FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

From high-precision glass micro-components to monolithically integrated glass micro-systems for fiber-to-chip connectivity

Rolando Ferrini

Photonics Integration and Packaging

CSEM - Neuchâtel, March 21st, 2024

pic Swiss Photonics Integration Center   csem   SWISS PHOTONICS

FEMTOprint SA
Via Industria 3, 6933 Muzzano | Switzerland
www.femtoprint.ch | info@femtoprint.ch

swiss made   TÜVRheinland CERTIFIED Management System EN ISO 13485:2016 www.tuv.com ID 9108638488

FEMTOprint IN A NUTSHELL

FEMTOprint is a Swiss high-tech Contract Development & Manufacturing Organization (CDMO) specialized in high-precision 3D microfabrication in glass.

FOUNDED IN 2013
Spin-off of the EU project *femtoprint*

40+ FTEs
Interdisciplinary and multicultural team

2 LOCATIONS IN SWITZERLAND
Muzzano (*Headquarters*) & Neuchâtel (*BU Photonics*)

WORLDWIDE SALES
Export in 30+ countries & Sales agents in KR, JP, IL, DACH

ISO CERTIFIED
ISO 9001 : 2015 & ISO 13485 : 2016

FEMTOprint TECHNOLOGY

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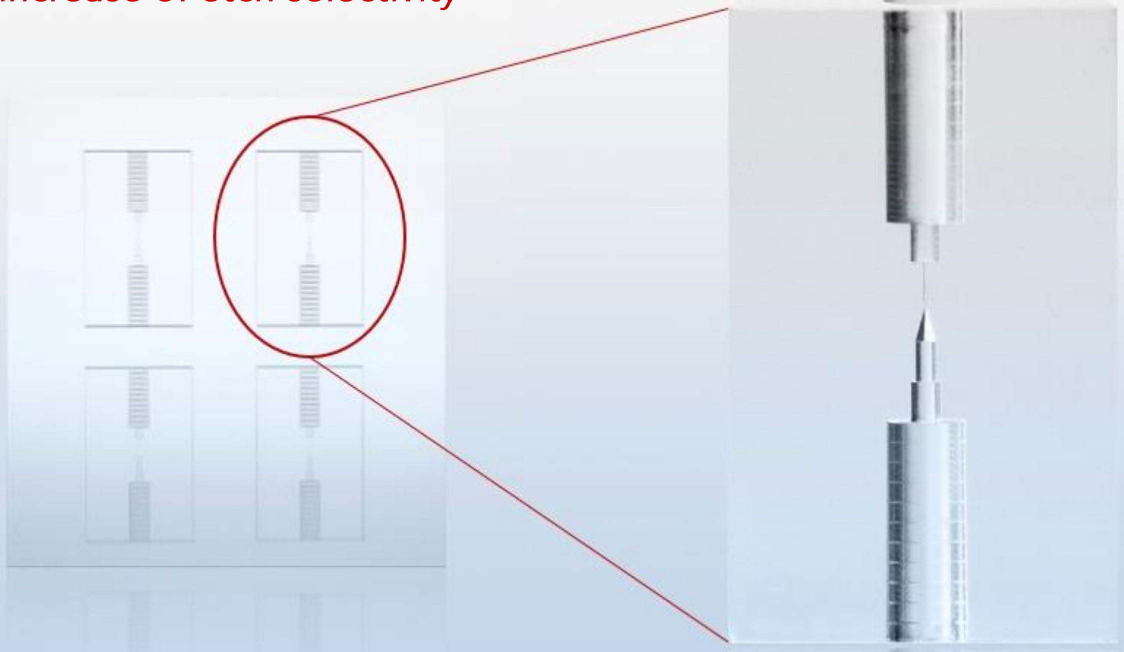
3D PRINTING FOR GLASS MICRODEVICES

Laser writing
- increase of etch selectivity -

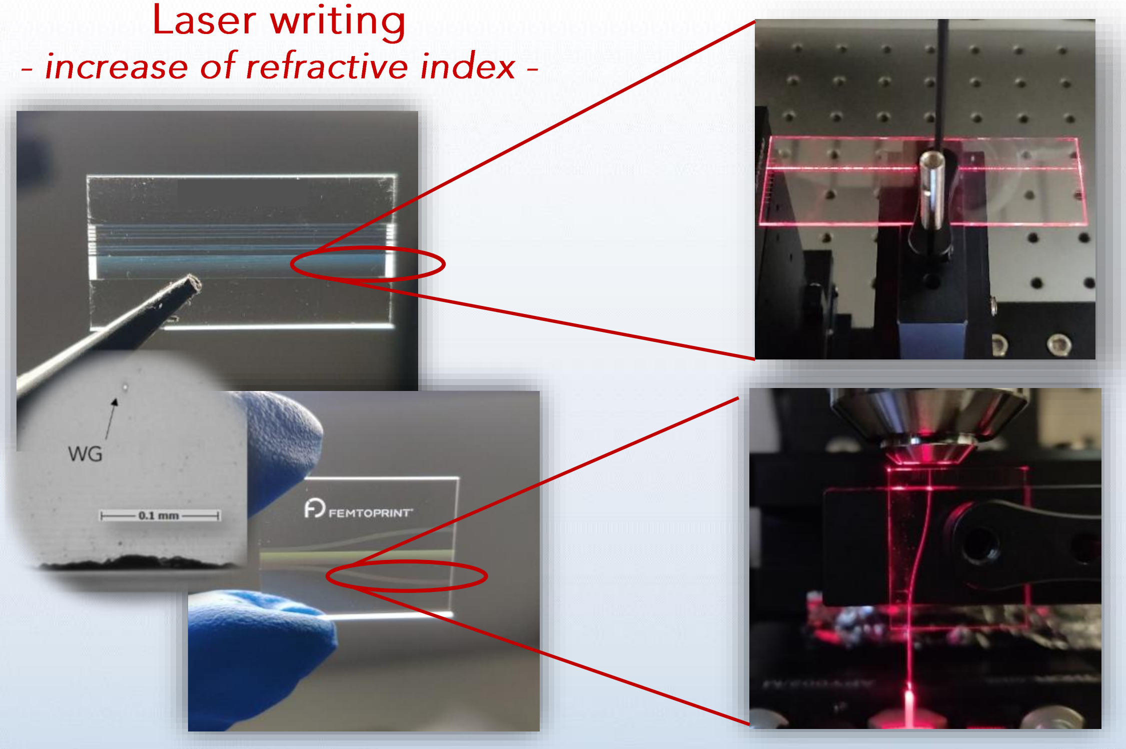
Material processing



Wafer-level processing

Manufactured device:
LxWxH 5.0x3.25x8.0 mm

Laser writing
- increase of refractive index -



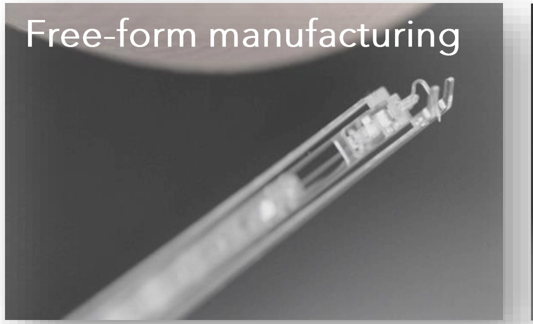
Wafer-level processing

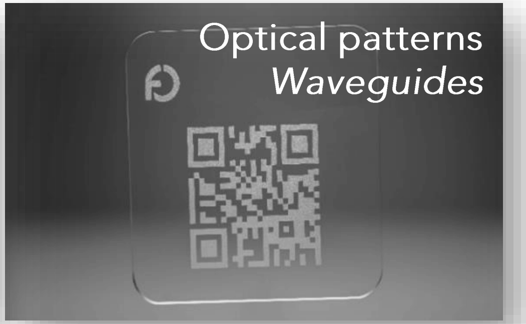
Refractive index increase up to 10^{-2}

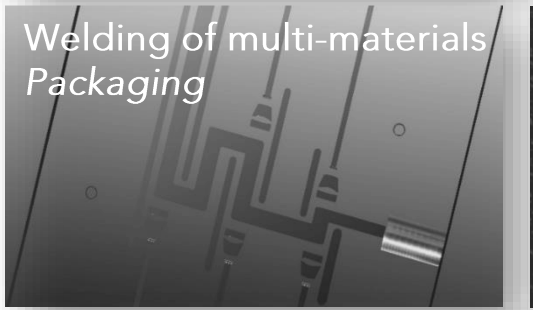
3D MANUFACTURING OF GLASS MICRO-DEVICES

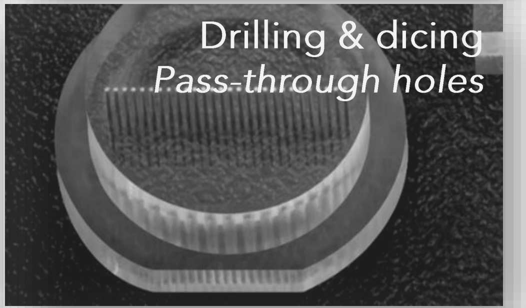
FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

