GALATEA LAB
RICHEMONT CHAIR IN MULTISCALE MANUFACTURING TECHNOLOGIES

ACTIVITY REPORT
2015–2016
On 28 April 2014, Richemont and EPFL jointly announced a new partnership with the creation of a research and teaching chair dedicated to multi-scale manufacturing technologies. Led by Professor Yves Bellouard and located at the Campus Microcity in Neuchâtel, the chair, inaugurated on 9 June 2015, will eventually have about fifteen doctoral students.

Multi-scale manufacturing combines disruptive technologies to produce high quality parts on any scale and level of precision. It focuses mainly on new technologies such as laser machining, 3D printing, lithography and plasma etching. The integration of these new technologies in production will reinforce Switzerland’s position as leader in high-precision industries and high-end watchmaking. In particular, it will improve the performance and quality of watches, allowing for the use of new materials and enabling the fabrication of the most complex components.

Microengineering, and the watchmaking sector in particular, are essential components of the industrial landscape in Western Switzerland. EPFL’s stake in the Microcity Campus in Neuchâtel is a clear sign of its ambition to support innovation and academic research in this field. Richemont, with its prestigious Maisons, which include Cartier, Van Cleef & Arpels, Piaget, Vacheron Constantin, Jaeger-LeCoultre, IWC, Panerai and Montblanc, is a leading employer with more than 8,000 employees in Switzerland representing a third of its worldwide headcount. It was therefore obvious that our two entities should intensify their collaboration with this new partnership.

Our internal investments for research and development amount to hundreds of millions of francs. The decision to support this professorial chair was driven by the desire to find new sources of inspiration; the crucial research carried out by this chair will enable our engineers, often coming from EPFL, to find new energy, perspective and inspiration.

Three years after the creation of our professorial chair, we decided to set up our new research and innovation center next to it. Inaugurated in April 2017, located within the Microcity Campus, our research and innovation center is part of a fantastic industrial and academic ecosystem.

Richard Lepeu, CEO Richemont
Nanoparticles network forming after ablation of the surface. These nanoparticles have interesting properties, in particular for novel sensing principles based on surface field enhancement effects.
Using laser to generate polymorphic phases

Ultrafast lasers generate high pressure conditions that open the possibility to generate polymorphic phases of a same material.

These polymorphic phases can, for instance, have higher or lower density, different thermal properties, or non-linear optical responses.

Finding new ways of generating these phases, in particular through direct-writing processes, would open up a broad number of design opportunities for three dimensional direct write systems.

Tailoring stress state in transparent materials

Stress plays an essential role at the micro-scale.

While it can be detrimental if not controlled, it can also be used, for instance, to create new optical components, like polarization devices, to induce a localized controlled anisotropy in a material or simply for repositioning elements with sub-nanometer accuracy.

We are investigating how ultrafast lasers can be used for locally tailoring stress-states and to distribute them in a controlled manner, in three dimensions. Applications are foreseen in integrated optical polarization devices as well as for fine contact-less positioning of micro-objects.

The picture illustrates photoelastic impression of a glass substrate. The stress anisotropy originates from the self-organized nano-structures introduced by the laser.
Investigating self-organization mechanisms

Remarkably, intriguing self-organization phenomena may take place when materials are exposed to intense laser beams, inducing high electrical field conditions.

These periodic structures can take various forms (straight nanoplanes, trail of micro-bubbles, curved shells, etc.) depending on the laser exposure conditions.

These self-organized patterns form naturally, for instance during continuous scanning. This is particularly interesting for applications requiring highly periodic elements over large surfaces or lengths.

Exploring the mechanical properties of glass at the micro-/nano-scale

Fused silica has very interesting mechanical properties. It is a perfect elastic material with nearly zero-damping. The ultimate stress the material can withstand is dictated by fracture mechanics and by the presence of surface flaws.

If properly processed, it can withstand very high stress, significantly higher than steel. Strength of several GPa have reported for fibers. We have demonstrated strength well above 2 GPa for non trivial shapes such as flexures.

This property is particularly interesting for micro-scale mechanisms, such as flexures. The material being transparent, stress distribution can also be directly observed using photoelasticity.

We investigate the behavior of silica material at the micro-/nano-scale and how the material behaves under high stress.

The picture shows a scanning electron microscope image of highly periodic semi-cylindrical patterns formed during continuous scanning at high velocity of a silica surface and after a brief etching step.

The picture illustrates a micro-hinge (cross pivot flexure) made out of glass. The three bridges are independent and lies on top of another. Such micro-structures cannot be easily manufactured using classical microsystems fabrication processes, such as lithography-based ones.

Exploring new manufacturing principles

Thanks to its non-linearity, femtosecond laser exposure allows for three-dimensional patterning of substrates. It is intrinsically a 3D printing process, albeit subtractive.

The process resolution is dominated by non-linear effects. It can therefore be smaller than the diffraction limit. Features the size of a few tens of nanometers have been achieved using this manufacturing principle.

