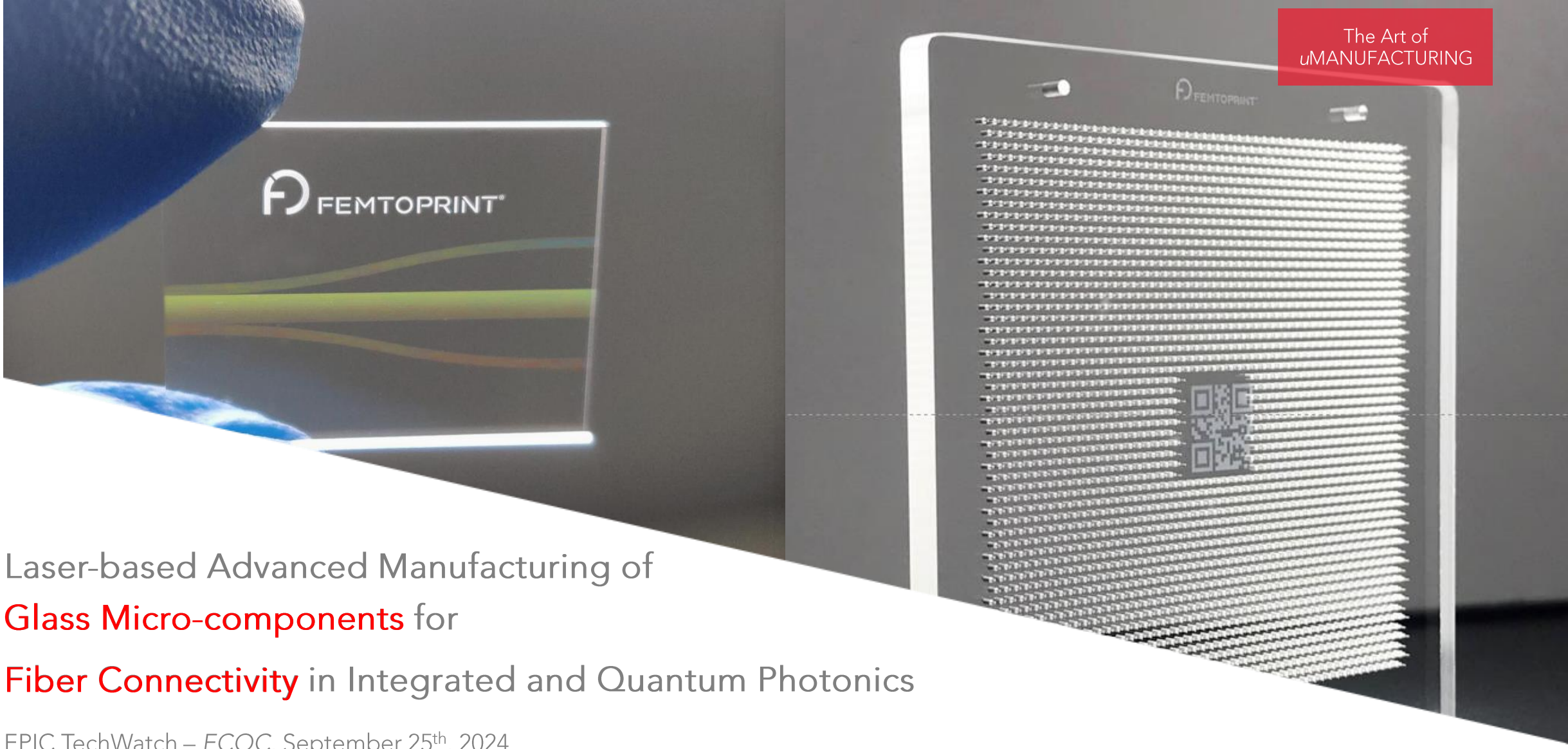


The Art of
*u*MANUFACTURING

Laser-based Advanced Manufacturing of Glass Micro-components for Fiber Connectivity in Integrated and Quantum Photonics

