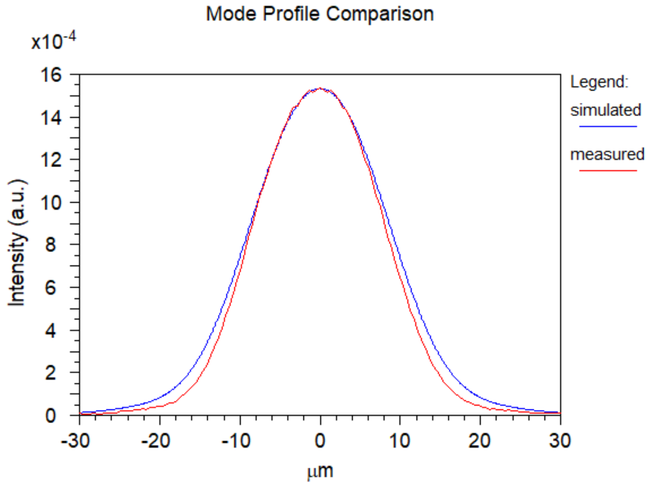
MFD – Simulation vs. Measurement

- Simulated: 33.5 µm x 33.5 µm
- Measured: 30-35 µm x 30-35 µm

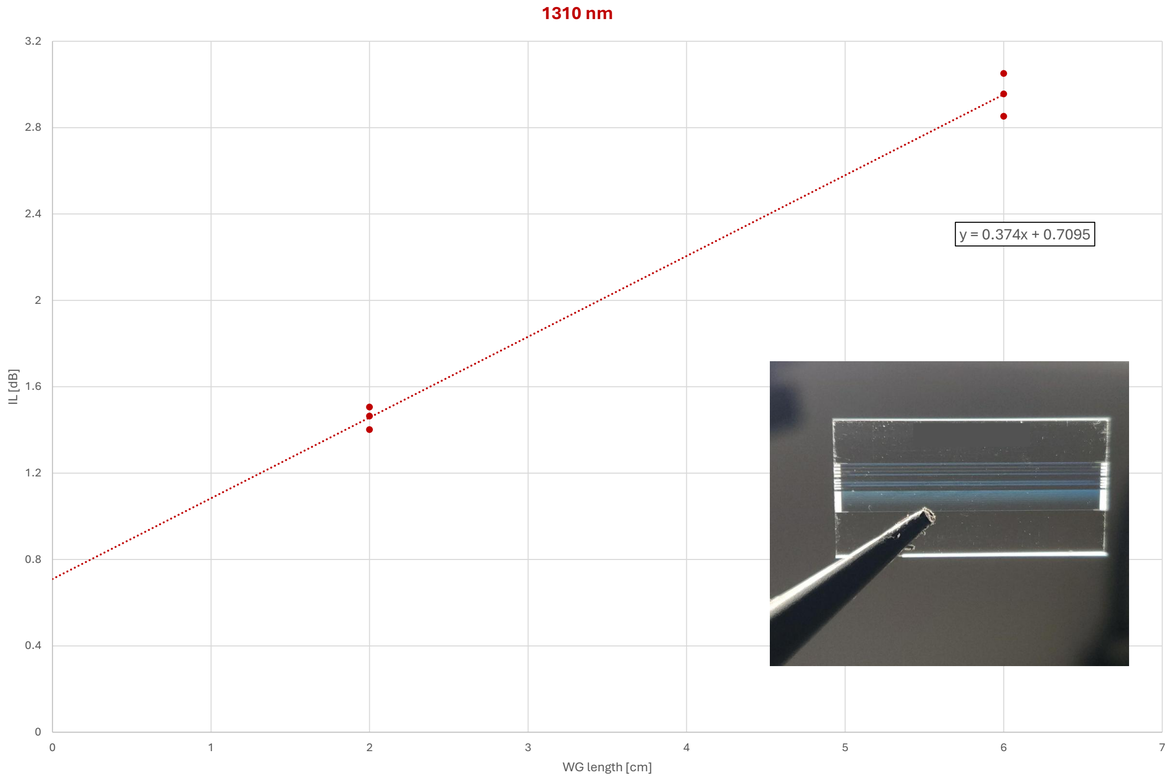
Intensity Profile at Z=250µm - Measured

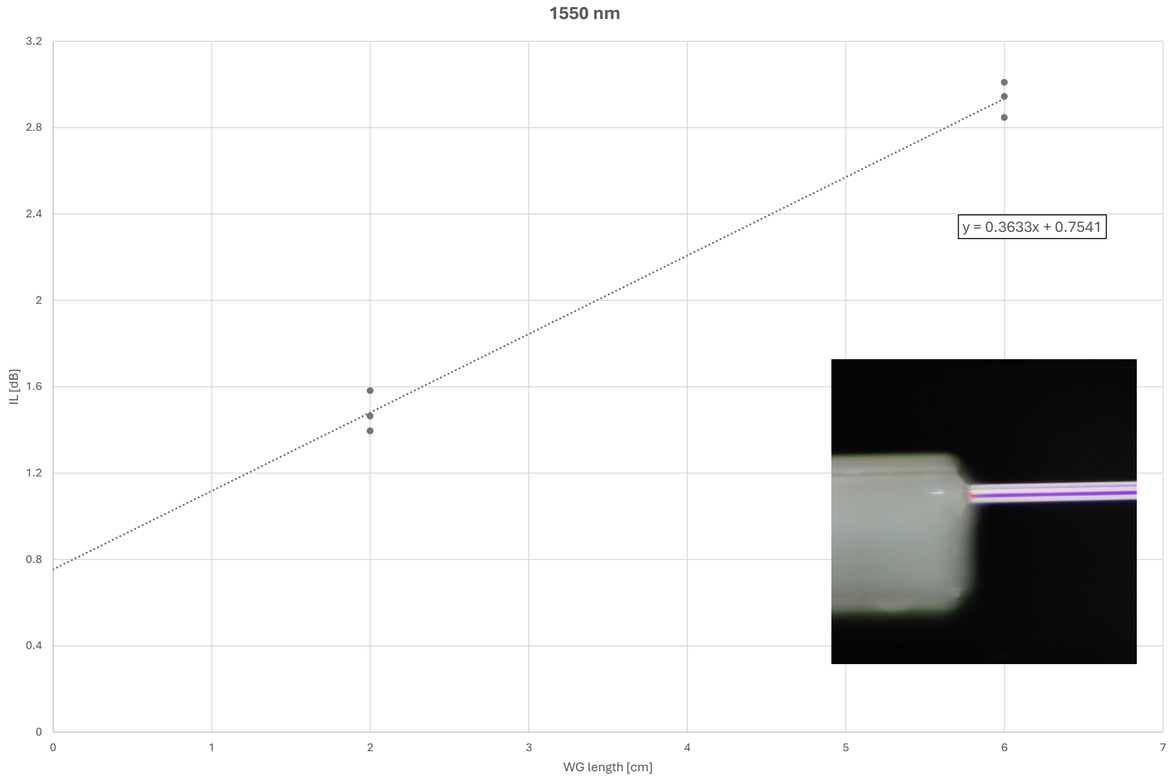






Linear waveguides





- Cut-back method : butt-coupling at input & output
- Fiber : SM980 - 5.8/125
- 0 deg polishing : Fresnel losses taken into account

@ 1310 nm & 1550 nm

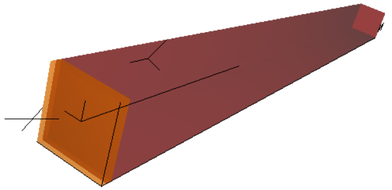
Propagation Losses ~ 0.35 dB/cm

Coupling Losses ~ 0.2 dB/interface

Propagation Losses (PL)

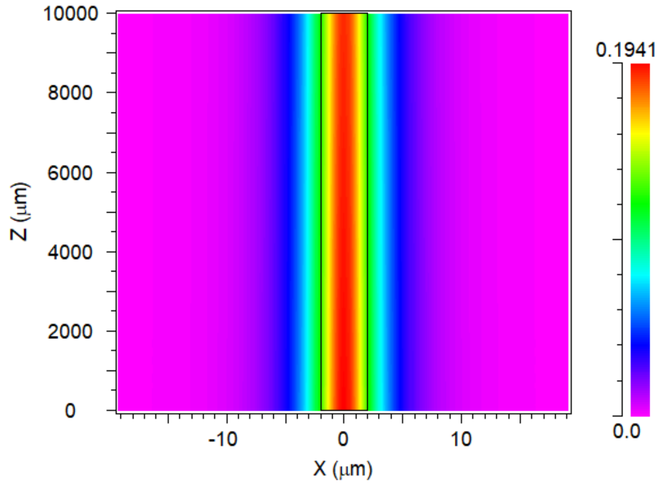
Simulation input

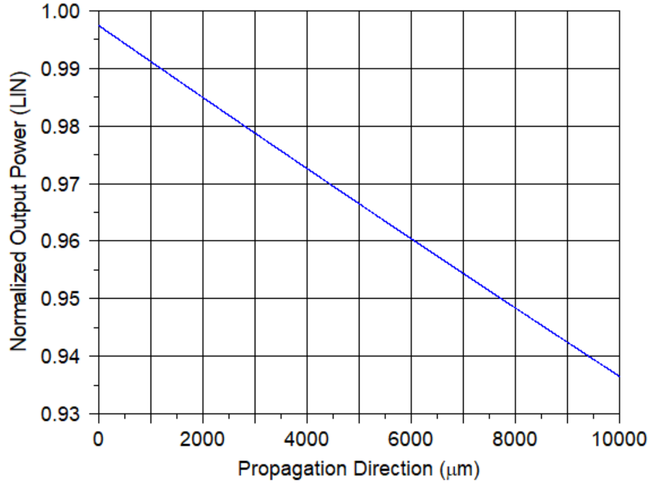
- Δn: 0.0093
- Alpha: 1.86e-06
- Profile: Gaussian
- Dimensions: 4µm x 4µm



