3D printing of glass structures for new surgical tools

Yves Bellouard & Charles Baur

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Galatea Lab

An extended campus

Geneva - **Campus Biotech**
- Bio- and neuroengineering (Wyss center)
- Human Brain Project
- Center for neuroprosthetics

• 320 staff
• 9 chairs
• 26,000 m²

Neuchâtel - **Microcity**
- Microengineering and nanotechnologies

• 230 staff
• 11 chairs
• 8035 m²

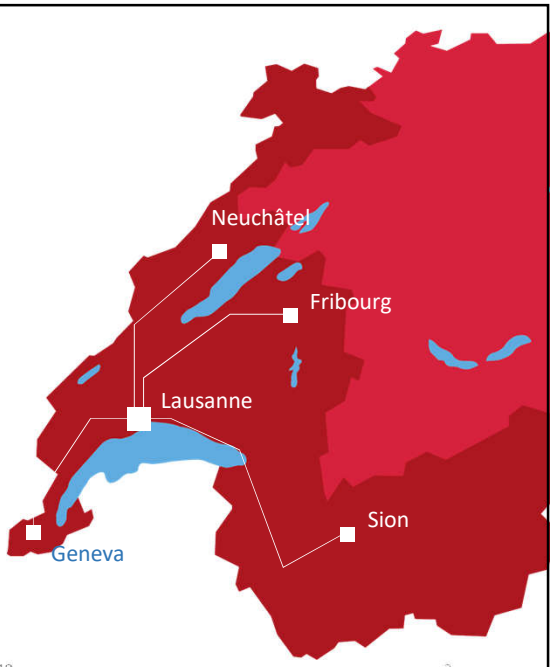
Fribourg - **Smart Living Lab**
- Building technology and sustainable architecture

• 19 staff
• 2 chairs + 1 RG*
• 1370 m²

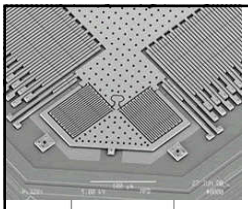
Sion - **Energypolis Campus**
- Industrial energy
- Green chemistry
- Environmental engineering
- Biotechnology
- Bioengineering

• 176 staff
• 10 chairs + 3 RG*
• 7600 m²

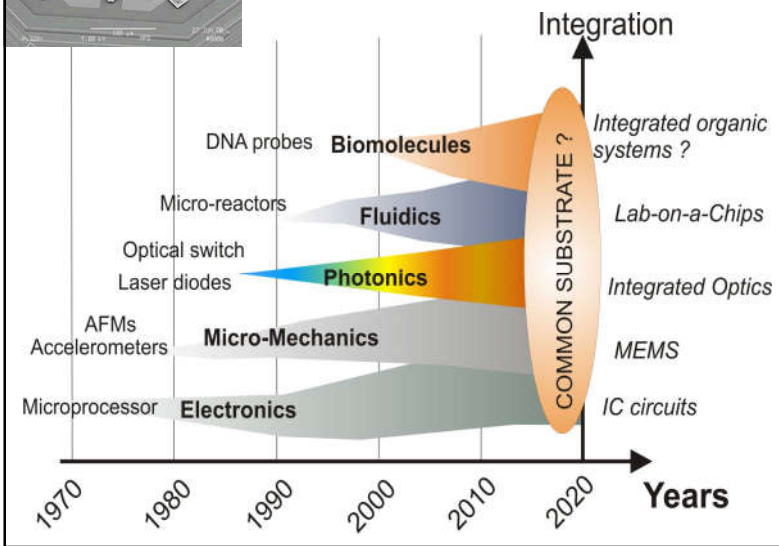
* Research groups



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



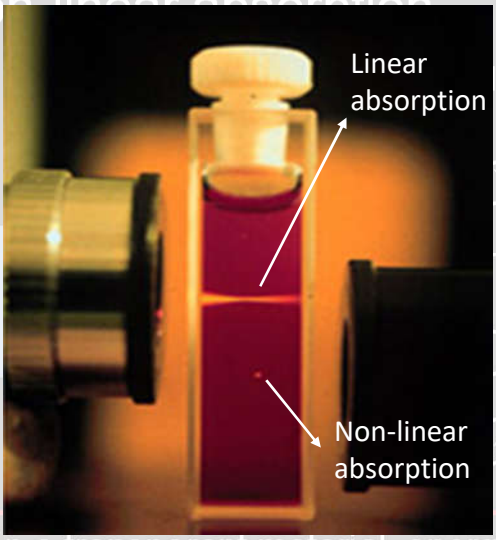
System integration at the microscale



Can we make complex devices out of a single monolith?

'Direct-write' 3D systems?

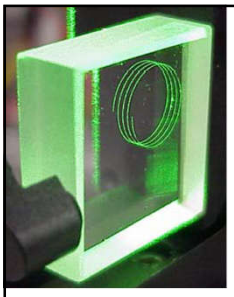
Non-linear absorption



(source: Amos, Cambridge)

Energy is only absorbed at the focal volume

In a transparent material, energy can be absorbed in the volume



(Translume Inc.)

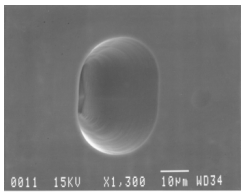
Femtosecond laser applied to fused silica leads to a variety of effects...

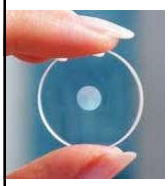
✦ Local increase of refractive index

K. M. Davis et al. , Opt. Lett. ***21****, 1729-1731 (1996).*
K. Miura et al., Appl. Phys. Lett. ***71****, 3329 (1997).*

✦ Increase of etching rate in HF or KOH

Y. Kondo et al., Jpn. J. Appl. Phys. ***37****, L94 - L96 (1998)*
A. Marcinkevičius et al., Opt. Lett. ***26****, 277-279 (2001)*
S. Kiyama, et al., J. of Phys. Chem. C ***113****, 11560-11566 (2009)*



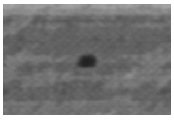


✦ Form birefringence

E. Bricchi, B. G. Klappauf, and P. G. Kazansky, Opt. Lett. ***29****, 119–121 (2004).*

✦ Voids

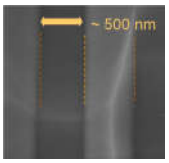
E.N Glezer, E. Mazur, APL ***71****, 882 (1997).*



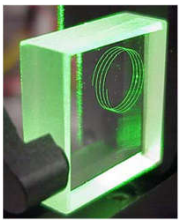
✦ Melt (cumulative regime)

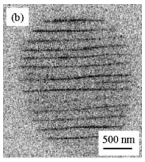
*C. Schaffer, et al., Appl. Phys. A****76****, 351–354 (2003)*
S. Eaton, et al., Opt. Express ***13****, 4708–4716 (2005)*

Functional integration...