EPIC TechWatch – *ECOC*, September 25th, 2024

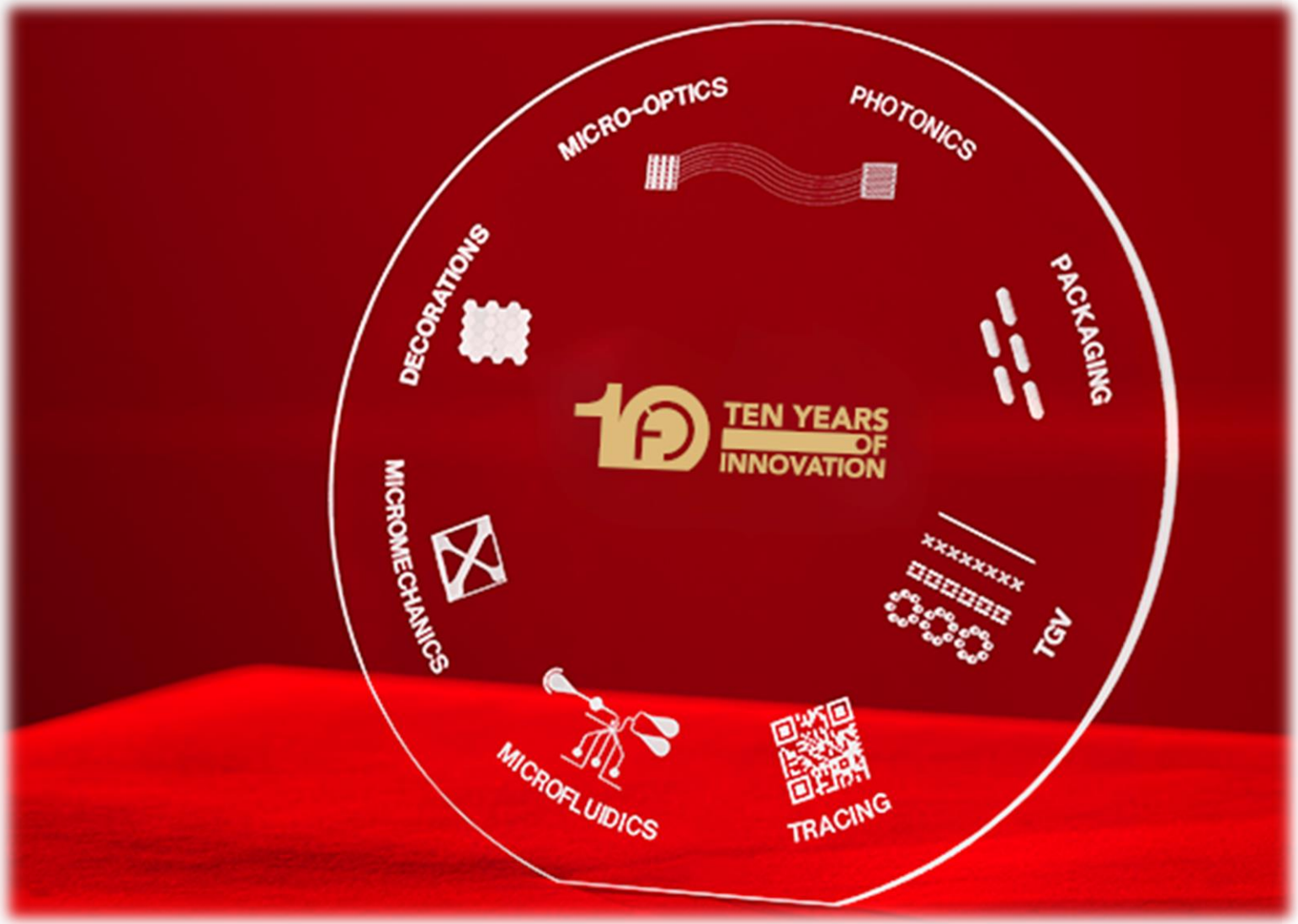
Rolando Ferrini

EPIC
EUROPEAN PHOTONICS INDUSTRY CONSORTIUM

FEMTOPRINT®
3D PRINTING FOR GLASS MICRODEVICES

The Company

01



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

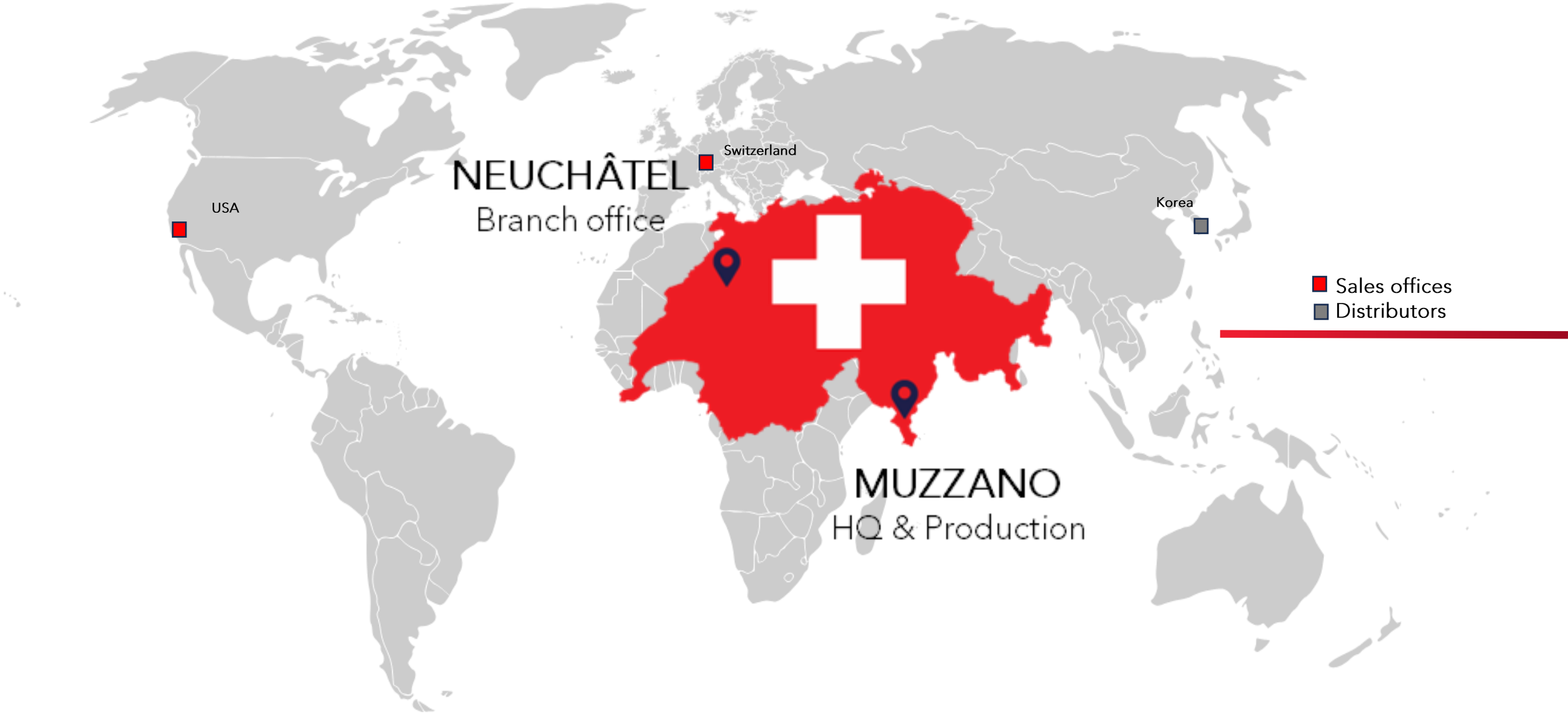
FOUNDED IN
2013

40+ TEAM
MEMBERS

EXPORT TO
30+ COUNTRIES

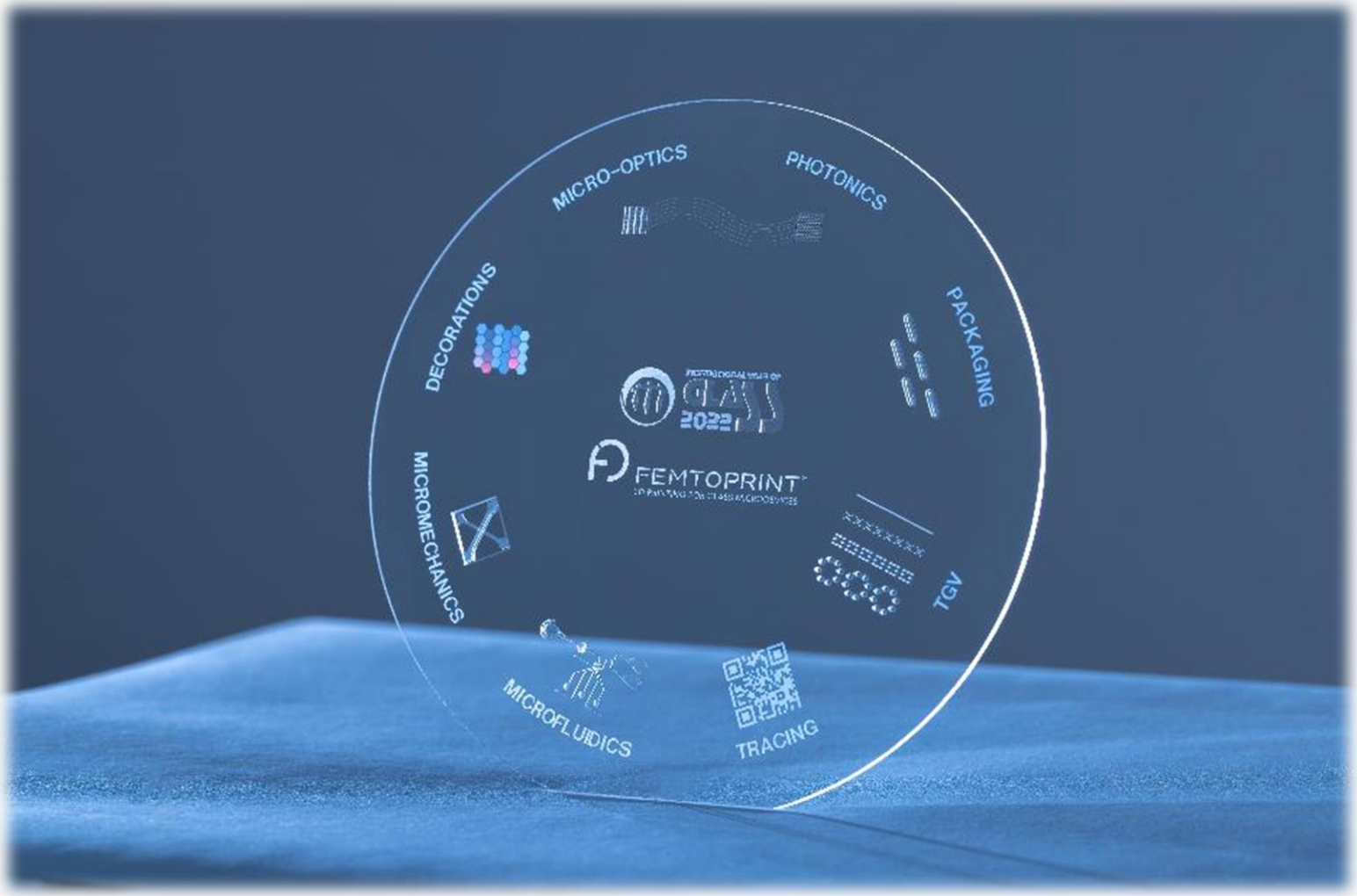
ISO 13485:2016
ISO 9001:2015

The Company


Switzerland
NEUCHÂTEL
Branch office
USA
Korea
MUZZANO
HQ & Production
Sales offices
Distributors

The Technology

02

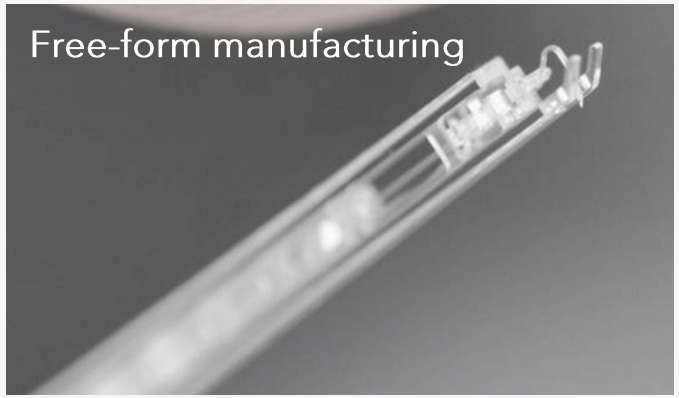


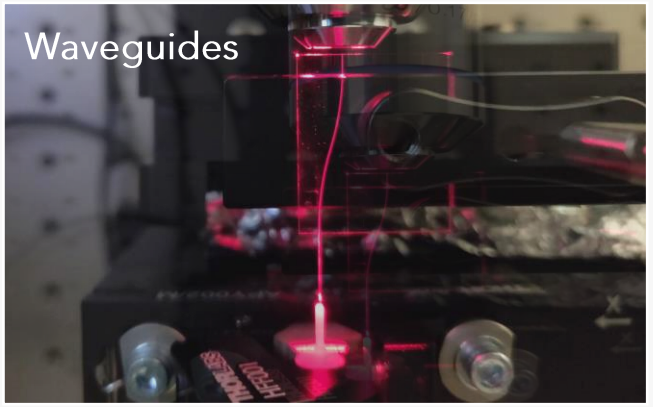
The Technology

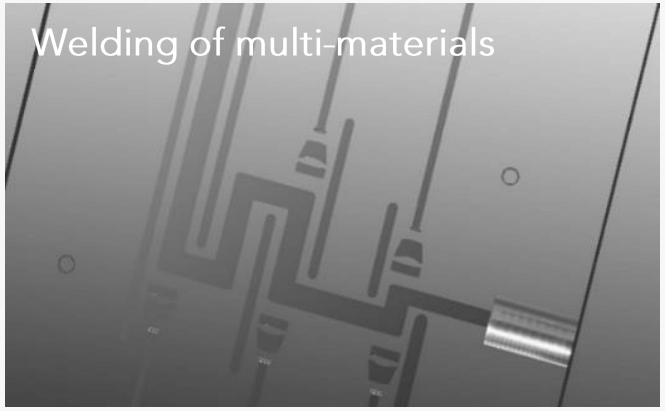
GLASS FAMILIES

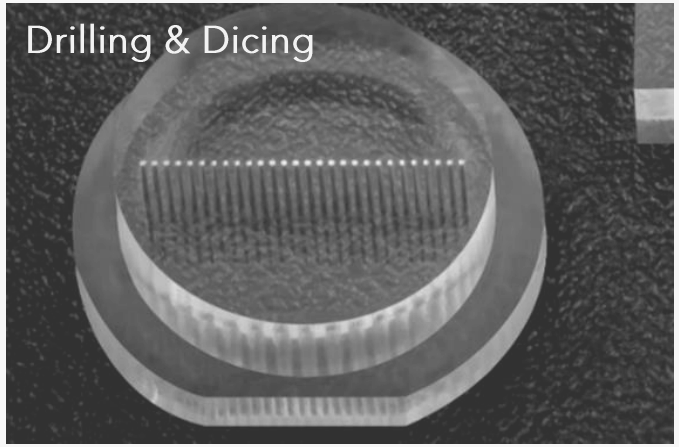
- Fused silica (SiO_2)
- Fused quartz
- Borosilicate
- ULE® (Ultra-Low Expansion)
- Aluminosilicate
- Alkali-free
- Other custom materials