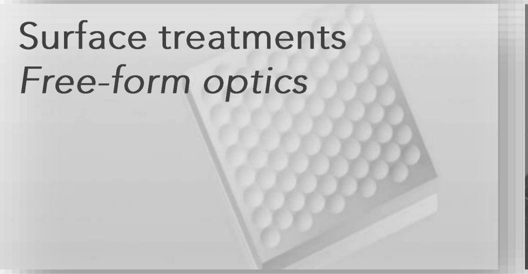
CAPABILITIES

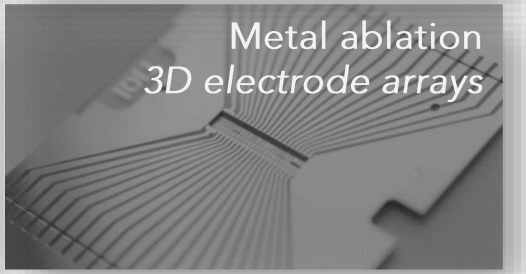










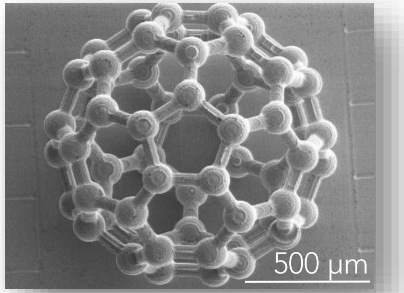


PERFORMANCES*

*in SiO_2

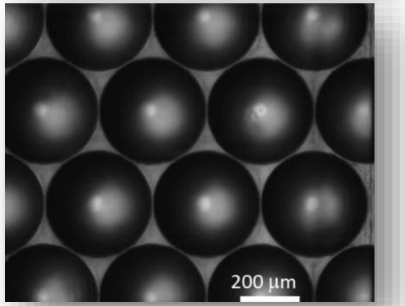
RESOLUTION AND TOLERANCES

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



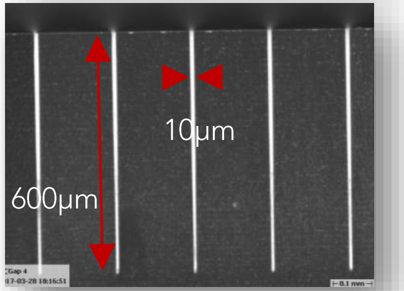
SURFACE QUALITY

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

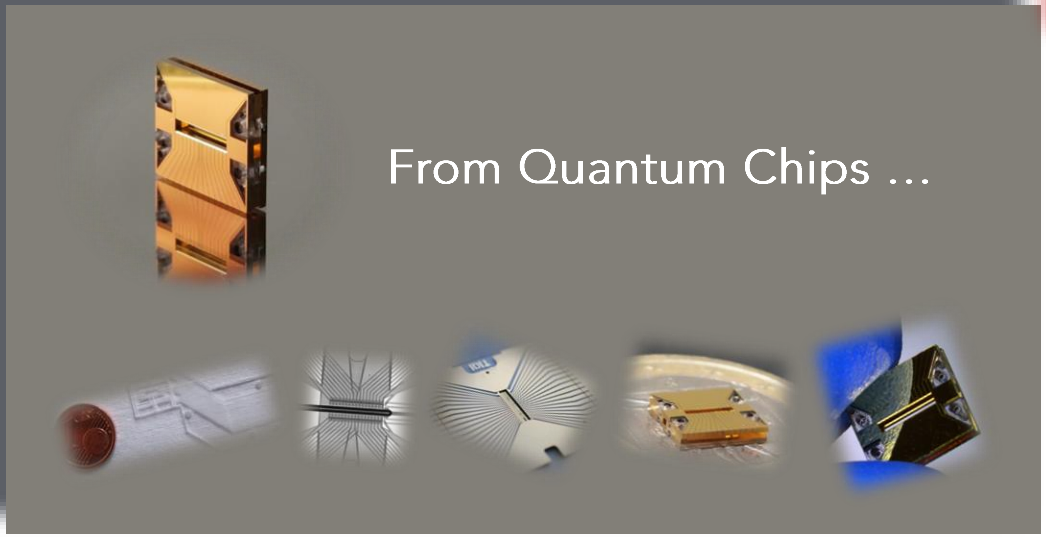


ASPECT RATIO

- Hole aspect ratio ≥ 1:500
- Substrate thickness up to 30 mm
- Min. hole diameter ≤ 5 µm Ø
- Sidewall deviation ≤ 0.1°
- Sidewall roughness *Sa* ≤ 100 nm

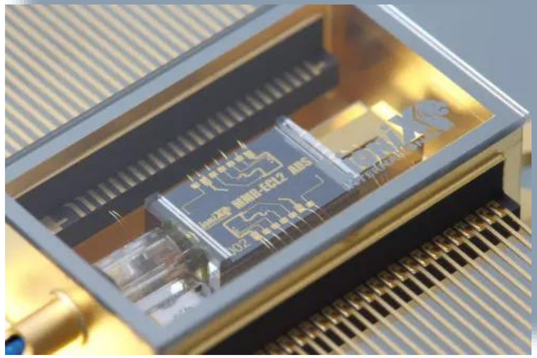


INTEGRATED & QUANTUM PHOTONICS

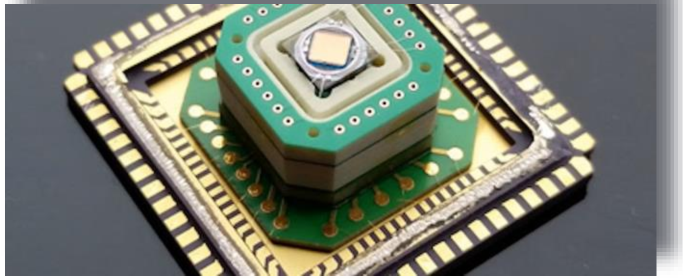


PACKAGING & ASSEMBLY

… to Integrated Photonics products



… to Quantum Photonics products



FIBER-TO-CHIP CONNECTIVITY

FIBER ARRAYS

MINIATURIZED OPTICS
MICRO-OPTICS

WAVEGUIDES

FIBER ARRAYS

GLASS FIBER FERRULES – PASSIVE ALIGNMENT ASSEMBLY

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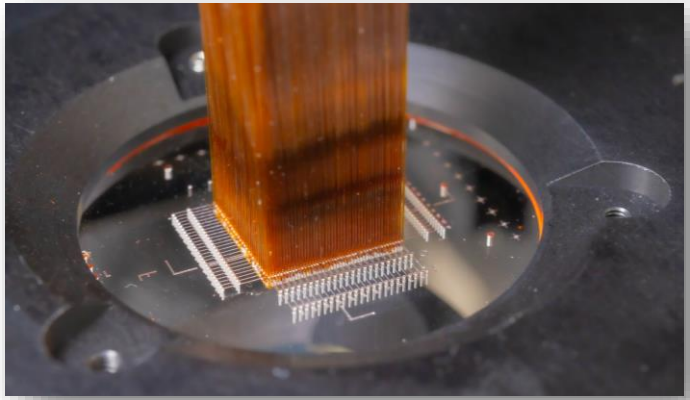
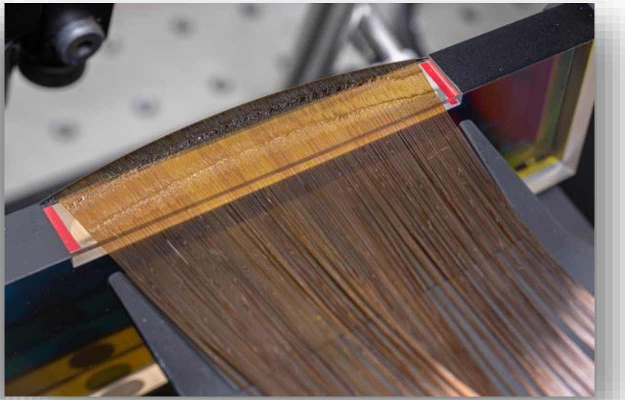
EXAMPLE

- Integral field spectrograph for astronomical telescope
- High precision 1D and 2D fibre arrays (2400-element) & MLA coupling





Courtesy of Gábor Fûrész, MIT Kavli Institute for Astrophysics and Space Research

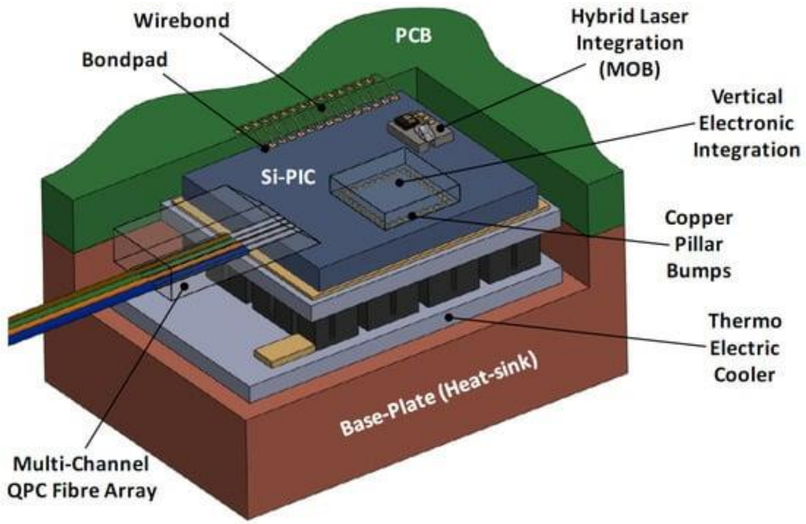
USPs

- Thin to thick glass ferrules for optimized mechanical stability
- Fully customizable 2D hole arrays with straight or tilted holes
- Sub- μm precision in hole diameter and positioning
- Monolithic integration with
  - mounting features
  - additional components (*e.g.* micro-lenses, waveguides, etc.)
- Integration of fiducials on the surface and/or in the bulk
  - Alignment precision < 2μm

MINIATURIZATION vs. FIBER CONNECTIVITY

The current trend in telecom & datacom …

- Miniaturization of photonic systems at chip level
- Introduction of integrated photonic circuits (PICs)
- Use of single-mode fibers



Lee Carroll et al., Photonic Packaging: Transforming Silicon Photonic Integrated Circuits into Photonic Devices, Appl. Sci. 2016, 6(12), 426

… requires

- More stringent tolerances for precise fiber-to-chip alignment
- Access to advanced micro-fabrication technologies providing
  - ➔ High resolution
  - ➔ Cost-effective deployment
  - ➔ Increased amount of integrated functionalities

CURRENT REQUIREMENTS FOR FIBER CONNECTIVITY

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IEC standards for quality grade of fiber connections