• 'Homogeneous' → Waveguides, Gratings, ...



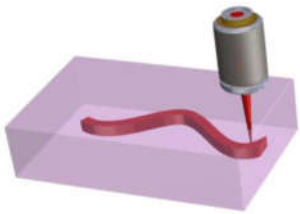


• Nanogratings → 3D machining, Controlled birefringence, ...

• Cumulative regime → Weld joints, Self-organized gratings,...

3D-machining in glass with femtosecond laser processing

1/ Laser exposure **(no ablation)**

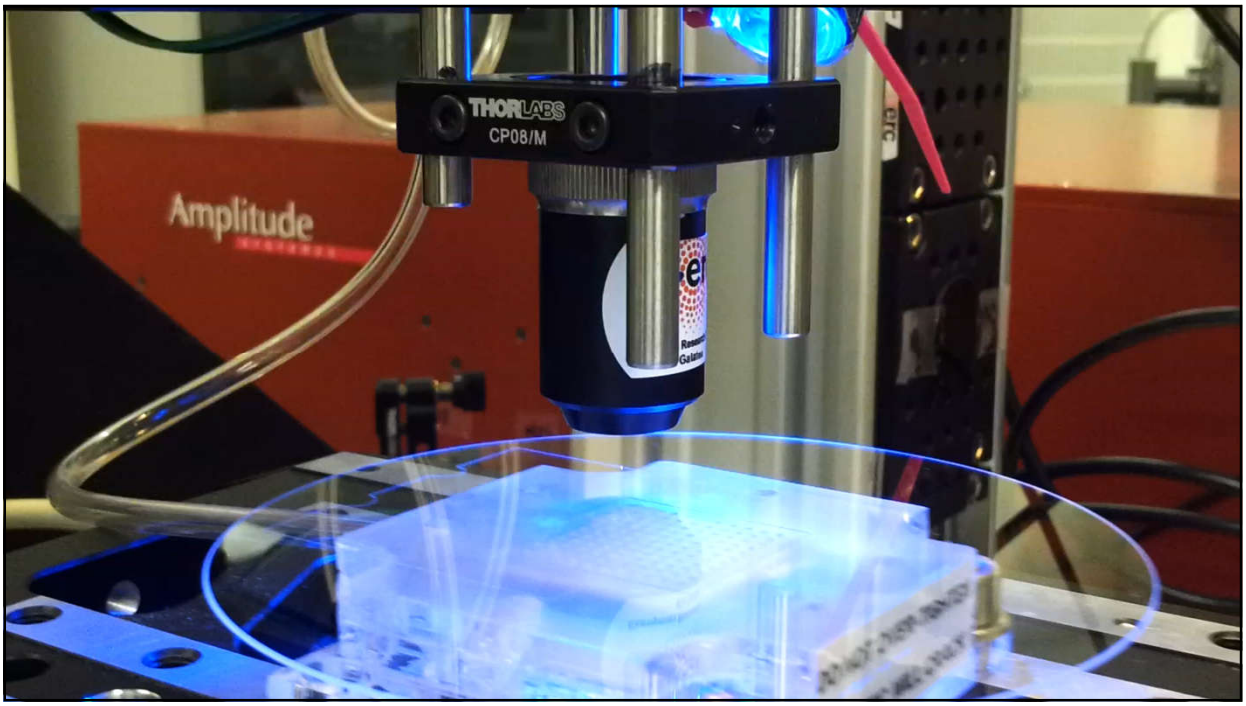


- Femtosecond laser exposure (Ti-Sapphire, ~100fs pulses, 250 kHz rep-rate**, low-pulse energy <1 μJ**) – "Exposure" (both fluidic and waveguide) and (Yb) 500fs pulses, 870kHz

2/ Chemical etching **('development step')**

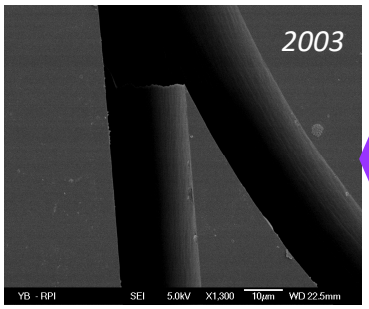
- Etching in a low concentration HF bath (2.5 to 5%) or KOH

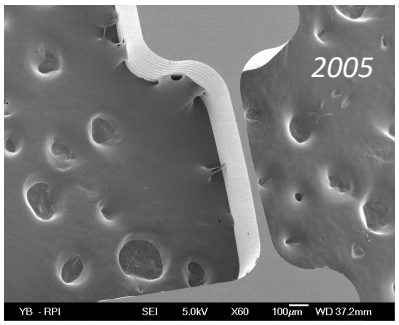
*Y. Bellouard, A. Said, M. Dugan, P. Bado, Optics Express, **12**, 2120-2129 (2004).*

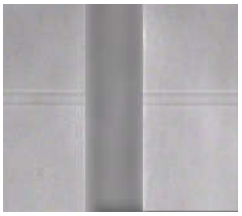


Applications in three-d microfabrication

Multifunctional integration

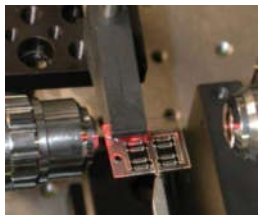






"Optofluidics"

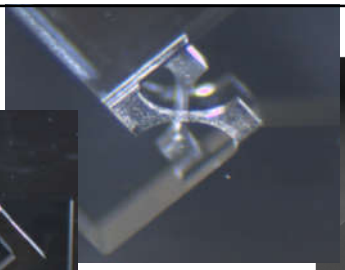
2003

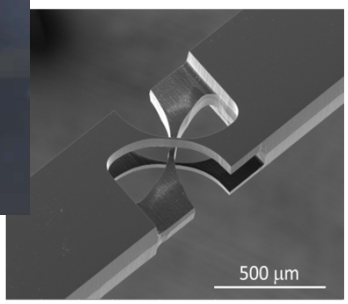


"Optomechanics"

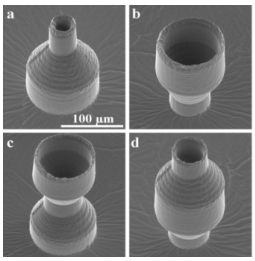
2005

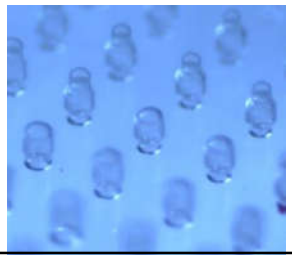
From three dimensional hinge...