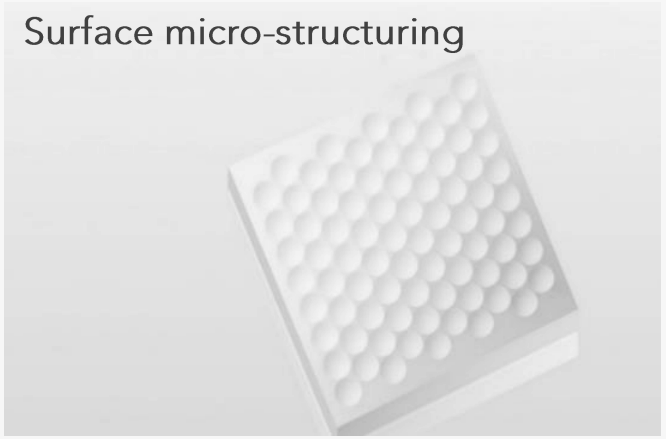
CAPABILITIES







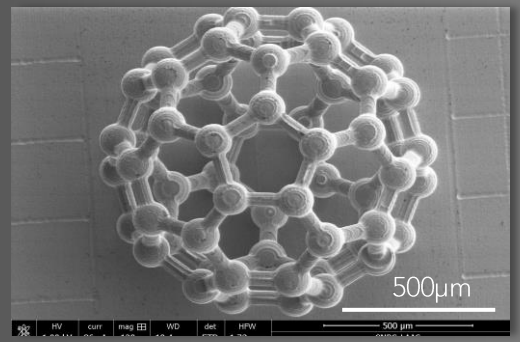


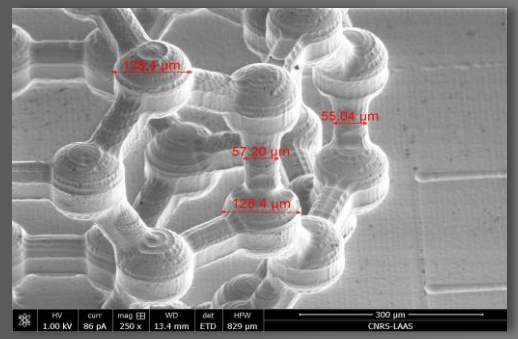


PERFORMANCES

RESOLUTION AND TOLERANCES

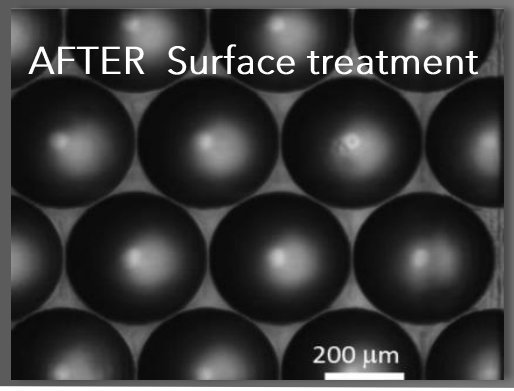
- Process resolution ~ 1 µm
- XY tolerances +/- 1 µm
- Z tolerance +/- 2 µm





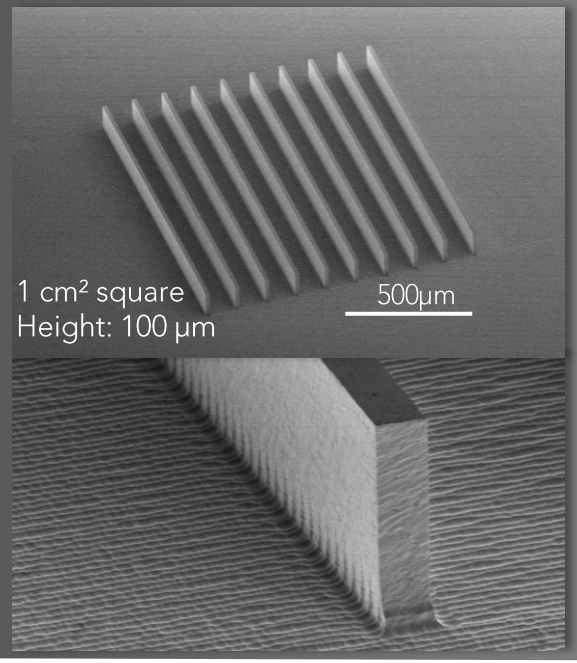
SURFACE QUALITY

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



ASPECT RATIO

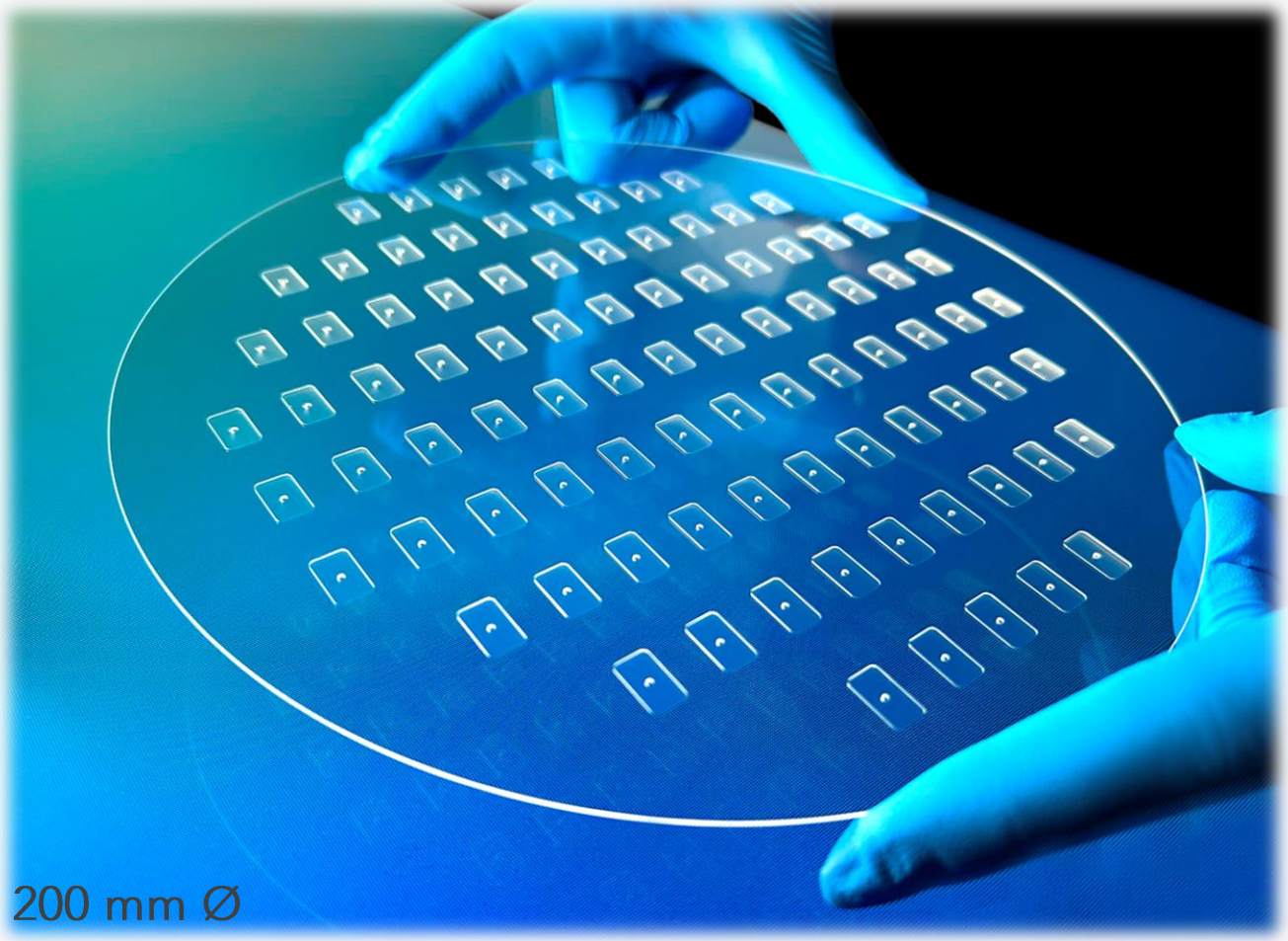
- Hole aspect ratio > 1:500
- Substrate thickness up to 30 mm
- Min. hole diameter < 5 µm Ø
- Sidewall deviation < 0.1°
- Sidewall roughness Sa < 100 nm