IEC

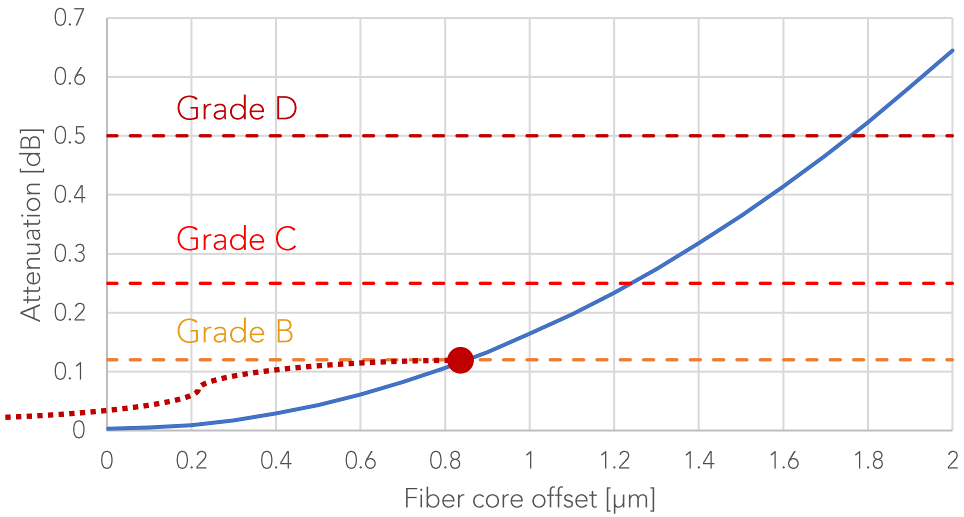
Attenuation grade	Attenuation (≥ 97%)	Mean attenuation	*Notes*
A			*Reserved for future application*
B	≤ 0.25 dB	≤ 0.12 dB	*Current state of the art*
C	≤ 0.5 dB	≤ 0.25 dB	
D	≤ 1.0 dB	≤ 0.5 dB	

**IEC-61753-1 connector loss grades (1310 nm and 1550 nm)*

- A connection between single-mode fibers (mode diameter ≈ 10 μm) with a core offset = 1 μm corresponds to attenuation ≈ 0.16 dB
- Attenuation can be further increased by angular misalignment, configurations involving free space propagation and/or recollimation, and refocusing optics

Sub-μm positioning precision is mandatory for Grade B connection

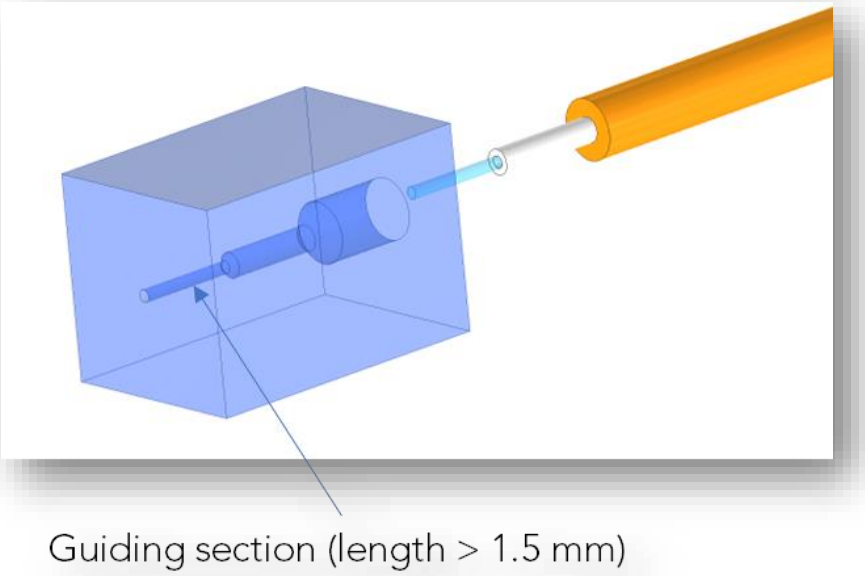
Need for high-precision ferrules to keep attenuation < 0.2 dB

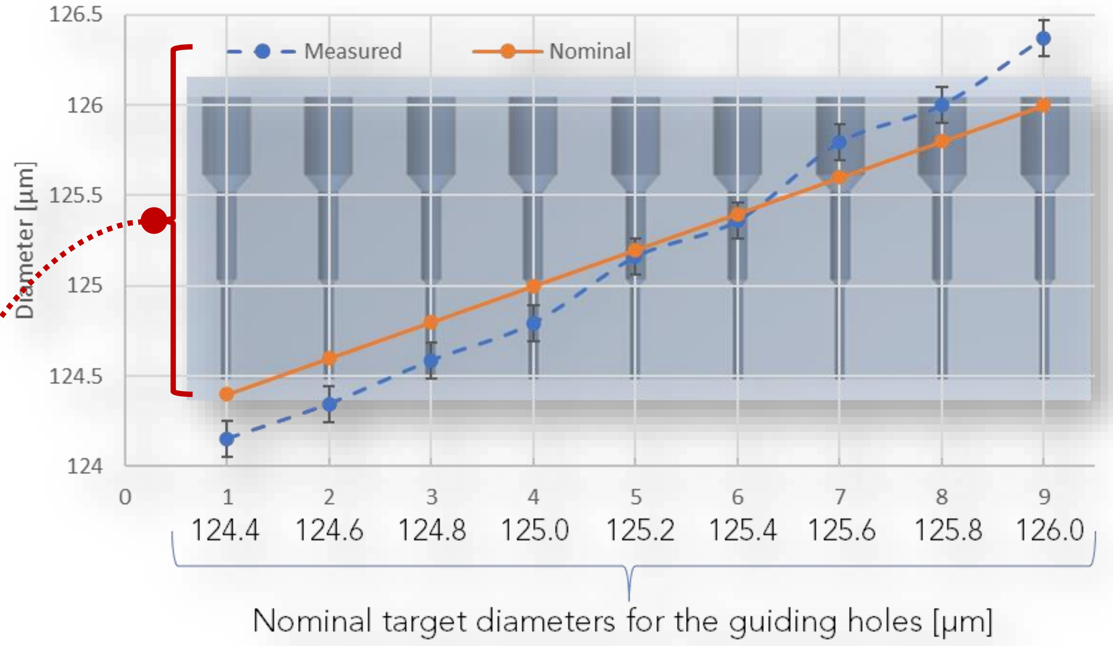


2D HOLE ARRAYS – SUB-μm CONTROL ON HOLE DIAMETER

- Fiber glass ferrules with varying nominal diameters of the guiding section (steps = 0.2 μm)

- Mechanical measurements of the effective diameter of the guiding section





The mechanical measurements confirm that

the diameters of the fabricated ferrules correspond to the nominal target values ➔ sub-μm control

2D HOLE ARRAYS – SUB-µm CONTROL ON HOLE POSITION

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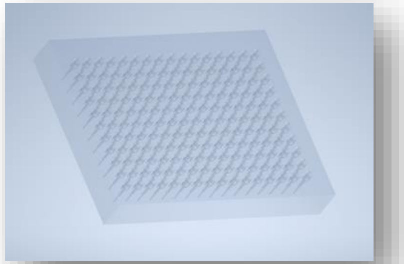
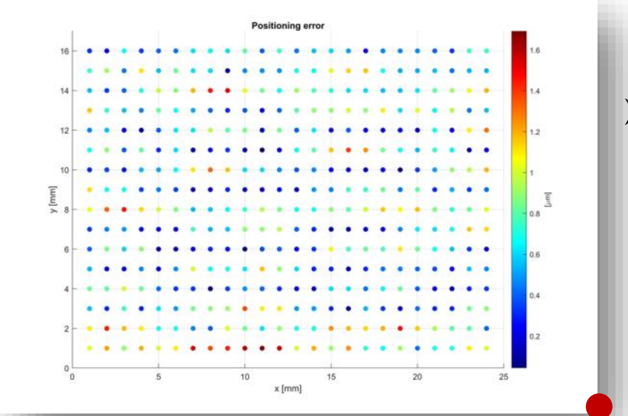
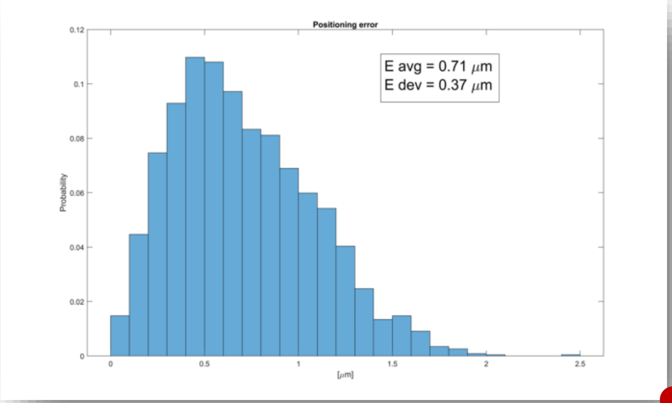
- 2D array of 24 x 16 holes
  - Hole diameter = 125.5 µm



- 5x identical 2D arrays



➢ Hole positioning: relative error better than the microscope resolution (± 2 µm)



➢ Average hole positioning error ± 0.7 µm

➢ Standard deviation < 0.4 µm

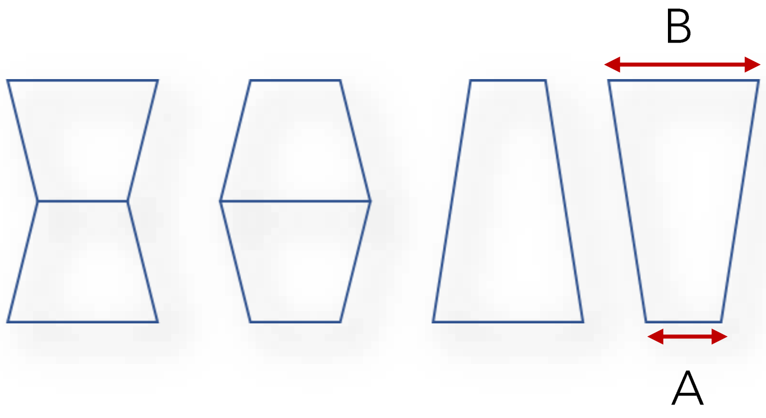
➢ Relative error better than the microscope resolution (± 2 µm)