*V. Tielen and Y. Bellouard, Micromachines **5**, 697–710 (2014).*

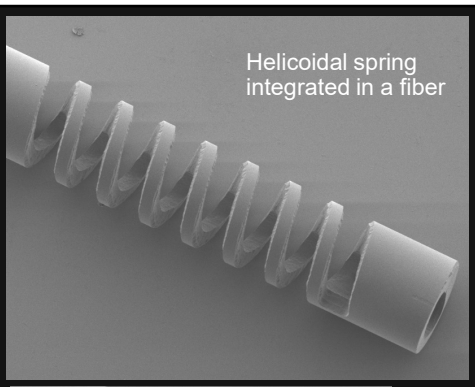


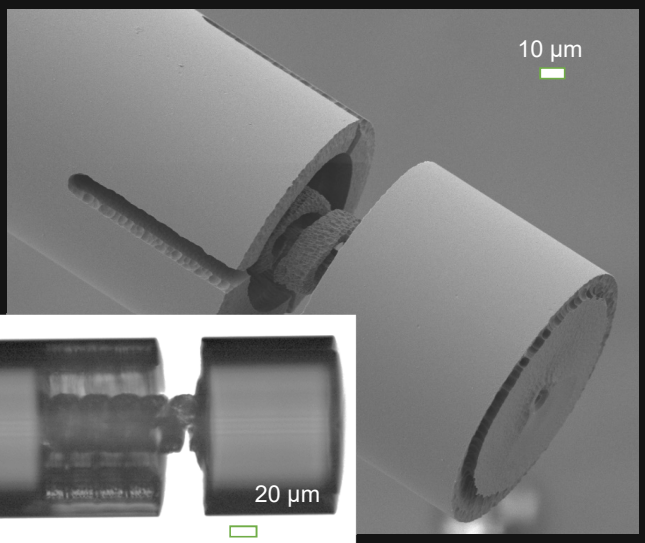


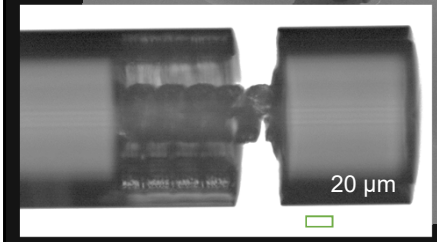
... to three dimensional moulds.

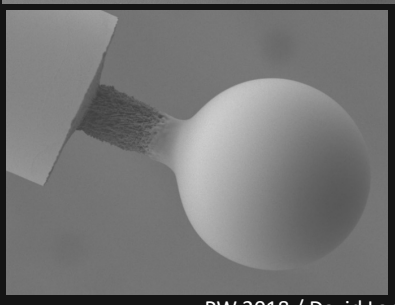
*A. Schaap and Y. Bellouard, Opt. Mater. Express **3**, 1428–1437 (2013).*

Machined fibers









PW 2018 / David Lambelet, et al.