WAFER-SCALE FABRICATION

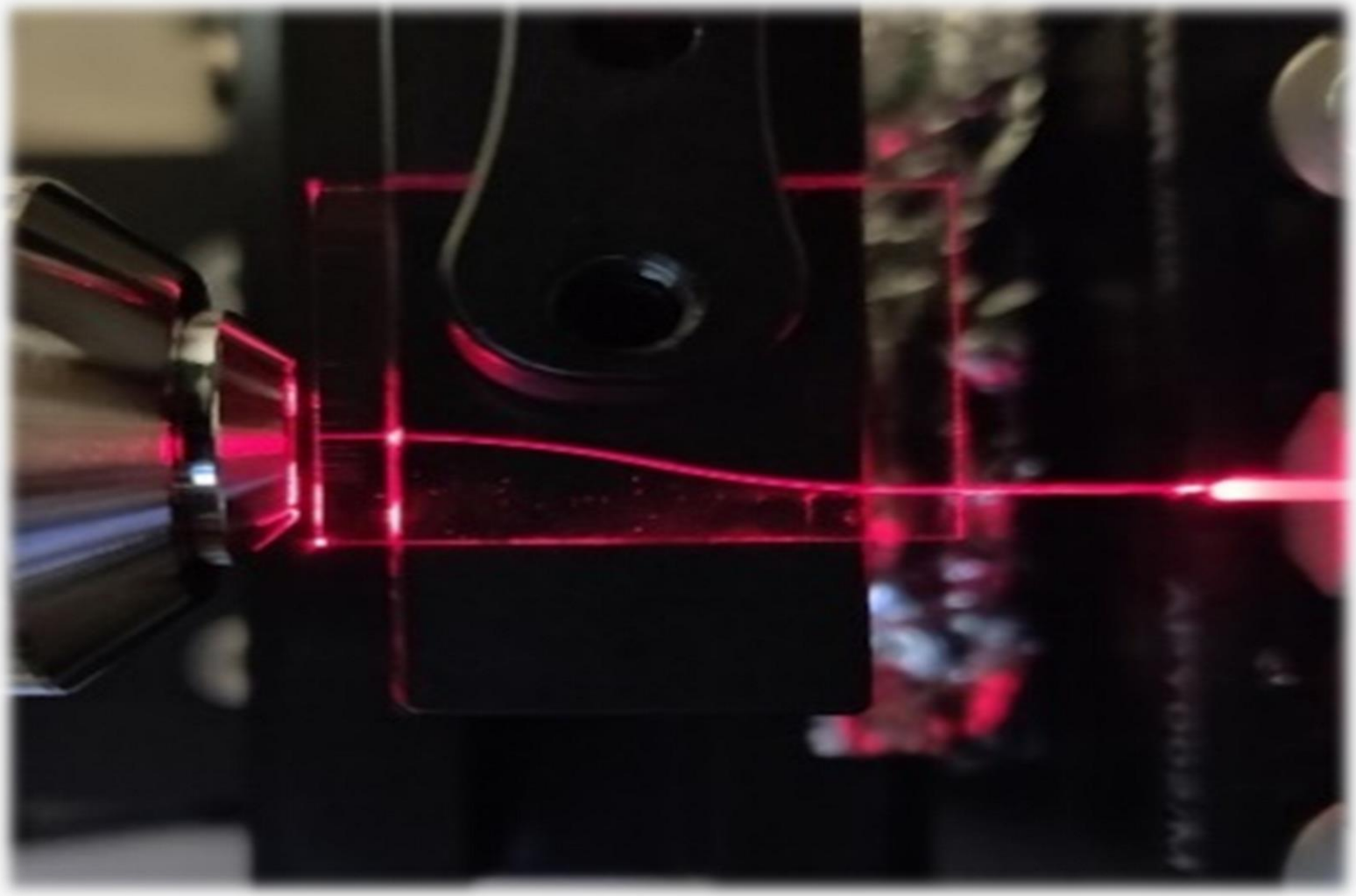
ADVANTAGES

- **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



Optics & Photonics

03

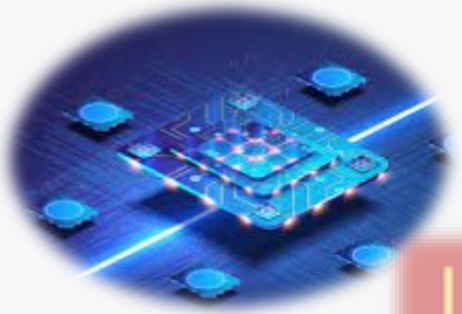


Fiber-to-chip connectivity for Integrated & Quantum Photonics

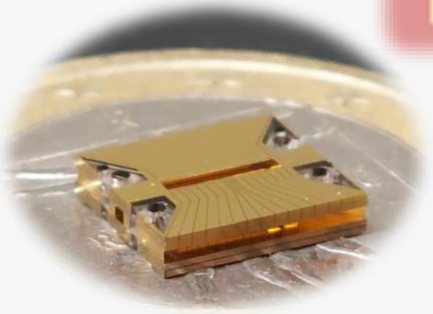
FROM DEVICES …

… TO PRODUCTS

PICs

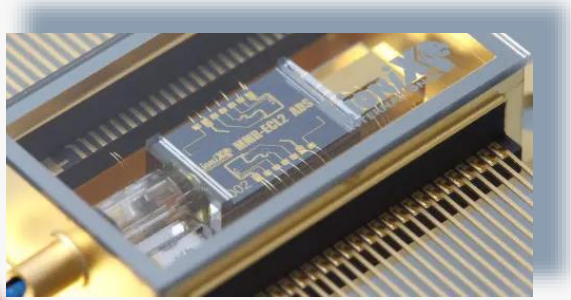


Quantum Chips

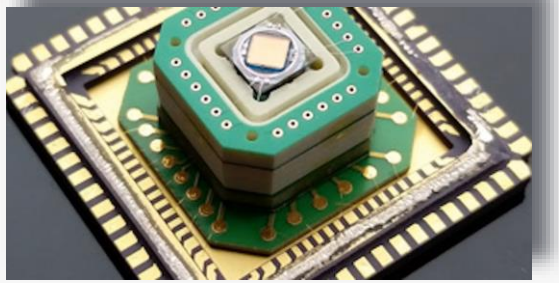


PACKAGING

ASSEMBLY



Optical Transceivers, Sensors, LIDAR, etc.



Sensors, Computing & Communication hardware, etc.