This manufacturing process opens up new design possibilities for miniature and micro-scale elements with sub-micron resolution and belongs to the category of 3D printing processes.

The picture shows a photoelastic measurement on a micro-scale beam (width is about 8 microns) subjected to a perfect tensile stress of 2.4 GPa.
Contact-less packaging and fine positioning
In micro-devices, achieving assembly and packaging with sub-micron resolution is often a daunting challenge and a bottleneck for further integration.

3D laser-matter interaction offers an interesting approach for contact-less repositioning of elements with ultra high accuracy.

We have demonstrated that a femto-second laser can induce controlled and localized nano-volume changes. By locally distributing these local changes of volume, one can induce local displacement in microscopic structures.

Here, we explore how this principle can be used in complex optical assembly for contact-less, fine positioning of optical elements.

The picture illustrates a close-up view of two flexures of a microstage forming a pivot, viewed in a photoelastic setup. The inset (lower-right corner of the image) shows laser-affected zones consisting of a set of parallel lines that induced a net expansion of the material volume causing a fine motion of the elastic structure.

New actuating principles
Three-dimensional machining allows for testing new actuator principles such as those based on dielectrophoresis.

The key question is to explore how to move non-conductive objects using electrostatic fields. The working principle is to use a non-linear effect by creating a non-uniform electrostatic field.

This principle is well-known for moving dielectric particles, for instance, using electrodes carrying travelling-wave field distributions. Here, we investigate its use for moving more complex objects as well as for monolithic glass actuators.

The rationale is to be able to actuate optical elements without the need for depositing electrodes directly on them.

The image shows a close-up view of a monolithic glass device consisting of a cantilever placed in a V-groove shape that is used to create the non-linear electrostatic field distribution. The cantilever remains free of electrodes and is displaced under the action of the electrostatic field.

‘Laser morphing’: a step towards the perfect shape
Manufacturing objects with nanometer resolution and yet with overall features the size of hundreds of microns or more is extremely difficult and requires new approaches.

Here, we investigate how this can be done by transforming a shape into another one. While this idea has been used for creating disc resonators or for melting optical fiber-tips into lenses, for instance using CO₂ lasers, here, we explore how this concept can be expanded to more complex shapes and eventually generalized.

The picture shows a micro-cube manufactured by femtosecond lasers that has been gradually transformed into a perfect sphere (the meshing of the finite element simulation of the process is superposed onto the image). Transforming a shape into another one, for instance using surface tension, offers a pathway toward perfect shapes such as spheres.
LAB INFRASTRUCTURE
Ultrafast light events as enablers for new manufacturing principles

The Galatea Lab features state-of-the-art laser facilities consisting of several femtosecond laser sources from a few tens to five hundred femtoseconds. The laser beams are redirected towards various motorized positioning platforms that are used to investigate the interaction of the laser with the material.
Self-organized patterns forming while continuously scanning a femtosecond laser beam on the surface of a substrate.
9 JUNE 2015
INAUGURATION OF THE GALATEA LAB

The Chair was inaugurated by Patrick Aebischer (President of the EPFL), Richard Lepeu (Richemont CEO), Jean-Nathanaël Karakash (Neuchâtel State Councillor) as well as Professor Yves Bellouard (Head of the Chair) on 9 June 2015 at the Campus Microcity in Neuchâtel, Switzerland.

▼ Left: Richard Lepeu, Yves Bellouard and Patrick Aebischer.
   Right: Jean-Nathanaël Karakash.
The ISOT conference gathered about eighty experts in the broad field of optomechatronics from all over the world. This symposium has been running yearly for more than a decade now and focuses on the science and technology at the crossroads between optics, mechanics, fluidics and electronics.

The conference featured seven plenary talks, fourteen invited speakers as well as regular oral contributions and posters.

Plenary talks were given by Michael Unser (EPFL, Switzerland), Jeff Squier (Colorado School of Mines, USA), Satoshi Kawata (Osaka University, Japan), Ya Cheng (SIOM, China), Demetri Psaltis (EPFL, Switzerland), Wolfgang Osten (Univ. Stuttgart, Germany).

Invited speakers were Nicholas Boechler (Univ. of Washington, USA), Daniel Lanzilloti-Kimura (CNRS, France), Oliver Wright (Hokkaido Univ., Japan), Hyungsuck Cho (KAIST, Korea), Tetsuo Kishi (Tokyo Inst. of Technology, Japan), Yanne Chembo (FEMTO-ST, France), Yves-Alain Peter (Ecole Polytechnique de Montréal, Canada), Gleb Vdovin (Delft Univ. of Tech., the Netherlands), Craig Arnold (Princeton Univ.), Ulrike Wallrabe (Imtek, Germany), Robert Thomson (Heriot Watt, UK), Martynas Beresna (Univ. of Southampton, UK), Yen-Shun Su (National Cheng Kung University, Taiwan).
This workshop focused on ultrafast laser-matter interactions, laser-induced phase transformation, 3D microfabrication processes through laser exposure and subsequent chemical etching and applications in integrated optics, optofluidics and optomechanics.