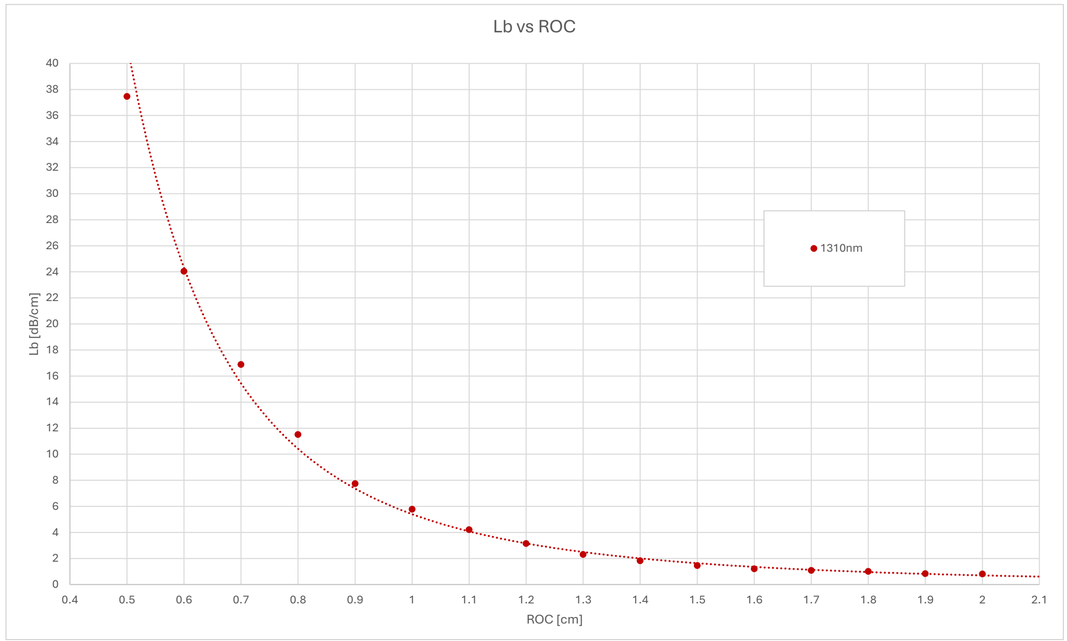
PL – Simulation vs. Measurement

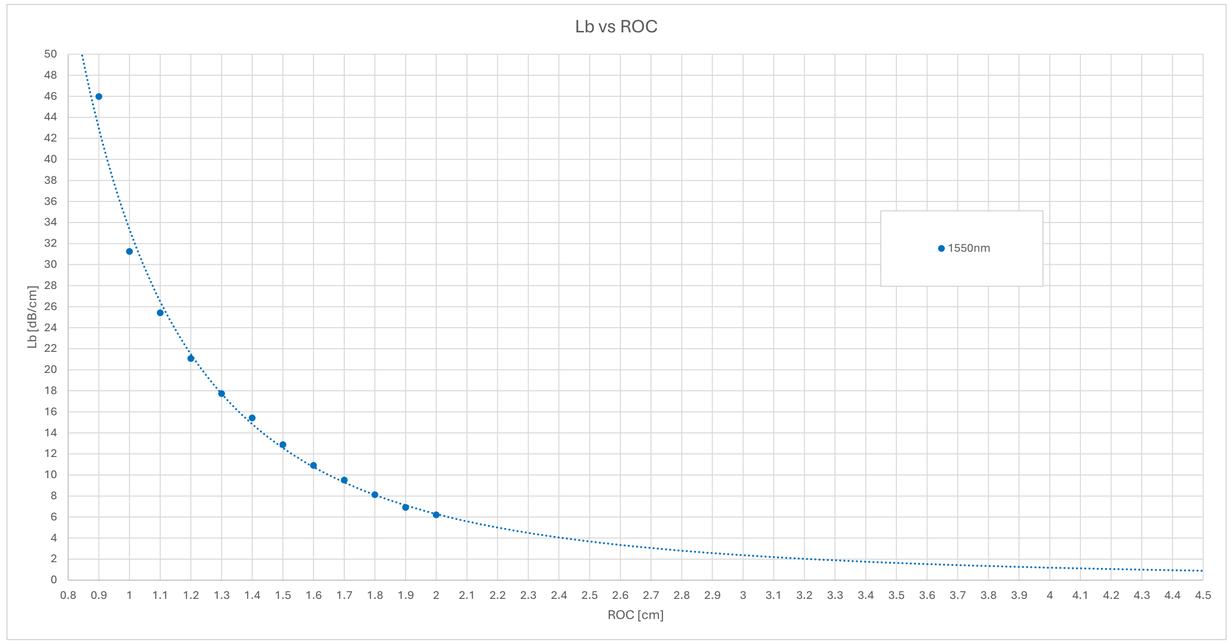
- Simulated: ~ 0.27 dB/cm
- Measured: ~ 0.30 dB/cm ± 0.05 dB/cm





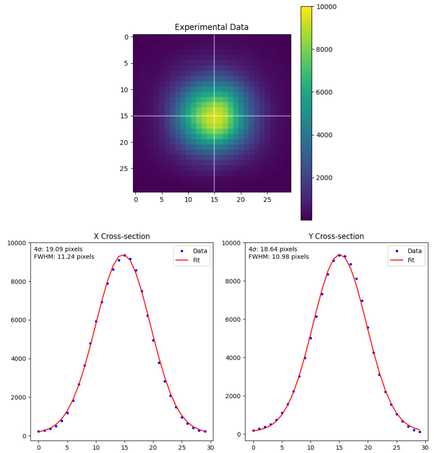
Bends





1310nm

- MFD = 7 – 8 µm
- Lc = 0.45 dB/facet
- Lp = 0.30 dB/cm
- Lb = 1 dB/cm @ 18 mm ROC



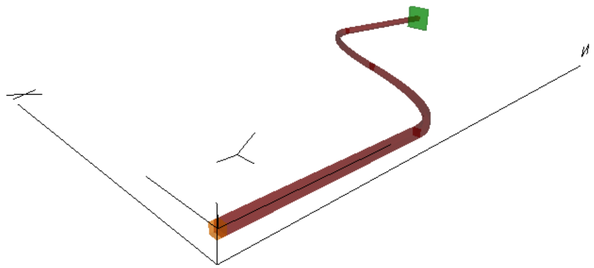
1550nm

- MFD = 8 – 9 µm
- Lc = 0.15 dB/facet
- Lp = 0.25 dB/cm
- Lb = 1 dB/cm @ 43 mm ROC

Lc : Coupling Losses ; Lp : Propagation Losses ; Lb : Bending Losses

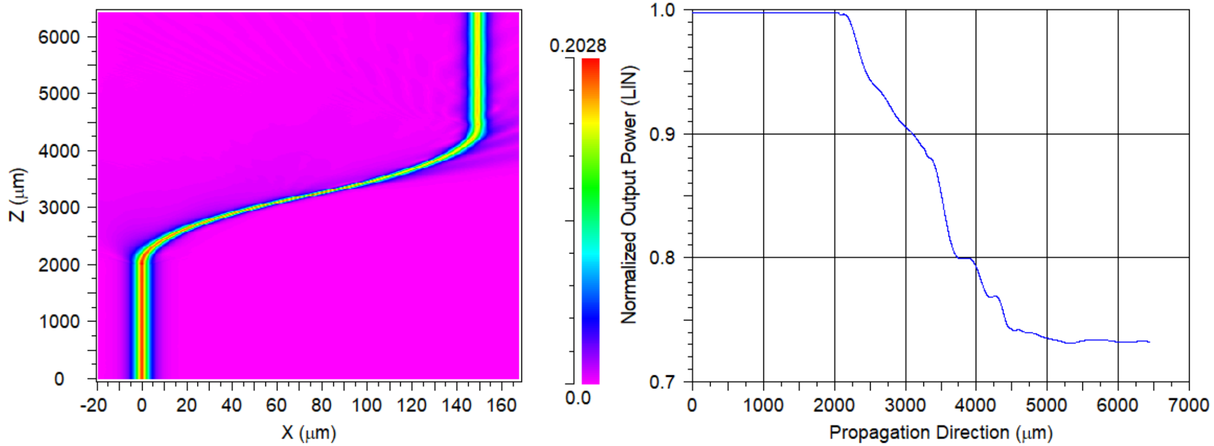
Bending Losses (BL)

Simulation input – ROC = 10mm
- Δn: 0.0093
- Alpha: 0 – *PL neglected*
- Profile: Gaussian
- Dimensions: 4 µm x 4 µm
- Arc length: 7° + 7°

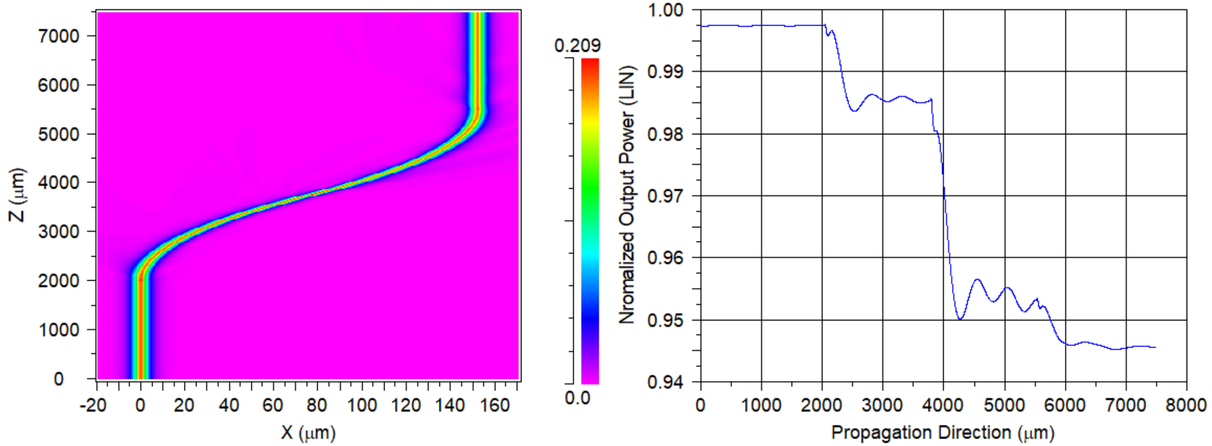


Simulation input – ROC = 20mm
- Δn: 0.0093
- Alpha: 0 – *PL neglected*
- Profile: Gaussian
- Dimensions: 4 µm x 4 µm
- Arc length: 5° + 5°

