



Laser-based **3D micro-manufacturing** of high precision components for **quantum photonics**

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EPIC Technology Meeting on
Industrial Quantum Photonics Technology



TOPTICA - Munich, October 11th - 12th, 2023

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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

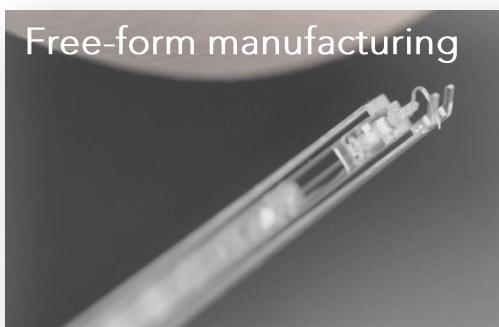
ISO 9001 : 2015 & ISO 13485 : 2016



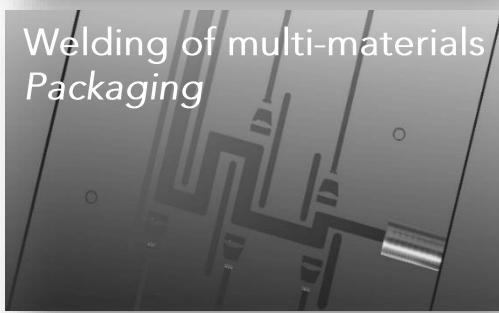
3D MANUFACTURING OF GLASS MICRO-DEVICES

CAPABILITIES

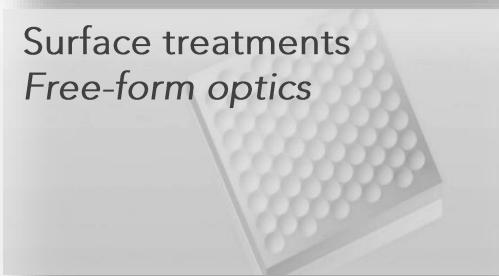
Free-form manufacturing



Welding of multi-materials
Packaging



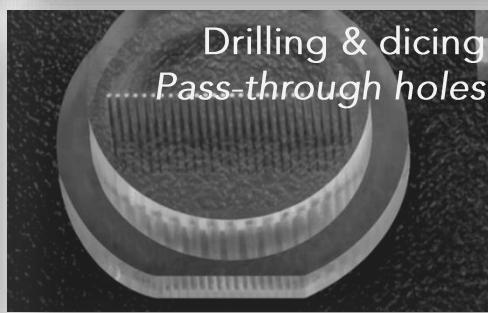
Surface treatments
Free-form optics



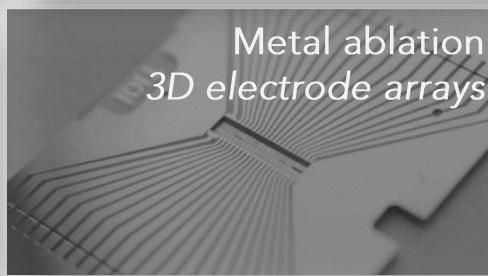
Optical patterns
Waveguides



Drilling & dicing
Pass-through holes



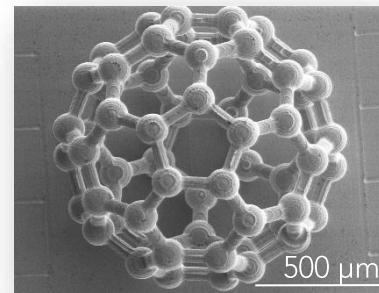
Metal ablation
3D electrode arrays



PERFORMANCES*

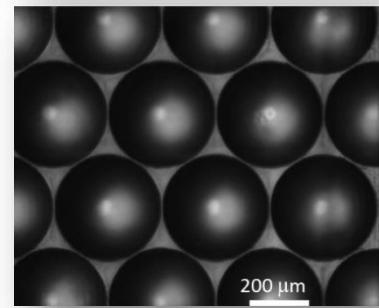
RESOLUTION AND TOLERANCES

- Process resolution $\sim 1 \mu\text{m}$
- XY tolerances $+/- 1 \mu\text{m}$
- Z tolerance $+/- 2 \mu\text{m}$



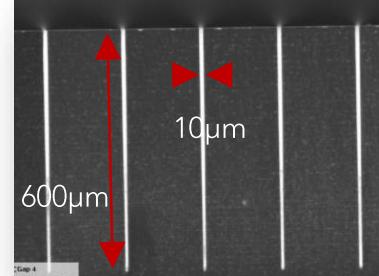
SURFACE QUALITY

- Patterned surface $\text{Sa} \leq 100 \text{ nm}$
- Surface treatment $\text{Sa} \leq 10 \text{ nm}$



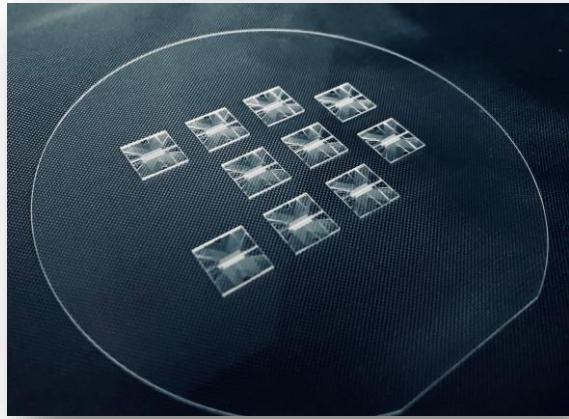
ASPECT RATIO

- Hole aspect ratio $\geq 1:500$
- Substrate thickness up to 30 mm
- Min. hole diameter $\leq 5 \mu\text{m} \varnothing$
- Sidewall deviation $\leq 0.1^\circ$
- Sidewall roughness $\text{Sa} \leq 100 \text{ nm}$