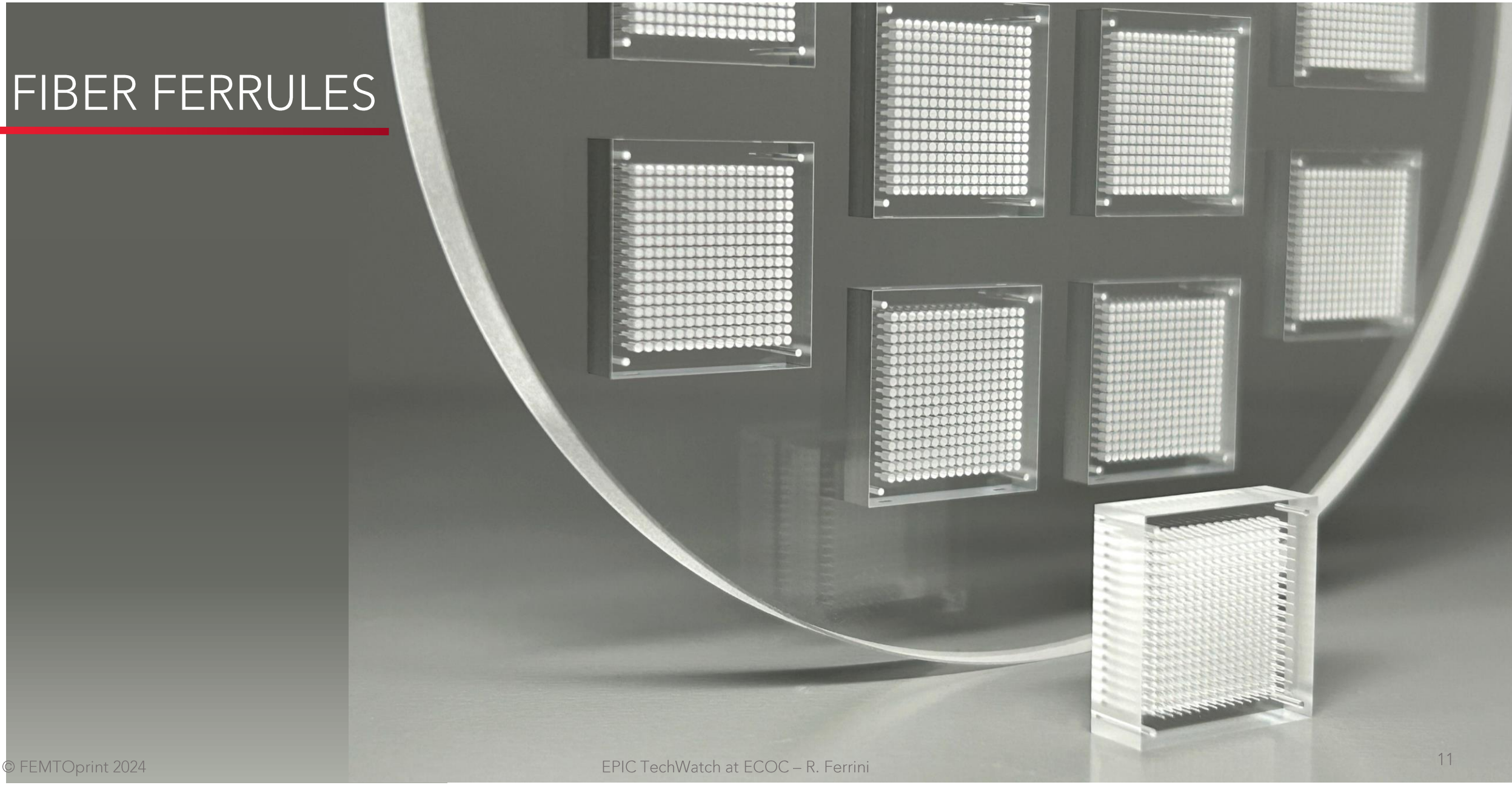
FIBER-TO-CHIP CONNECTIVITY

FIBER FERRULES

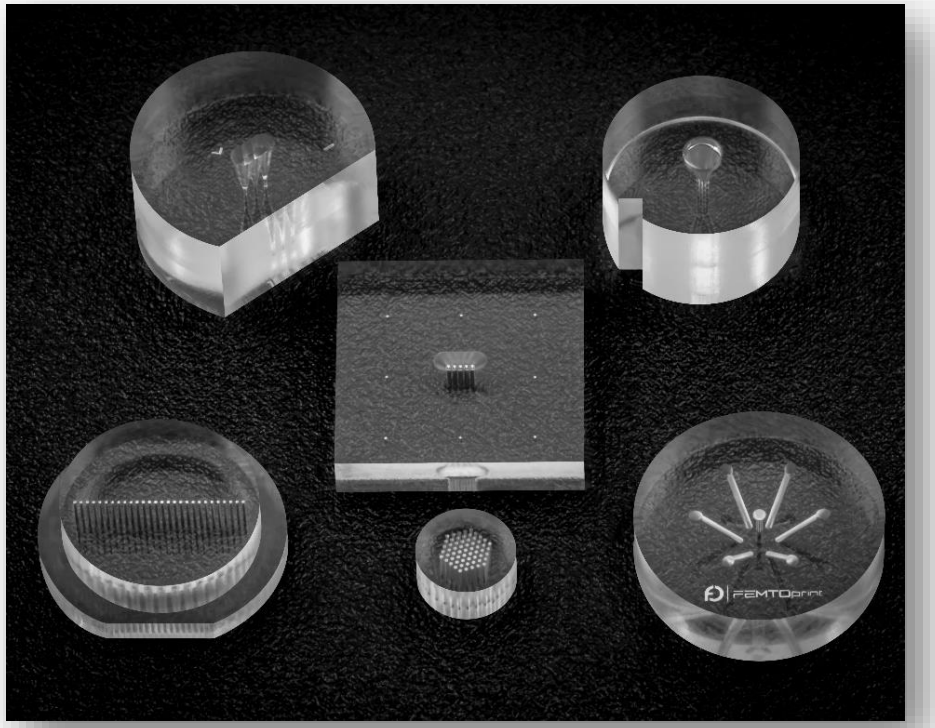
WAVEGUIDES

MICRO-OPTICS

FIBER FERRULES



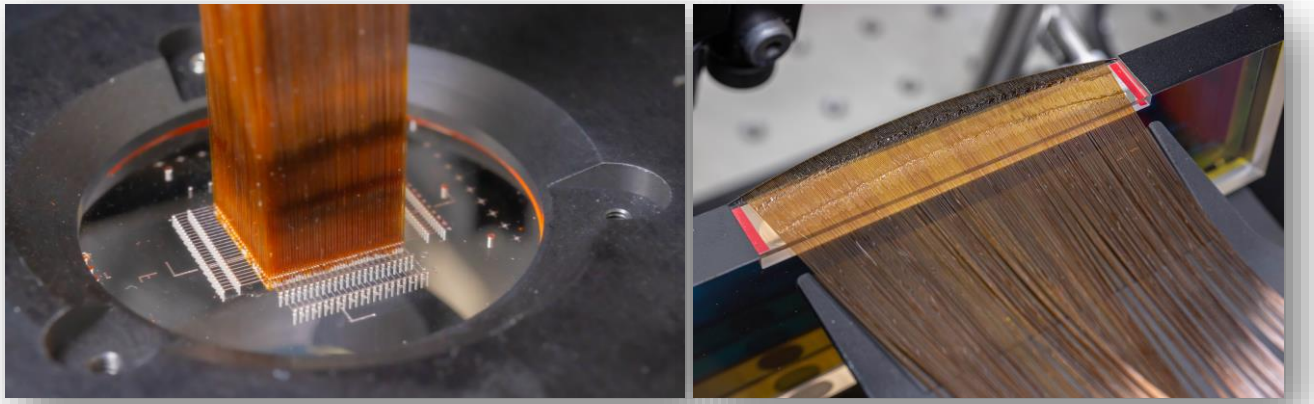
Glass ferrules for high-precision fiber alignment



MECHANICAL POSITIONING

EXAMPLE

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



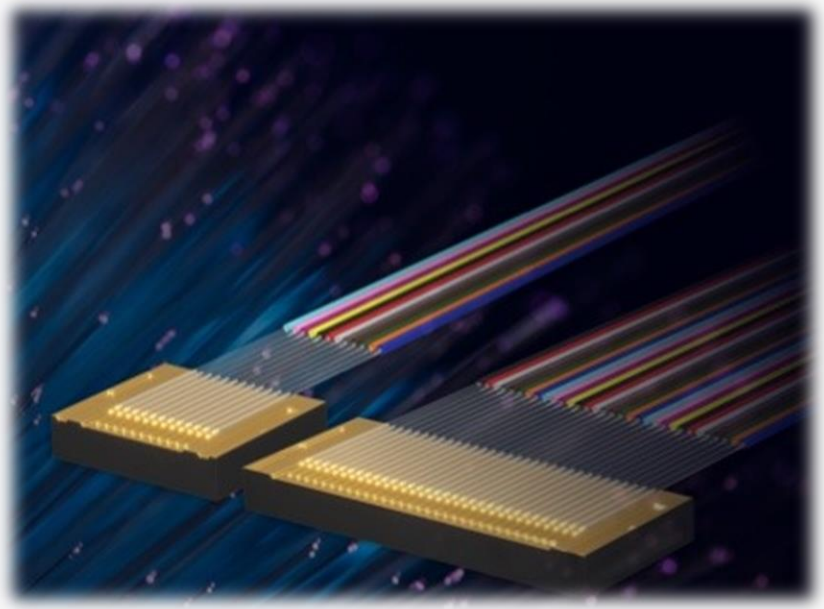
Courtesy of Gábor Fûrész, MIT Kavli Institute for Astrophysics and Space Research

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

New requirements for fiber connectivity in telecom & datacom

MECHANICAL POSITIONING



The current trend in telecom & datacom …

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

… requires

- High-precision fiber-to-chip connectivity
- Advanced micro-manufacturing technologies
  - ➔ High resolution
  - ➔ Cost-effective deployment
  - ➔ Increased amount of integrated functionalities

New requirements for fiber connectivity in telecom & datacom

MECHANICAL POSITIONING

IEC standards for quality grade of fiber connections

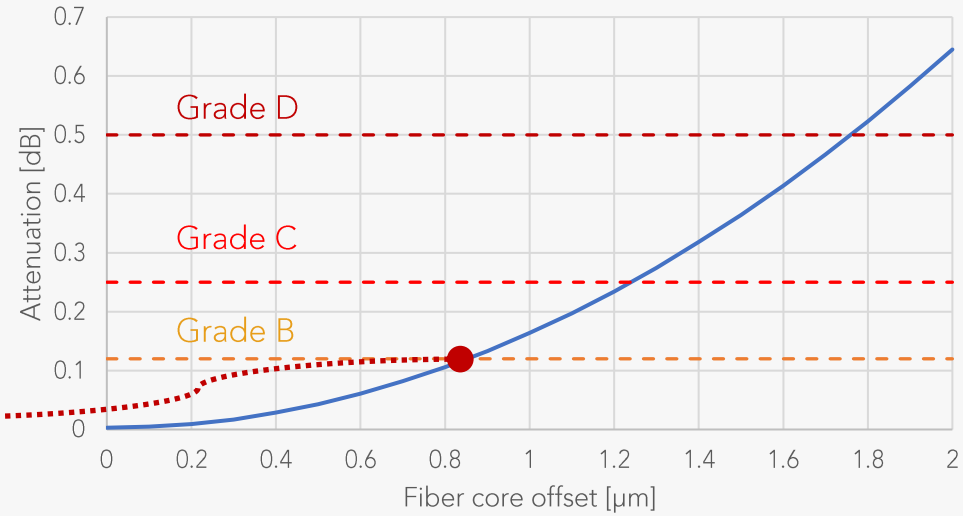
Attenuation grade	Attenuation (≥ 97%)	Mean attenuation	*Notes*
A			*Reserved for future application*
B	≤ 0.25 dB	≤ 0.12 dB	*Current state of the art*
C	≤ 0.5 dB	≤ 0.25 dB	
D	≤ 1.0 dB	≤ 0.5 dB	

**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 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



Advanced manufacturing of high-precision fiber ferrules

MECHANICAL POSITIONING

1D - *V-grooves* -		2D - *Hole arrays* -	
TECHNOLOGY	CENTER-TO-CENTER ACCURACY	TECHNOLOGY	CENTER-TO-CENTER ACCURACY
Grinding	± 1 µm	Drilling	± 10 µm
Photolitho + Etching	< ± 1 µm ↓ ± 0.5 µm	Photolitho + Etching	± 1-2 µm
Laser writing + Etching		Laser writing + Etching	< ± 1 µm ↓ ± 0.5 µm