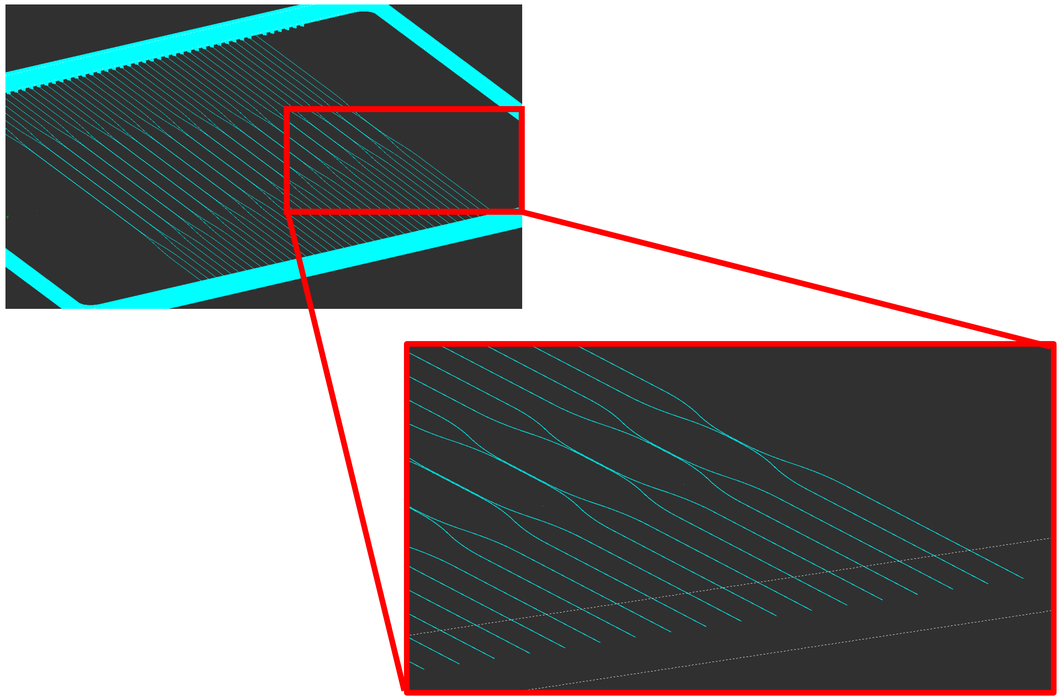
BL (ROC = 10mm) – Simulation vs. Measurement
- Simulated: 5.52 dB/cm
- Measured: 5.77 dB/cm ± 0.05 dB/cm

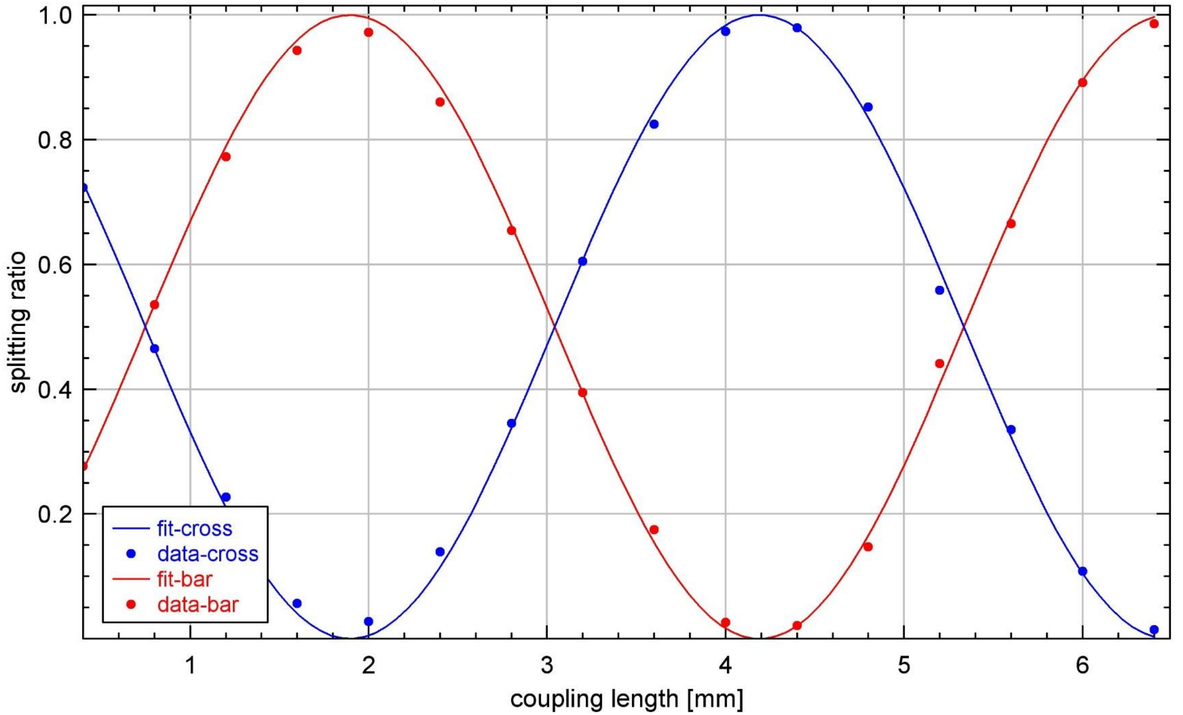


BL (ROC = 20mm) – Simulation vs. Measurement
- Simulated: 0.70 dB/cm
- Measured: 0.81 dB/cm ± 0.05 dB/cm



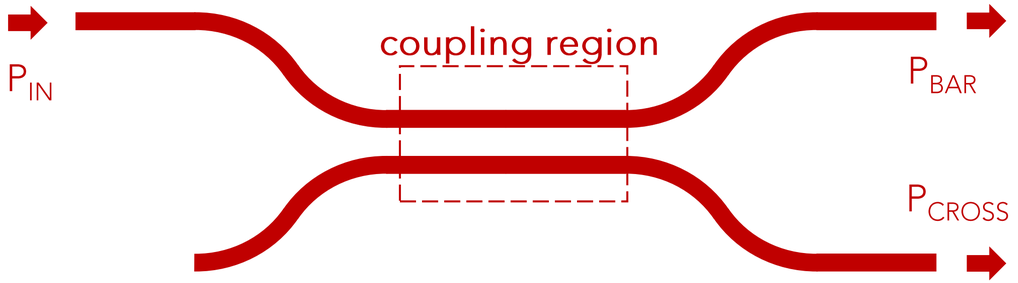
Directional couplers





1310nm

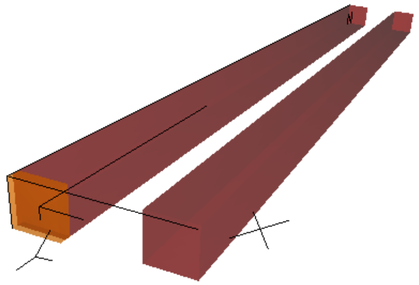
- Output channel pitch : 250 µm
- Full power transfer at approx. 2.3 mm
- Total Loss for 50/50 splitting approx. 1.6dB



Cross-Talk (XT)

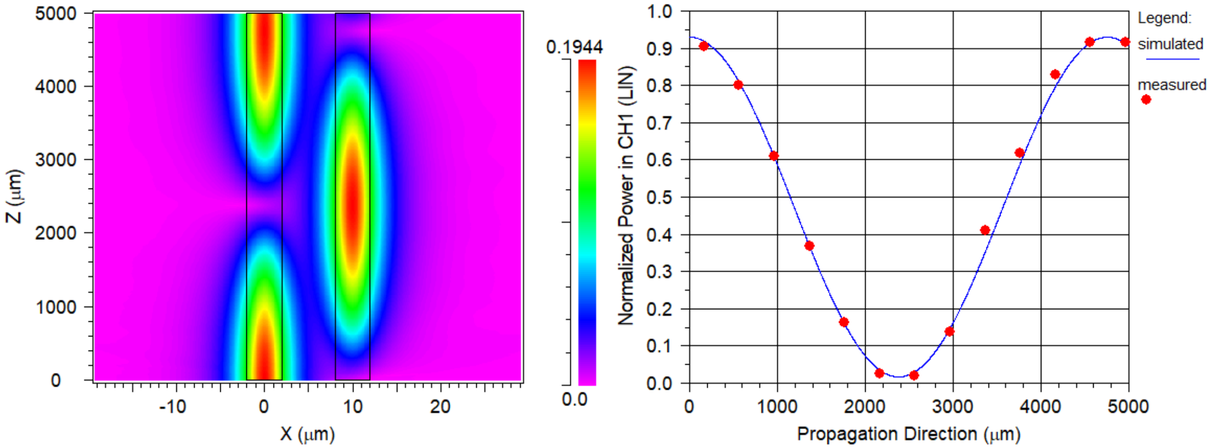
Simulation input

- Δn: 0.0093
- Alpha: 0 – *PL neglected*
- Profile: Gaussian
- Dimensions: 4 µm x 4 µm
- Power monitor: 10 µm x 10 µm



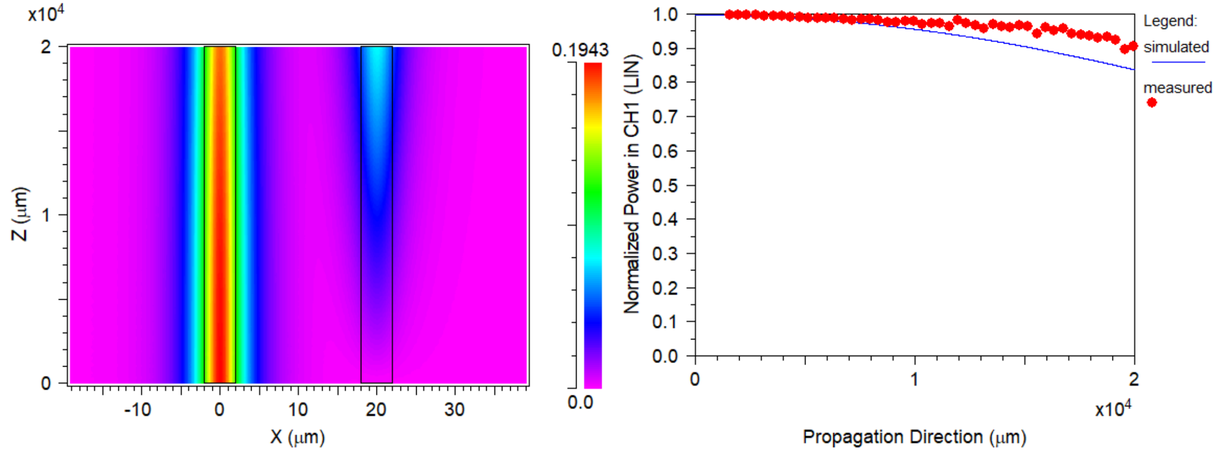
Full Power Transfer (Gap = 10µm) – Simulation vs. Measurement