QUANTUM PHOTONICS

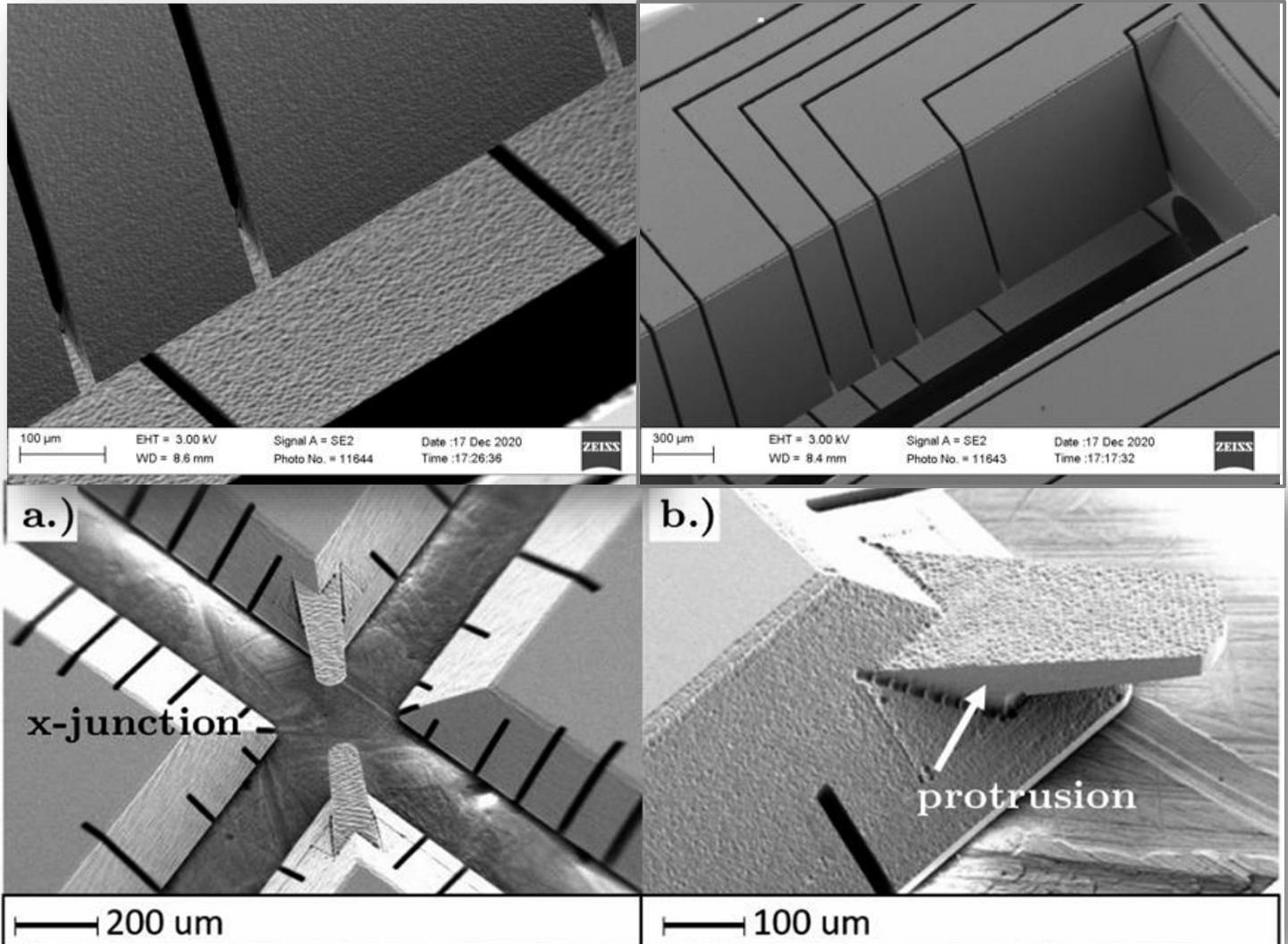
ION TRAPS: 3D MICRO-MANUFACTURING



Courtesy of University of Sussex

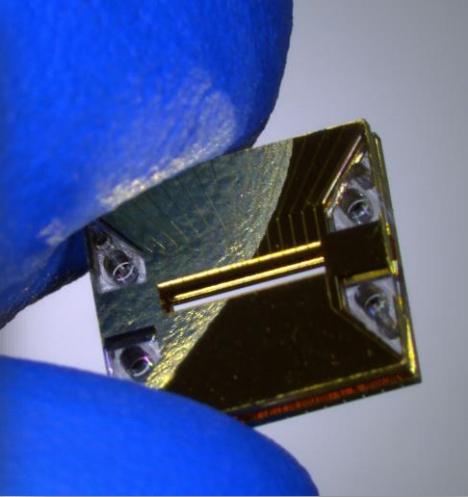
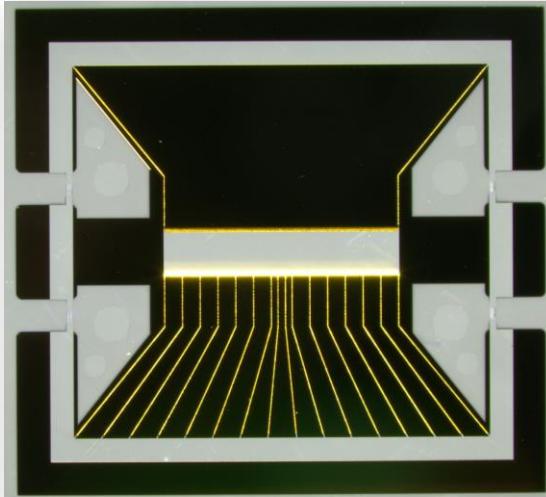
What we can do

- Monolithic fabrication
- Complex 3D geometries
- Overhanging structures
- Minimum trench width < 10 µm
- Sharp or curved edges
- Single-µm tolerances
- Wafer scale fabrication



Courtesy of ETHZ

ION TRAPS: ELECTRICAL CONNECTIVITY

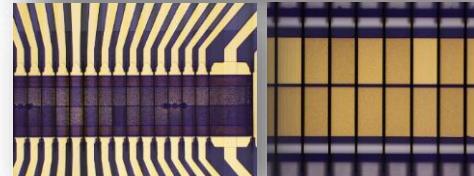
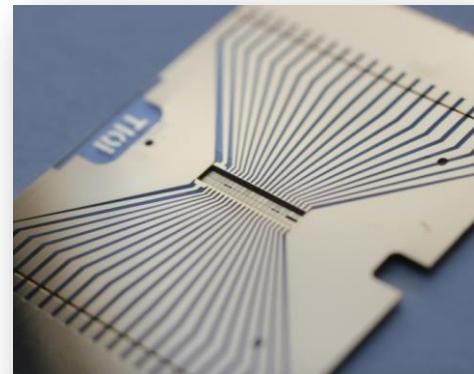


What we can do

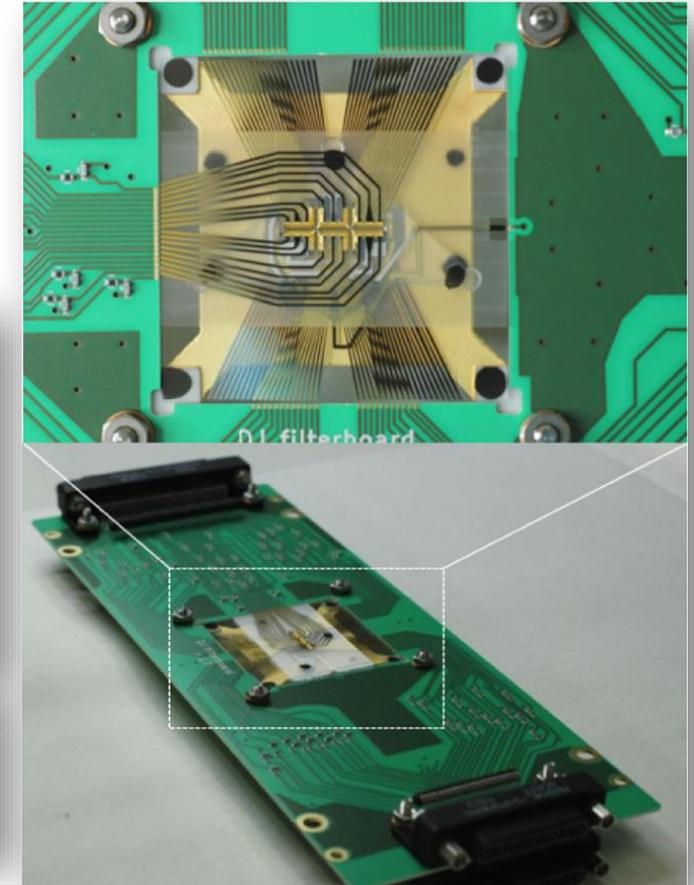
- Advise on trench shape design for optimized insulation
- Deposition of metal films (Ti, Cr, Pt, Au)
- Sputtering or e-beam evaporation
- Deposition at different angles
- Realization of masks
- Metallization of Through Glass Vias
- Laser ablation of thin films for electrode insulation



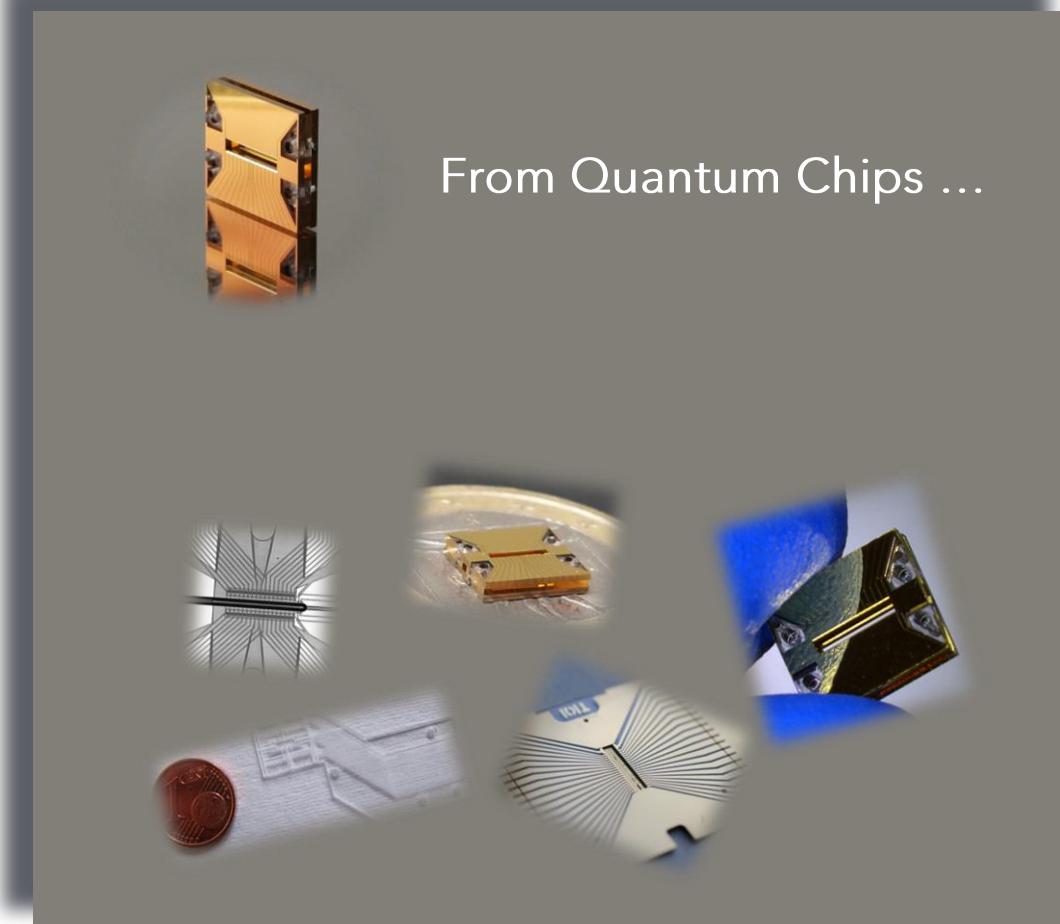
45° tilted electrodes, 30um width.
Ablation width 20um.



