FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

Laser-based 3D micro-manufacturing of high precision components for fiber-to-chip connectivity in integrated & quantum photonics

Rolando Ferrini

EPIC TechWatch at ECOC

EPIC EUROPEAN PHOTONICS INDUSTRY CONSORTIUM

ecoc 2023 GLASGOW

ECOC - Glasgow, October 4th, 2023

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swiss made

FEMTOprint IN A NUTSHELL

FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

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

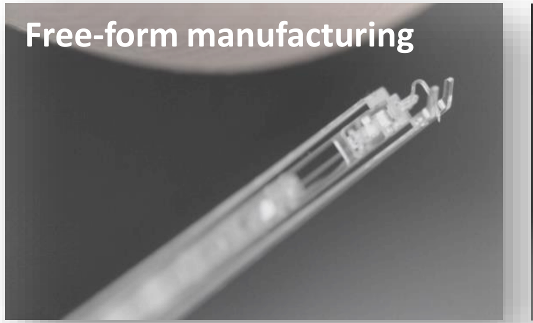
ISO CERTIFIED
ISO 9001 : 2015 & ISO 13485 : 2016

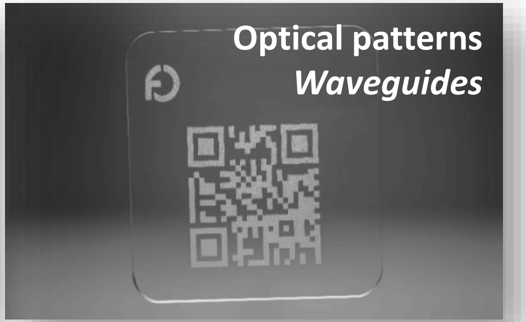
TÜVRheinland CERTIFIED

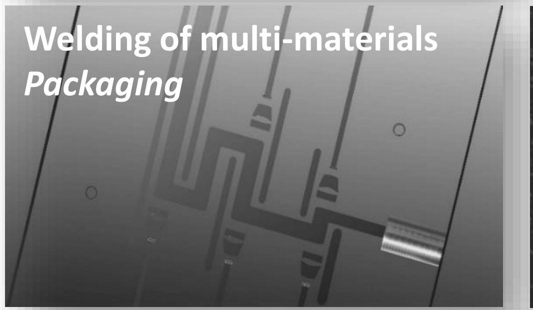
3D MANUFACTURING OF GLASS MICRO-DEVICES

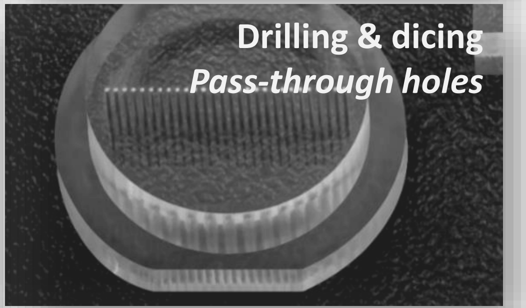
FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