- Simulated: 2.38 mm
- Measured: ~ 2.30 mm



Split Ratio (Gap = 20µm) – Simulation vs. Measurement

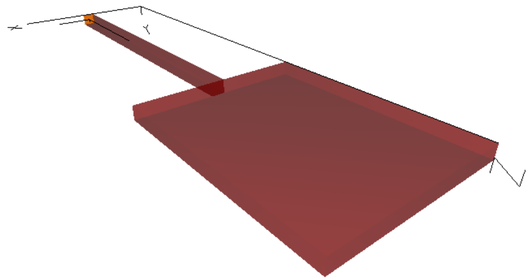
- Simulated: 0.84
- Measured: ~ 0.90



Multi Mode Interferometer (MMI)

Simulation input

- Δn: 0.0093
- Alpha: 0 – *PL neglected*
- Profile: Step
- Dimensions: 50 µm x 637 µm



Simulation vs. Measurement

Peak to peak

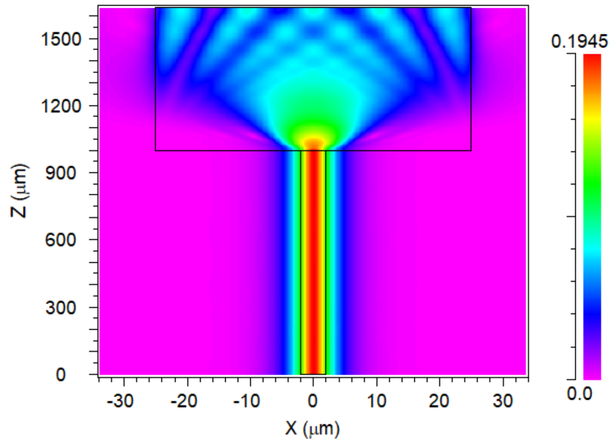
- Simulated: 10.5 µm
- Measured: 11 µm±1µm

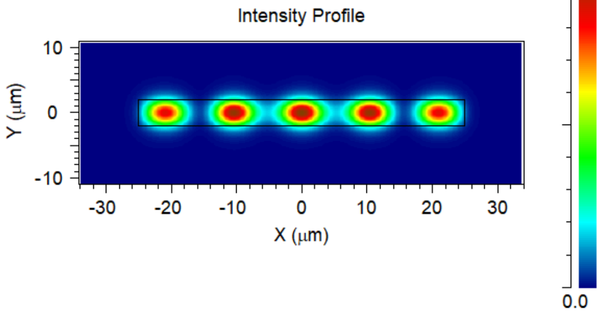
Length

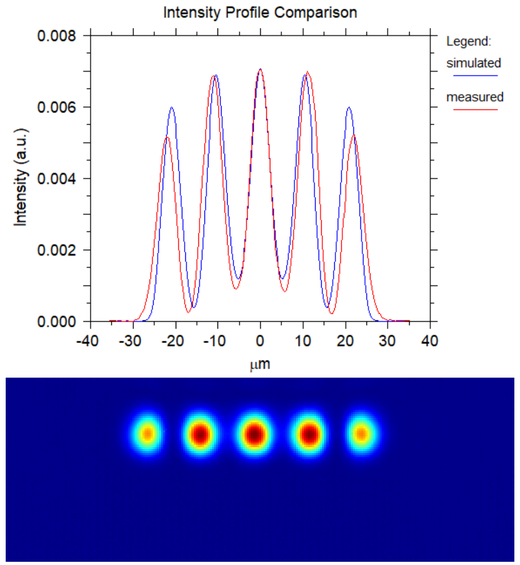
- Simulated: 637 µm
- Measured: 650 µm ±10µm

Side attenuation

Less prominent in simulation







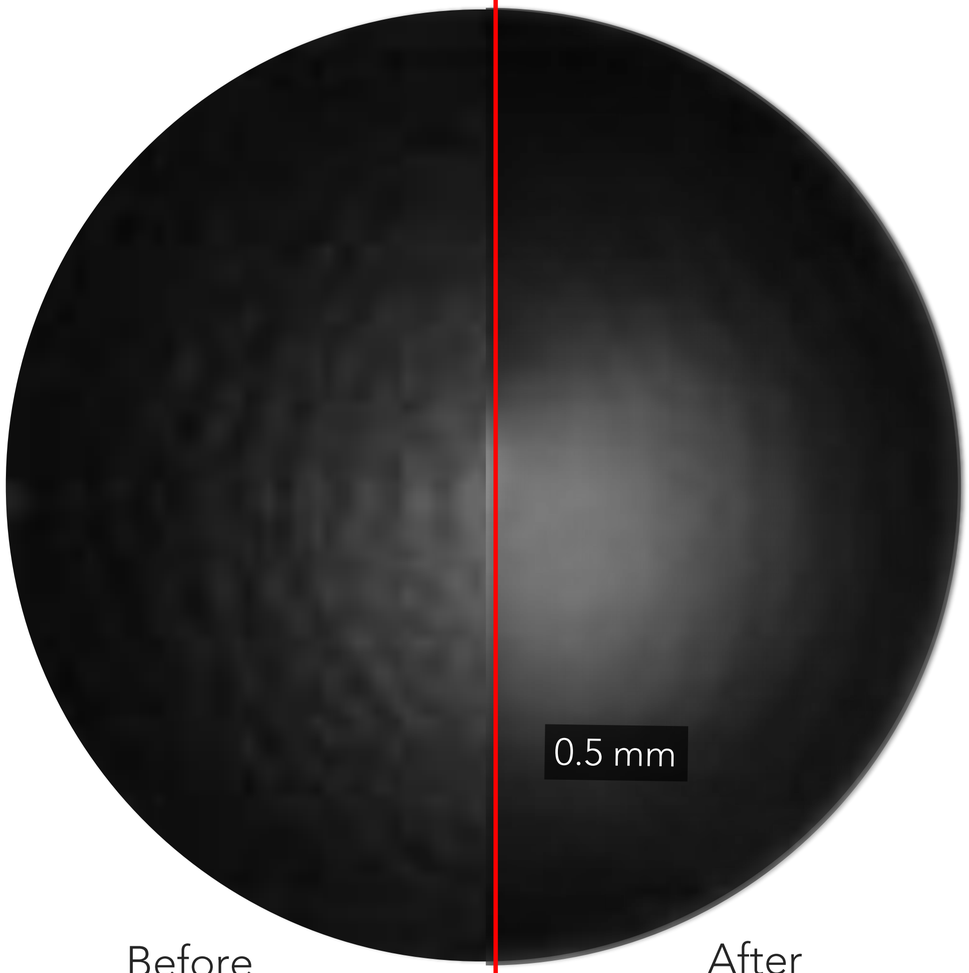
MICRO-OPTICS

Shallow Micro-Lens Array

Beam Shaping

Hexagonal closely packed MLA
100x spherical micro-lenses

- Diameter = 500 µm
- RoC = 650 µm
- SAG = 50 µm



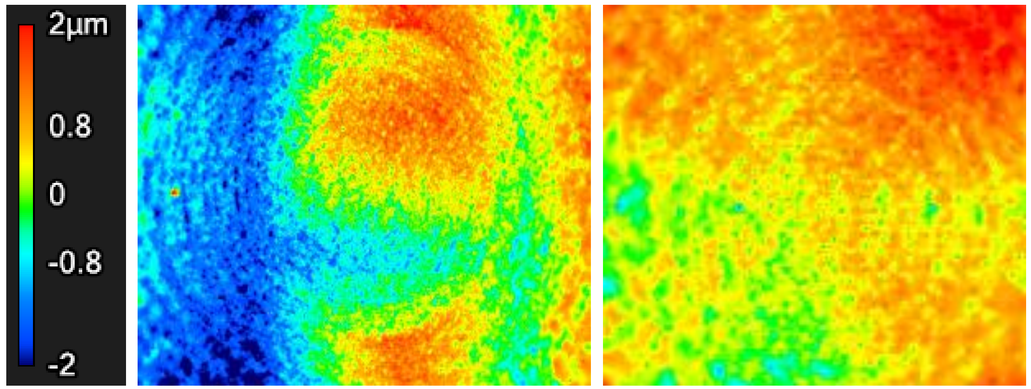
Micro-machined MLAs
in Fused Silica

- RoC = 625 ± 5.0 µm
- SAG = 51.1 ± 1.5 µm
- Sa = 4.8 ± 3.3 nm
- Shape accuracy: ≈ 1 µm

Shape accuracy

Process

Diameter: 1600 µm
SAG: 300 µm
ROC: Aspheric



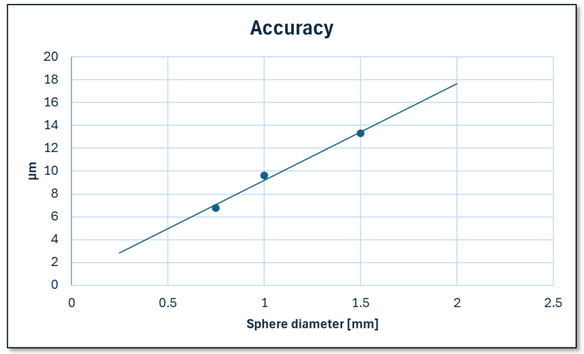
AvD ~ 1 µm

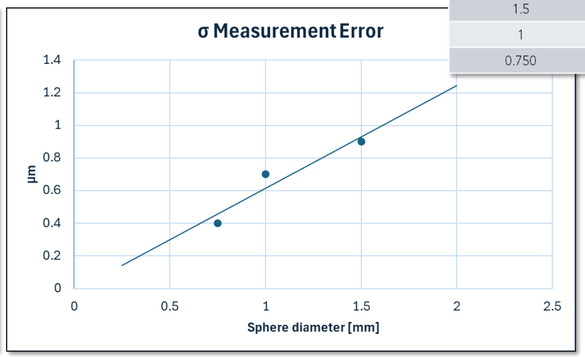
AvD ~ 0.2 µm

AvD : Average difference between the 3D CAD model and the measurement point cloud