Courtesy of ETH Zurich

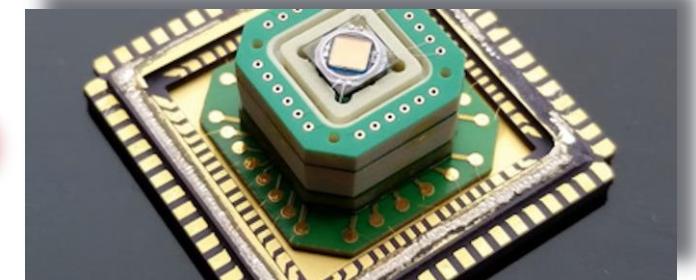


QUANTUM PHOTONICS vs. PACKAGING & ASSEMBLY

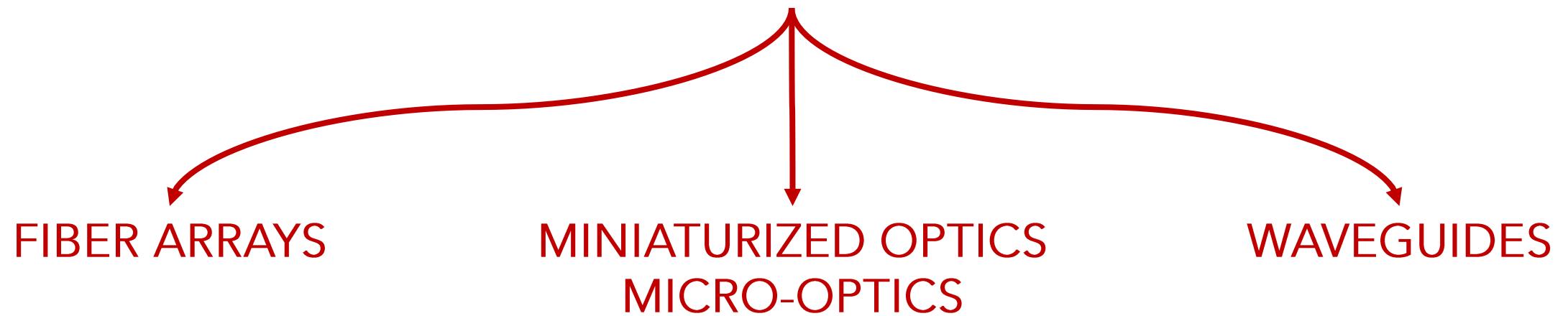


From Quantum Chips ...

... to Quantum Photonics products

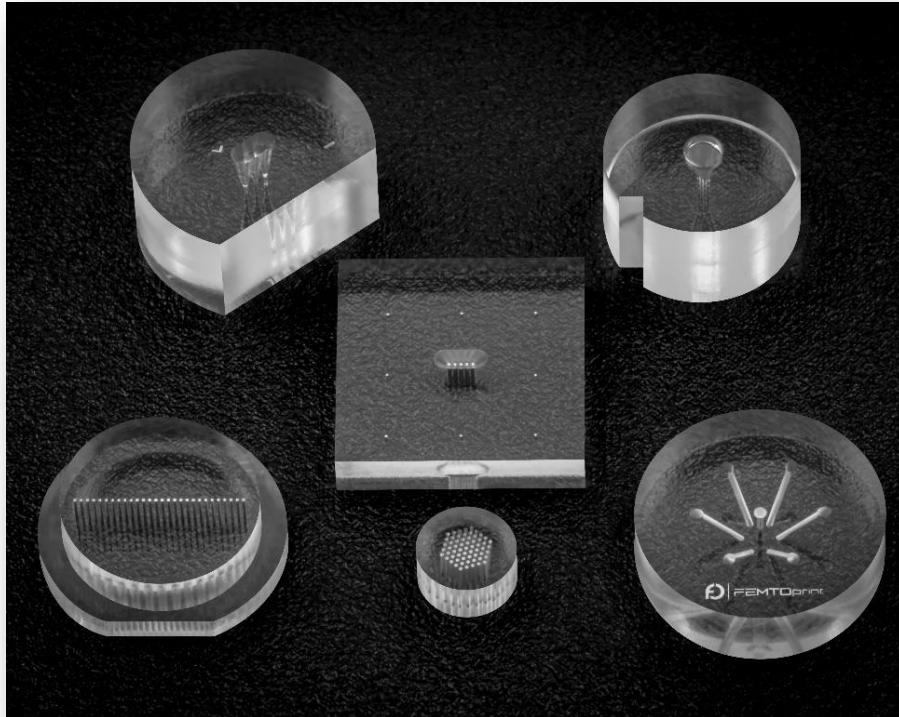


FIBER-TO-CHIP CONNECTIVITY



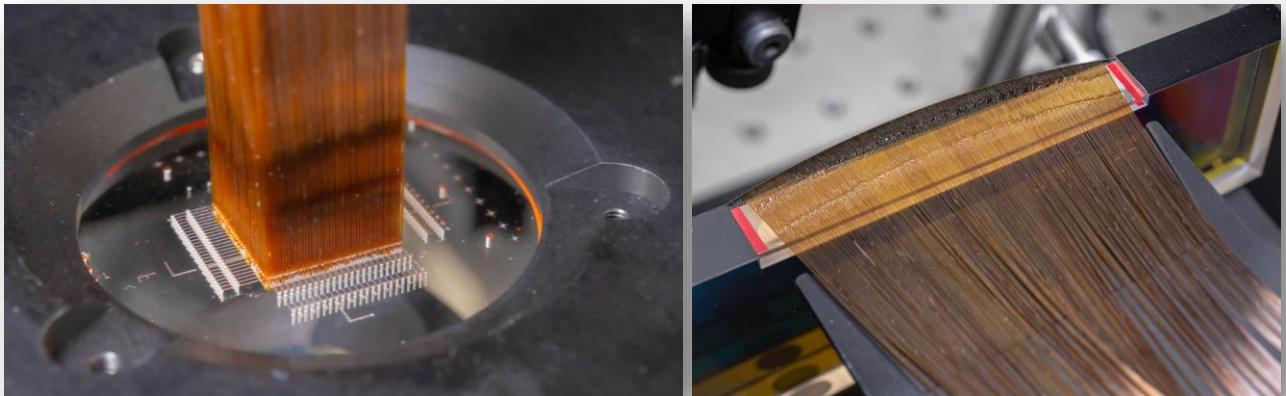
FIBER ARRAYS

GLASS FIBER FERRULES – PASSIVE ALIGNMENT ASSEMBLY



EXAMPLE

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



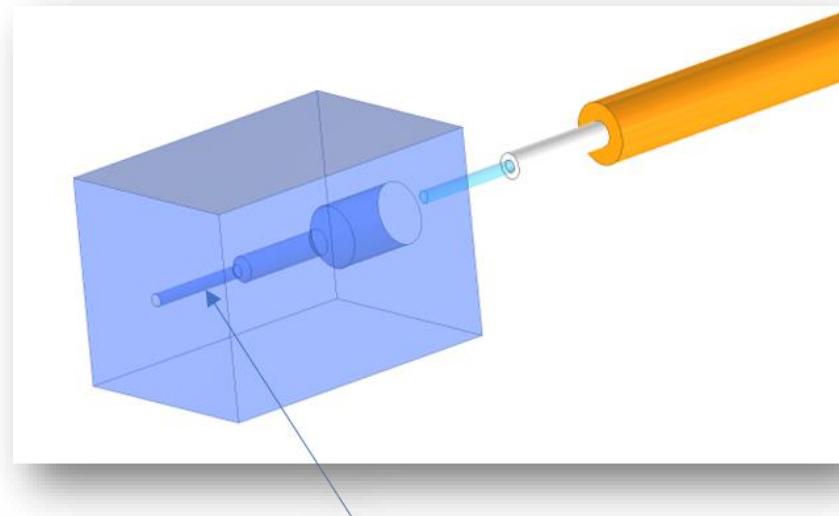
Courtesy of Gábor Fűrész, MIT Kavli Institute for Astrophysics and Space Research

USPs

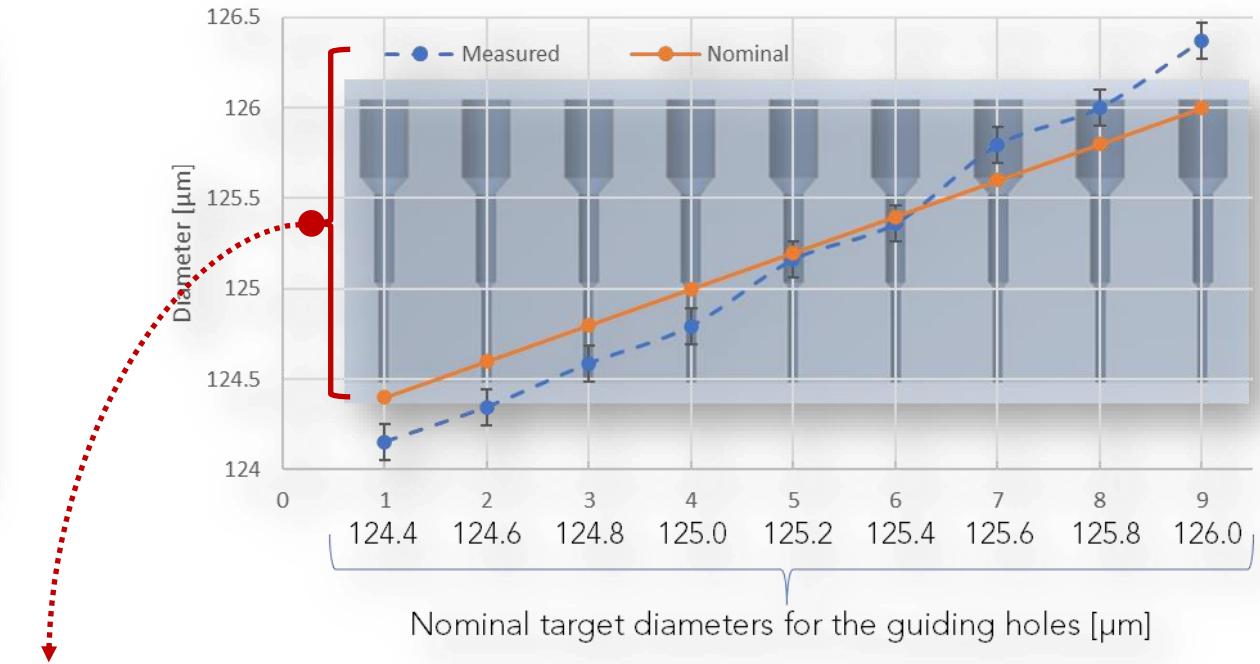
- Thin to thick glass ferrules for optimized mechanical stability
- Fully customizable 2D hole arrays with straight or tilted holes
- Sub- μm precision in hole diameter and positioning
- Monolithic integration with
 - mounting features
 - additional components (e.g. micro-lenses, waveguides, etc.)
-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