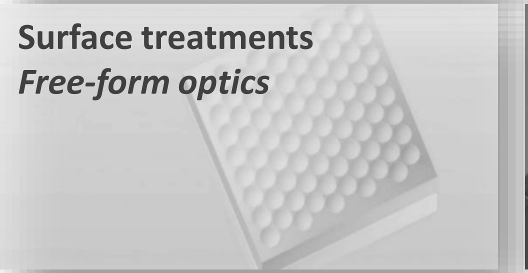
CAPABILITIES

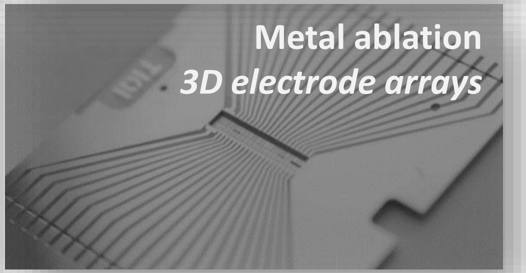










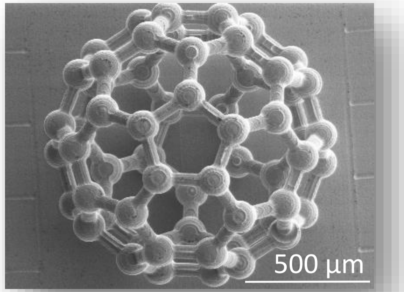


PERFORMANCES*

*in SiO2

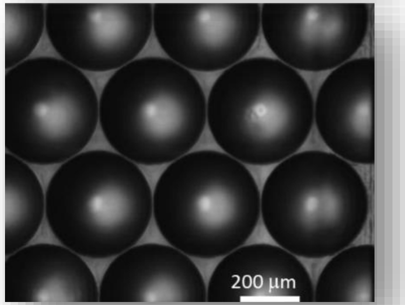
RESOLUTION AND TOLERANCES

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



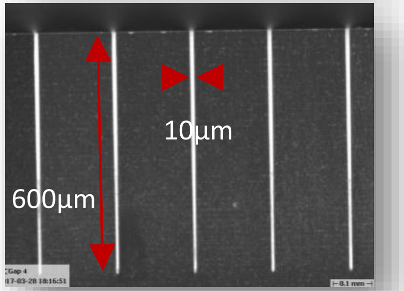
SURFACE QUALITY

- 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

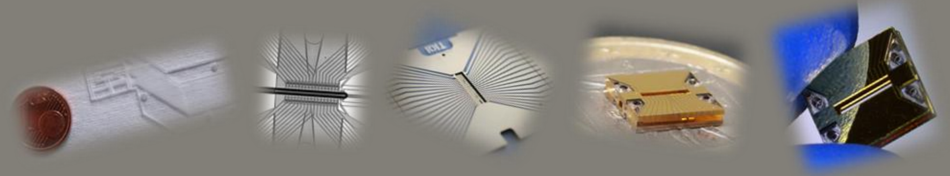


INTEGRATED & QUANTUM PHOTONICS

PICs & QUANTUM PHOTONICS vs. PACKAGING & ASSEMBLY

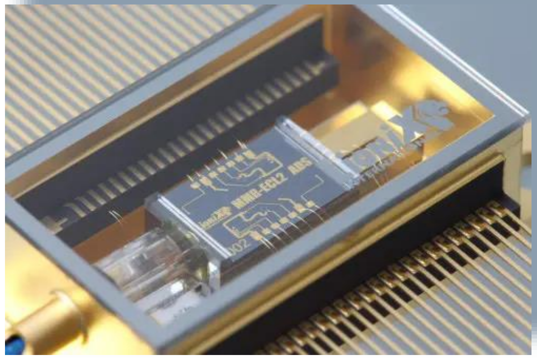
From PICs …

From Quantum Chips …

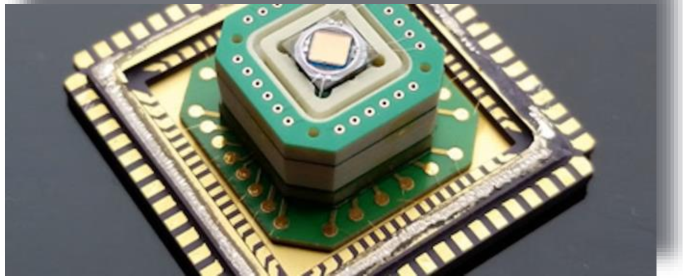


PACKAGING & ASSEMBLY

… to Integrated Photonics products



… to Quantum Photonics products



FIBER-TO-CHIP CONNECTIVITY

FIBER ARRAYS

MINIATURIZED OPTICS
MICRO-OPTICS

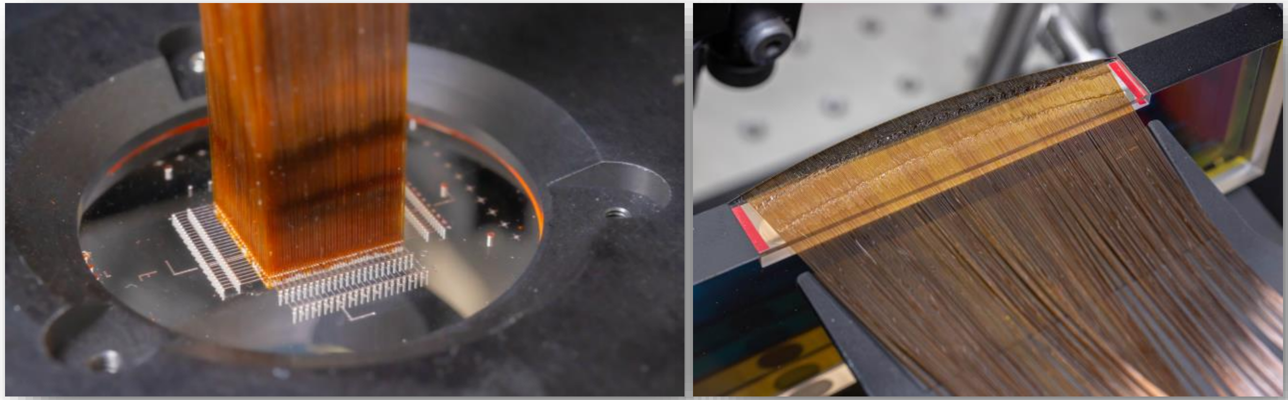
WAVEGUIDES

FIBER ARRAYS

GLASS FIBER FERRULES – PASSIVE ALIGNMENT ASSEMBLY

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

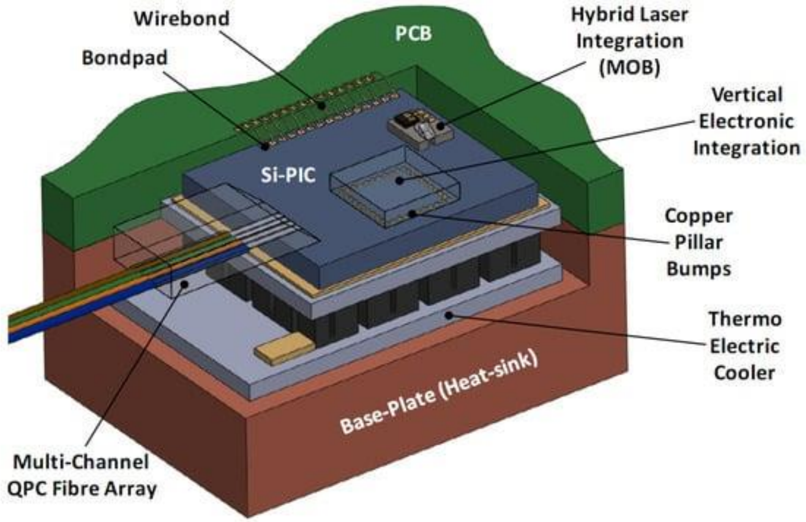
- Thin to thick glass ferrules for optimized mechanical stability
- Fully customizable 2D hole arrays with straight or tilted holes
- Sub- µm precision in hole diameter and positioning

- 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

IEC standards for quality grade of fiber connections

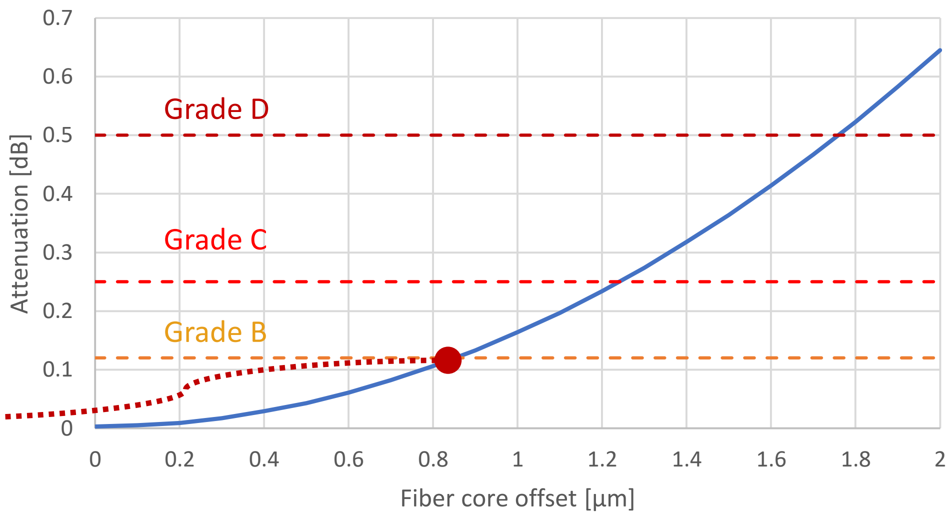
Attenuation grade	Attenuation (≥ 97%)	Mean attenuation	*Notes*
A			*Reserved for future application*
B	≤ 0.25 dB	≤ 0.12 dB	*Current state of the art*
C	≤ 0.5 dB	≤ 0.25 dB	
D	≤ 1.0 dB	≤ 0.5 dB	

**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 recollimating, and refocusing optics

Sub-µm positioning precision is mandatory for Grade B connection

Need for highly precise ferrules



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

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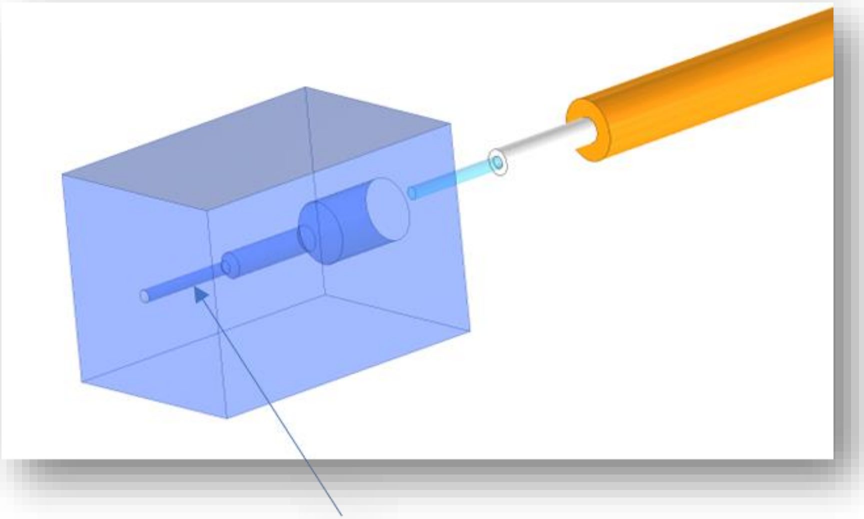
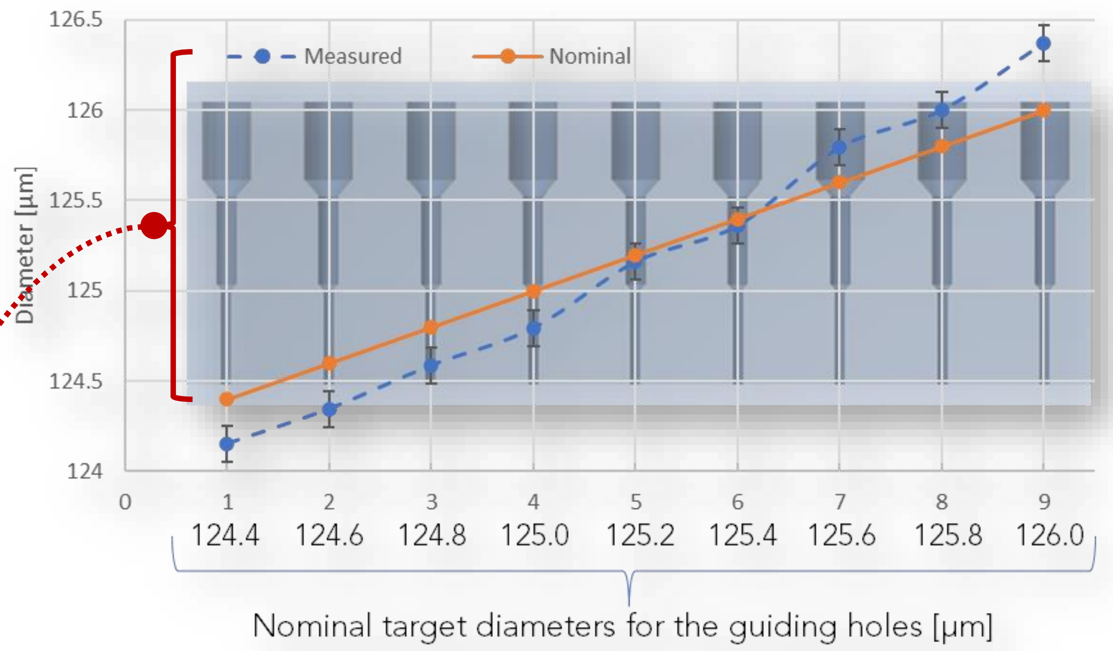
- Fiber glass ferrules with varying nominal diameters of the guiding section (**steps = 0.2 μm**)