Metrology

– ROC Gage R&R –

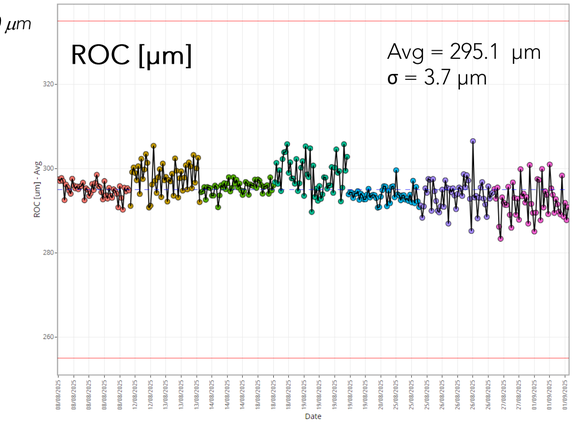


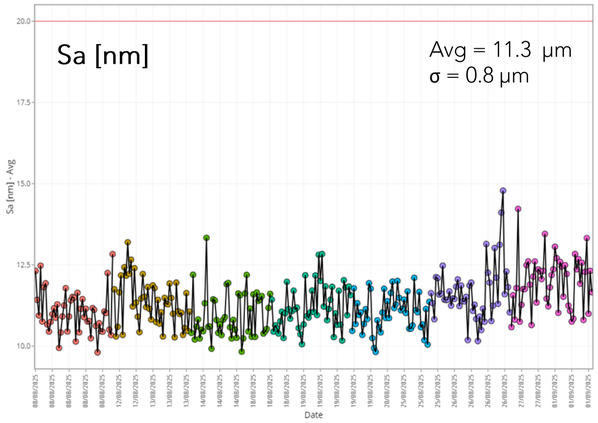


Sphere Diameter [mm]	ROC [mm]
1.5	0.75
1	0.5
0.750	0.375

Process variability

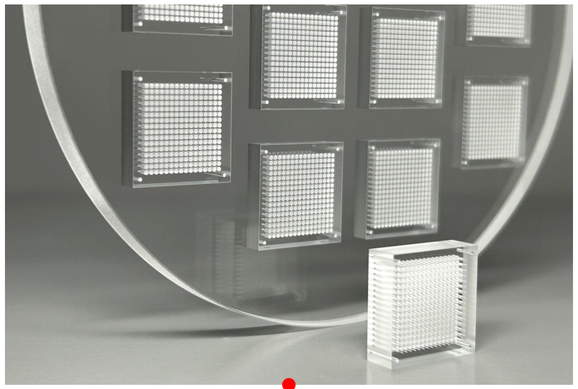
Diameter: 130 µm
SAG: 8 µm
ROC: 300 µm



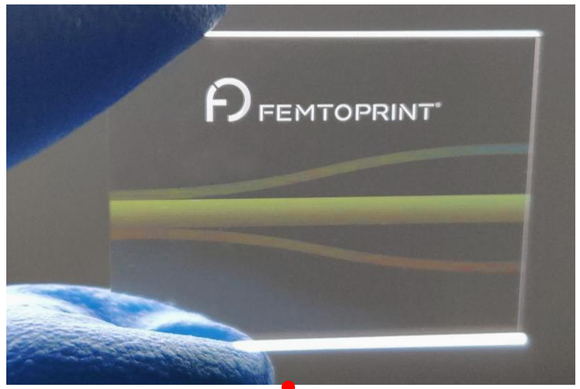


Monolithic integration

HIGH-PRECISION FIBER ALIGNMENT



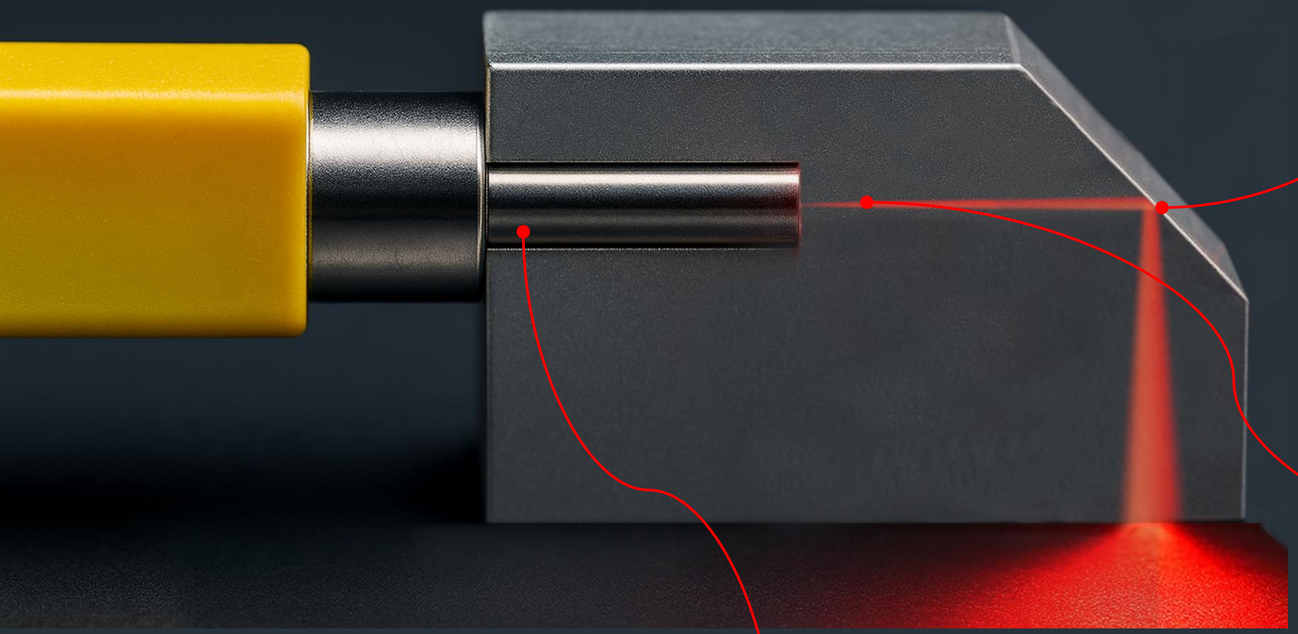
BEAM ROUTING



BEAM SHAPING

- *< ± 1µm relative positioning*
- *Monolithic integration of several functionalities*
- *Optical systems for fiber-to-chip connectivity*

Glass micro-connectors



TIR or METALLIZED MIRROR

- Free-form
- Diameter = 100-500 µm
- Shape accuracy < 1-2 µm
- Roughness < 10 nm
- Clear aperture < 90%

GLASS WAVEGUIDE

Coupling Loss (Lc), Propagation Loss (Lp), Bending Loss (Lb)

<u>1310nm</u>

- MFD = 7 – 8 µm
- Lc = 0.45 dB/facet
- Lp = 0.30 dB/cm
- Lb = 1 dB/cm @ 18 mm ROC

<u>1550nm</u>

- MFD = 8 – 9 µm
- Lc = 0.15 dB/facet
- Lp = 0.25 dB/cm
- Lb = 1 dB/cm @ 43 mm ROC

- NA ≈ 0.06/0.07
- Minimum pitch for X-talk > 30dB: 20 µm
- Substrate thickness < 1.2 mm

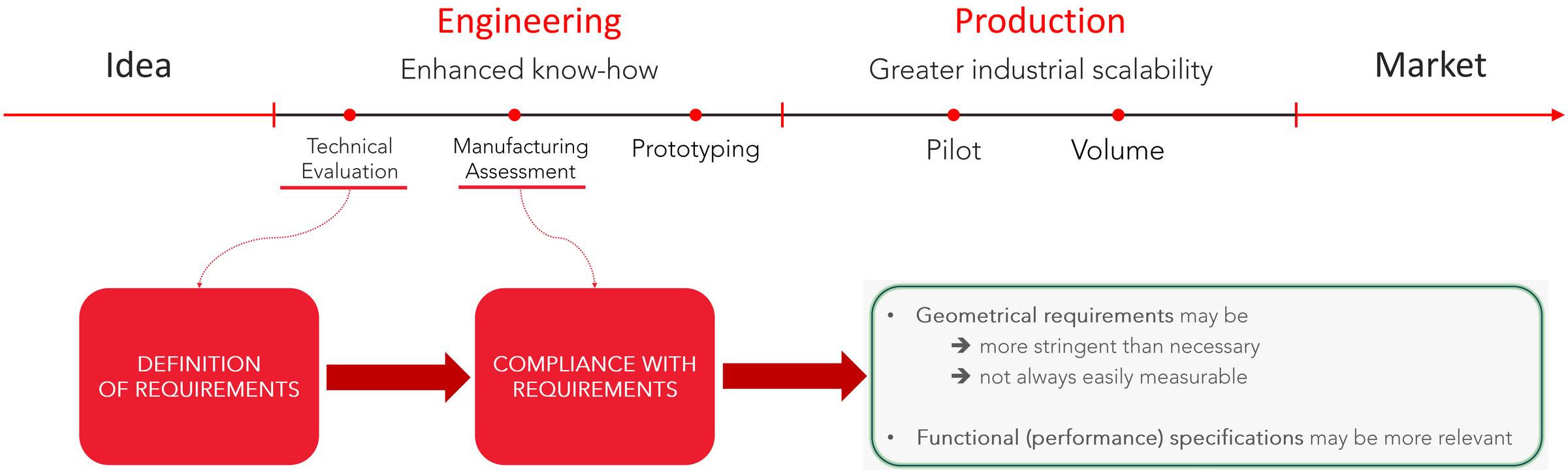
Input fiber

- Mode field diameter: 10 ± 0.4 µm
- Wavelength: 1310 nm
- NA (@ 1310 nm): 0.14
- Cladding diameter: 125.0 ± 0.7 µm
- Core-clad concentricity: ≤ 0.5 µm

GLASS FERRULE

- Diameter tolerance: ± 1 µm to ± 0.5 µm
- Positioning tolerance: ± 1 µm to ± 0.5 µm
- Circularity error < 1 µm
- Hole bottom roughness ≈ 200-300 nm → *index matching glue*
- Substrate thickness < 5-10 mm

Design For Manufacturing (DFM)
Motivation



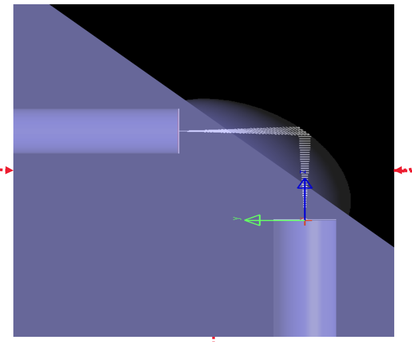
- **Geometrical requirements** may be
  - ➔ more stringent than necessary
  - ➔ not always easily measurable
- **Functional (performance) specifications** may be more relevant