2D HOLE ARRAYS – SUB- μ m CONTROL ON HOLE DIAMETER

- Fiber glass ferrules with varying nominal diameters of the guiding section (**steps = 0.2 μ m**)
- Mechanical measurements of the effective diameter of the guiding section



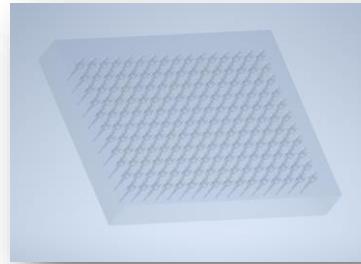
Guiding section (length > 1.5 mm)



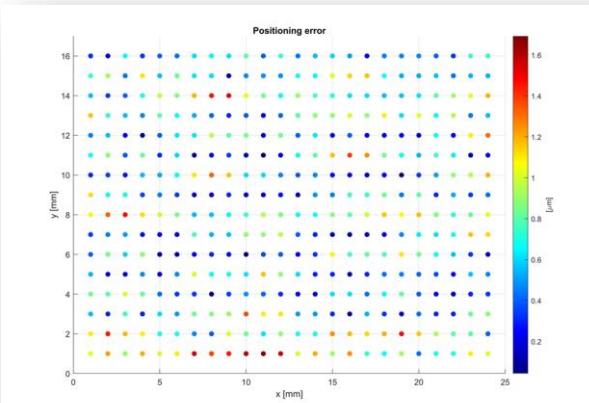
The mechanical measurements confirm that
the diameters of the fabricated ferrules correspond to the nominal target values → sub- μ m control

2D HOLE ARRAYS – SUB- μ m CONTROL ON HOLE POSITION

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

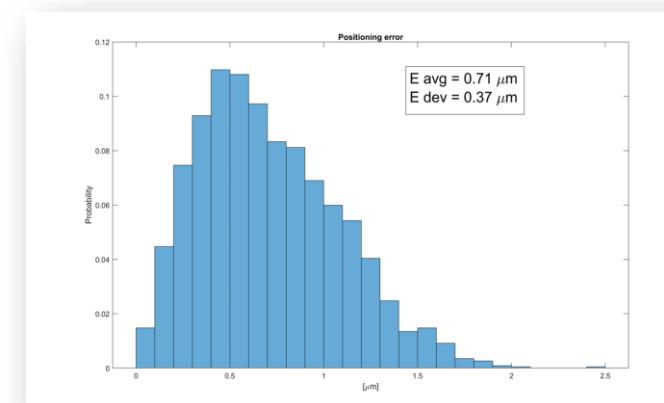


- 5x identical 2D arrays



➤ Hole positioning: relative error better than the microscope resolution ($\pm 2 \mu\text{m}$)

Hole positioning verified on a single array



- Average hole positioning error $\pm 0.7 \mu\text{m}$
- Standard deviation $< 0.4 \mu\text{m}$
- Relative error better than the microscope resolution ($\pm 2 \mu\text{m}$)



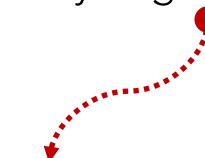
Repeatability verified on multiple arrays

FIBER FERRULES: SUB-° CONTROL ON HOLE CYLINDRICITY

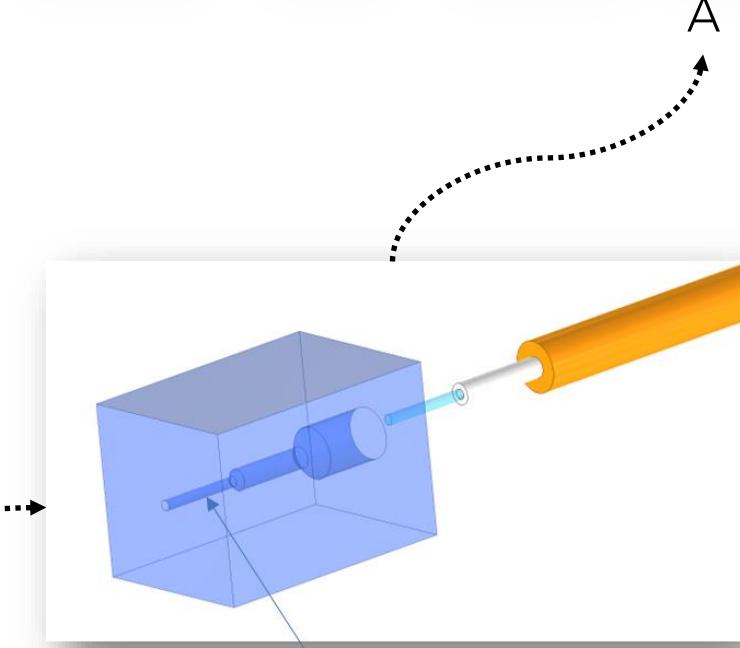
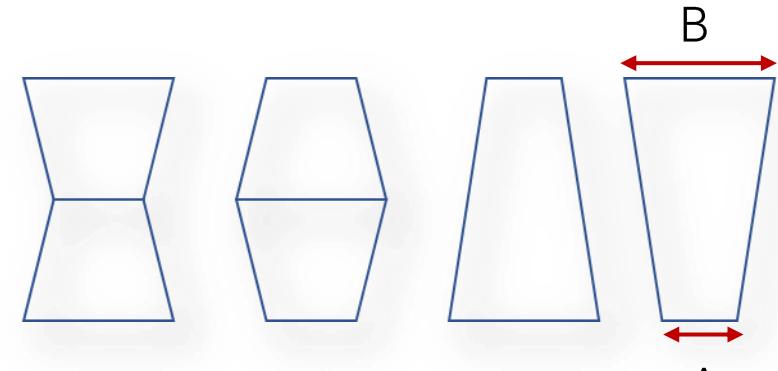
- Mechanical measurements → minimum diameter over the hole length
- The hole shape can vary



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

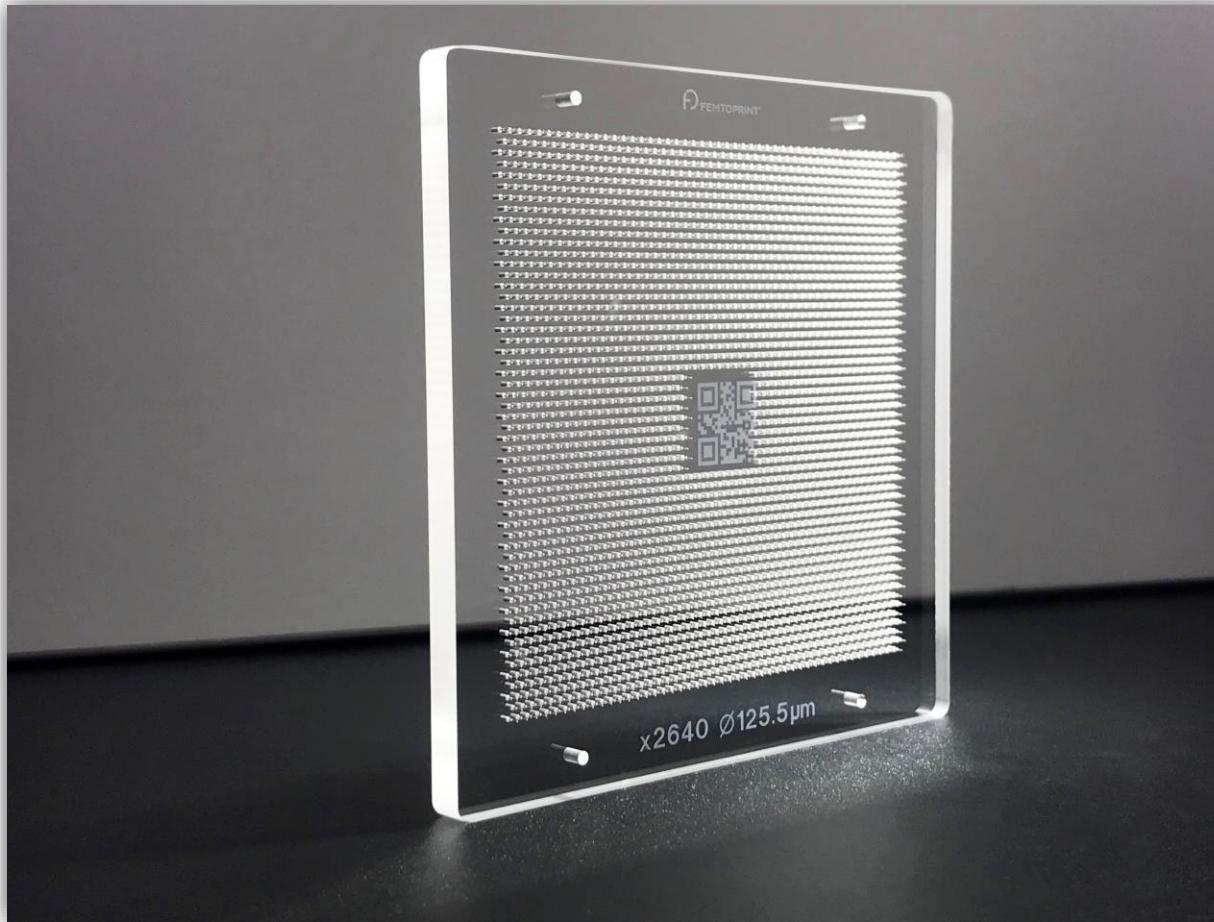


- No evidence of diameter difference along single holes
- **Error on hole cylindricity $<< 0.1^\circ$**
Note: 0.1° over the 1.5mm guiding section → $A-B = 5\mu m$
- Very limited losses due to fiber tilt