Hole positioning verified on a single array

Repeatibility verified on multiple arrays

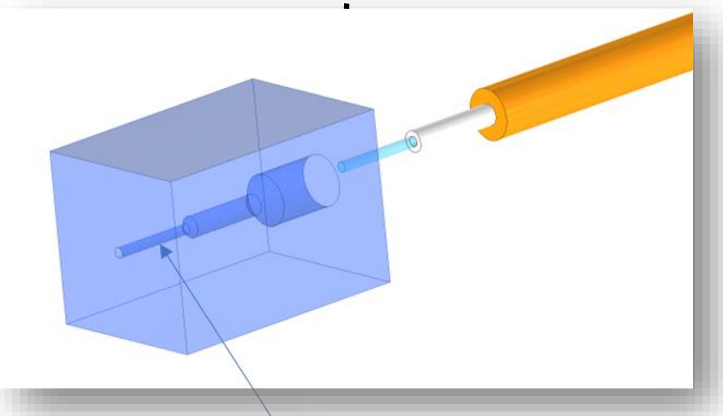
FIBER FERRULES: SUB-° CONTROL ON HOLE CYLINDRICITY

- Mechanical measurements ➔ minimum diameter over the hole length
- The hole shape can vary



- Optical measurements to verify angular misalignment & conicity of the holes

> - No evidence of diameter difference along single holes
> - Error on hole cylindricity << 0.1°
>   *Note: 0.1° over the 1.5mm guiding section ➔ A-B = 5µm*
> - Very limited losses due to fiber tilt



Guiding section (length > 1.5 mm)

2D HOLE ARRAYS FOR HIGH-PRECISION FIBER FERRULES

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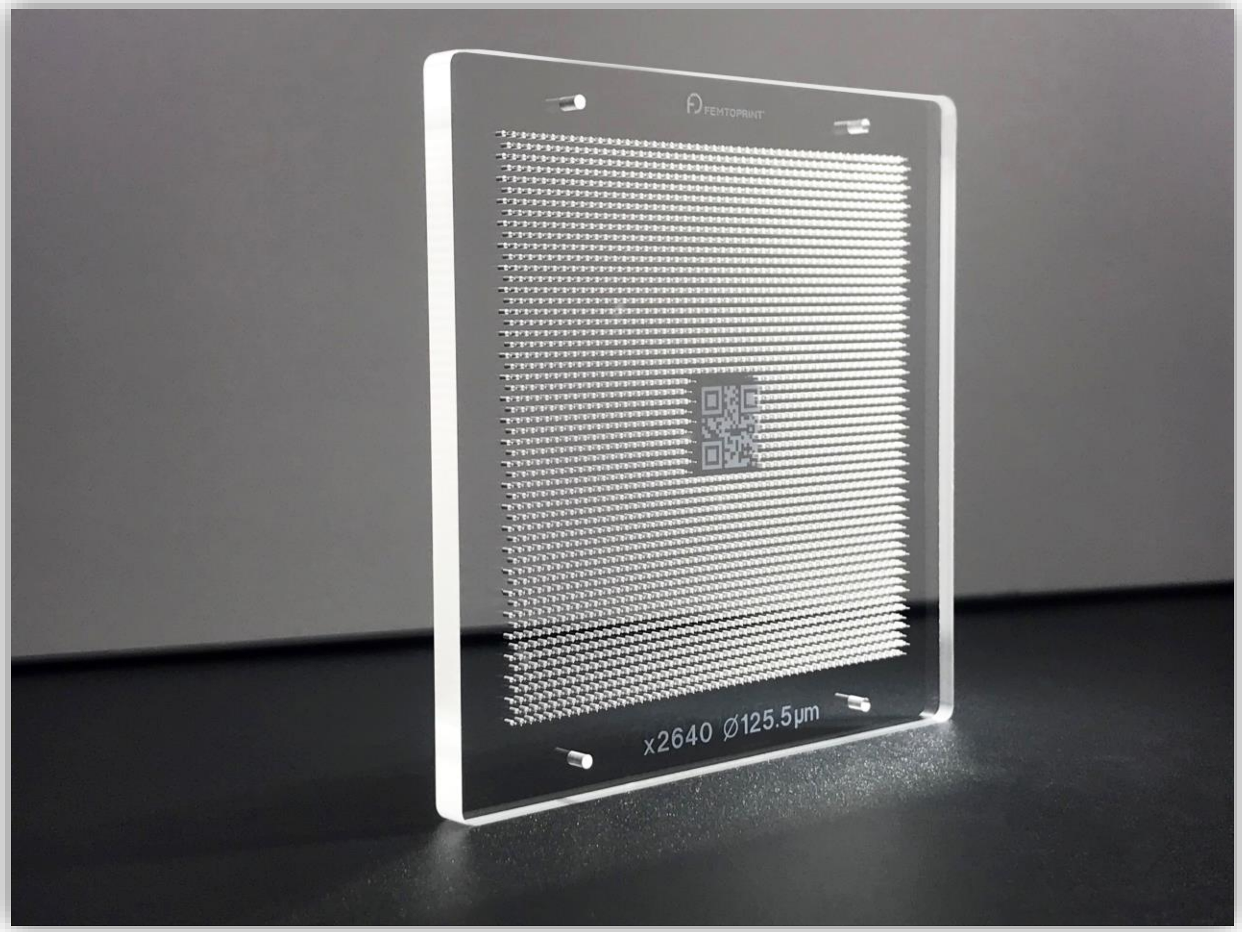


- Available on various substrates
  - Fused silica (FS)
    ➔ thermal match with silica fibers
  - Borofloat 33 (BF33)
    ➔ thermal match with SiPh
- Available with a large range of thicknesses
  - typically 3 - 7mm
    ➔ enhanced mechanical robustness
- Tailored hole shapes with multiple sections:
  - *e.g.* core-cladding, coating, jacket
    ➔ enhanced stability
- Tilted holes
  ➔ reduced Fresnel losses
  ➔ improved grating in-coupling

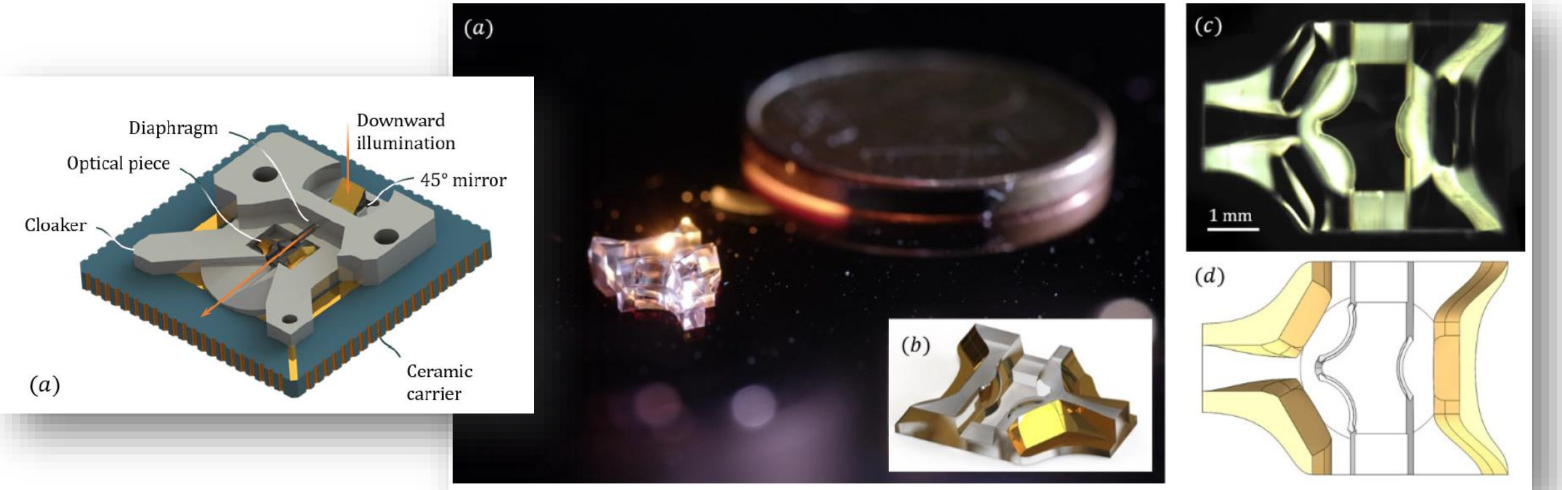
MINIATURIZED OPTICS

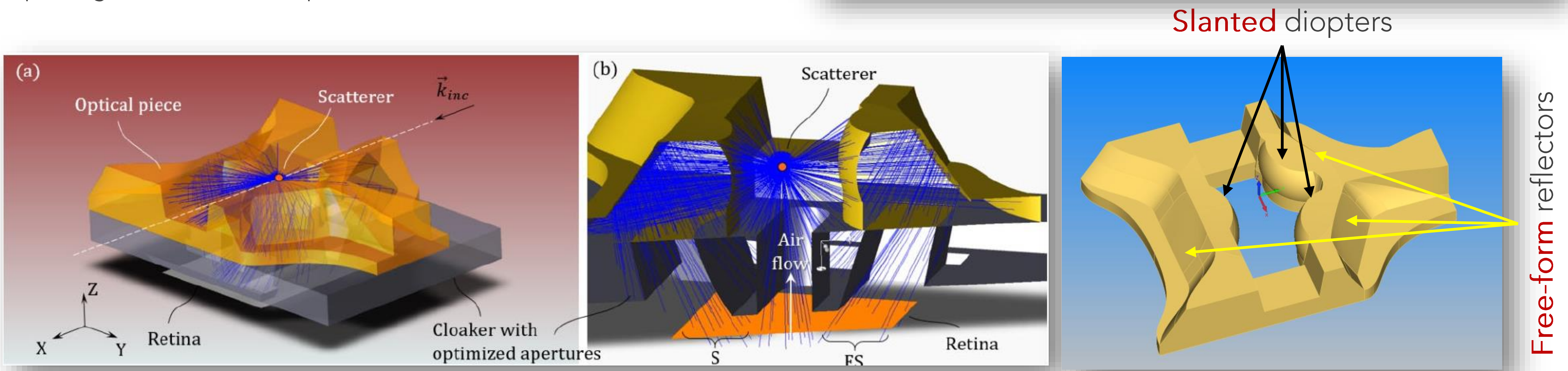
MICRO-OPTICS

BEAM SHAPING – MINIATURIZED OPTICS

APPLICATION
- Air quality monitoring
- Improved sensitivity by the integration of a miniaturized refractive/reflective optical system

USPs
- Monolithic integration of optical functions
- Free-form fabrication in 3D
- Co-packaged miniaturized optics





CEA-LETI Minatec & Institut des Nanotechnologies de Lyon.
Jobert G. et al. Miniature Optical Particle Counter and Analyzer Involving a Fluidic-Optronic CMOS Chip Coupled with a Millimeter-Sized Glass Optical System. Sensors 2021, 21, 3181.