- Modification of initial design based on manufacturing guidelines
- Assessment of the impact on the device functionality
- Definition of functional requirements & tests

Design For Manufacturing (DFM)

Value proposition

Design



Redesign

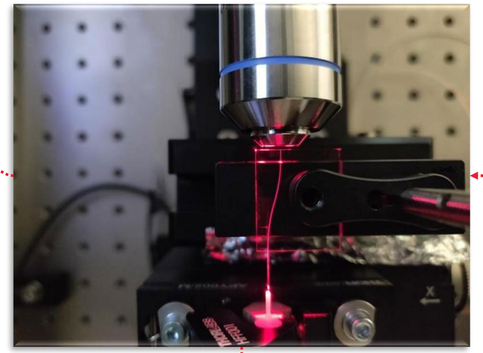
Performance comparison

Redesign

Performance comparison

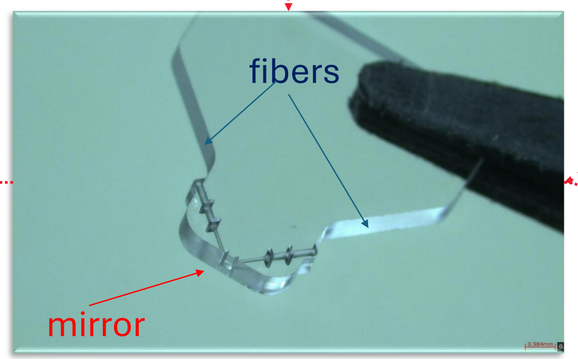
Quasi-empirical simulations

Functional testing



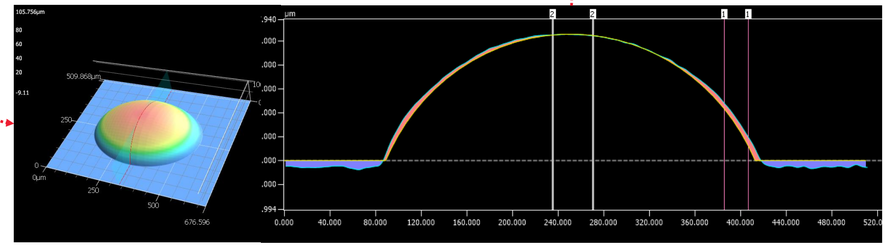
Performance assessment

Fabrication



Partial fabrication

Surface metrology

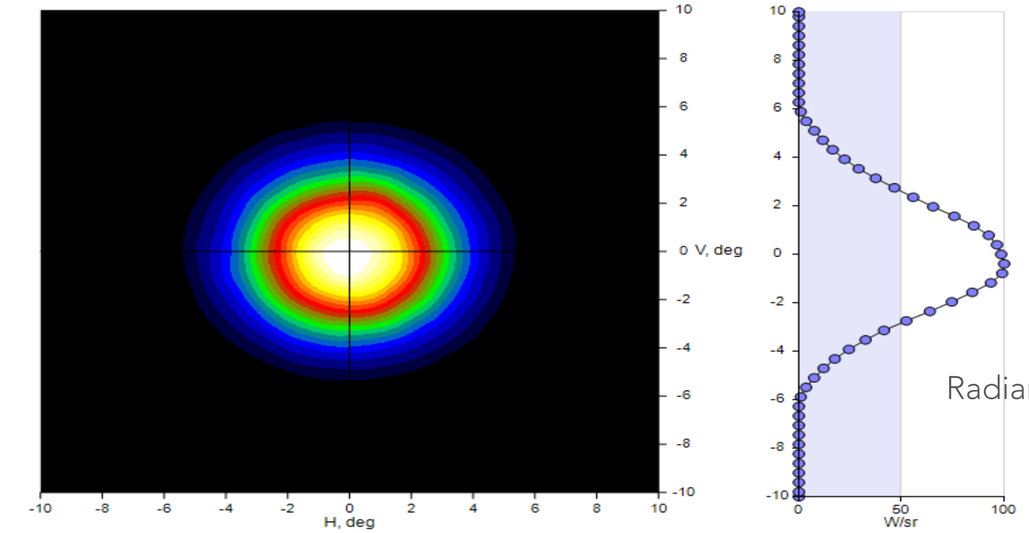


SPEED

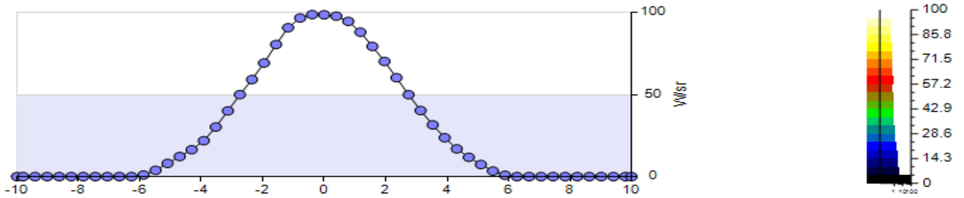
COST

Simulation results – ideal case

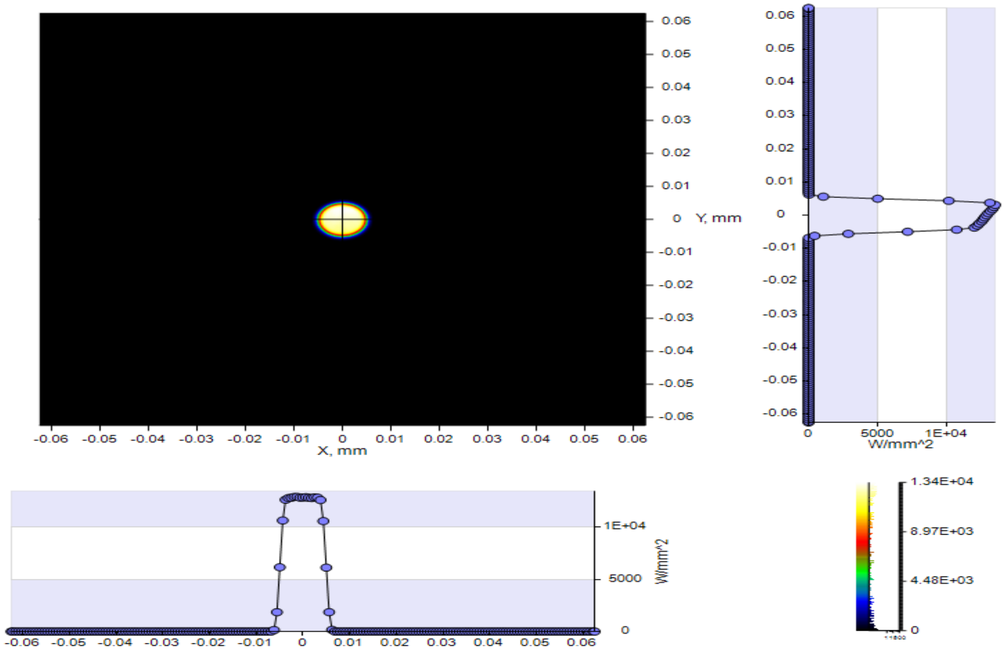
- **10um MFD:** 4.6% of light is clipped
- **5.5° light divergence :** 4.0% of light is lost
- **Resulting efficiency:** 91.9% (8.1% loss) = -0.37 dB

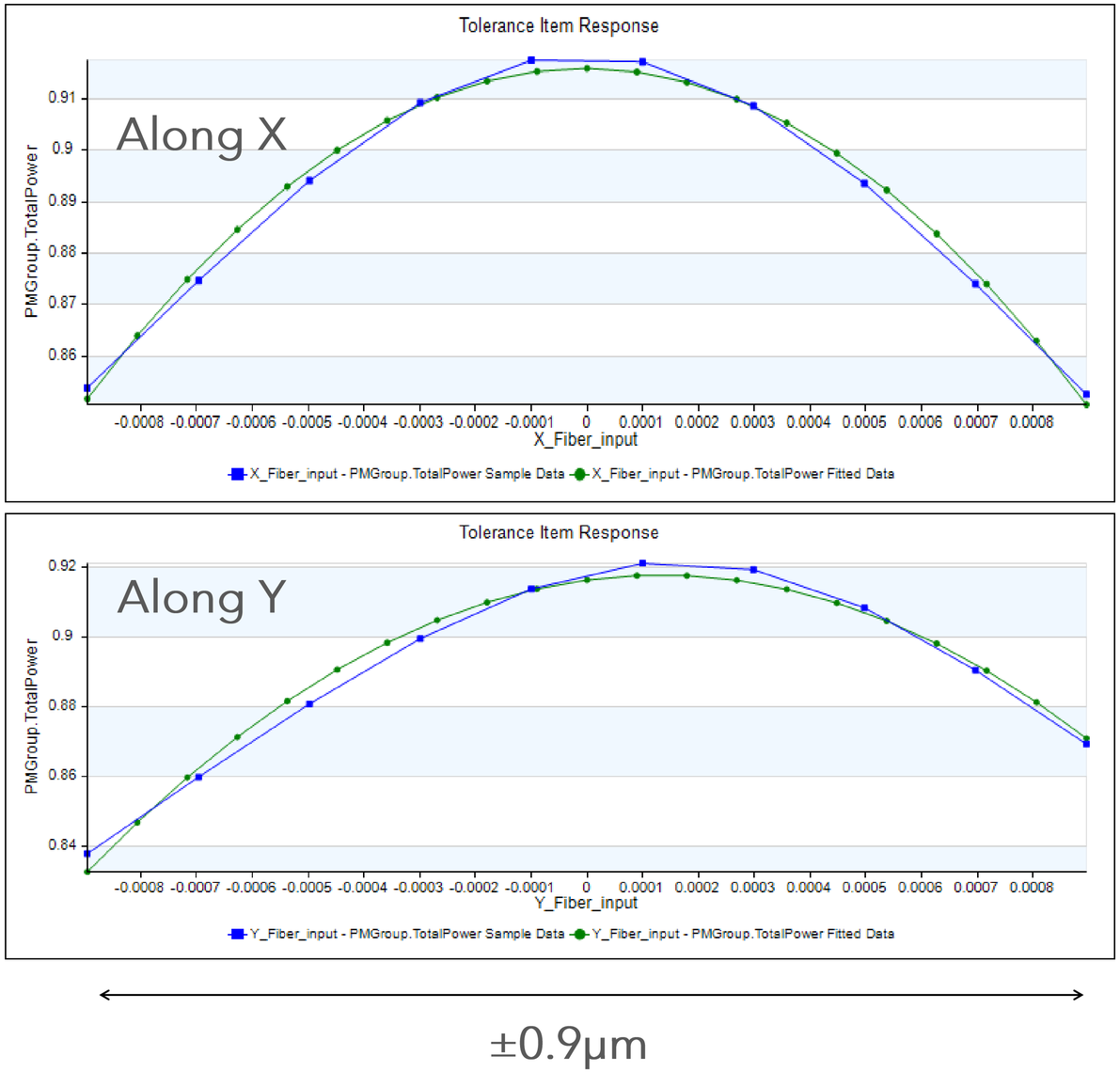


Radiant intensity (W/srad)