➔ Quality control with sub-micron precision

➔ Fiber tolerances

➔ Assembly & Process tolerances

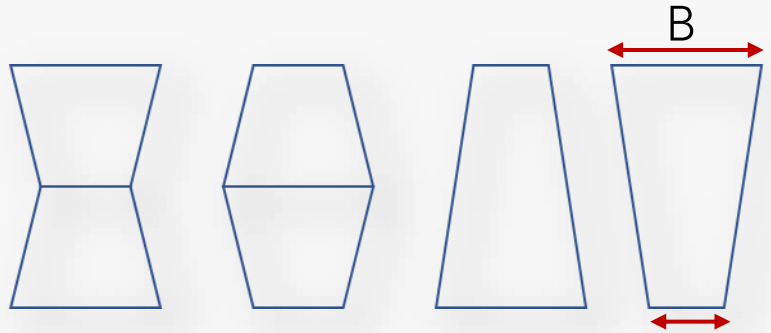
Hole shape

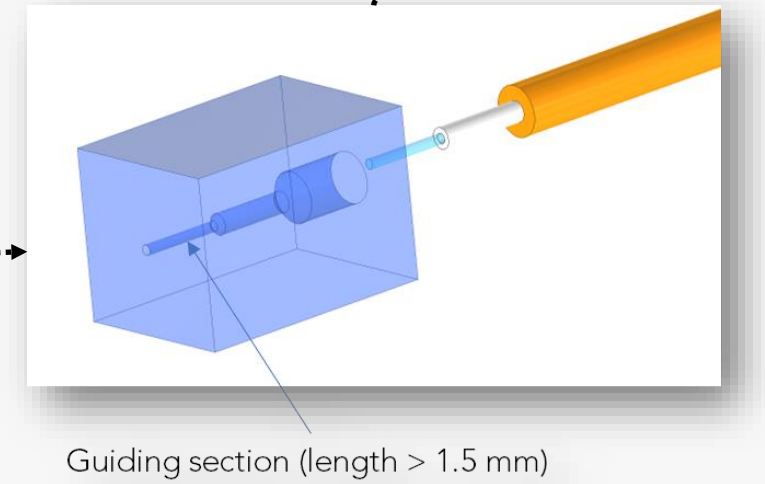
- The hole shape can vary

- Mechanical measurements
- Optical measurements

- 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

MECHANICAL POSITIONING

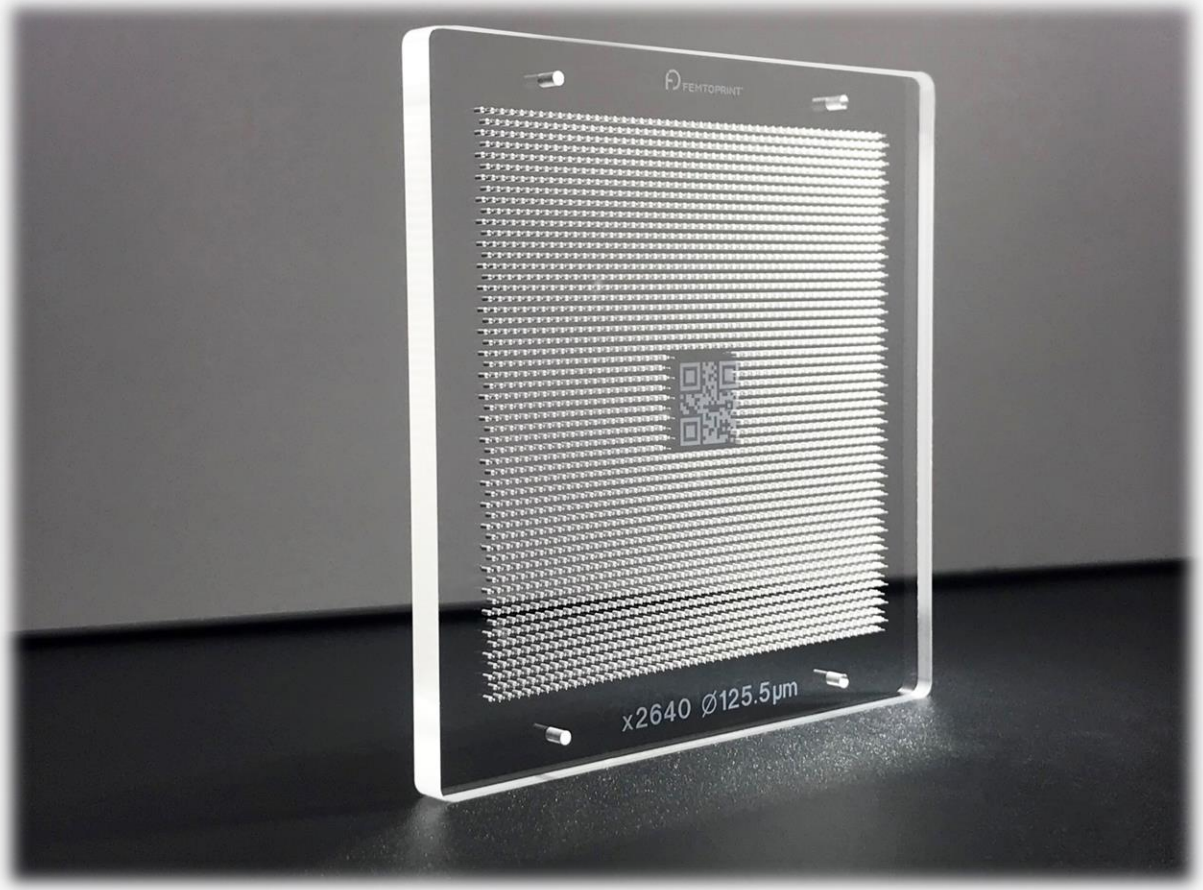




2D hole arrays for high-precision fiber ferrules

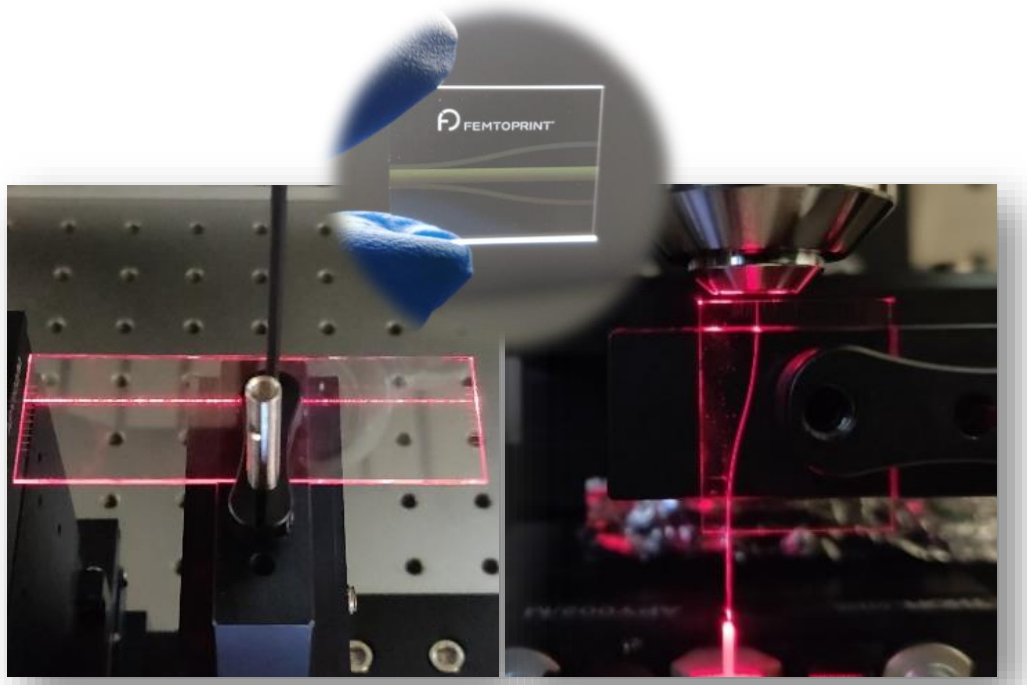
MECHANICAL POSITIONING

- 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

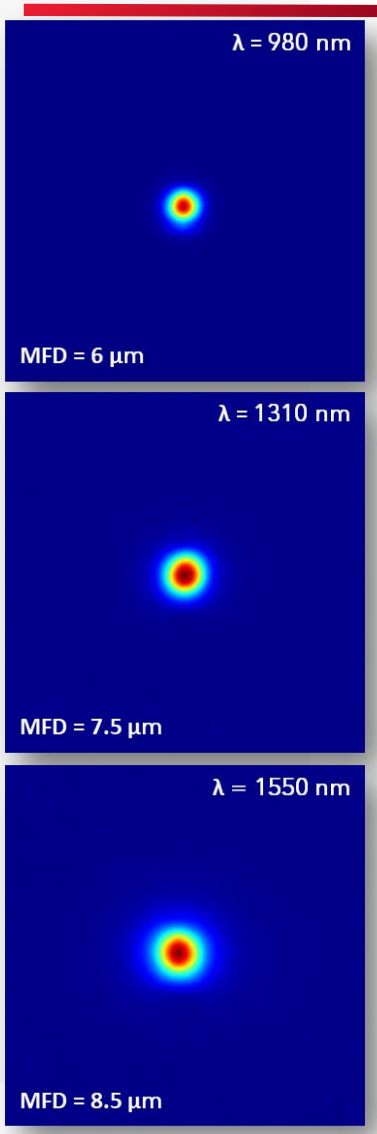
3D GLASS WAVEGUIDES



- 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 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}

LIGHT GUIDING



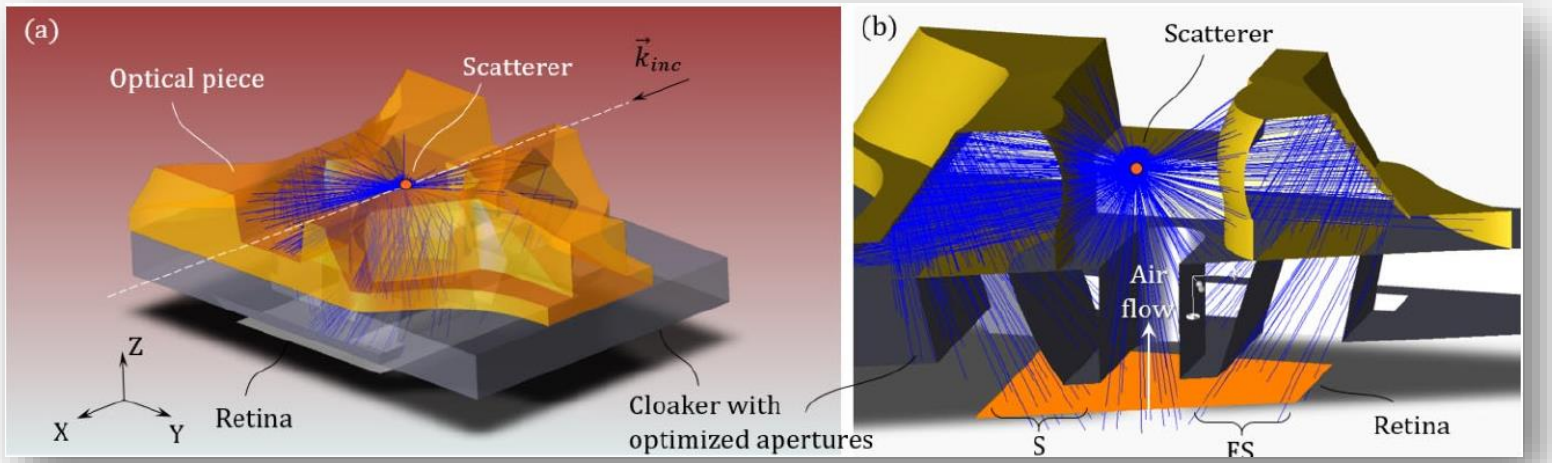
MICRO-OPTICS

Miniaturized optics

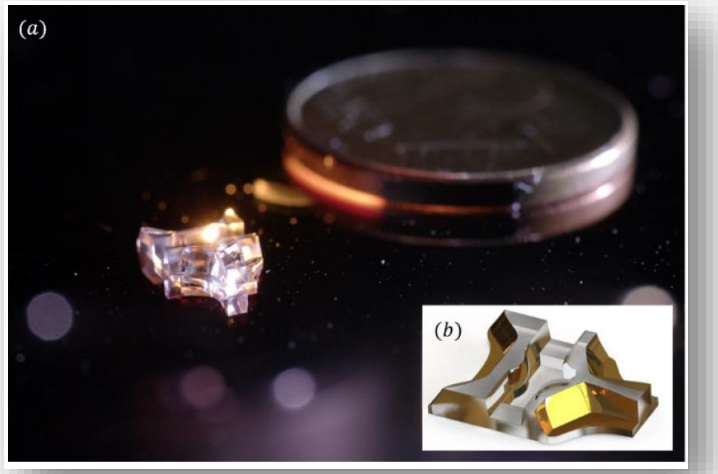
BEAM SHAPING

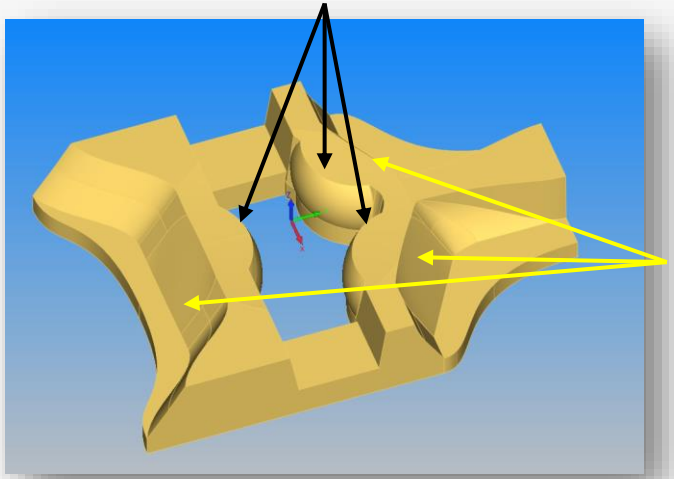
APPLICATION
- Air quality monitoring
- Improved sensitivity
- Integration of a miniaturized refractive/reflective optical system