Examples of applications in microfluidics

Buried waveguides and flu

8 µm

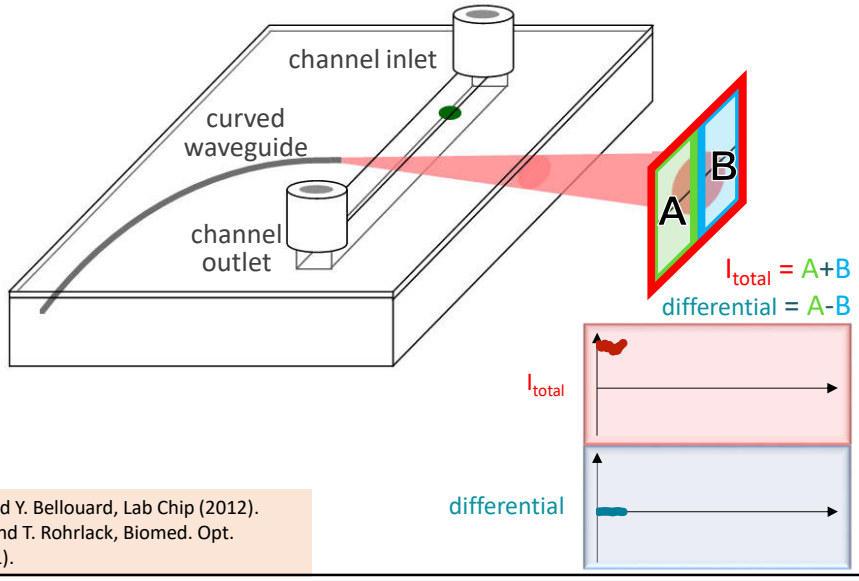
Wavegu

50 µm

Fluidic channel

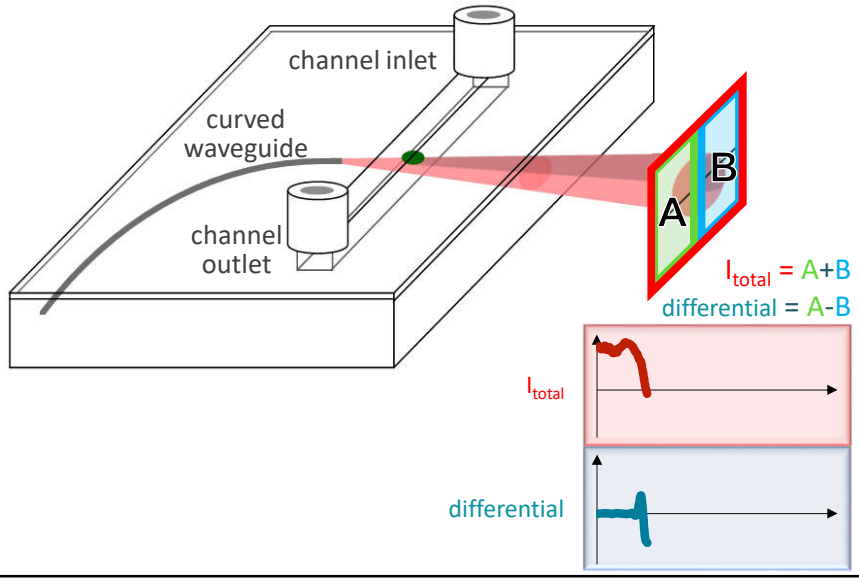
SPIE PW 2004

Photodetector signals

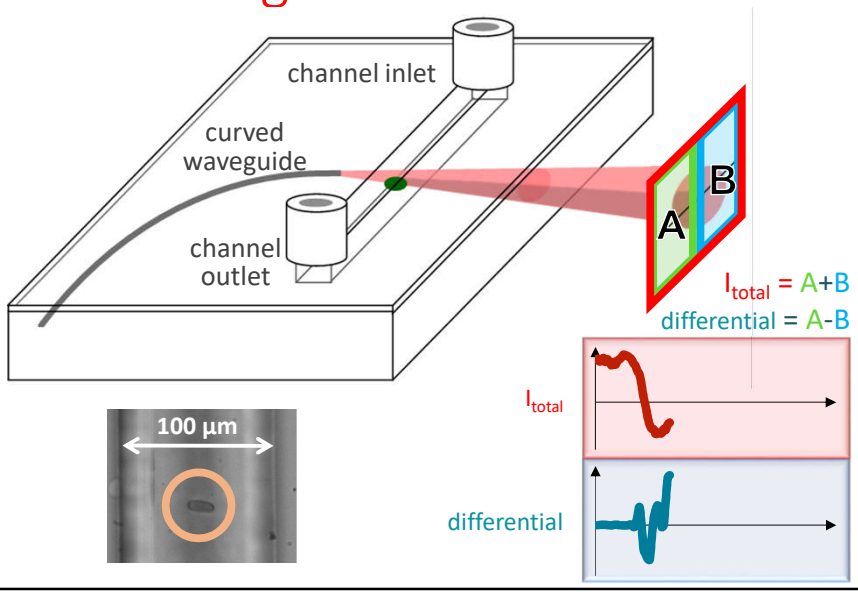


A. Schaap, T. Rohrlack, and Y. Bellouard, Lab Chip (2012).
A. Schaap, Y. Bellouard, and T. Rohrlack, Biomed. Opt. Express **2**, 658–664 (2011).

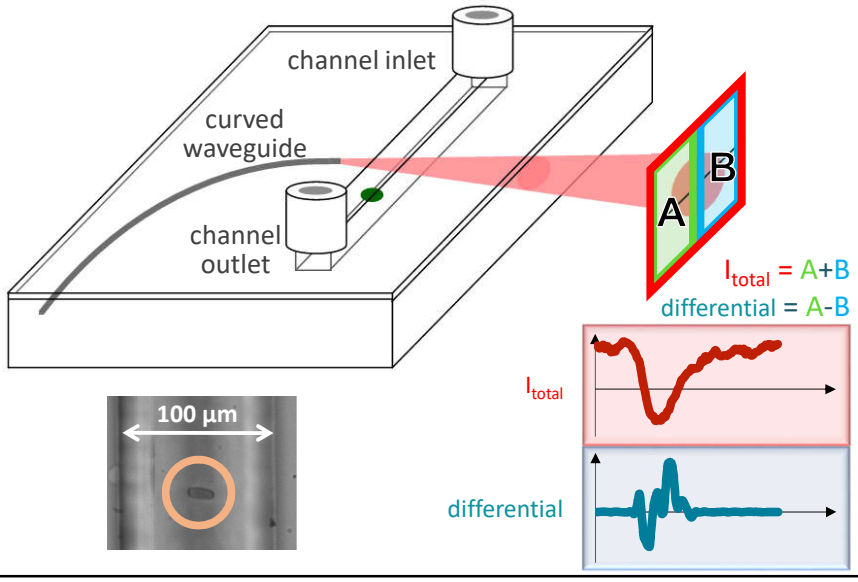
Photodetector signals



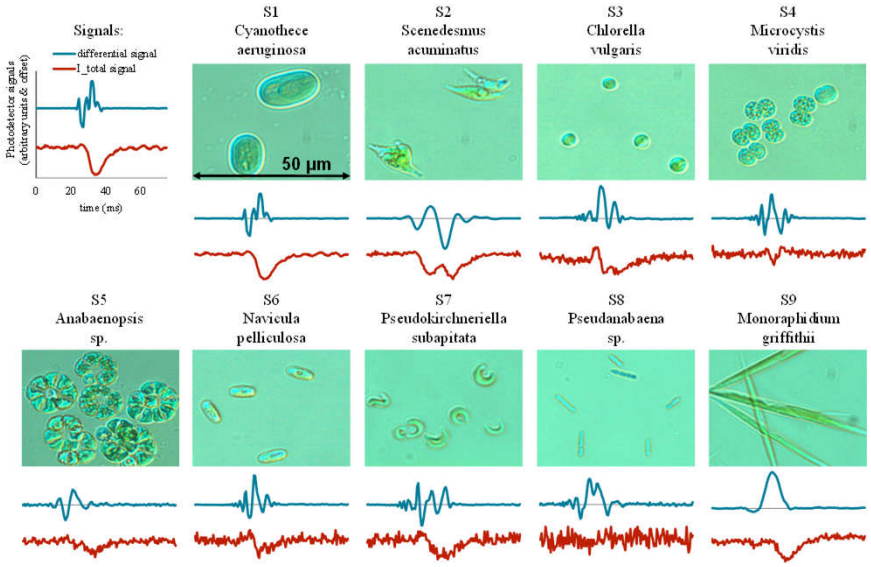
Photodetector signals



Photodetector signals

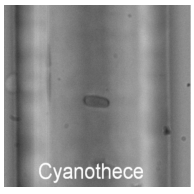


Phytoplankton library

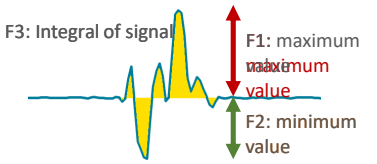


Species classification: neural networks

1. identify species



2. Extract features of each photodiode signal



F4: Integral of rectified signal / max. value

3. Put photodiode signal features into neural network

#1[F1, F2, …] + speciesID
#2[F1, F2, …] + speciesID
#3[F1, F2, …] + speciesID
#4[F1, F2, …] + speciesID
#5[F1, F2, …] + speciesID
#6[F1, F2, …]
#7[F1, F2, …]
#8[F1, F2, …]
…
…