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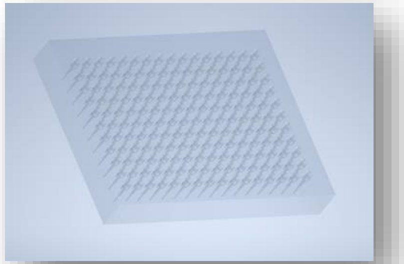
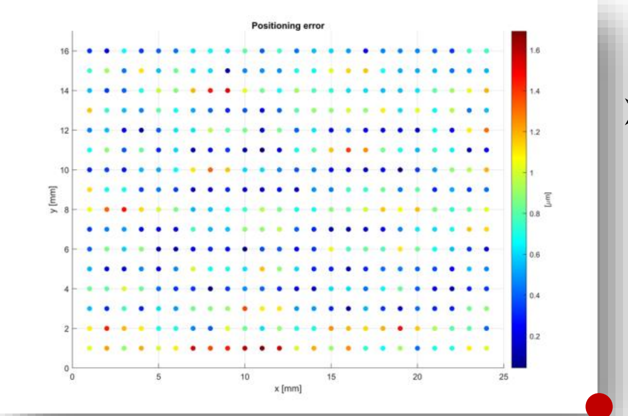
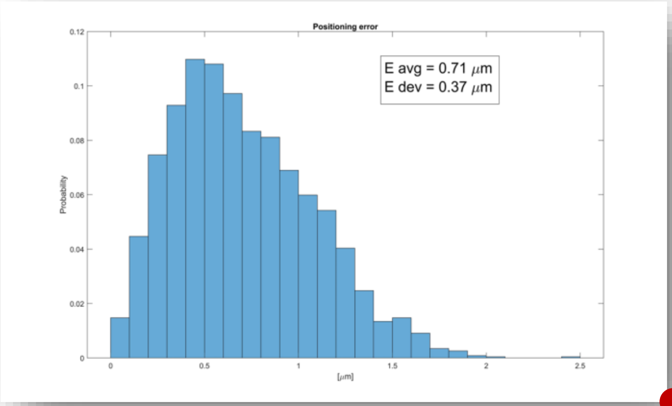
- **2D array of 24 x 16 holes**
  - Hole diameter = 125.5 µm



- **5x identical 2D arrays**



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



➢ Average hole positioning error ± 0.7 µm

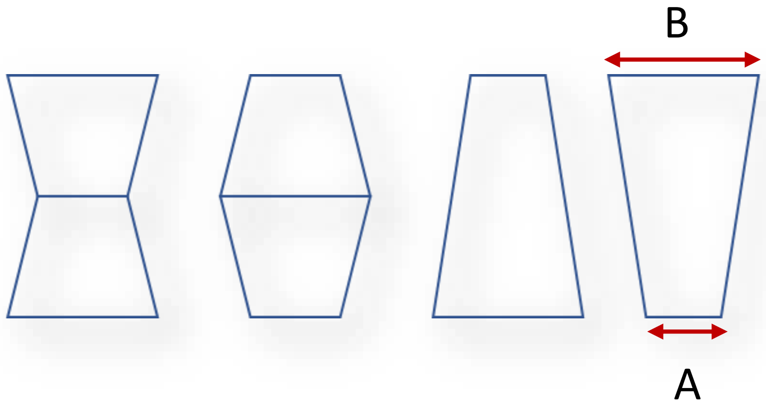
➢ Standard deviation < 0.4 µm

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

Hole positioning verified on a single array

Repeatability verified on multiple arrays

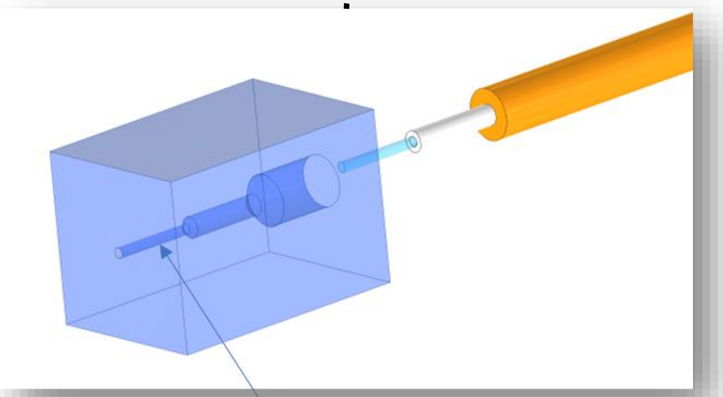
FIBER FERRULES: SUB-° CONTROL ON HOLE CYLINDRICITY



- 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



2D HOLE ARRAYS FOR HIGH PRECISION FIBER FERRULES

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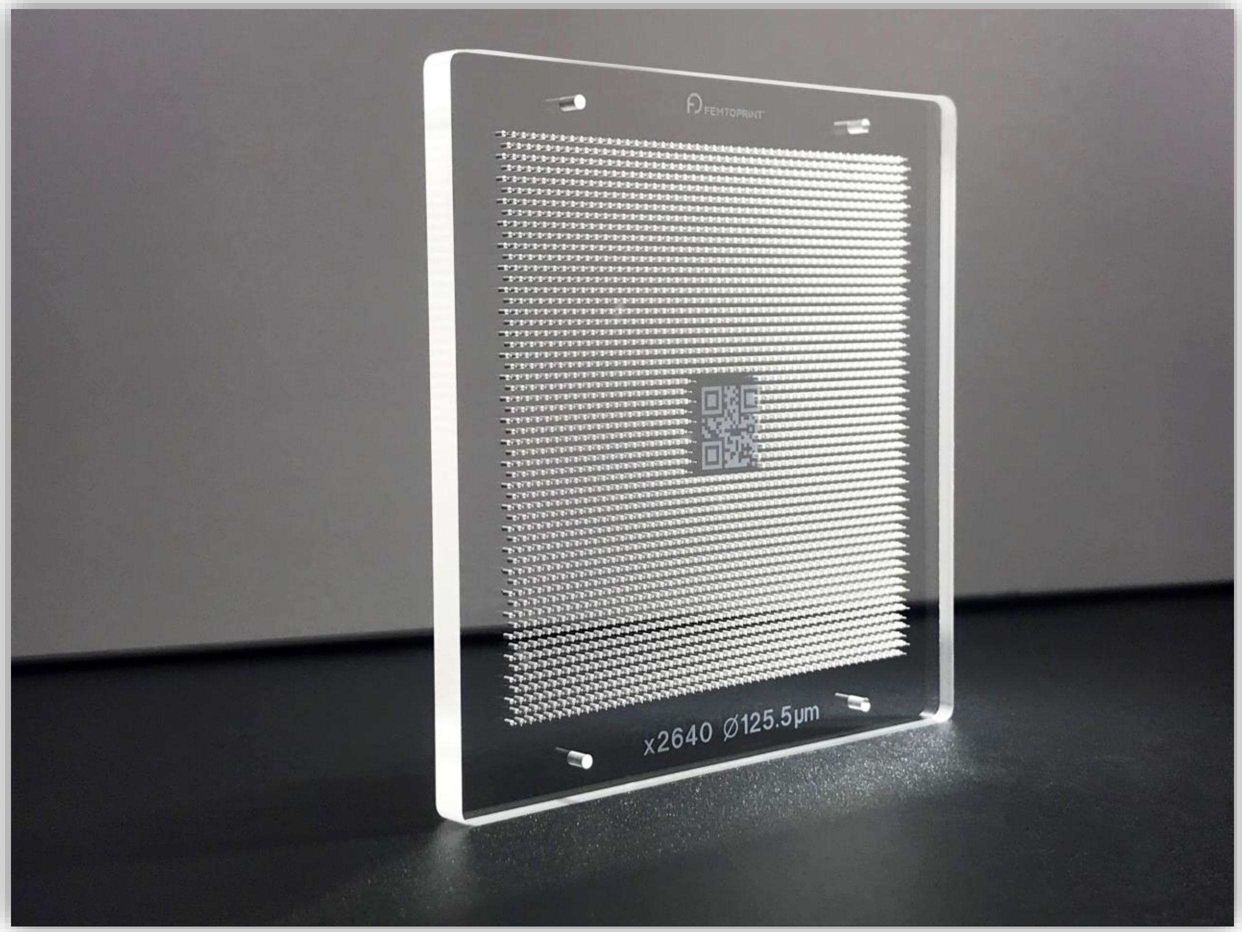