MINIAUTIZED OPTICS – SURFACE QUALITY

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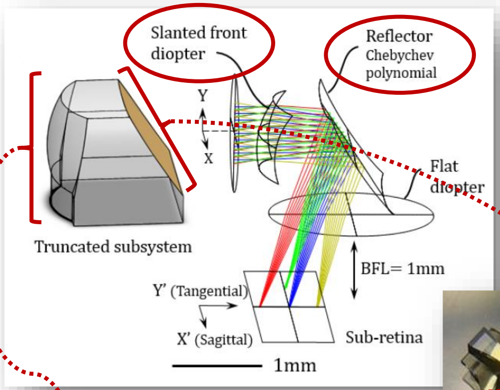
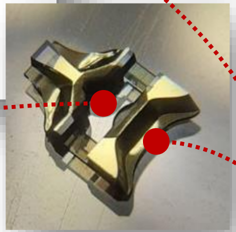
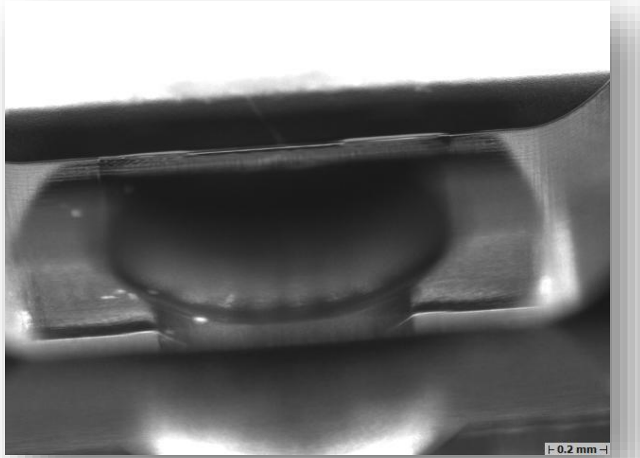
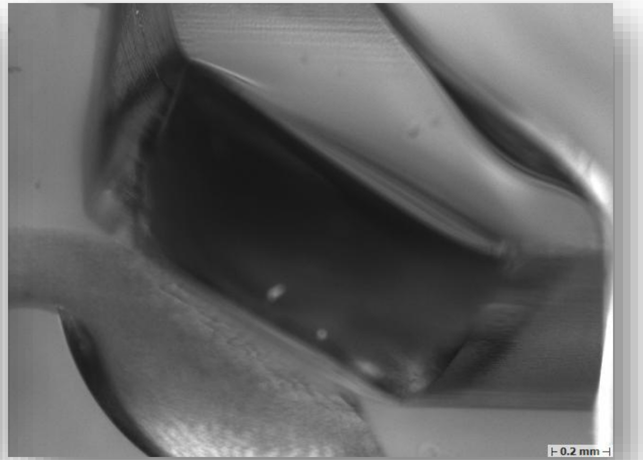




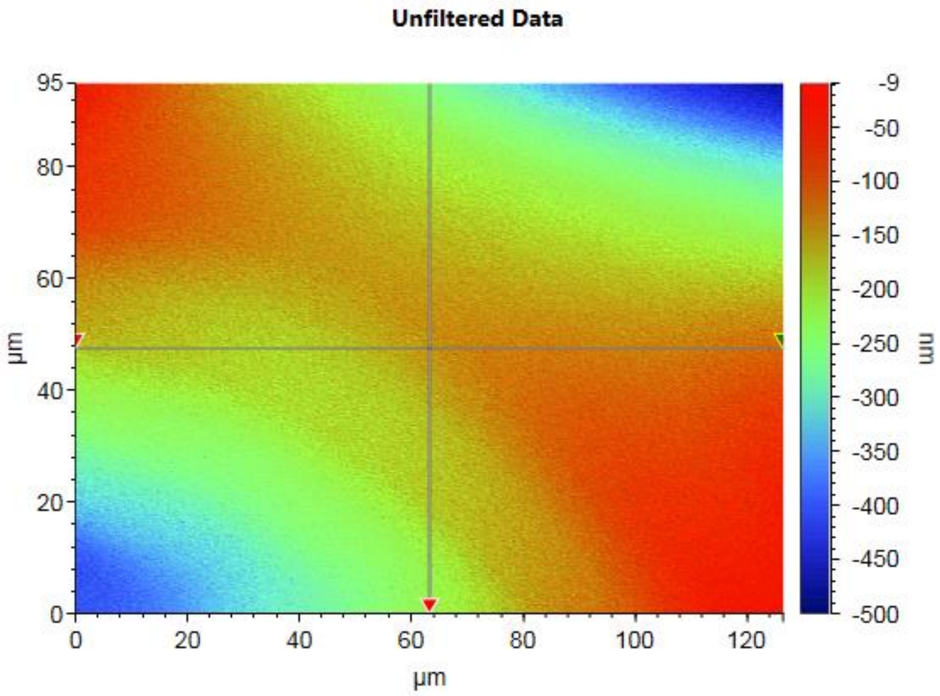
Slanted diopter



Free-form reflector



Interferometric image of the reflector surface



Surface roughness: Sa = 6nm

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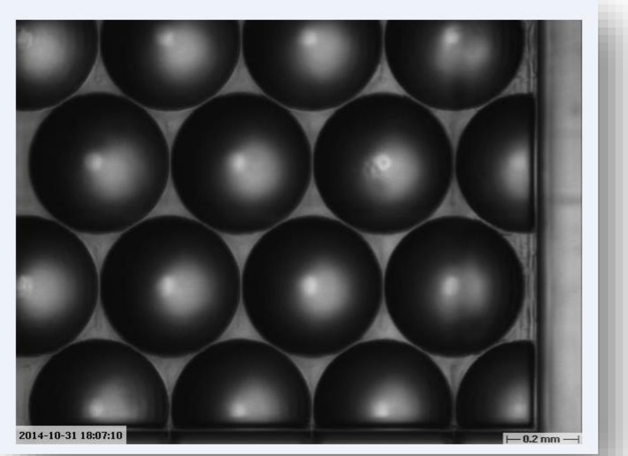
BEAM SHAPING – FREE-FORM MICRO-OPTICS

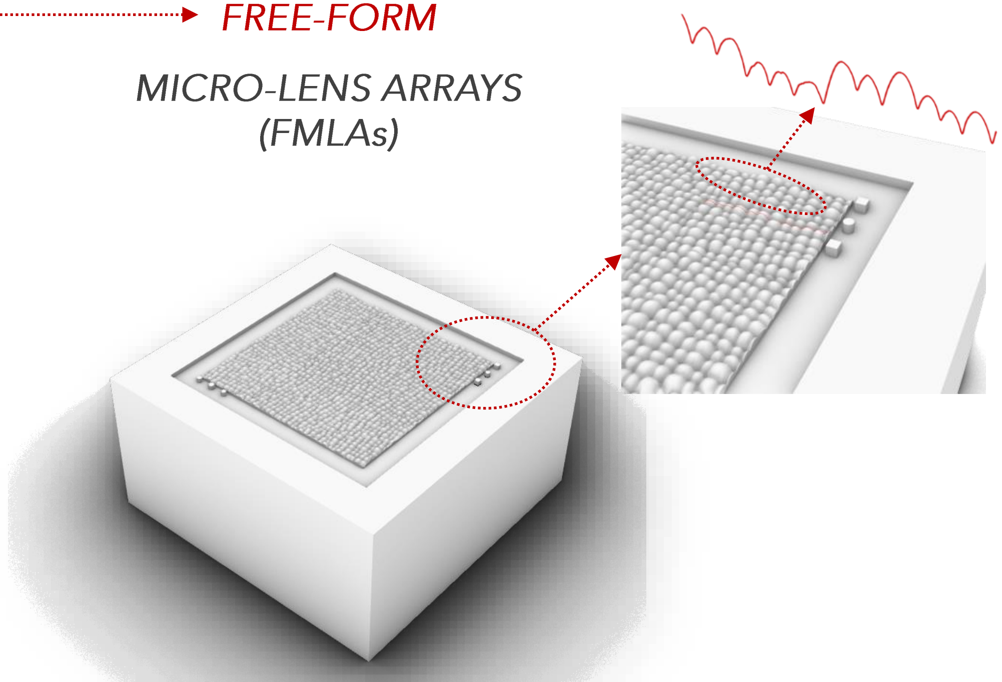
SPHERICAL or ASPHERICAL → *NON-SPHERICAL* → *FREE-FORM*

MICRO-LENSES
&
MICRO-LENS ARRAYS
(MLAs)

MICRO-OPTICAL ARRAYS

MICRO-LENS ARRAYS
(FMLAs)





Engineered diffuser (SAG = 75 µm)
Courtesy CSEM

Feasibility → Fast prototyping → Pilot manufacturing → Small-to-medium volume production → ORIGINATION & TOOLING

DEVELOPMENT: rapid cycles from concept to prototypes and small-to-medium product series