training

unknown

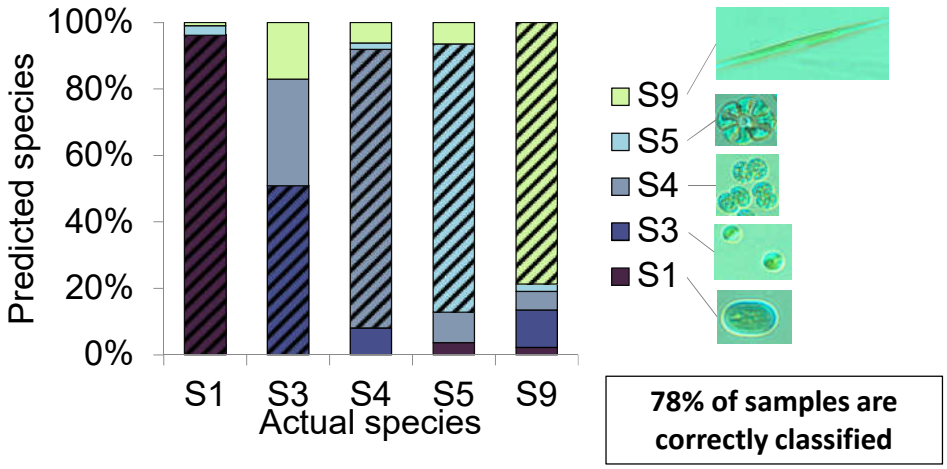
neural network

classification

Correct?

Results: species classification

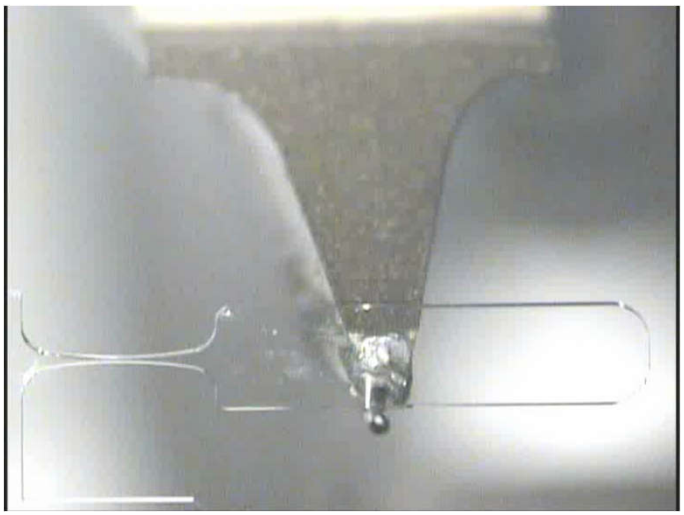
Sample: five mixed species of phytoplankton, ~100 per species
Classification: neural network pattern matching



78% of samples are correctly classified

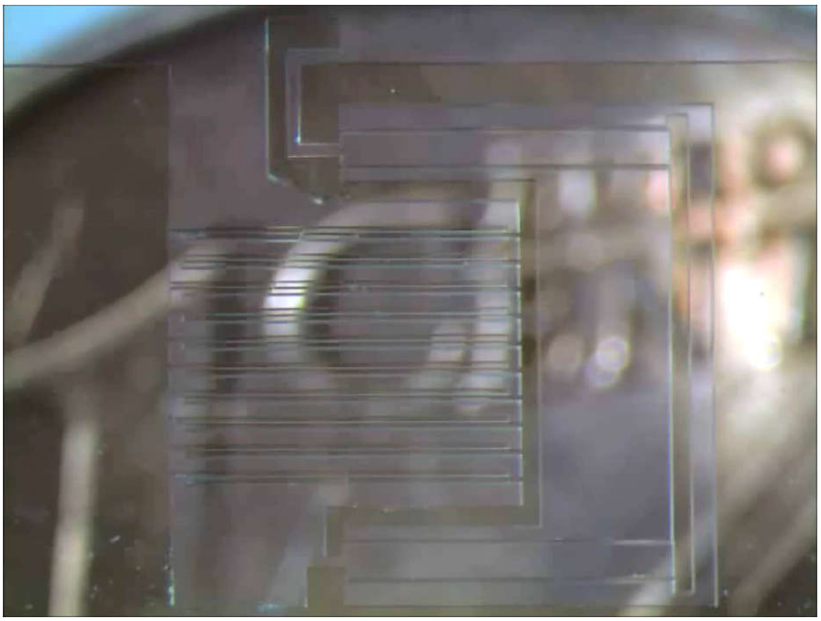
Actuators

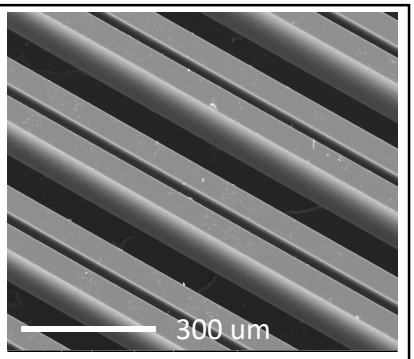
Fused silica flexures and micromechanisms

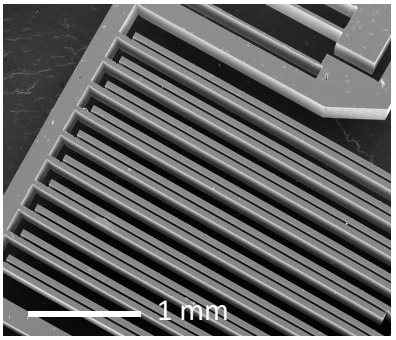


Stress > 2 GPa demonstrated

Opt. Mater. Express (2011).