Guiding section (length > 1.5 mm)

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

MINIATURIZED OPTICS

MICRO-OPTICS

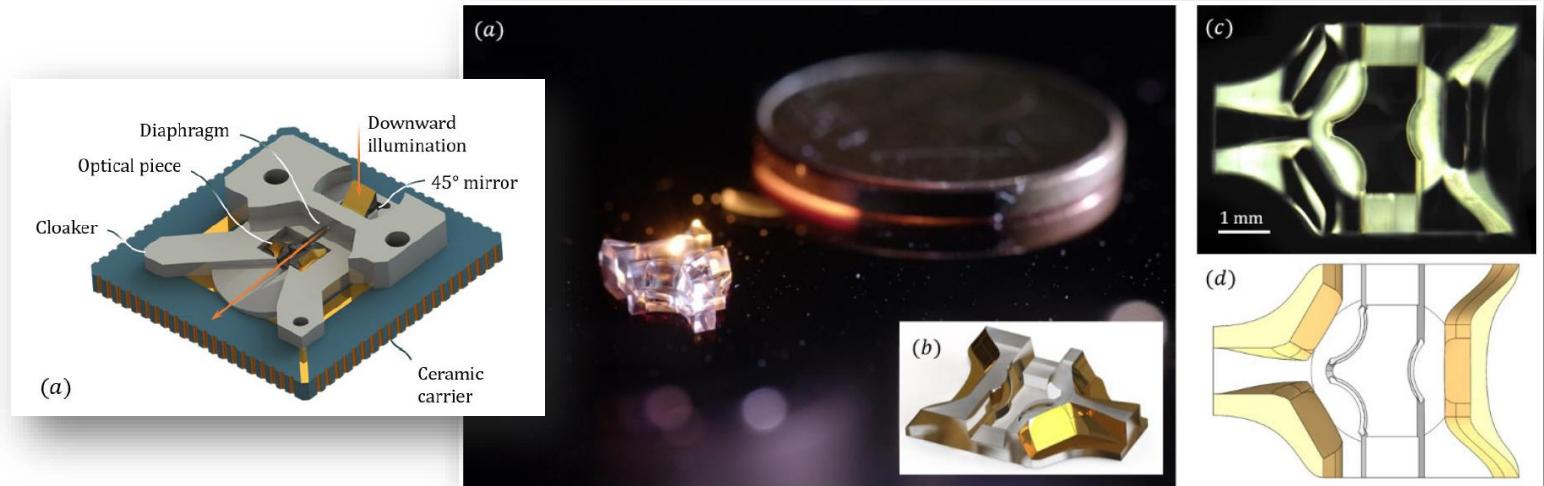
BEAM SHAPING – MINIATURIZED OPTICS

APPLICATION

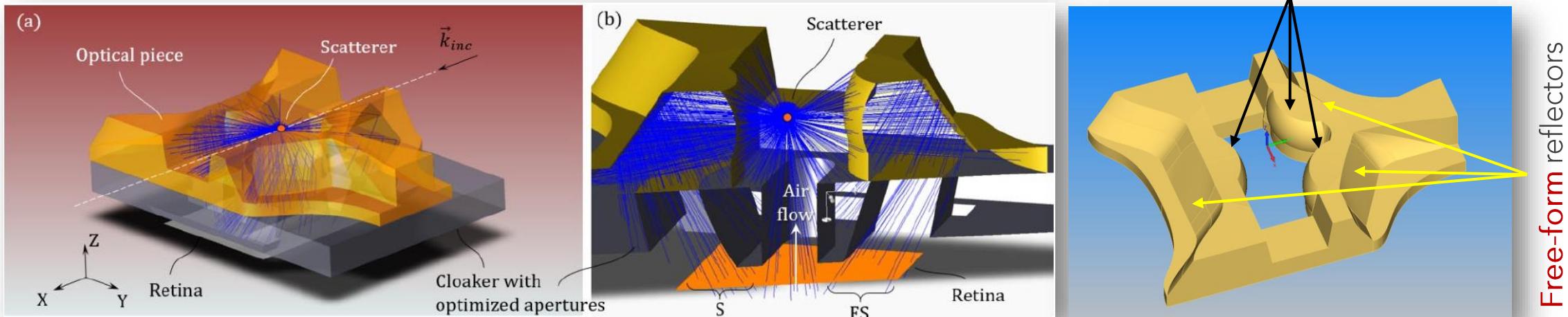
- Air quality monitoring
- Improved sensitivity by the integration of a miniaturized refractive/reflective optical system

USPs

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



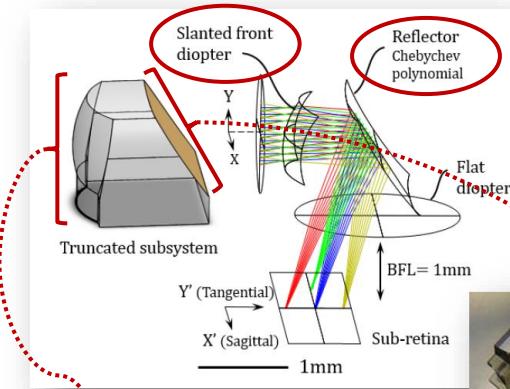
Slanted diopters



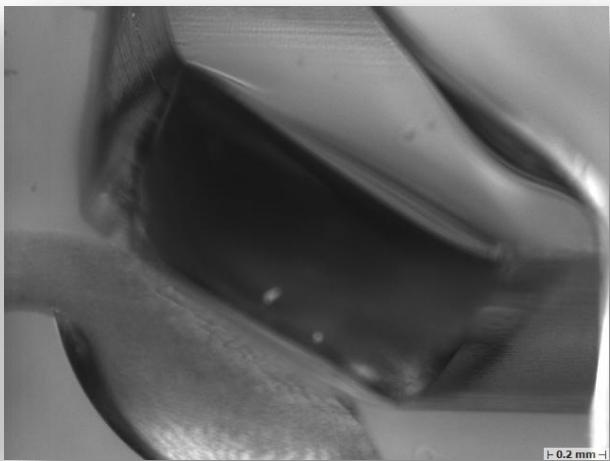
CEA-LETI Minatec & Institut des Nanotechnologies de Lyon.

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.