Irradiance mesh (W/mm^2)

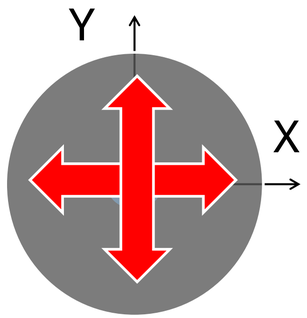




Coupling efficiency

±0.9µm

Tolerancing – fiber transversal positioning



Benchmark efficiency 91.9%

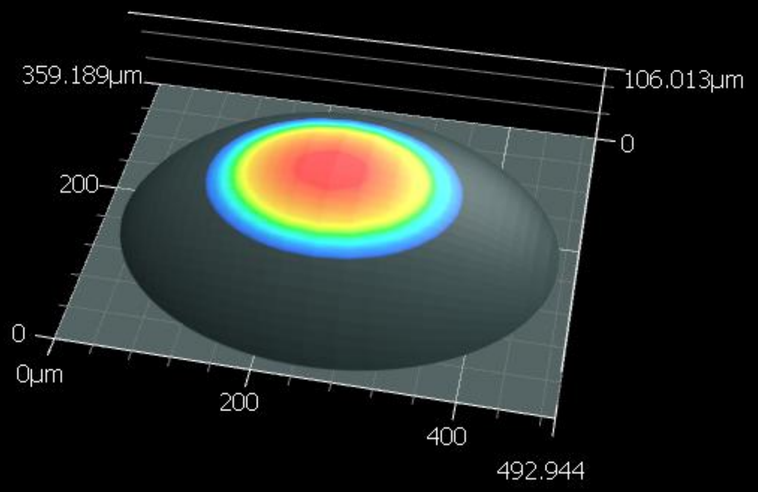
Tolerance boundaries are calculated via sum-of-squares method, considering:

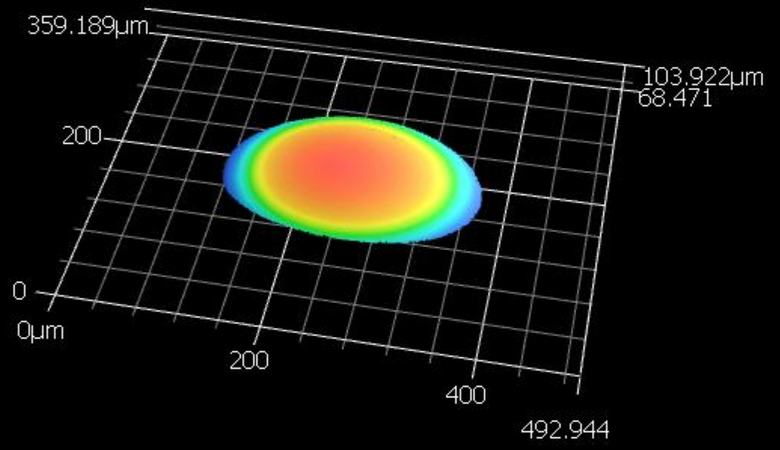
- 0.25 µm cladding-core concentricity
- 0.7 µm cladding diameter tolerance
- 0.5 µm FEMTOprint ferrule tolerance

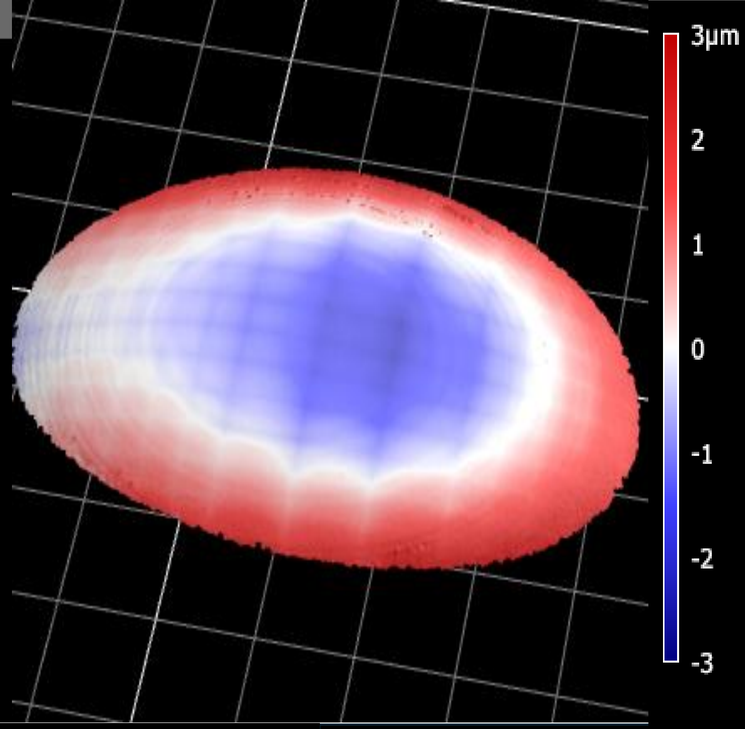
Efficiency may go below 86% (14% loss) = -0.65 dB

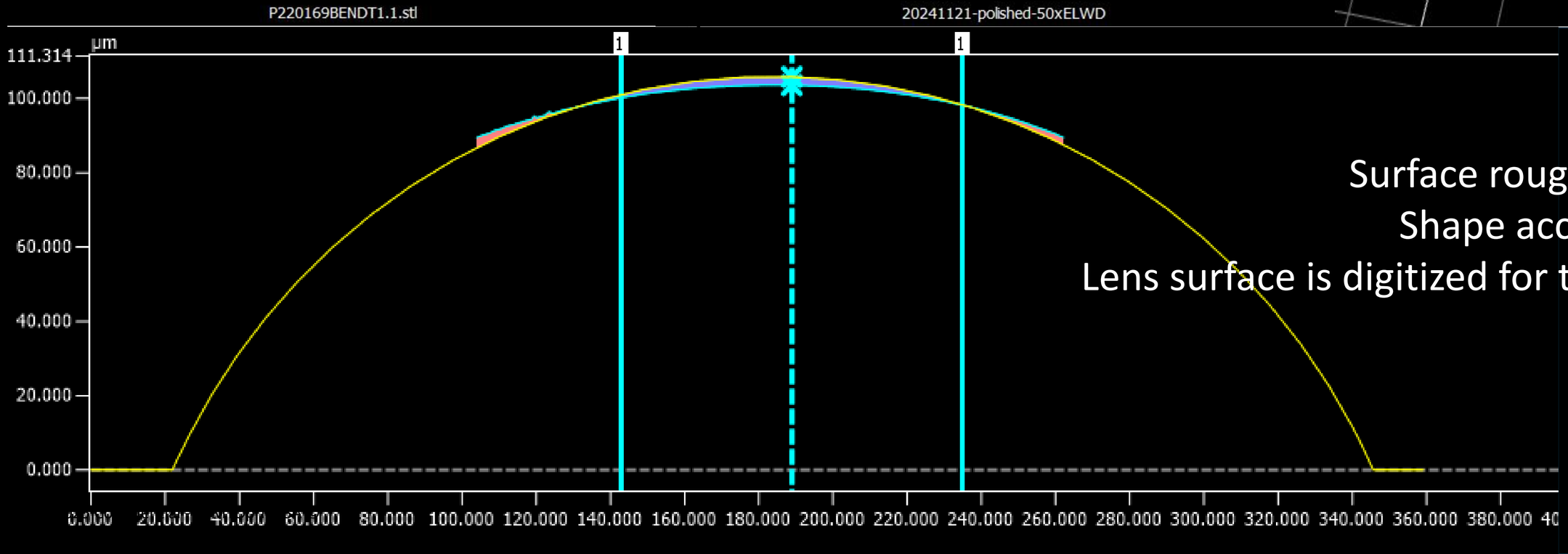
System asymmetries: non-symmetric positioning error

DEVICE CHARACTERIZATION









Surface roughness <10 nm
Shape accuracy < ±3µm
Lens surface is digitized for the simulation

Quasi-empirical simulation

Input for simulation

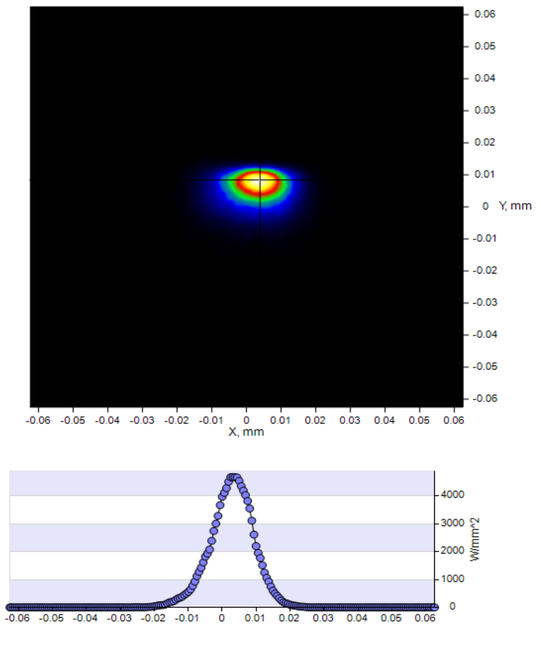
Measured mirror shape vs. ideal mirror shape

- Irradiance mesh:

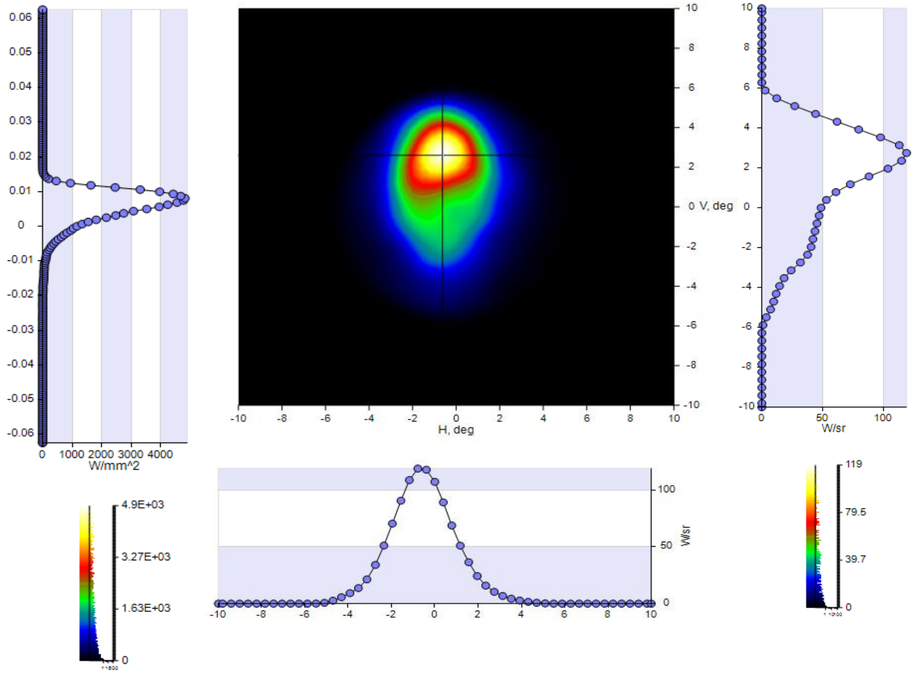
  Peak not centered: :+3 µm,+8 µm.
  Peak too wide: 34 µm x 23 µm *vs.* 11 µm x 11 µm
  Light clipping: 63.4%

- Angular intensity mesh:

  Not centered peak: -0.6°,+2.6°
  Peak dimensions a bit off: 5.5° x 8.8° *vs.* 8.9° x 8.9°
  Light clipping: 5.3%



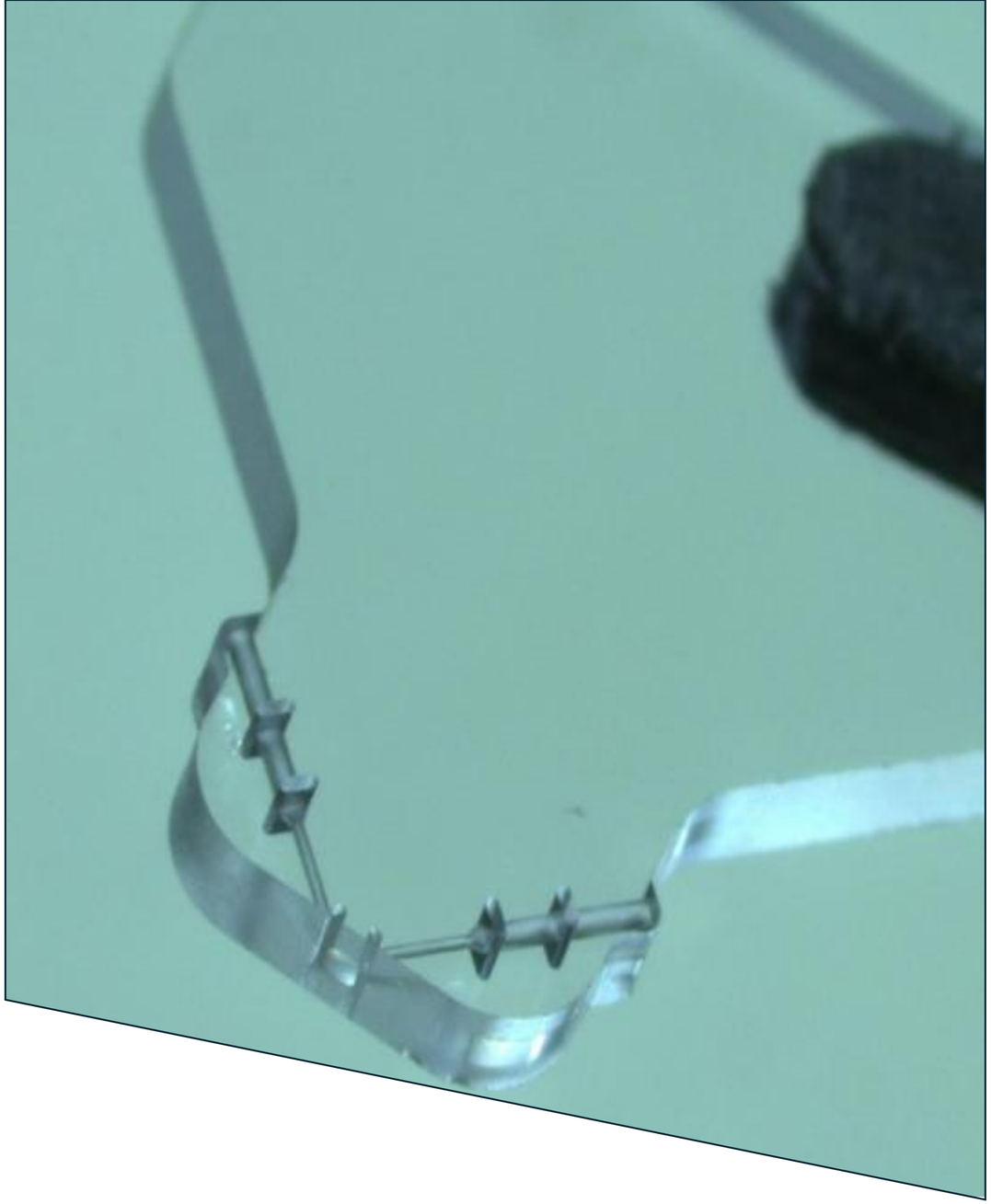
Irradiance mesh (W/mm²)



Radiant intensity mesh (W/mm²)

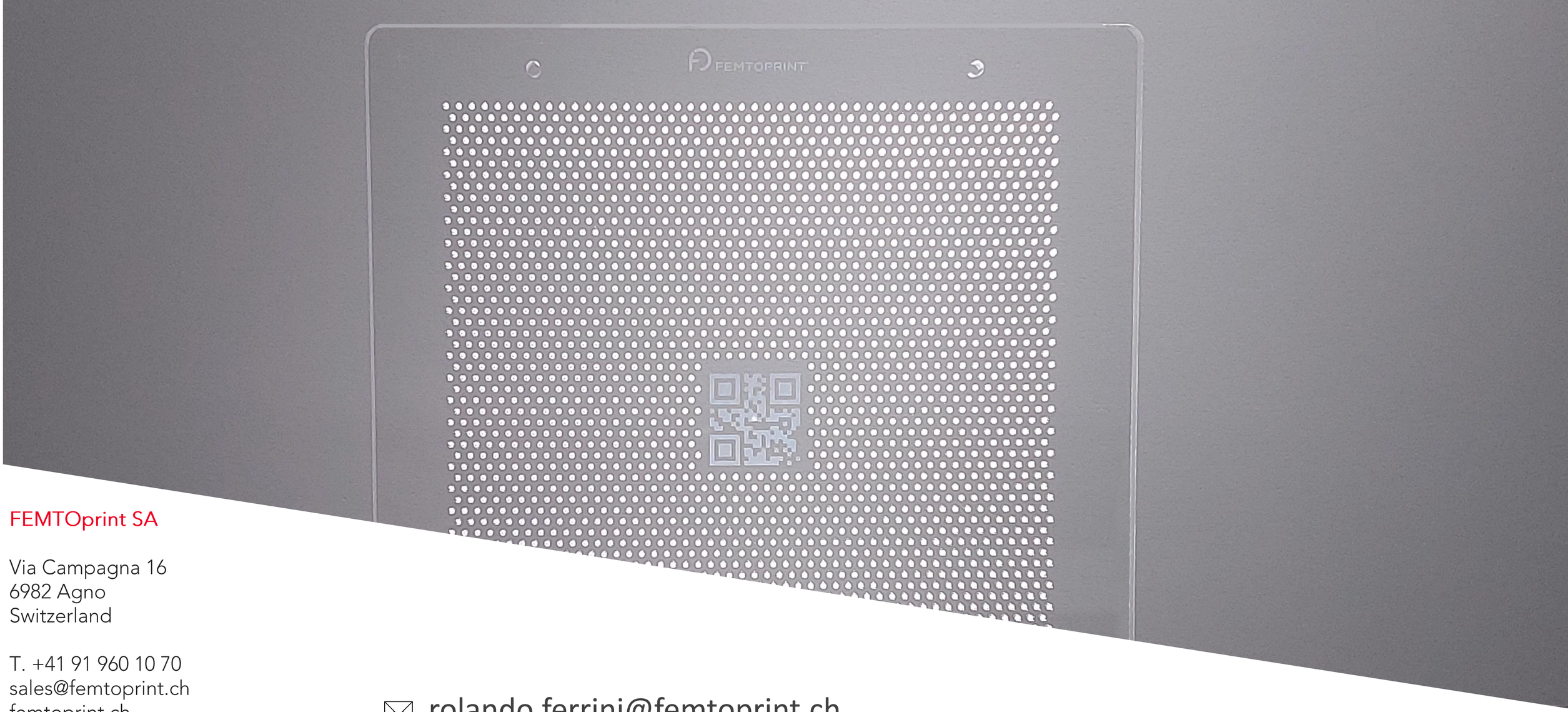
Shape accuracy needs to be improved

Simulation model	Irradiance mesh Peak location	Irradiance mesh Peak width ($1/e^2$)	Efficiency with 10 µm aperture	Intensity mesh Peak location	Intensity mesh Peak width ($1/e^2$)	Efficiency with 5.5° filter	Overall efficiency
Ideal	Centered	11 µm x 11 µm	95.4%	Centered	8.9° x 8.9°	96%	91.9%
Quasi-empirical	(+3 µm, +8 µm)	34 µm x 23 µm	36.6%	(-0.6°,+2.6°)	5.5° x 8.8°	94.7%	35.9%



From “dfm” to “DFM”

- Reduce the number of “fabricate & measure” steps.
- Reduce cost & time for optimization.
- Reduce lead time for manufacturable components with performances close to/within target for real effective *rapid prototyping*.



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