Enabling large volume production

EXAMPLE – SHALLOW MICRO-LENS ARRAYS

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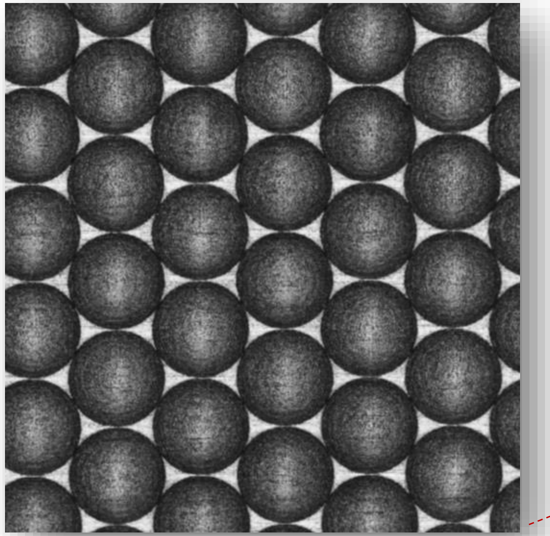
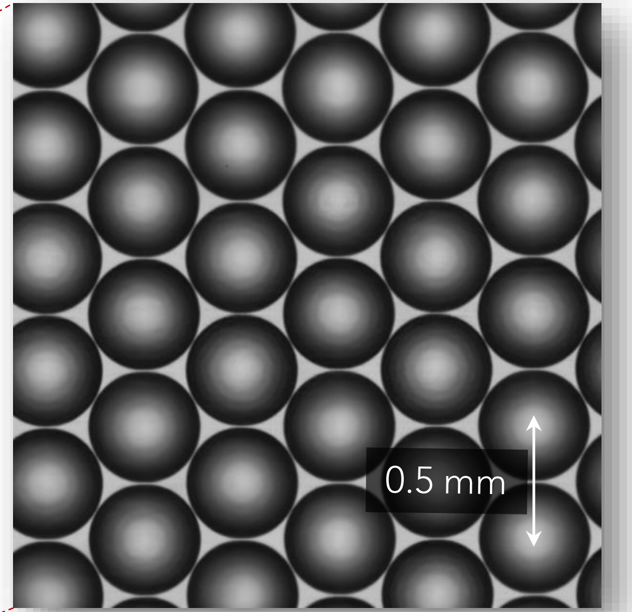
Hexagonal closely packed MLA

100x spherical micro-lenses

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



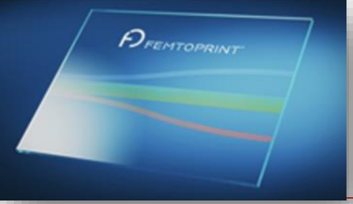
Without surface processing



With surface processing

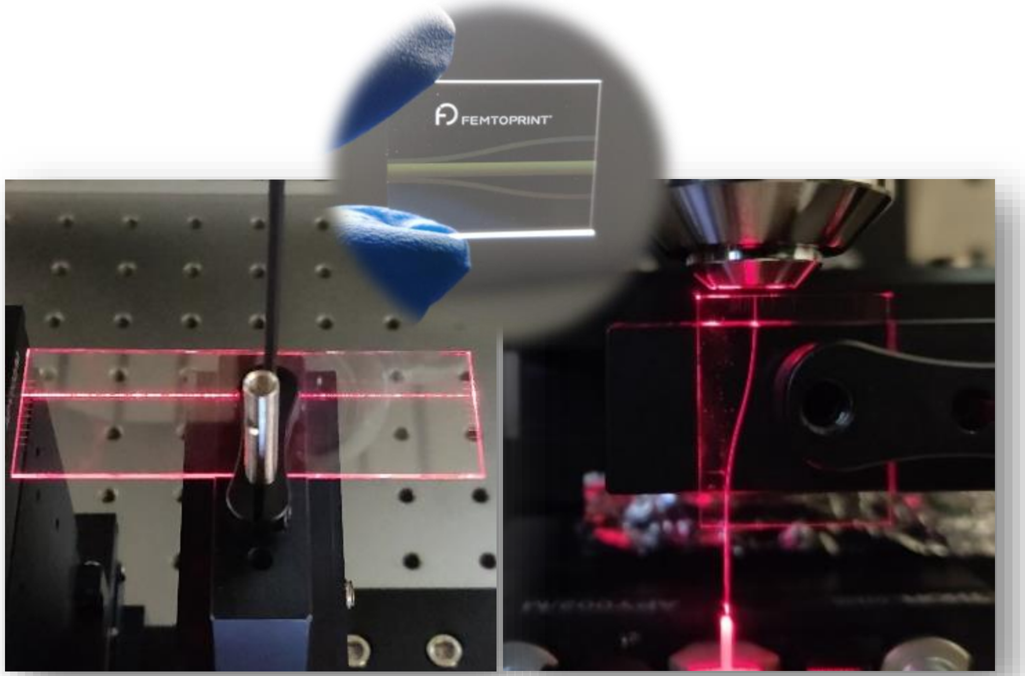
Micro-machined MLAs in Fused Silica

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



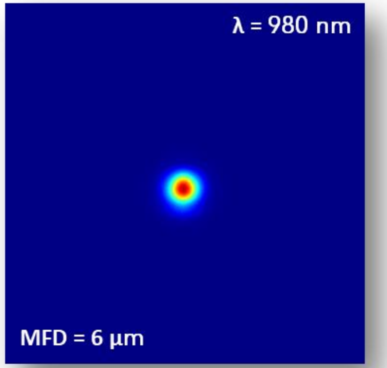
WAVEGUIDES

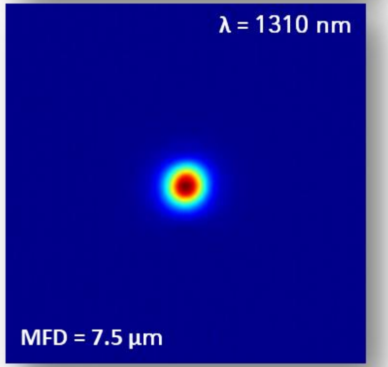
3D GLASS WAVEGUIDES

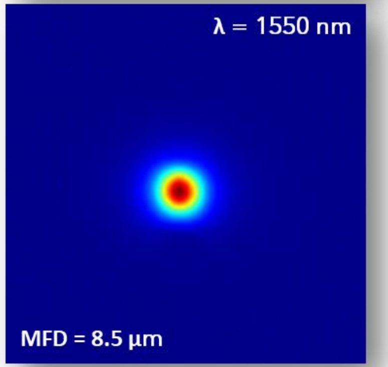


- Single mode & Multi-mode waveguides
- 3D waveguides with bending in XYZ
- In-bulk termination and tapering
- Alignment markers for assembly & packaging
- Facet polishing for rapid prototyping and characterization

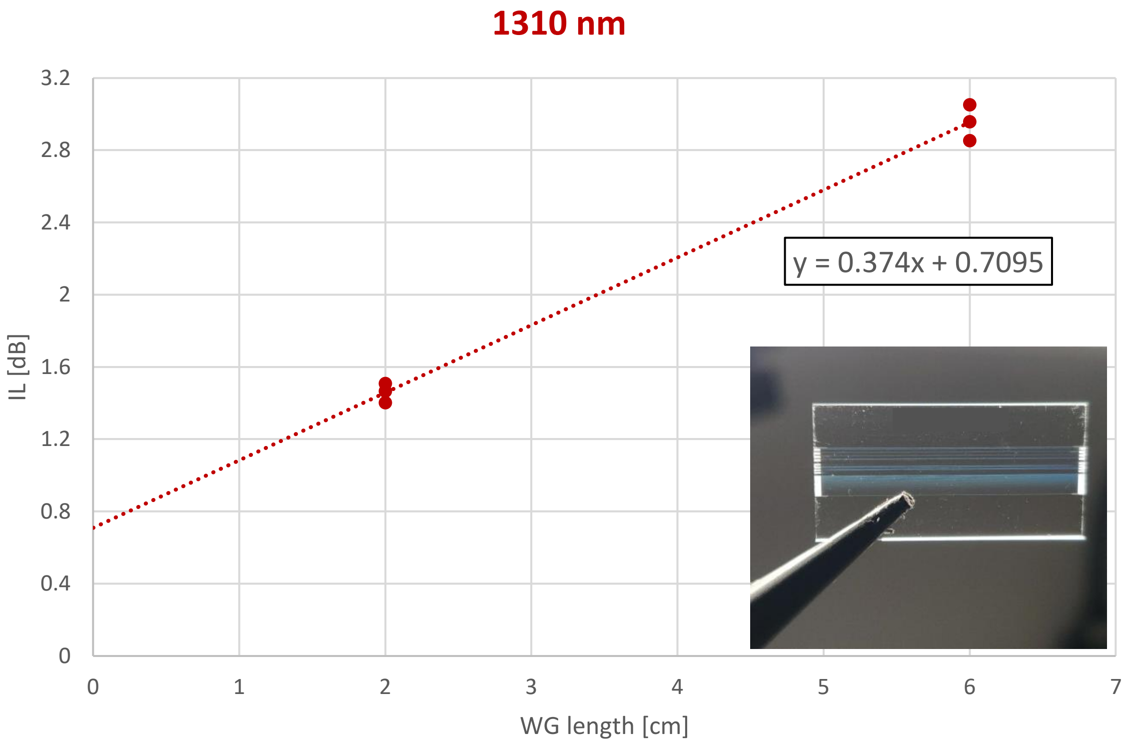
Materials	Fused Silica (FS) Borofloat (BF33) Eagle (EXG)
Machining area	200 x 200 x 3 mm Whatever shape
Wavelength λ [nm]	980, 1310, 1550
MFD for SM [µm]	Tunable between 6 and 12 µm Circularity > 95%
Relative positioning	< ± 1 µm
Min. Bending Radius	≤ 20 mm
Propagation Loss	≤ 0.2 - 0.3 dB/cm
Δn	10^{-2}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