- **Available on various substrates**
  - ➢ Fused silica (FS)
    - ➔ thermal match with silica fibers
  - ➢ Borofloat 33 (BF33)
    - ➔ thermal match with SiPh
- **Available with a large range of thicknesses**
  - ➢ **typically 3 - 7mm**
    - ➔ enhanced mechanical robustness
- **Tailored hole shapes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

MINIATURIZED OPTICS

MICRO-OPTICS

BEAM SHAPING – MINIATURIZED OPTICS

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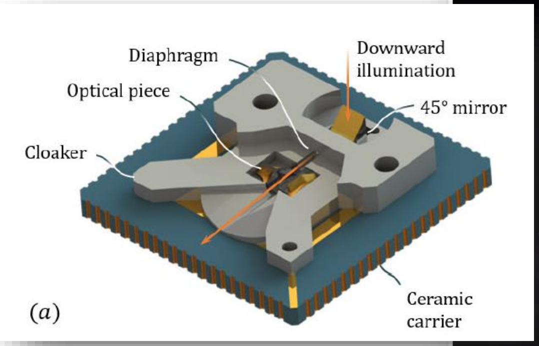
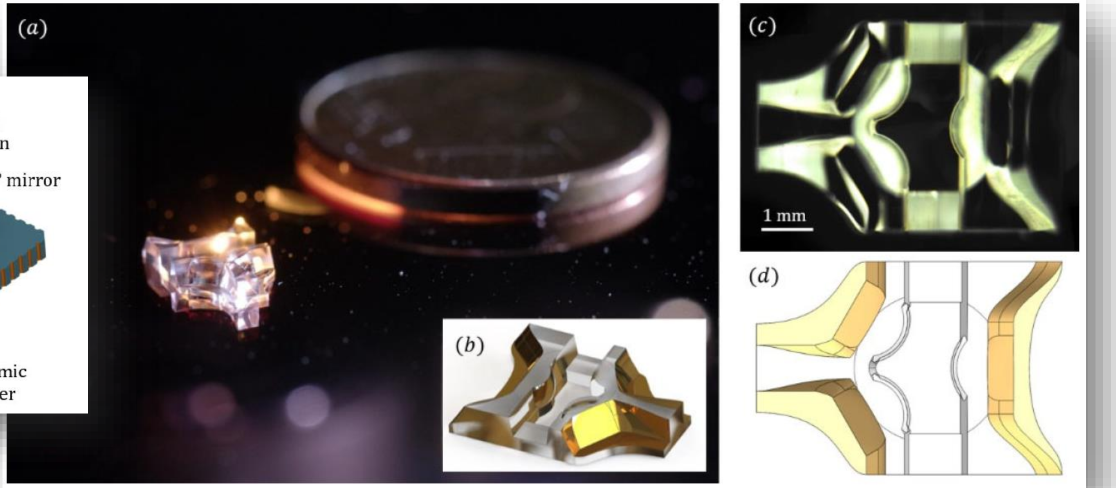
APPLICATION

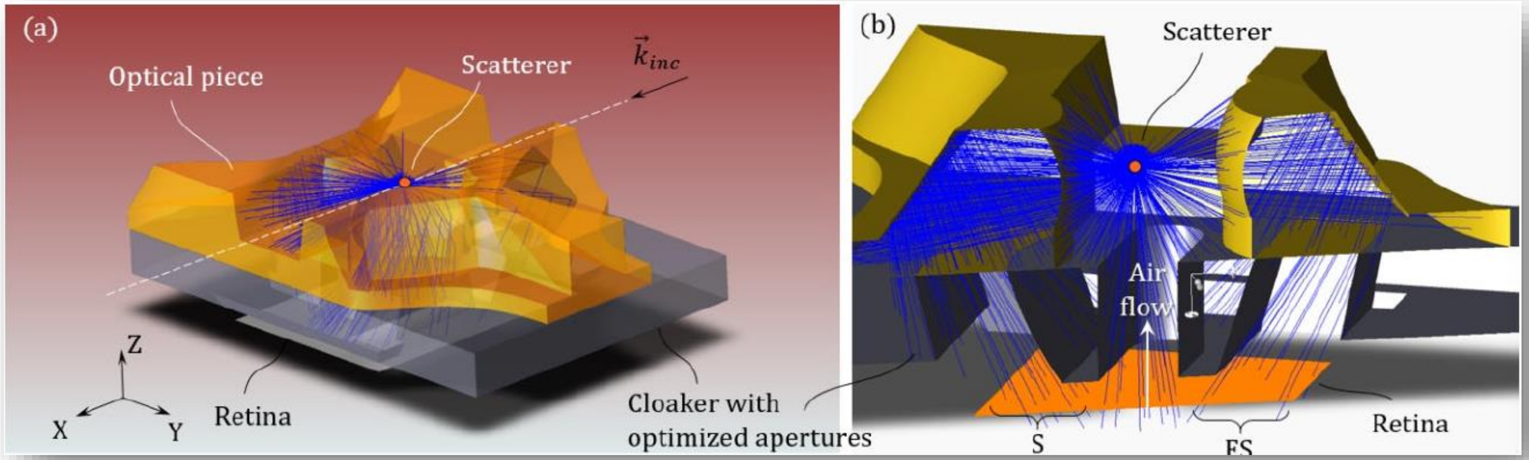
- Air quality monitoring
- Improved sensitivity by the integration of a miniaturized refractive/reflective optical system