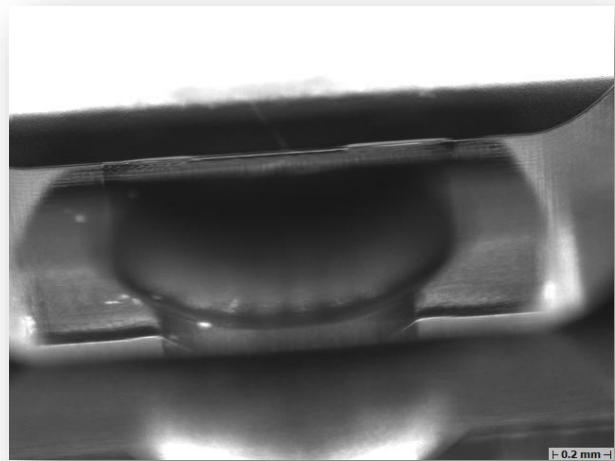
MINIAUTIZED OPTICS – SURFACE QUALITY



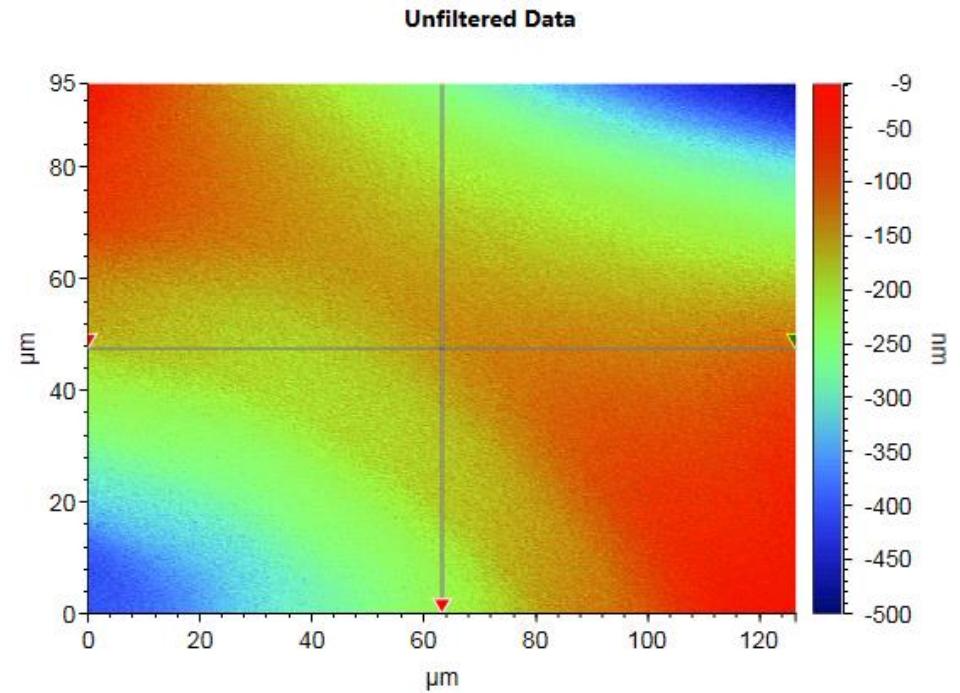
Slanted diopter



Free-form reflector



Interferometric image of the reflector surface



Surface roughness: $S_a = 6\text{nm}$

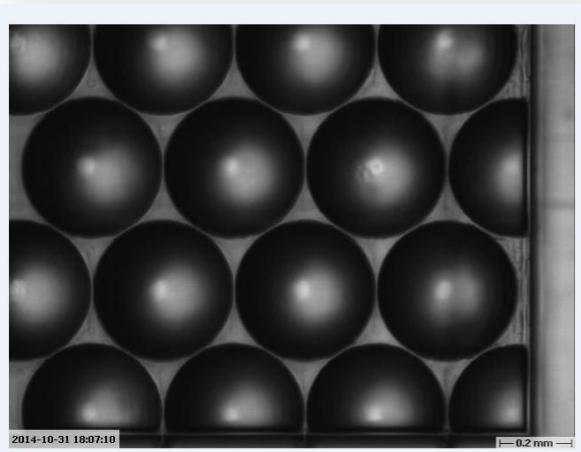
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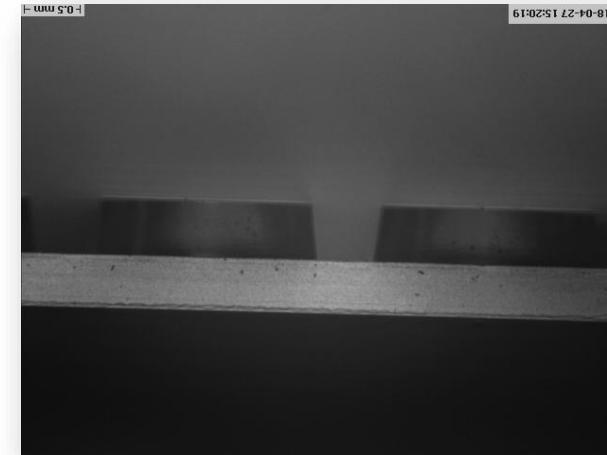
BEAM SHAPING – FREE-FORM MICRO-OPTICS

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

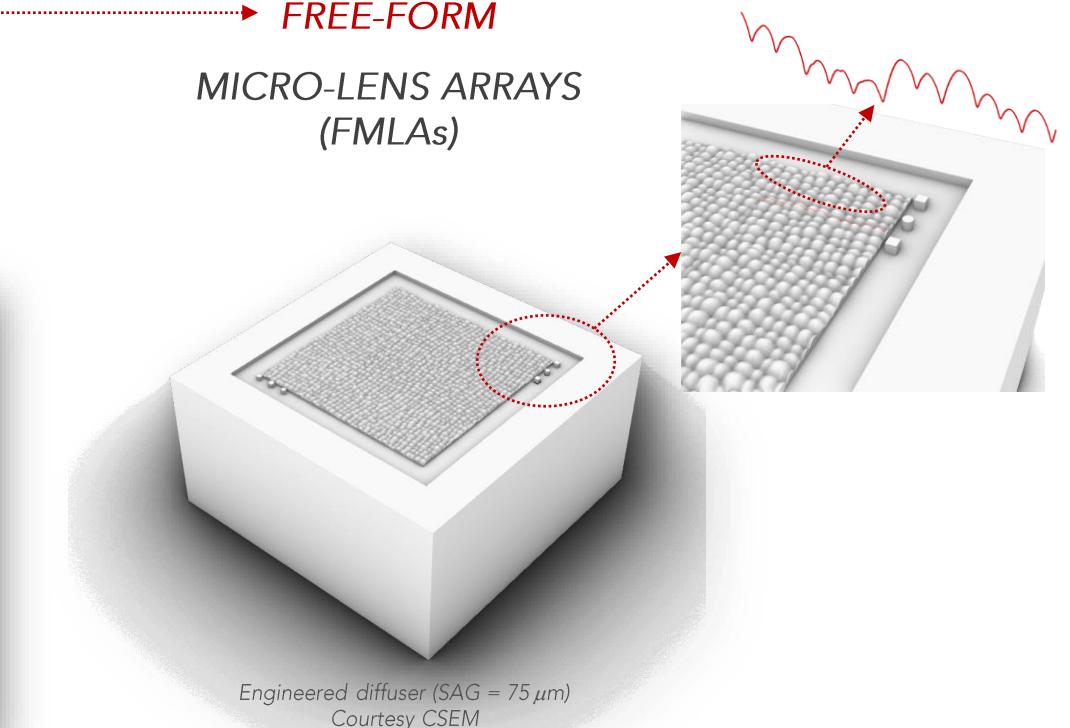
MICRO-LENSES
&
MICRO-LENS ARRAYS
(MLAs)



MICRO-OPTICAL ARRAYS



MICRO-LENS ARRAYS
(FMLAs)



Feasibility

Fast prototyping

Pilot manufacturing

Small-to-medium
volume production

ORIGINATION
&
TOOLING

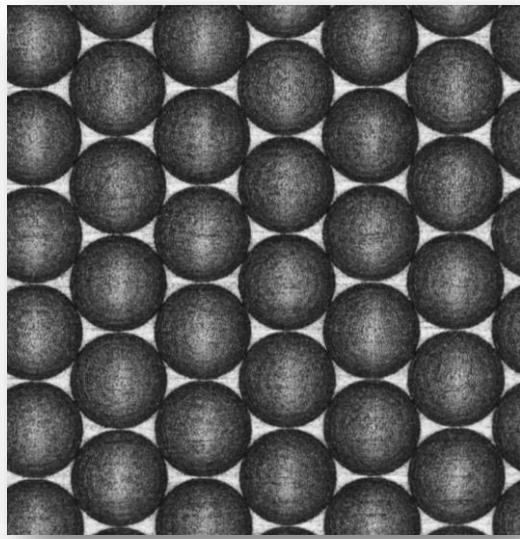
DEVELOPMENT: rapid cycles from concept to prototypes and small-to-medium product series

Enabling large volume production

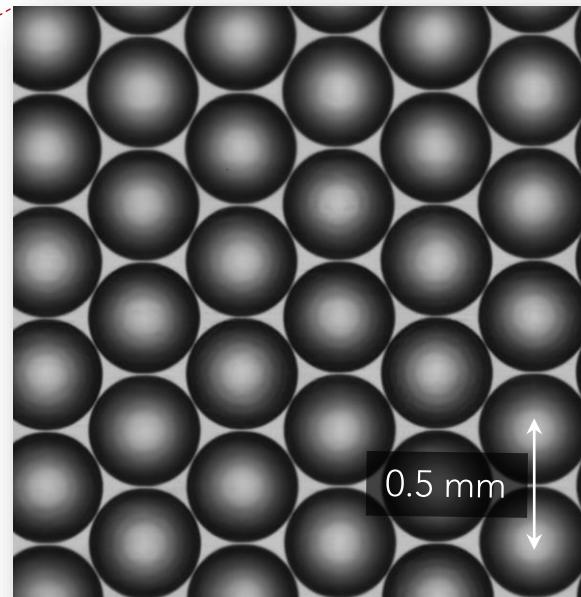
EXAMPLE – SHALLOW MICRO-LENS ARRAYS

Hexagonal closely packed MLA 100x spherical micro-lenses

- Diameter = $500 \mu\text{m}$
- RoC = $650 \mu\text{m}$
- SAG = $50 \mu\text{m}$



Without surface processing

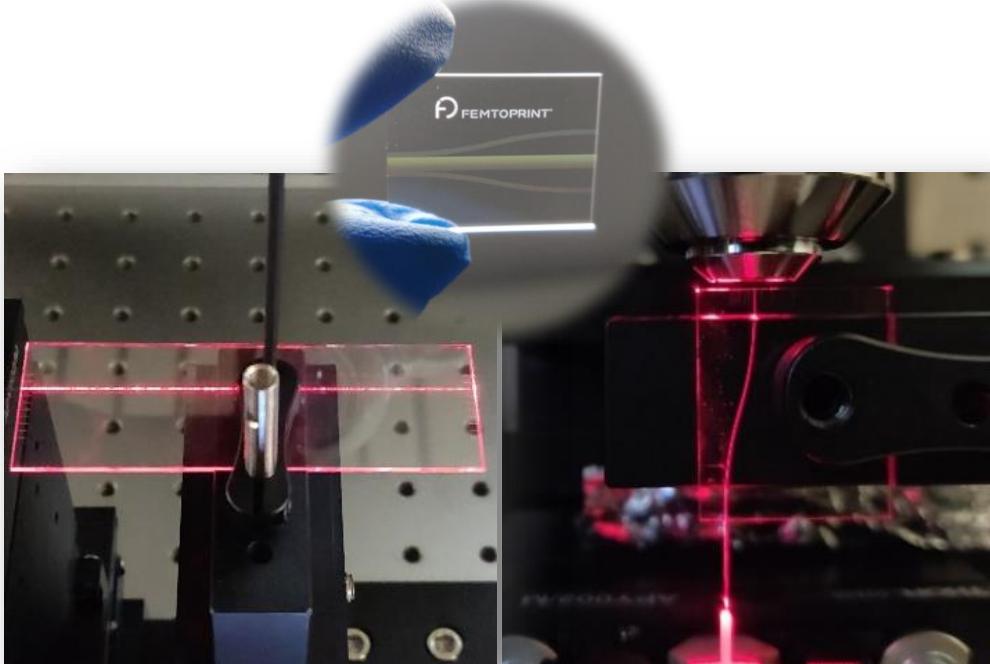


Micro-machined MLAs in Fused Silica

- RoC = $625 \pm 5.0 \mu\text{m}$
- SAG = $51.1 \pm 1.5 \mu\text{m}$
- $S_a = 4.8 \pm 3.3 \text{ nm}$
- Shape accuracy: $< 1.5 \mu\text{m}$