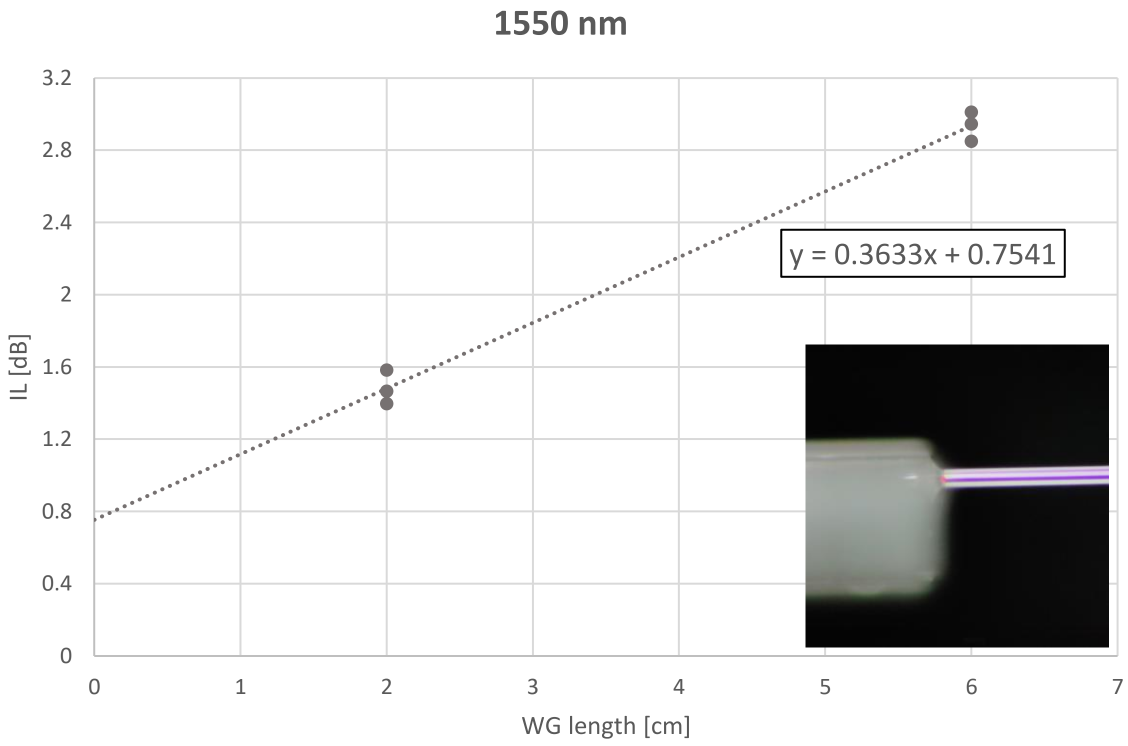






PROPAGATION LOSSES





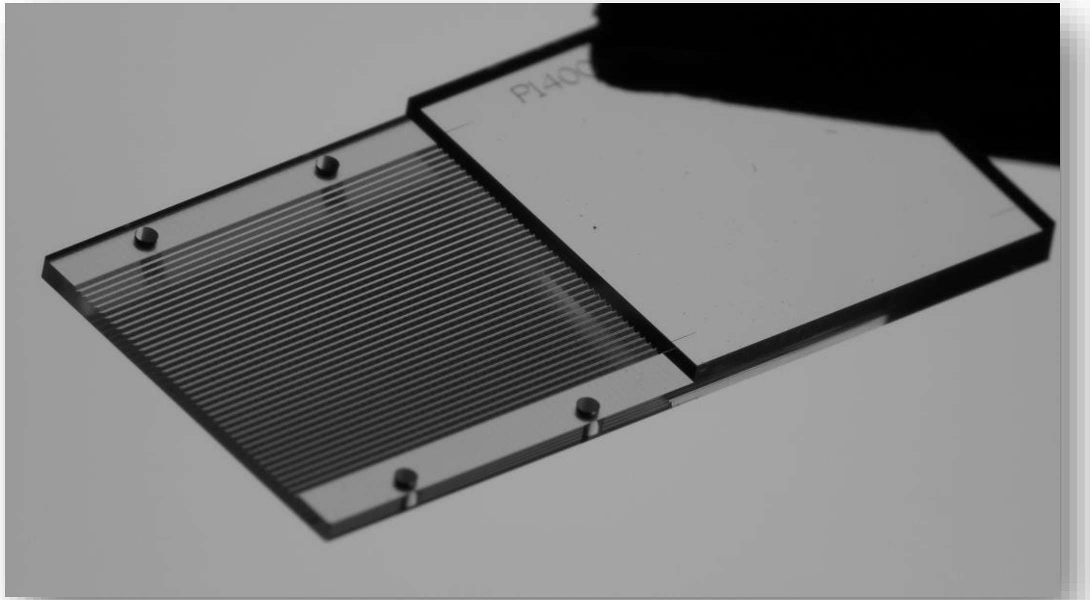
- Cut-back method : butt-coupling at input & output
- Fiber : SM980 - 5.8/125
- 0 deg polishing : Fresnel losses taken into account

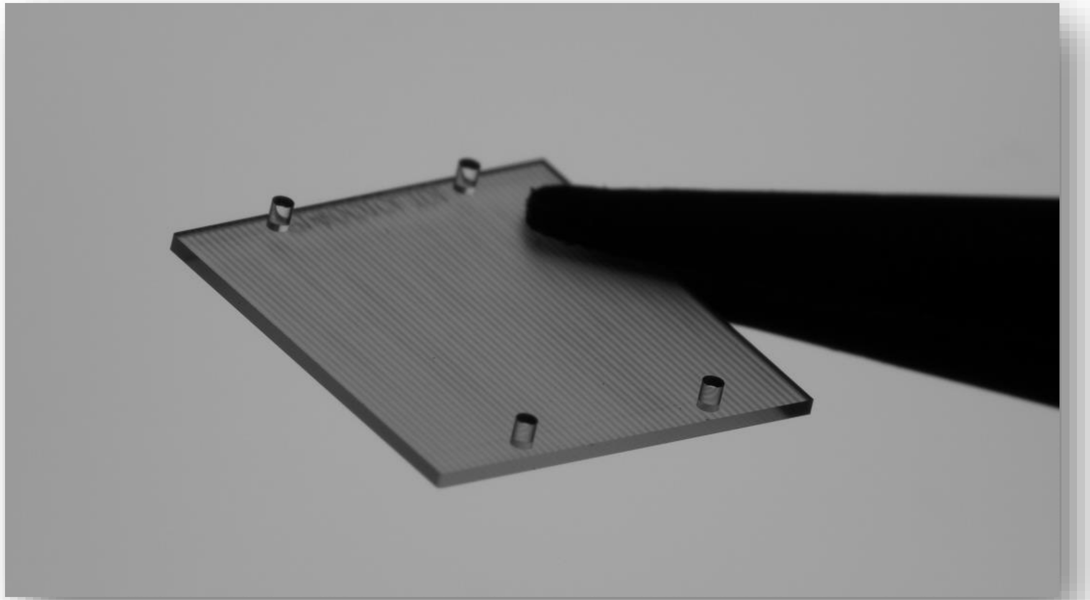
@ 1310 nm & 1550 nm

➔ Propagation Losses ~ 0.35 dB/cm

➔ Coupling Losses ~ 0.2 dB/interface

MONOLITHIC INTEGRATION – WAVEGUIDES & V-GROOVES





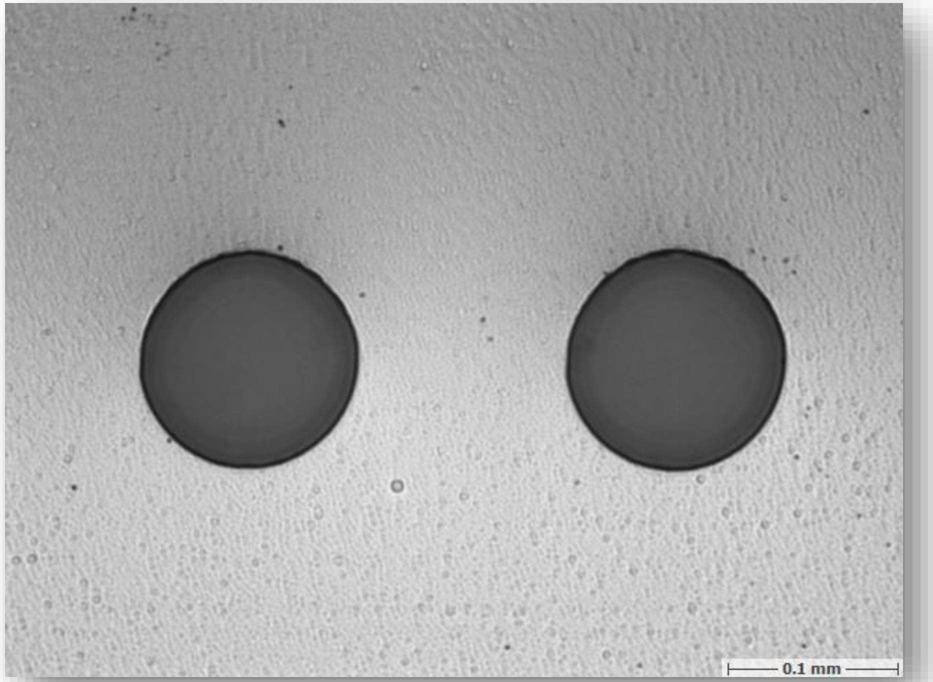
- Single fabrication step: < ± 1µm relative positioning
- 127µm pitch v-groove array connector with its cover lid
- In-bulk termination and tapering
- Alignment markers for assembly & packaging