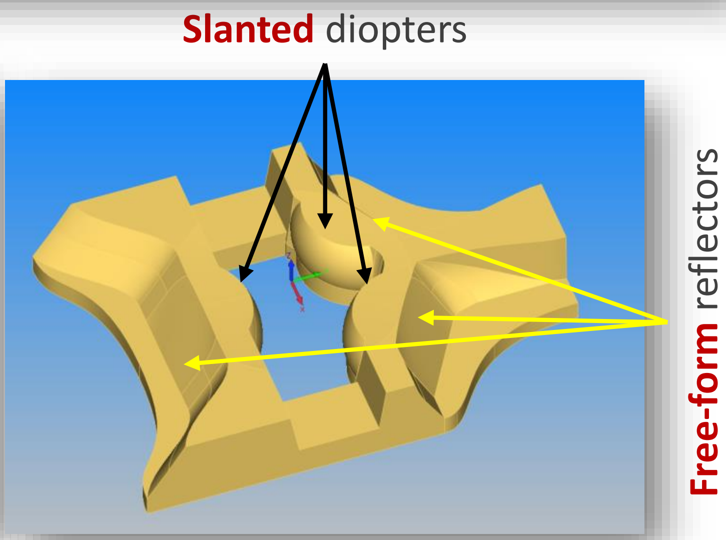
USPs

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



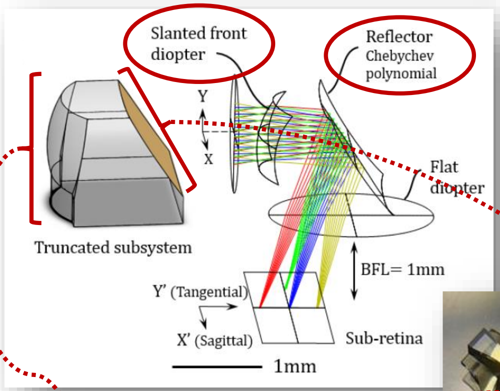


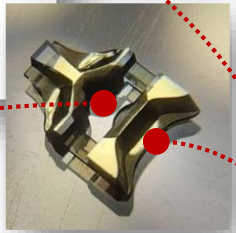




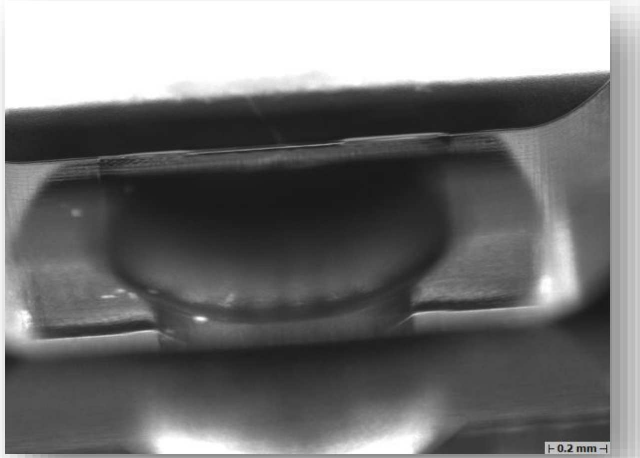
CEA-LETI Minatec & Institut des Nanotechnologies de Lyon.
Jobert G. et al. Miniature Optical Particle Counter and Analyzer Involving a Fluidic-Optronic CMOS Chip Coupled with a Millimeter-Sized Glass Optical System. Sensors 2021, 21, 3181.

MINIAUTIZED OPTICS – SURFACE QUALITY

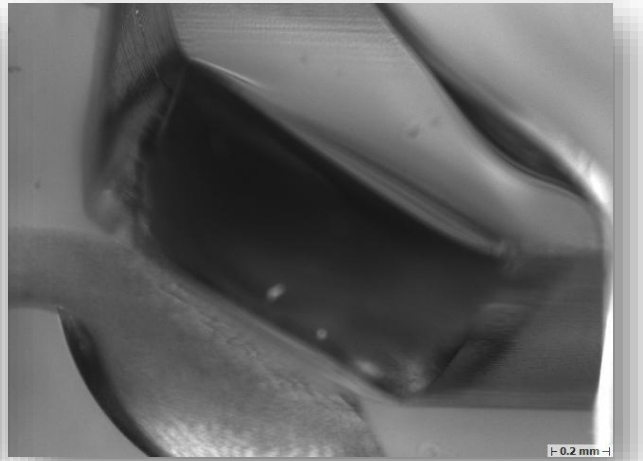




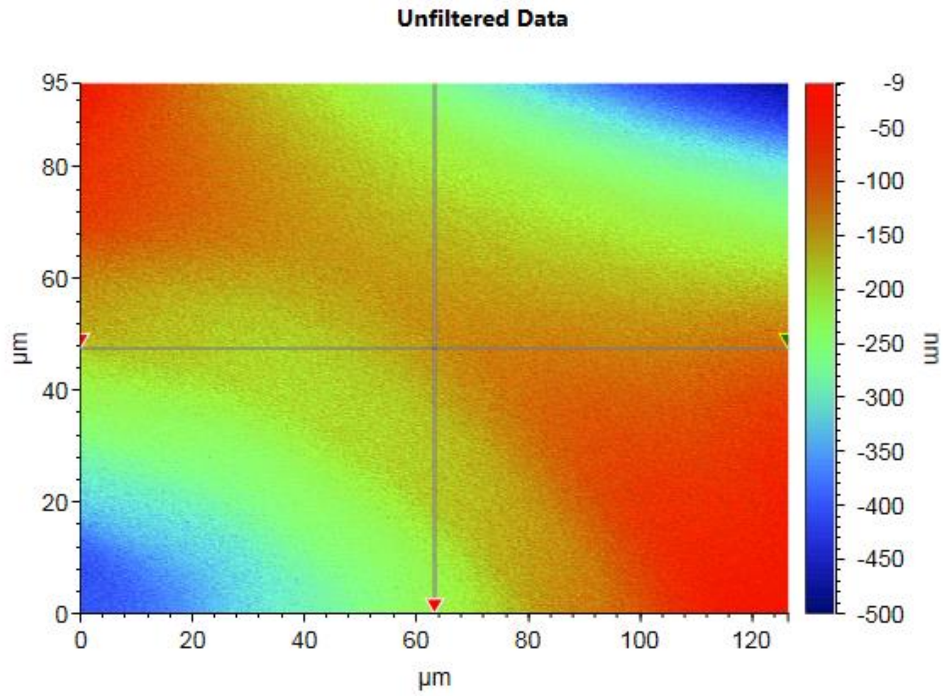
Slanted diopter



Free-form reflector



Interferometric image of the reflector surface



Surface roughness: **Sa = 6nm**

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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.

BEAM SHAPING – FREE-FORM MICRO-OPTICS

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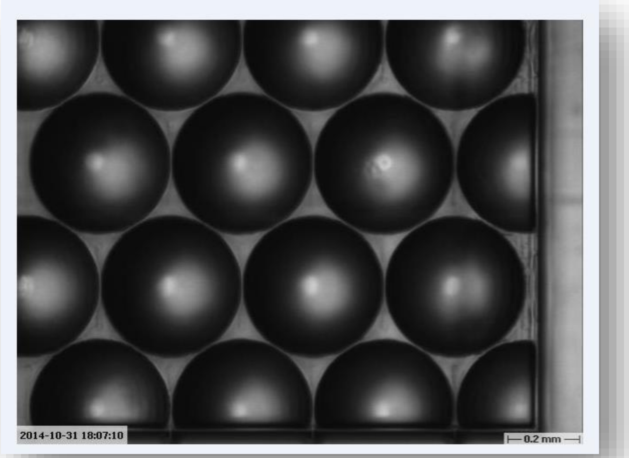
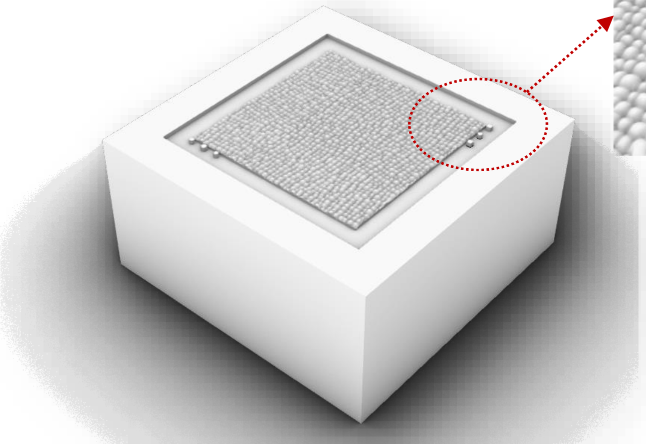
SPHERICAL or ASPHERICAL → ***NON-SPHERICAL*** → ***FREE-FORM***