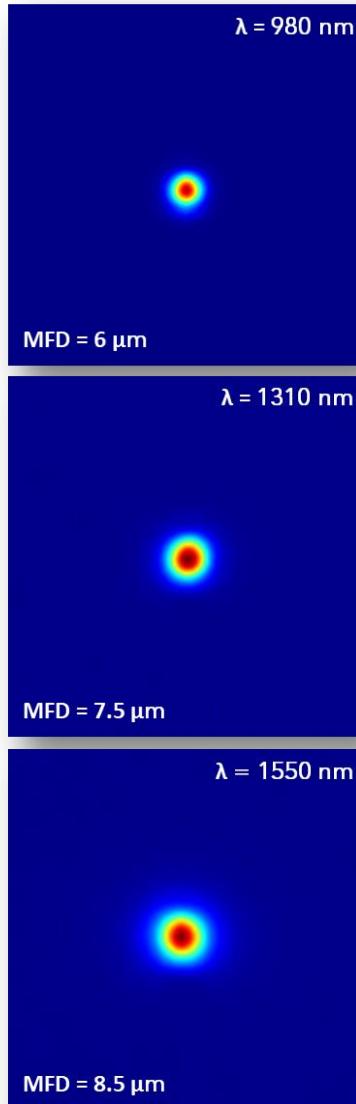
WAVEGUIDES

3D GLASS WAVEGUIDES

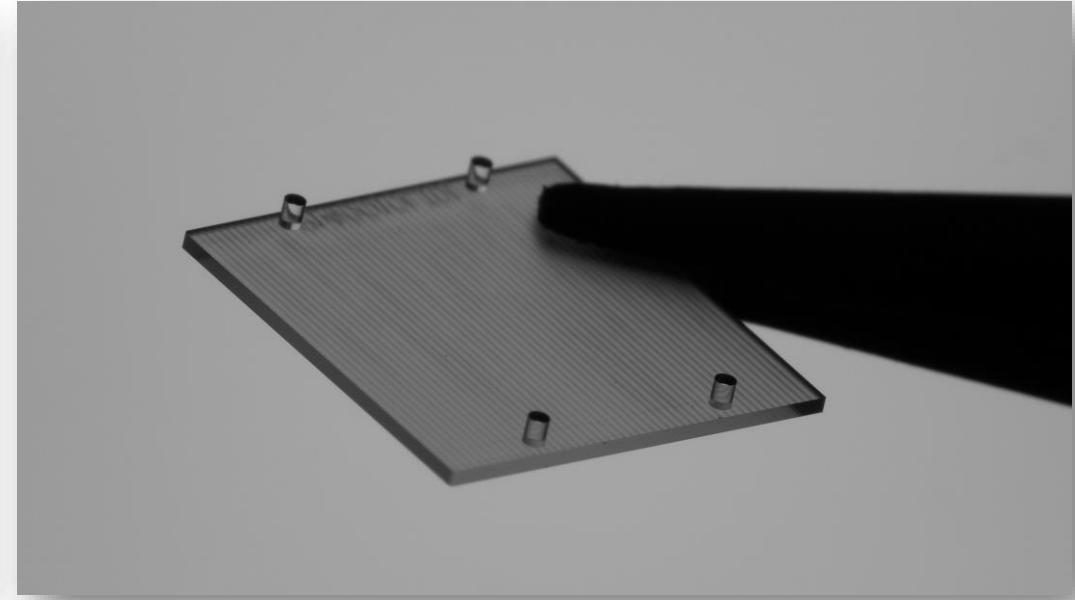
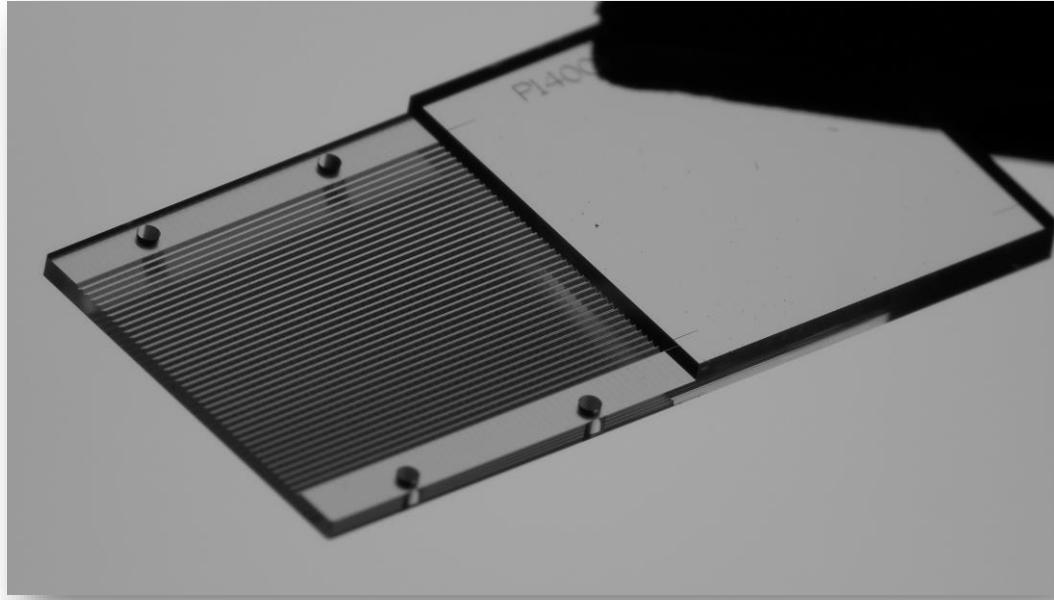


- Single mode & Multi-mode waveguides
- 3D waveguides with bending in XYZ
- In-bulk termination and tapering
- Alignment markers for assembly & packaging
- Facet polishing for rapid prototyping and characterization

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



MONOLITHIC INTEGRATION – WAVEGUIDES & V-GROOVES

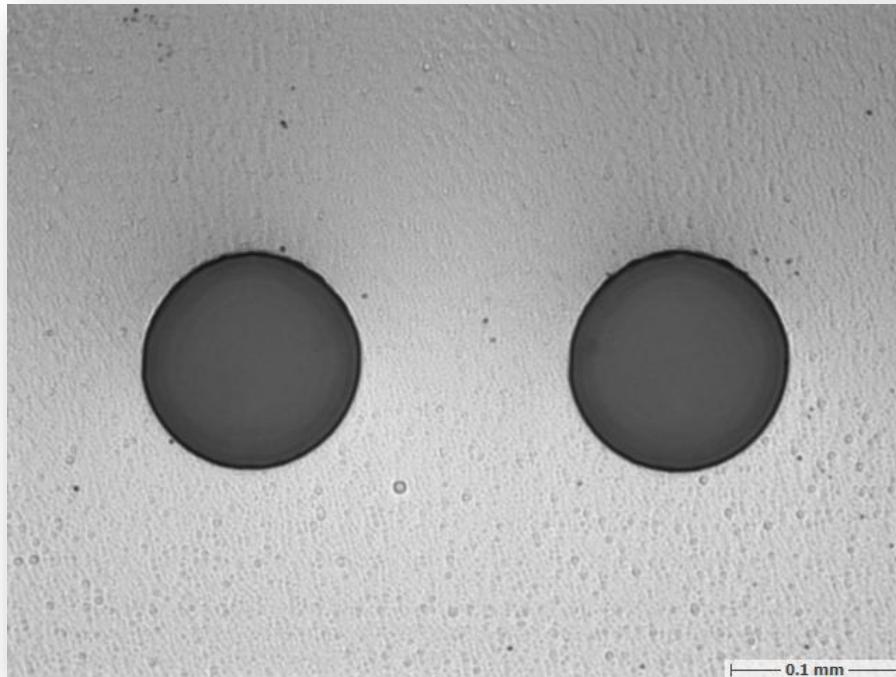


- Single fabrication step: $< \pm 1\mu\text{m}$ relative positioning
- 127 μm pitch v-groove array connector with its cover lid
- In-bulk termination and tapering
- Alignment markers for assembly & packaging