USPs

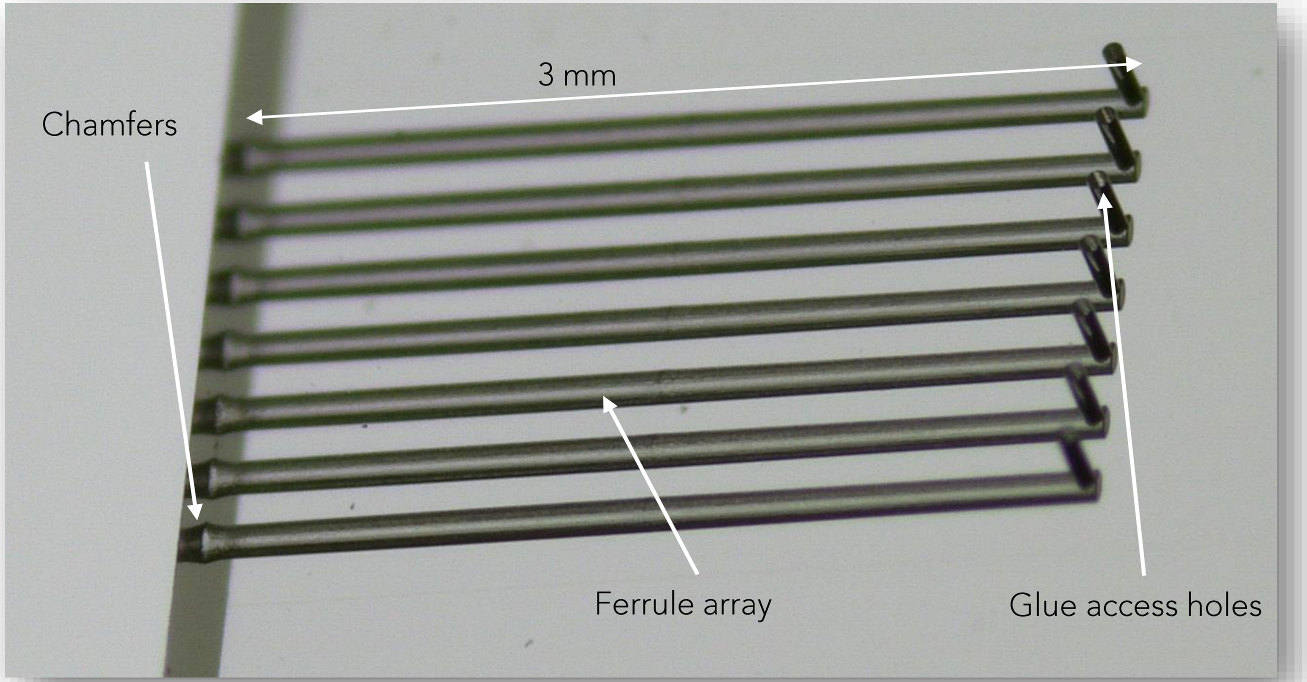
- 3D waveguides in glass
- Monolithic integration of functionalities
- Photonic systems for fiber-to-chip connectivity

MONOLITHIC INTEGRATION – WAVEGUIDES & HOLE ARRAYS

In-plane fabrication of ferrule arrays for monolithic integration with (tapered) waveguides



Horizontal ferrules with no chamfer, 0.002 µm circularity



Horizontal ferrules with chamfers and access holes, 0.002 µm circularity

MONOLITHIC INTEGRATION – WAVEGUIDES & MICRO-LENSES

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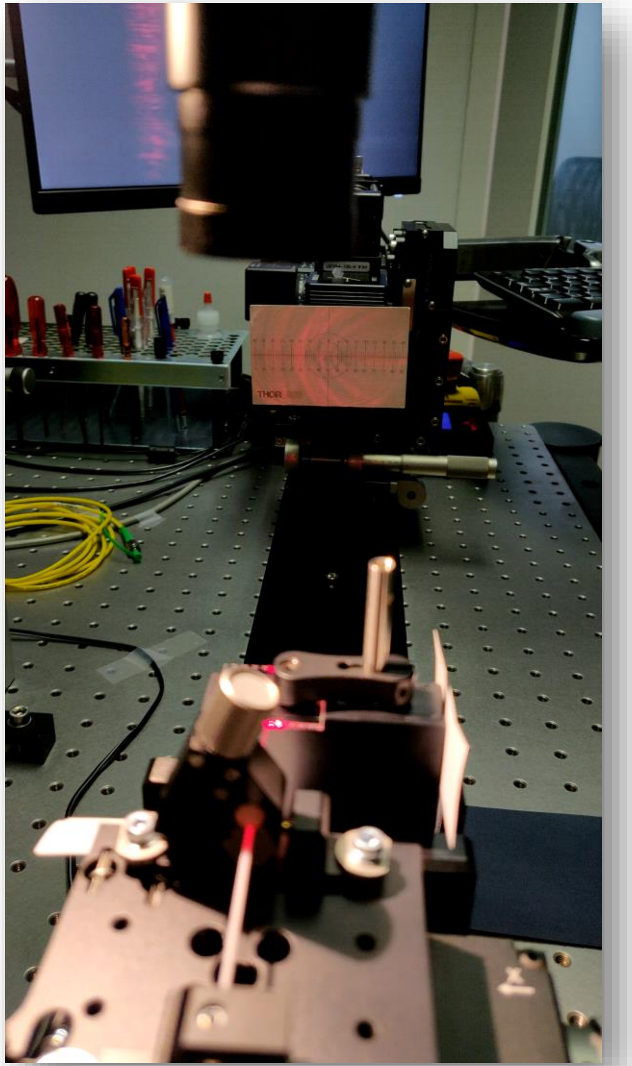
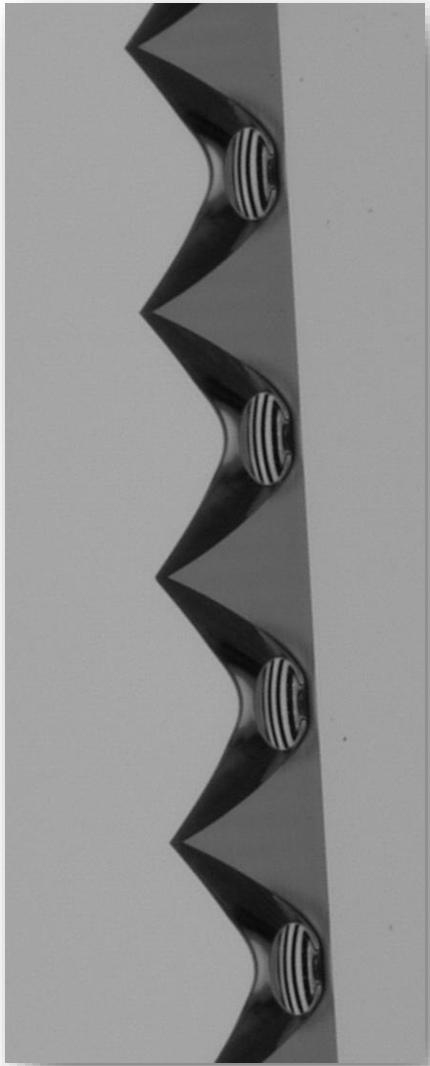
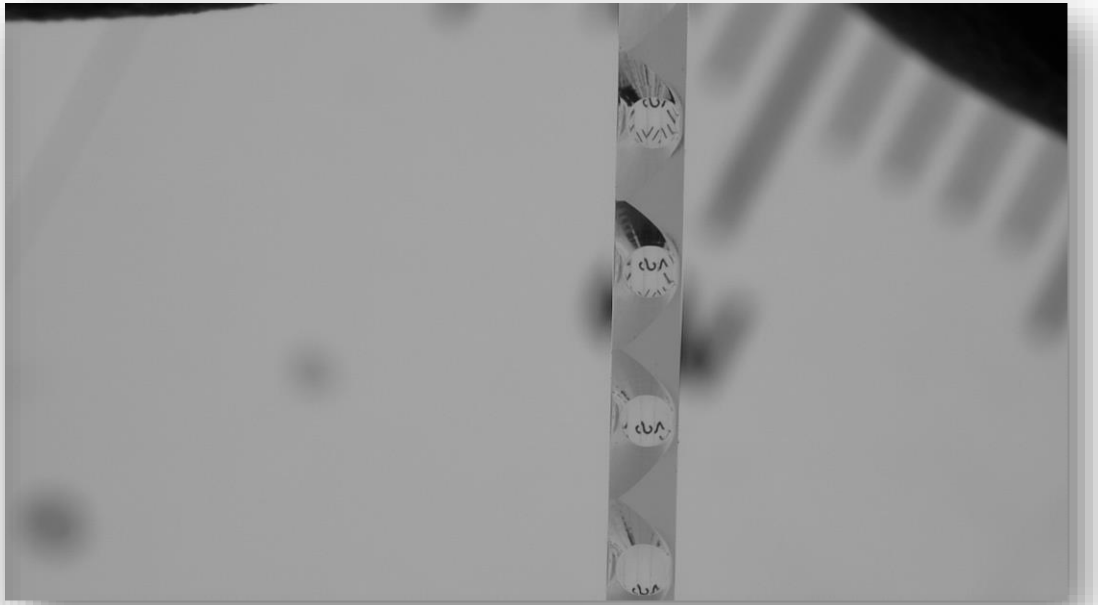
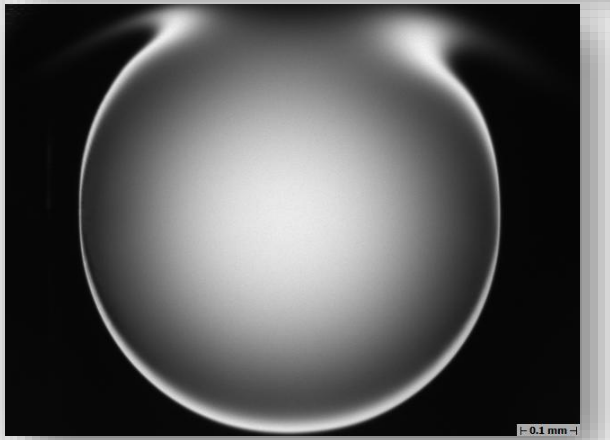
3D PRINTING FOR GLASS MICRODEVICES









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Thank you!

Via Industria 3
6933 Muzzano
Switzerland

Fbg. de l'Hôpital 19
2000 Neuchâtel
Switzerland

www.femtoprint.ch
info@femtoprint.ch
rolando.ferrini@femtoprint.ch