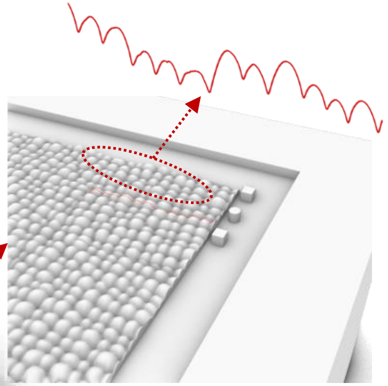
MICRO-LENSES
&
MICRO-LENS ARRAYS (MLAs)

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

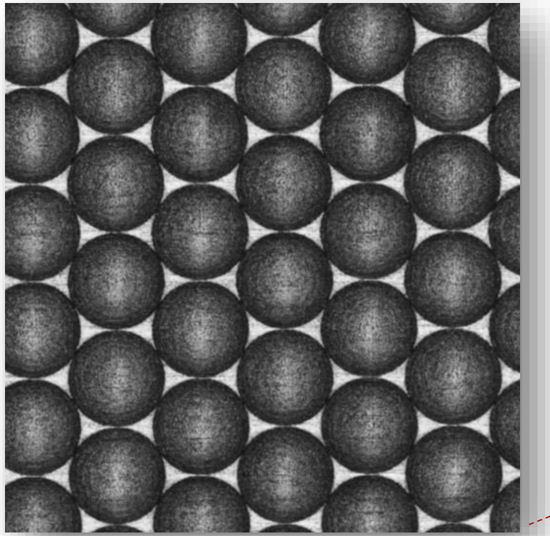
Enabling large volume production

EXAMPLE – SHALLOW MICRO-LENS ARRAYS

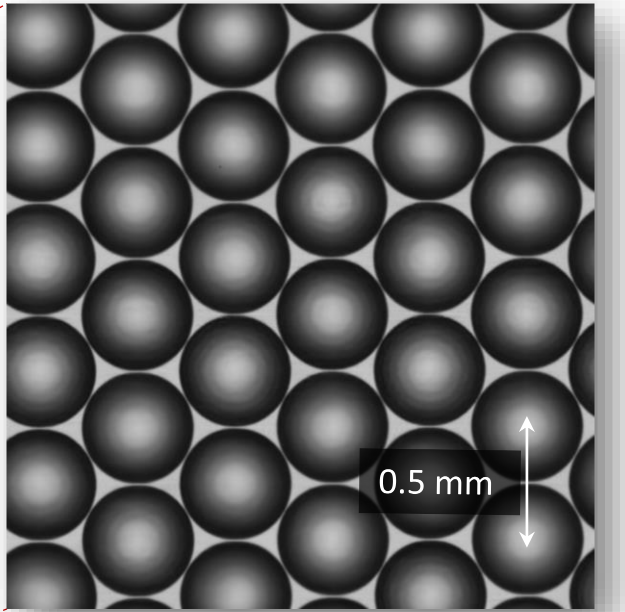
Hexagonal closely packed MLA

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

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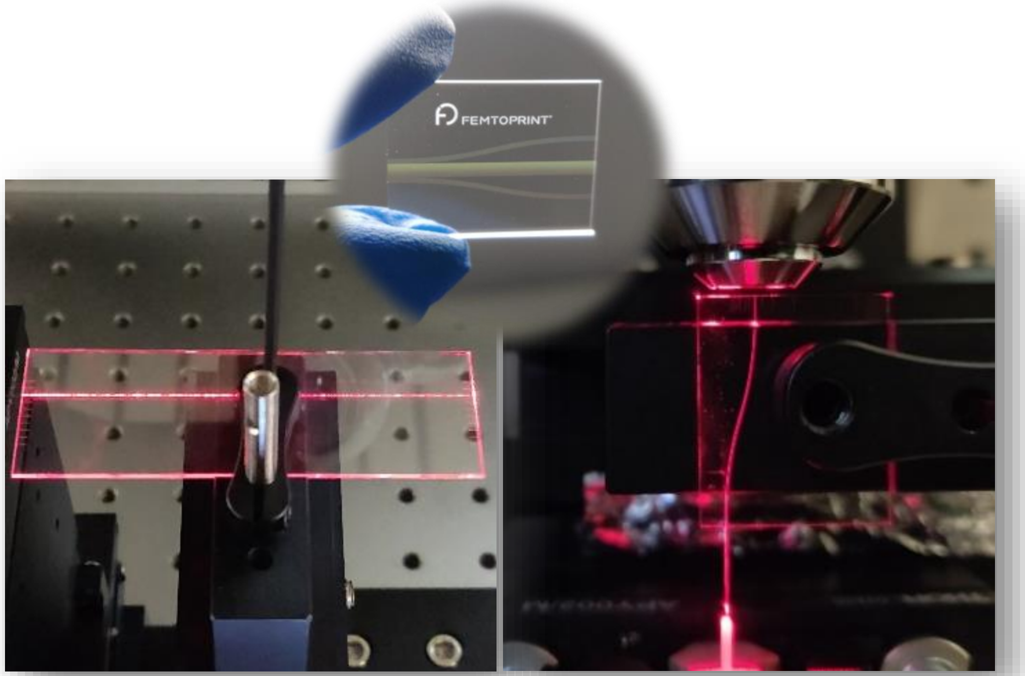
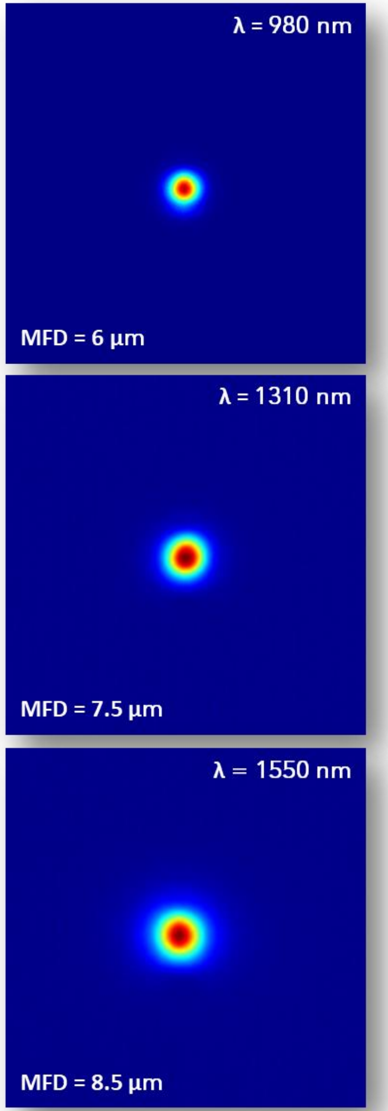
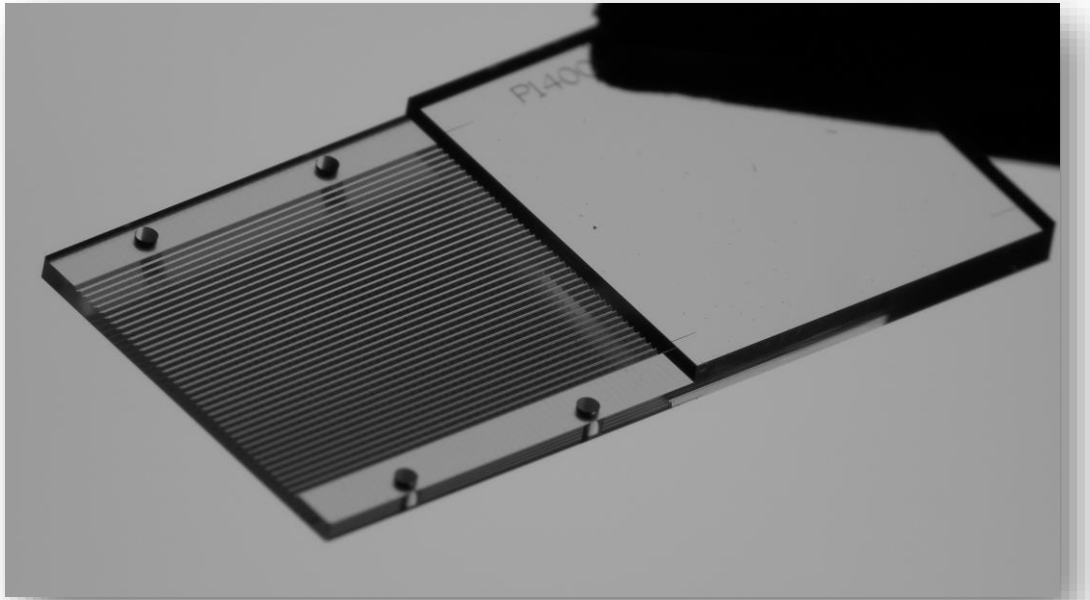