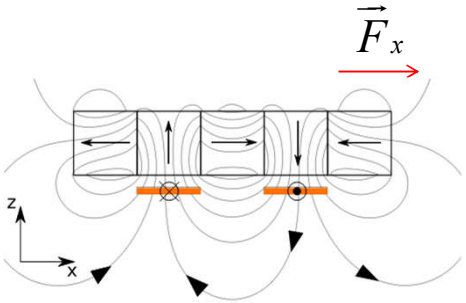


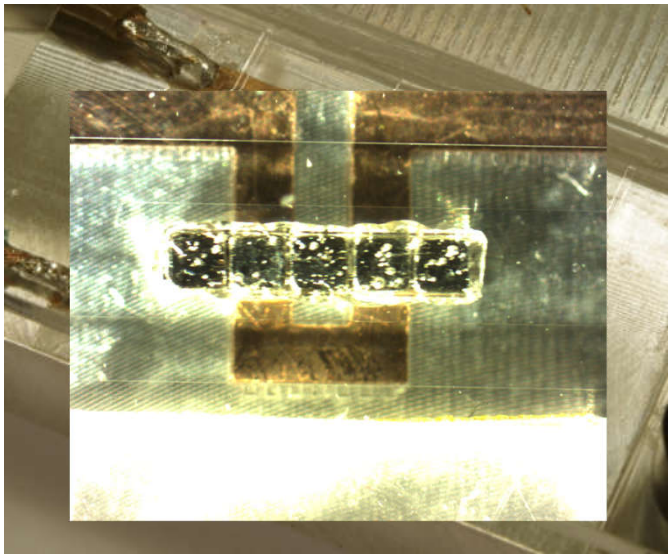


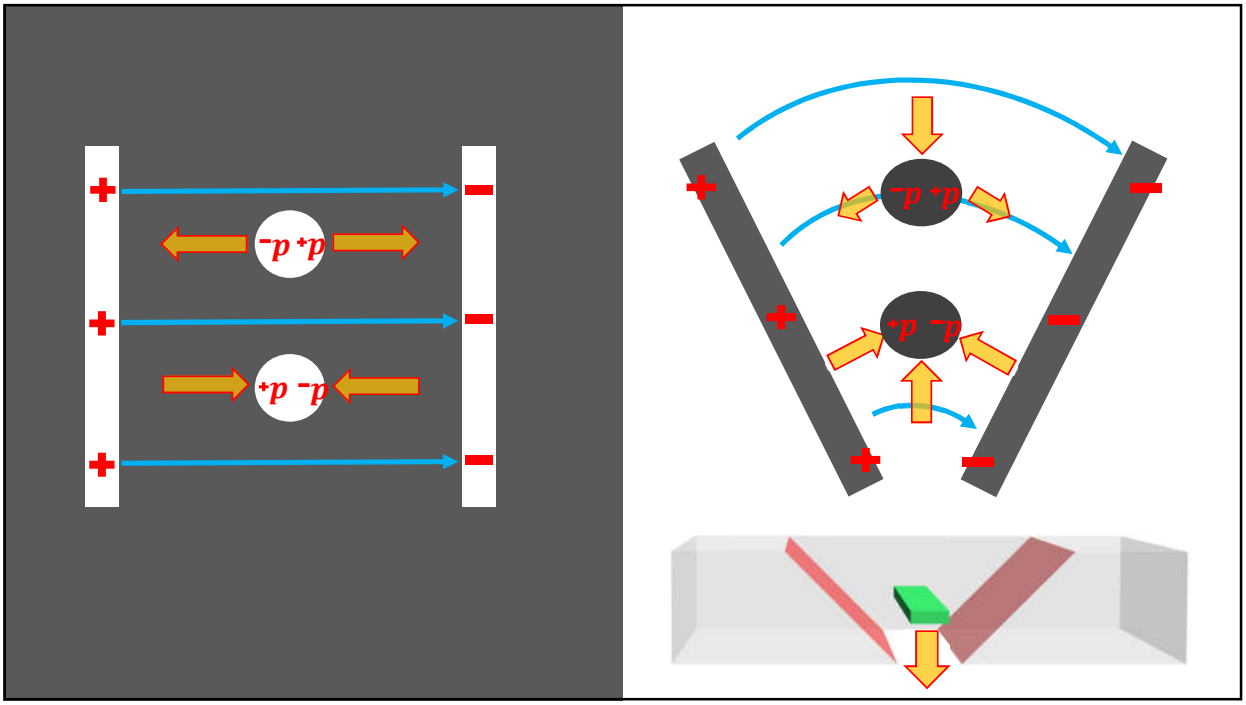
Lenssen, Bellouard, App. Phys. Lett. 101, 103503 (2012).

Magnetically-driven Actuator

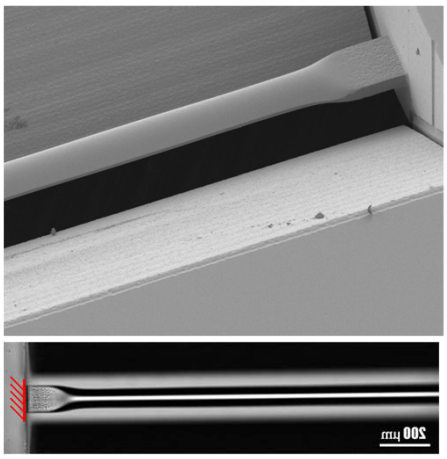
- Single side desing
- Halbach magnets array
- Bi-lateral force