USPs
- Monolithic integration
- 3D free-form fabrication
- Miniaturized optics



Slanted diopters



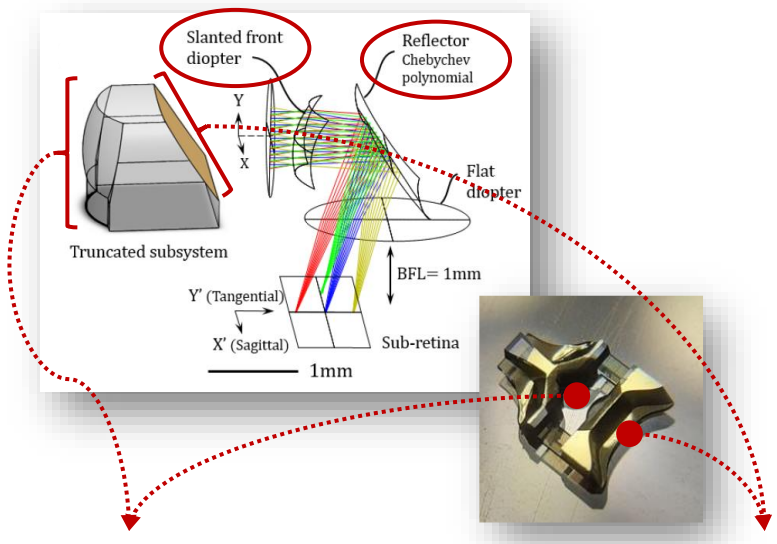


Free-form reflectors

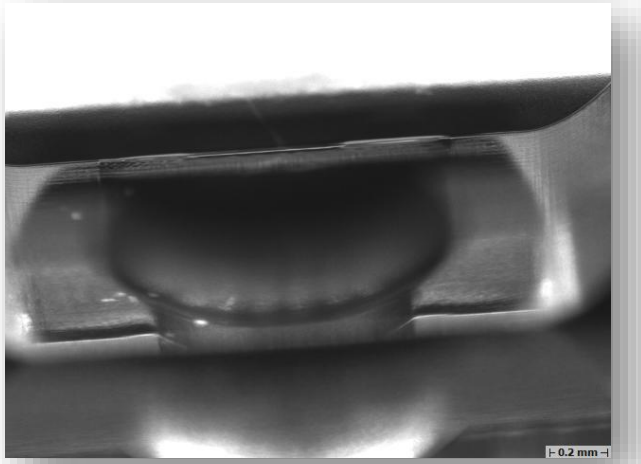
CEA-LETI Minatec & Institut des Nanotechnologies de Lyon : Jobert G. et al., Sensors 2021, 21, 3181.

Miniaturized optics

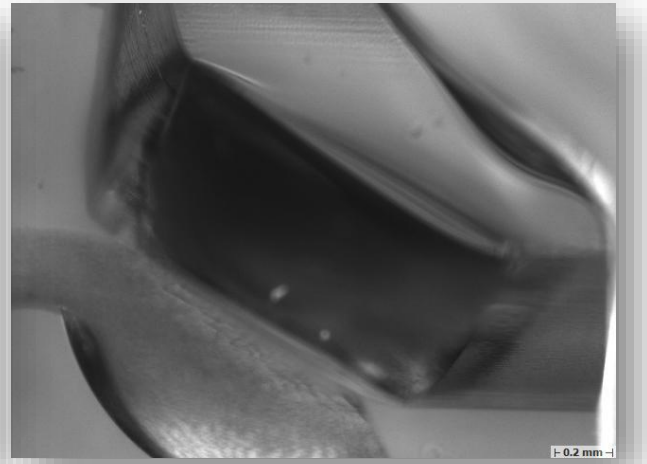
BEAM SHAPING



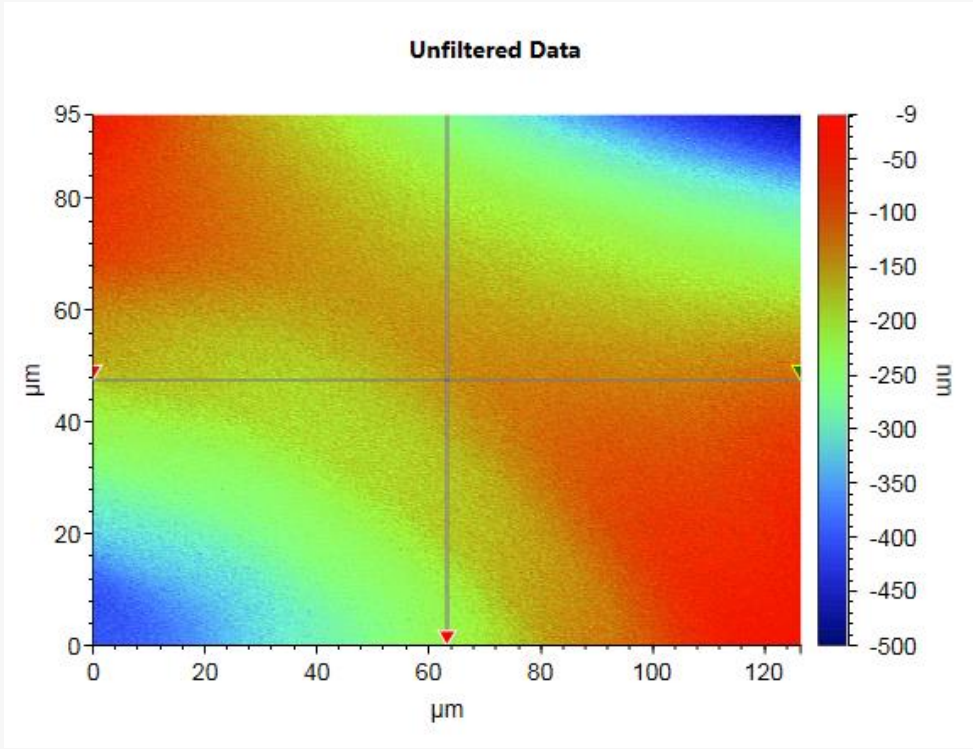
Slanted diopter



Free-form reflector



Interferometric image of the reflector surface



Surface roughness: Sa = 6nm

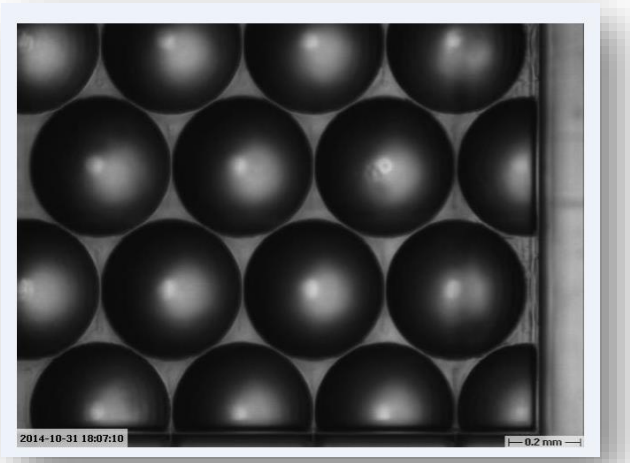
CEA-LETI Minatec & Institut des Nanotechnologies de Lyon : Jobert G. et al., Sensors 2021, 21, 3181.

Micro-optics

BEAM SHAPING

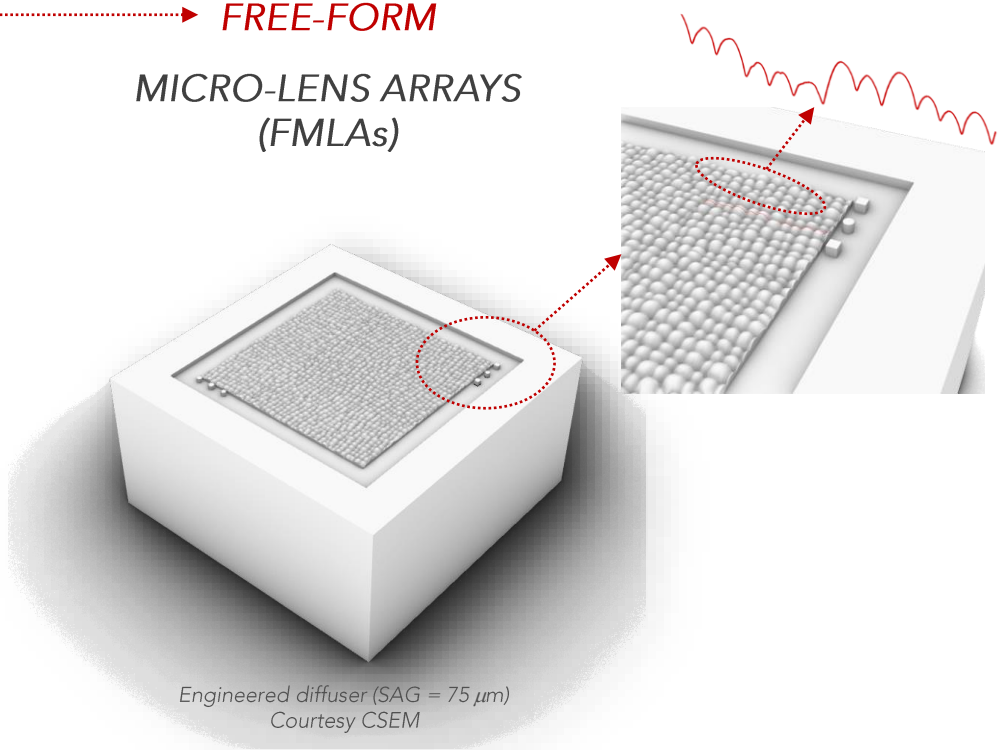
SPHERICAL or ASPHERICAL → *NON-SPHERICAL* → *FREE-FORM*