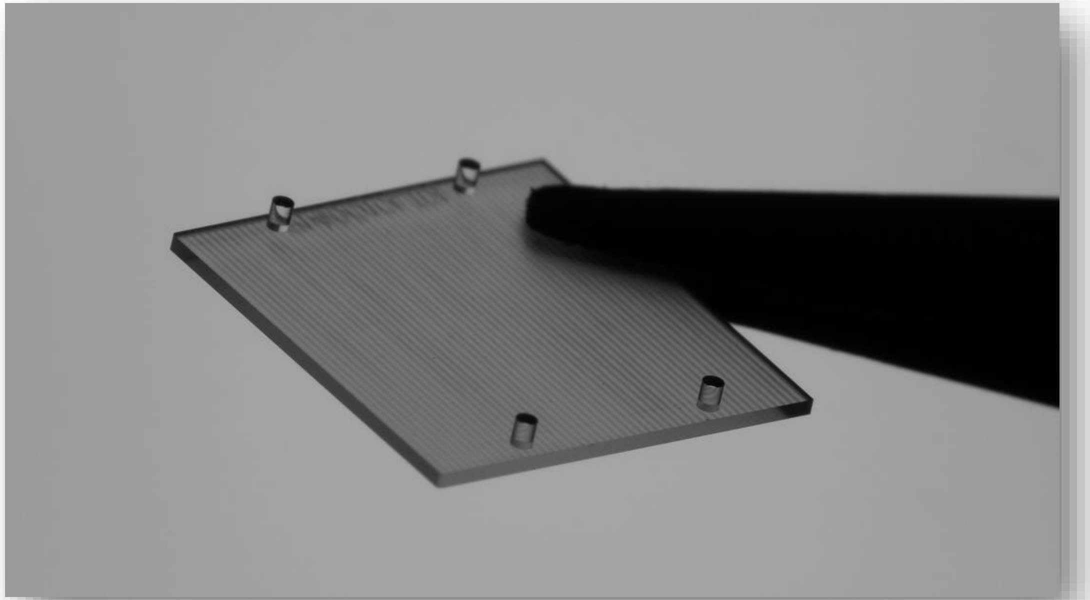
- Single mode & Multi-mode waveguides
- 3D waveguides with bending in XYZ
- In-bulk termination and tapering
- Alignment markers for assembly & packaging
- Facet polishing for rapid prototyping and characterization

Materials	FS, BF33, EXG
Working λ [nm]	630, 980, 1310, 1550
MFD SM [µm]	7 ± 1 @ 980 nm 8 ± 1 @ 1310 nm 9 ± 1 @ 1550 nm
Relative positioning	< ± 1 µm
Min. Bending Radius	≤ 20-25 mm
Propagation Loss	< 0.2 dB/cm
Δn	10^{-2} - 10^{-3}



MONOLITHIC INTEGRATION – WAVEGUIDES & V-GROOVES





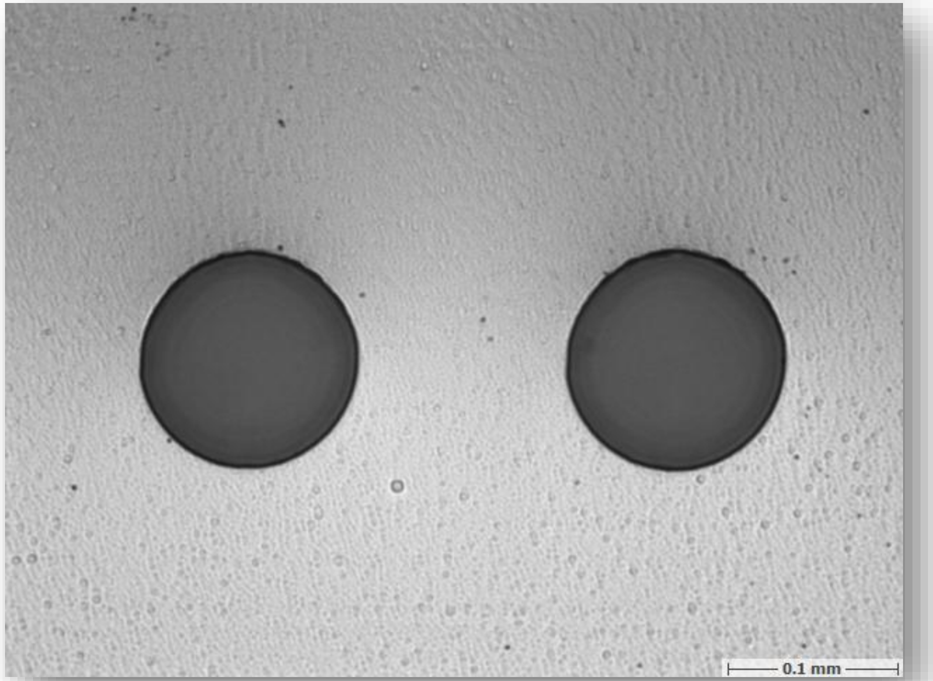
- Single fabrication step: < ± 1µm relative positioning
- 127µm pitch v-groove array connector with its cover lid
- In-bulk termination and tapering
- Alignment markers for assembly & packaging

USPs

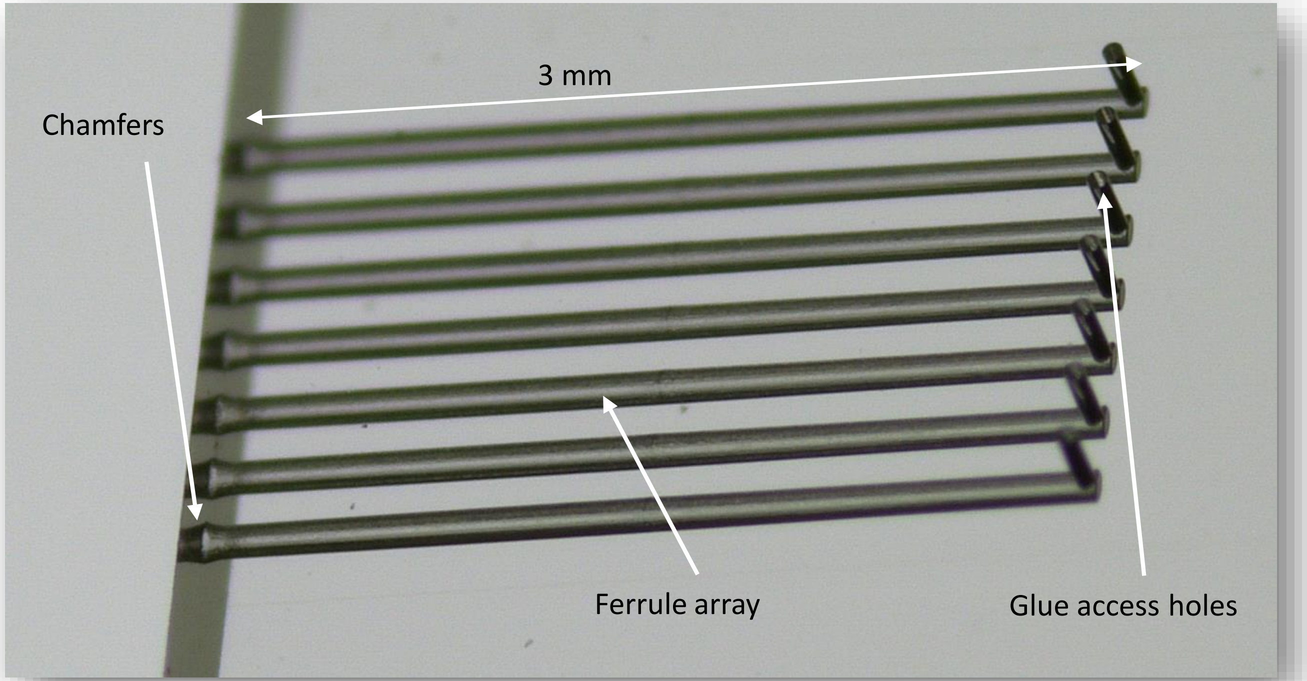
- 3D waveguides in glass
- Monolithic integration of functionalities
- Photonic systems for fiber-to-chip connectivity