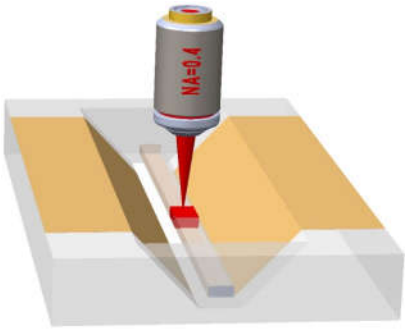






Tuning of non-linear optomechanical resonator



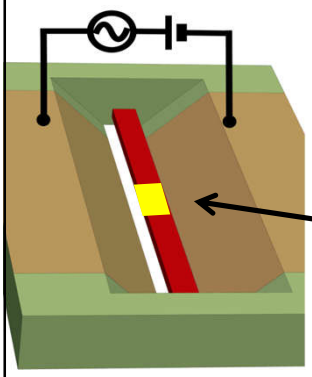


- vary stress states
- modify beam curviness

change nonlinear term k

T. Yang, Y. Bellouard, Phys. Rev. Appl. **7**, 064002 (2017)

Tuneable resonator

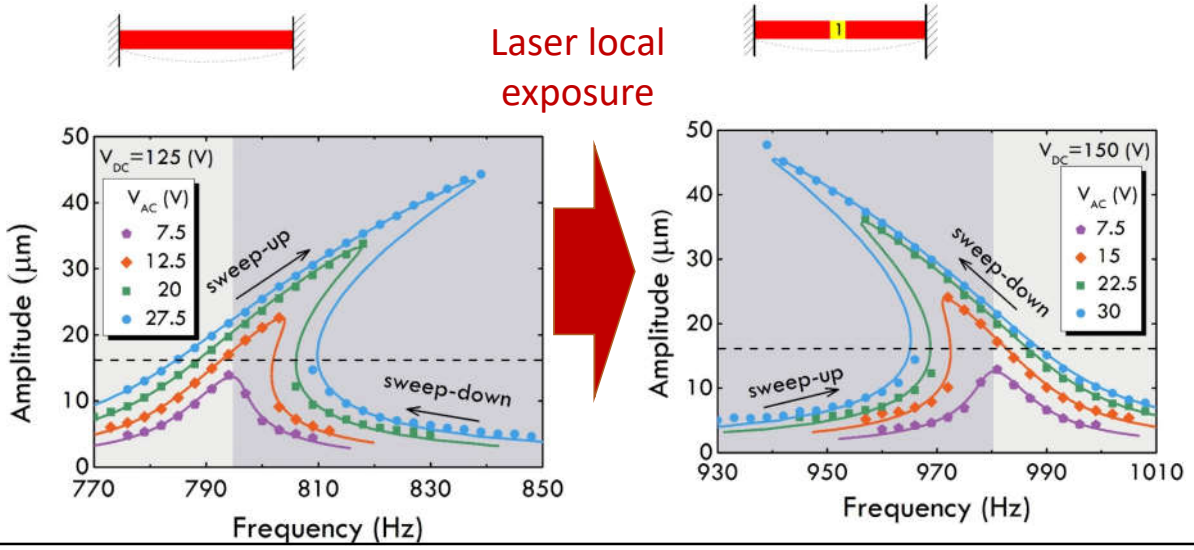


local re-exposure

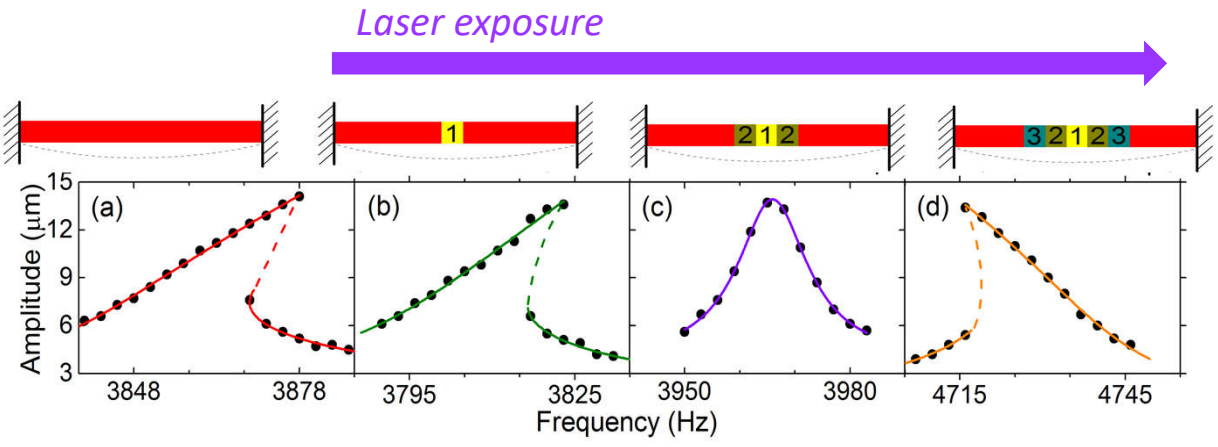
- vary stress states
- change beam volume
- modify beam shape

T. Yang, Y. Bellouard, Phys. Rev. Appl. **7**, 064002 (2017)

Tuning of non-linear opto-mechanical resonator



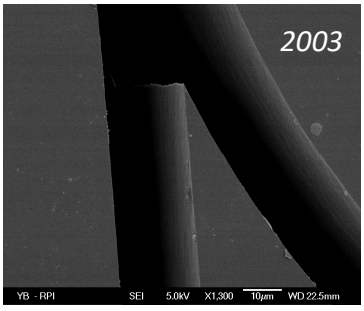
From hardening to linear, to softening dynamical response...



T. Yang, Y. Bellouard, Phys. Rev. Appl. **7**, 064002 (2017)

How about commercialization?

A process becoming commercial...