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

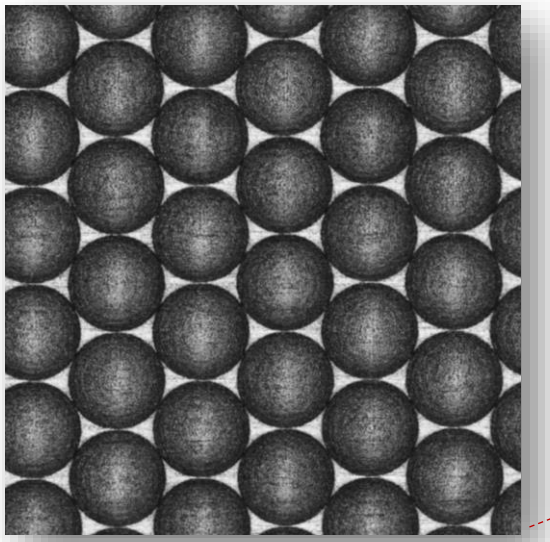
Enabling large volume production

Shallow Micro-Lens Array

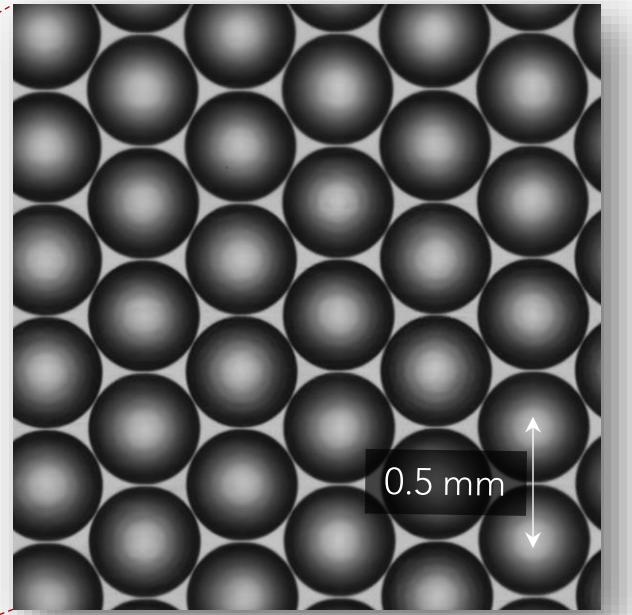
Hexagonal closely packed MLA

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

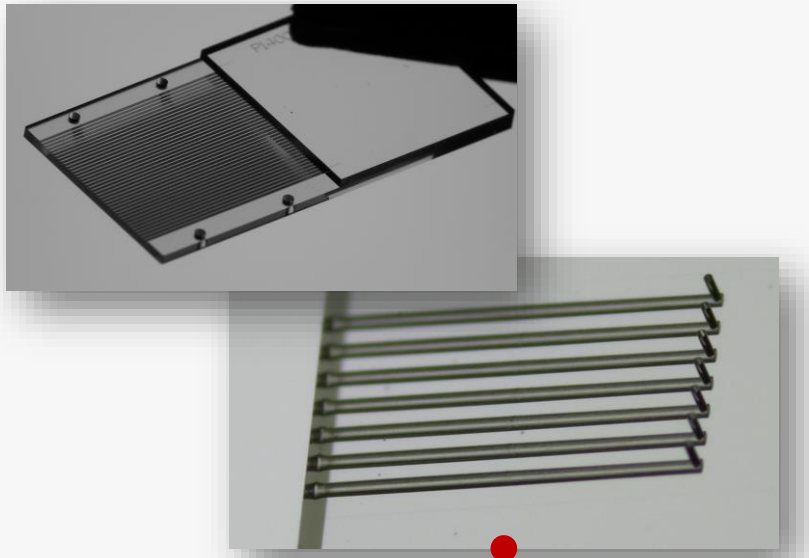
Value proposition for optics & photonics products

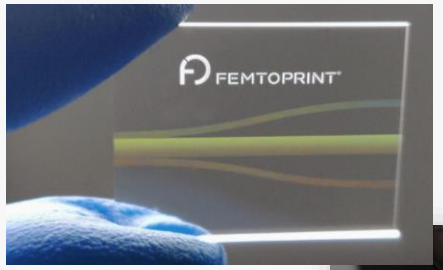
MONOLITHIC INTEGRATION

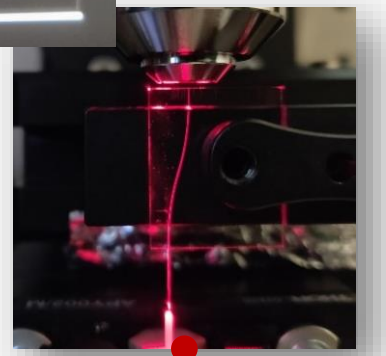
HIGH-PRECISION FIBER ALIGNMENT

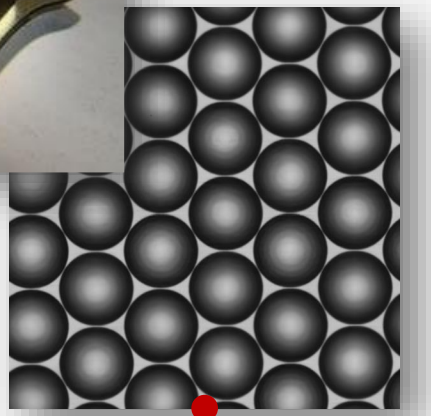
BEAM ROUTING

BEAM SHAPING

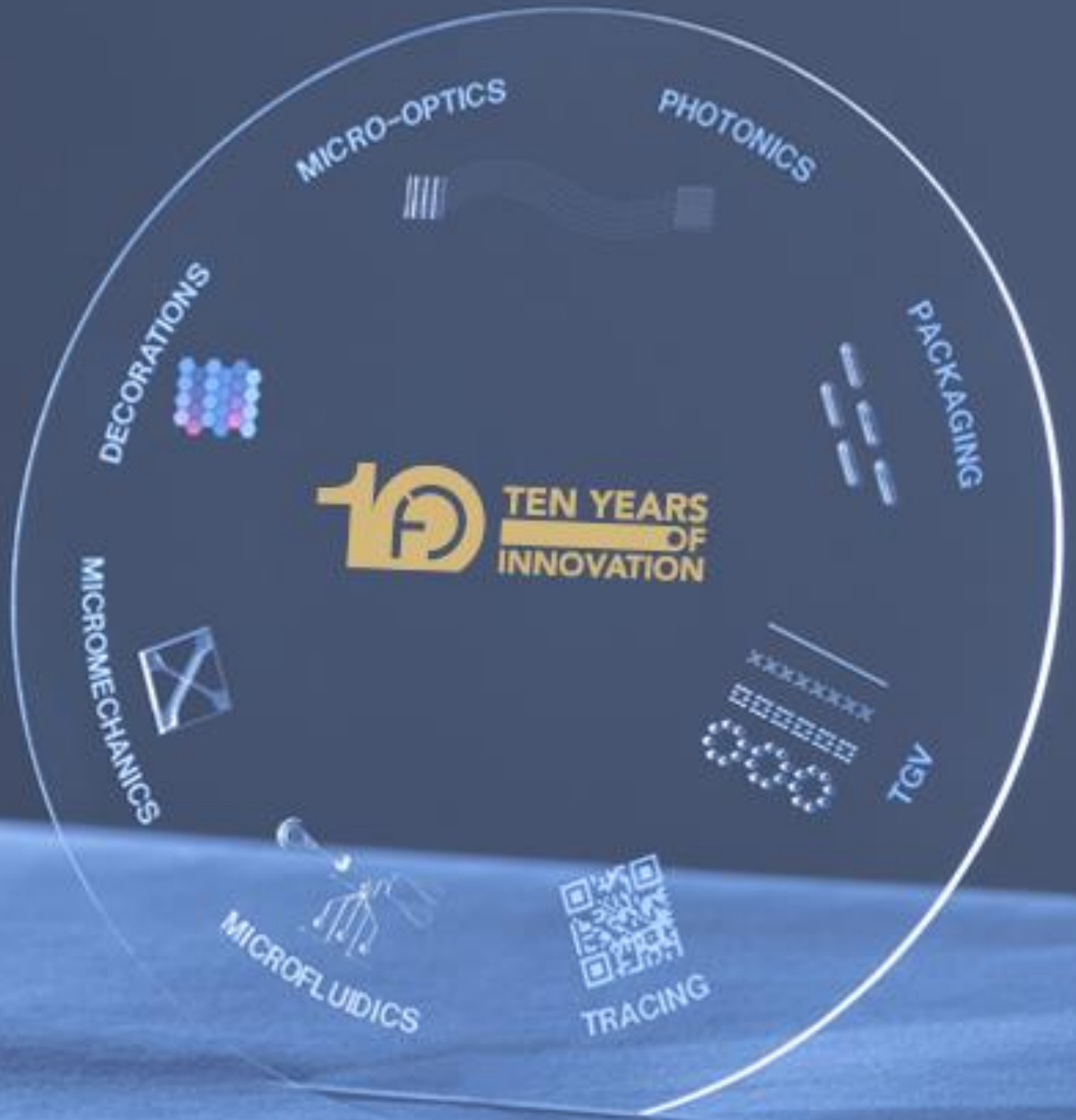








- < ± 1µm relative positioning
- Monolithic integration of several functionalities
- Optical systems for fiber-to-chip connectivity



Thank you!

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