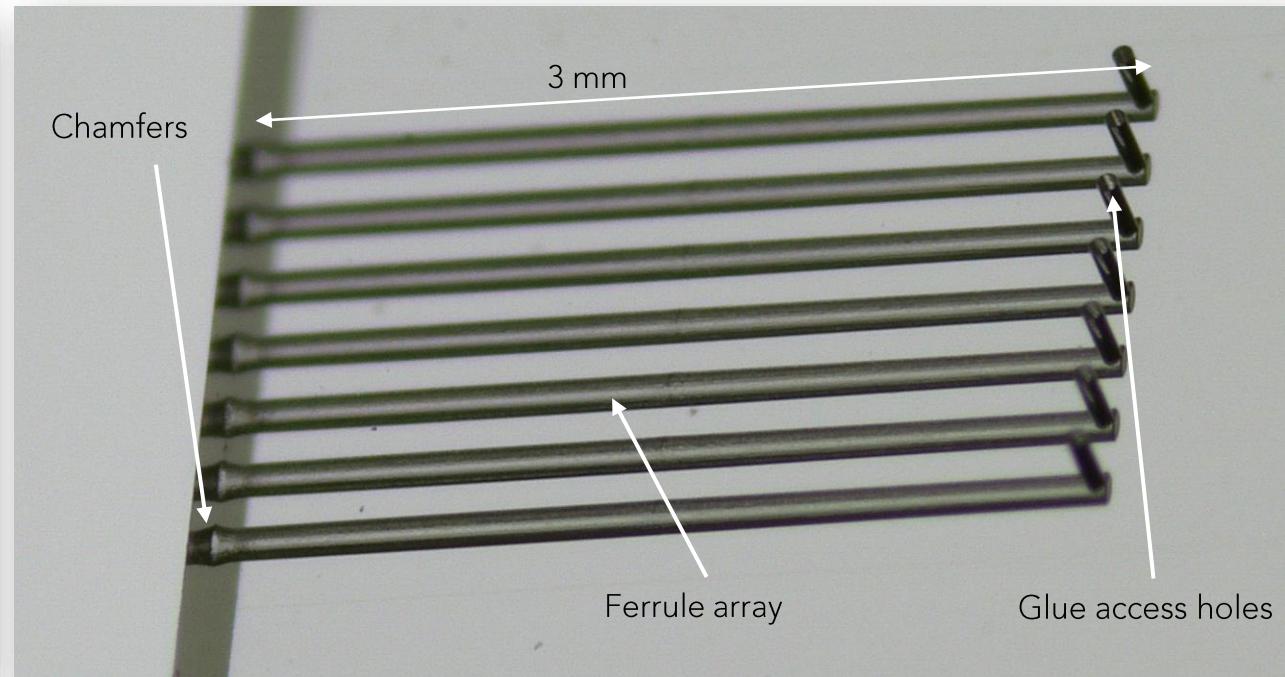
USPs

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

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

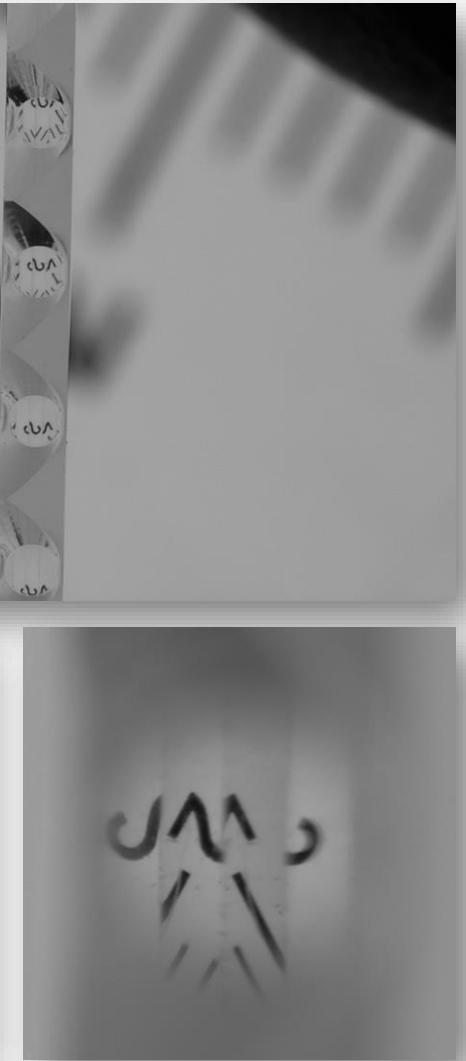
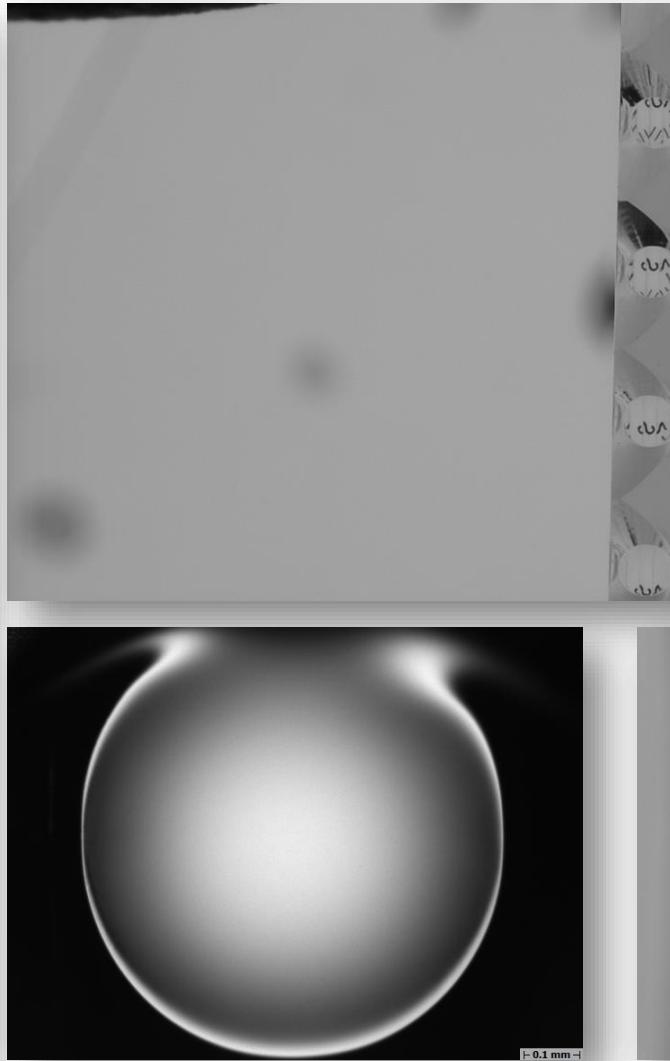
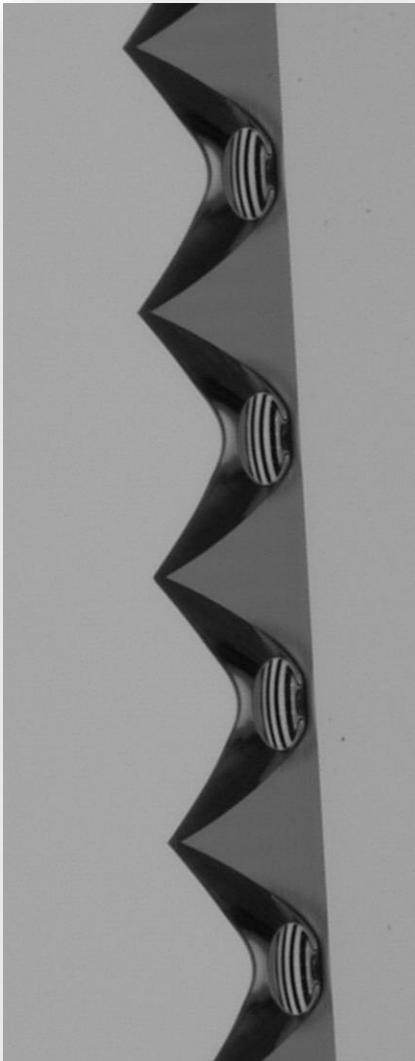
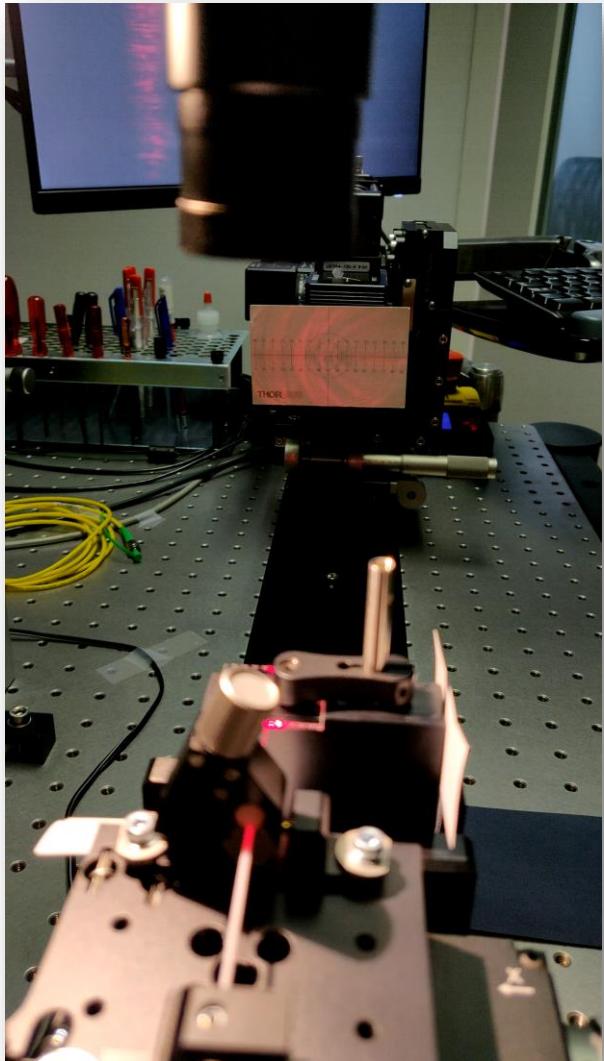


Horizontal ferrules with no chamfer, 0.002 µm circularity



Horizontal ferrules with chamfers and access holes, 0.002 µm circularity

MONOLITHIC INTEGRATION – WAVEGUIDES & MICRO-LENSES





*Thank
you!*



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