2012

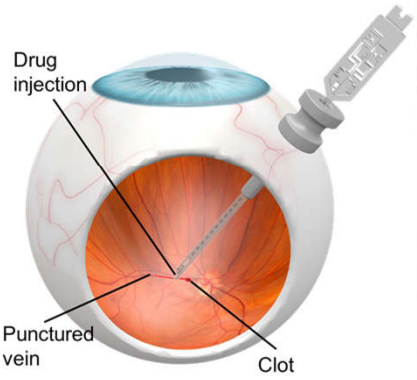
FP7 - Femtoprint

FEMTOprint
3D printing for glass microdevices

2014

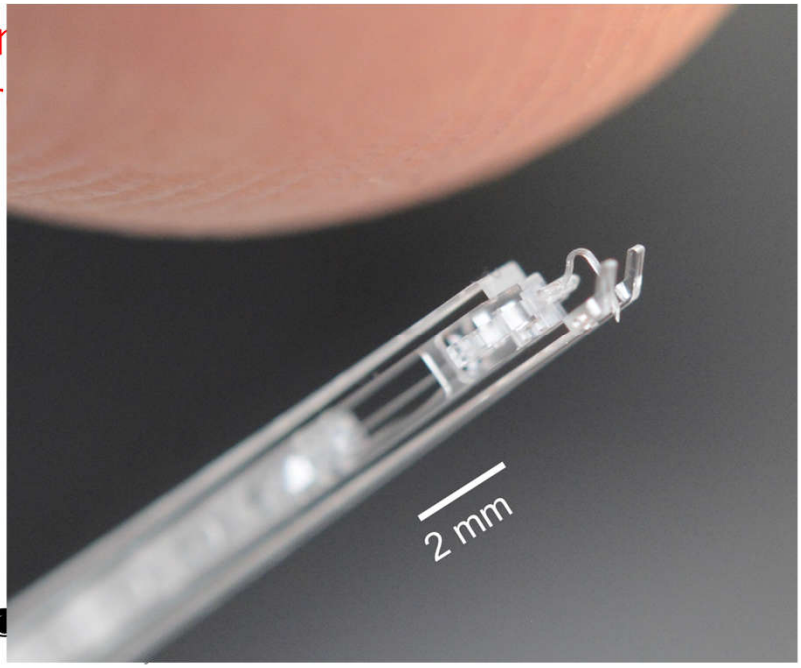
Medical applications

Buckling mechar
frontiers of micr

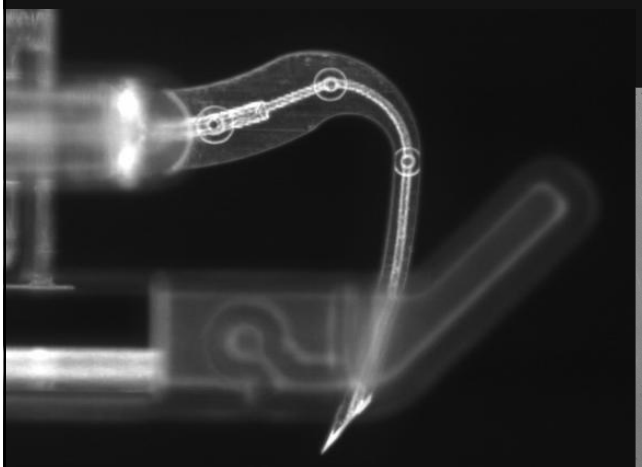


FEMTOprint

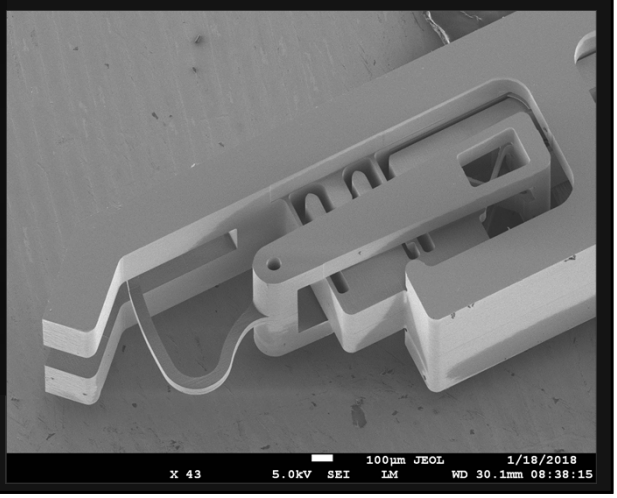
EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

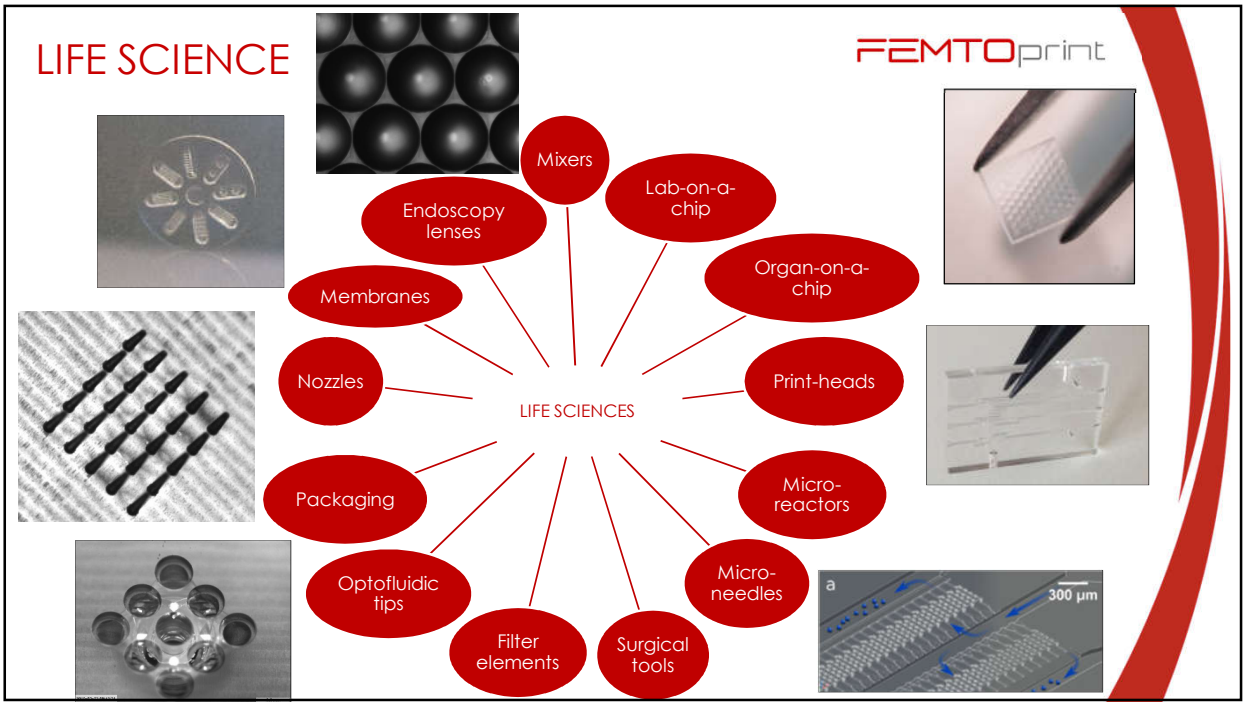


Close-up view



FEMTOprint





Present 'Femto' enthusiasts

Saood Nazir, Pieter Vlugter, Arunkhrisnan Radakrishnan, Enrico Casamenti, David Lambelet, Sacha Pollonghini, Olivier Bernard, Dr Julien Gateau, Dr Sargis Hakobian

Thanks!

- European Research Council (Galatea)
- FNS / SNF – Swiss National Science Fondation
- InnoSuisse
- Sponsoring Richemont International