MONOLITHIC INTEGRATION – WAVEGUIDES & HOLE ARRAYS

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

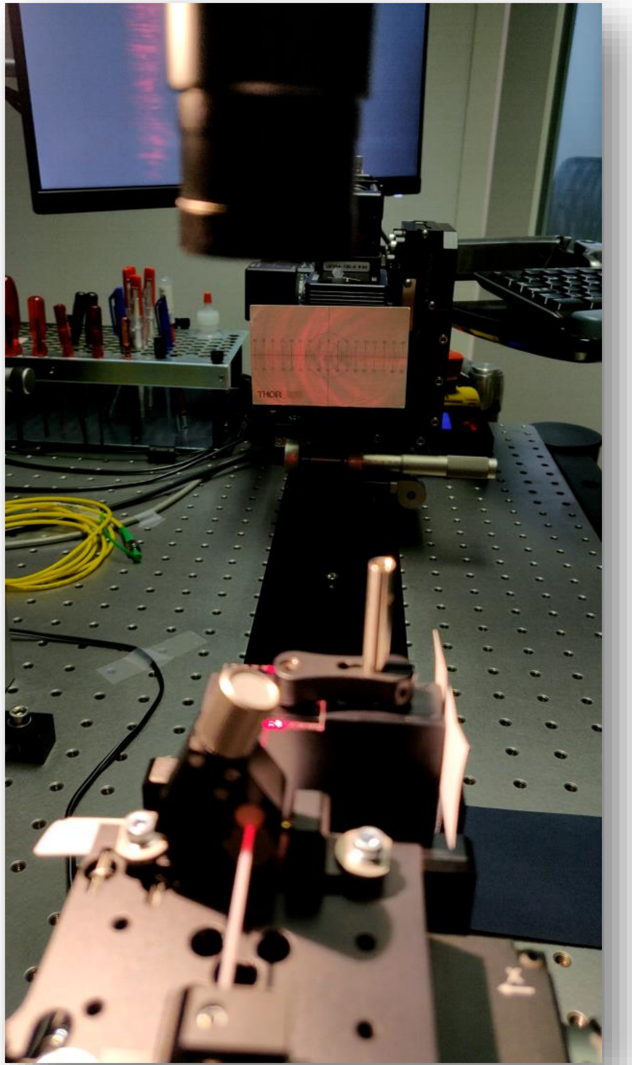


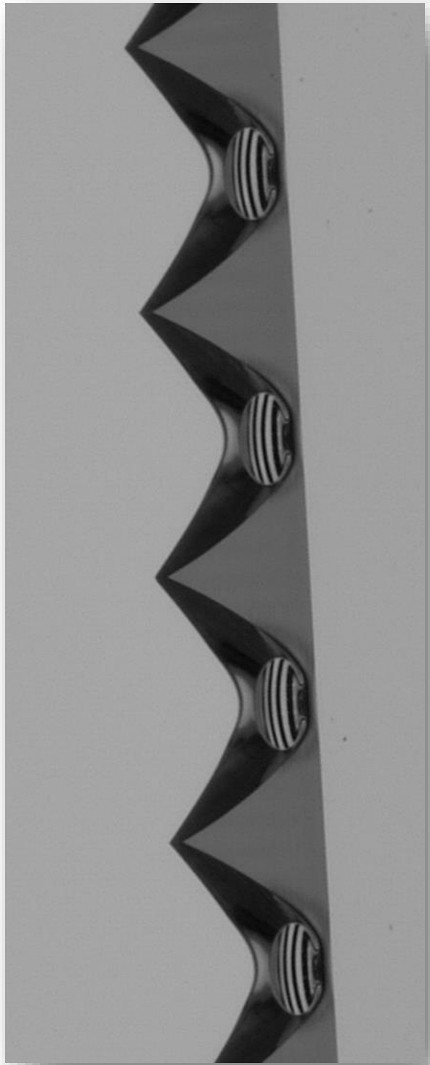
Horizontal ferrules with no chamfer, 0.002 µm circularity

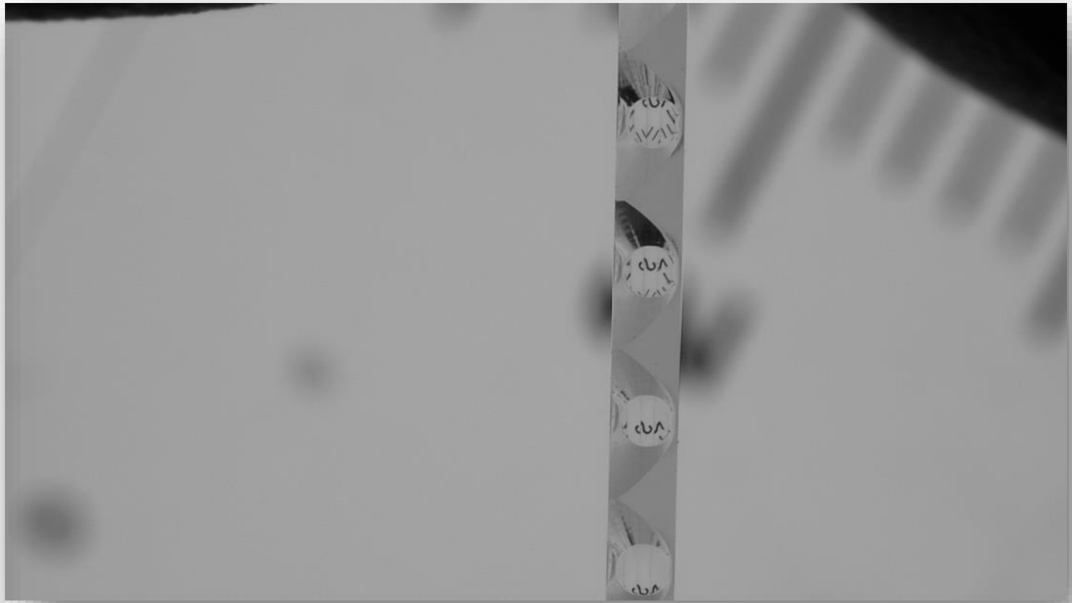


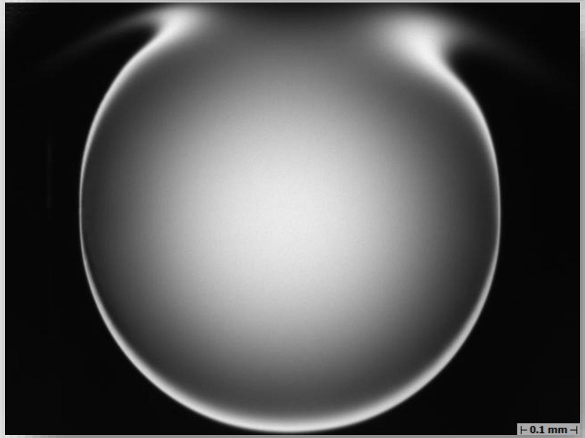
Horizontal ferrules with chamfers and access holes, 0.002 µm circularity

MONOLITHIC INTEGRATION – WAVEGUIDES & MICRO-LENSES









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Thank you!

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