The workshop model was a single session conference with mainly invited speakers, supplemented by a few selected talks from abstract submissions and solid poster sessions.

The primary objective was to gather experts, students and young researchers in a stimulating and mind-lifting environment where participants would have a chance to present their latest results, interact and exchange ideas on the exciting topic of ultrafast laser modification of materials.

Among the invited speakers were Yoshio Hayasaki (Utsunomiya Univ., Japan), Ruediger Grunwald (Max Born Inst., Germany), Robert Thomson (Heriot Watt Univ., UK), Roberto Osellame (Italian Nat. Res. Council), Stefan Nolte (Univ. Jena, Germany), Mangirdas Malinauskas (Vilnius Univ., Lithuania), Lynn Paterson (Heriot Watt Univ., UK), Javier Solís (Instituto de Optica, CSIC, Spain), François Courvoisier (FEMTO-ST, France), Feng Chen (Shandong Univ., China), Hongbo Sun (Jilin Univ., China), Yasuhiko Shimotsuma (Kyoto Univ., Japan), Stelios Tzorakis (FORTH, Greece), Wataru Watanabe (Ritsumeikan Univ., Japan), Alexander Szameit (Univ. Jena, Germany), Koji Sugioka (RIKEN, Japan), Pavel Polynkin (Univ. of Arizona, USA), Wiesław Krolikowski (Australian National Univ., Australia), Stéphane Guizard (CEA, France), Boris Chichkov (Laser Zentrum Hannover, Germany), Cornelia Denz (Univ. Münster, Germany), Thomas Calmano (Univ. Hamburg, Germany), Feng Chen (Xi’an Jiatong University, China), Yannick Petit (Univ. of Bordeaux, France), Patrick Salter (Oxford University, UK), Olivier Utéza (LP3, Univ. Aix-Marseille, France), Maria Farsari (FORTH, Greece), Emmanuel Stratakis (FORTH, Greece), Jeff Squier (Colorado School of Mines, USA), Shigeki Matsuo (Shibaura Institute of Technology, Japan), Ya Cheng (SIOM, China), Michael Withford (univ. of Macquarie, Australia)
TEAM & COLLABORATION

**Head of the Lab**

Prof. Yves Bellouard is associate professor in Microengineering at Ecole polytechnique fédérale de Lausanne (EPFL) in Switzerland, where he heads the Galatea Lab and the Richemont Chair in micromanufacturing.

He received a BS in Theoretical Physics and an MS in Applied Physics from Université Pierre et Marie Curie in Paris, France in 1994–1995 and a PhD in Microengineering from Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland in 2000. For his PhD work, he received the Omega Scientific prize (2001) for outstanding contribution in the field of micro-engineering for his work on Shape Memory Alloys. Before joining EPFL in 2015, he was Associate Professor at Eindhoven University of Technology (TU/e) in the Netherlands and prior to that, Research Scientist at Rensselaer Polytechnic Institute (RPI) in Troy, New York, for about four years where he started working on femtosecond laser processing of glass materials.

From 2010 until 2013, Yves Bellouard initiated and coordinated the Femtoprint project, a European research initiative aimed at investigating a table-top printer for microsystems ('3D printing of microsystems').

Since January 2012, he has been the editor-in-chief for the International Journal of Optomechatronics, edited by Taylor & Francis Ltd. In 2013, he received a prestigious ERC Starting Grant (Consolidator-2012) from the European Research Council and a JSPS Fellowship from the Japan Society for the Promotion of Science.

His current research interests are on new paradigms for system integration at the microscale and in particular laser-based methods to tailor material properties for achieving higher level of integration in microsystems, such as integrating optics, mechanics and fluidics in a single monolith. These approaches open new opportunities for direct-write methods of microsystems (3D printing).
Post-doctoral researchers
› Dr Benjamin McMillen (since 01.2015), PhD Univ. Pittsburgh.
› Dr Alexandros Mouskeftaras (01.2015–10.2016), PhD Ecole Polytechnique.
› Dr Erica Block (since 06.2016), PhD Colorado School of Mines.

PhD candidates
› Jakub Drs (since 01.2015), MSc Czech University of Technology.
› Christos Athanasiou (since 01.2015), MSc Technical University of Athens.
› Tao Yang (since 01.2015), MSc Harbin Institute of Technology.
› Eric Ofusu Kissi (01.2015–06.2016), MSc University of Jena.
› Fathmah Ebrahim (10.2015–03.2017), MSc EPFL/INPG/University Torino.
› Matthieu Perrenoud (01.2016–01.2017), MSc EPFL.
› Pieter Vlugter (since 07.2016), MSc Technische Universiteit Eindhoven.
› Saood Nazir (since 04.2017), MSc Indian Institute of Technology, Kharagpur.

Scientific assistants
› Alessandro Pontearso (since 06.2016) HES Genève.
› David Lambelet (since 06.2016), MSc EPFL.
› Sacha Pollonghini (since 03.2017), MSc EPFL.

Administrative assistant
› Josiane Pachoud.

Visiting professors
› Prof. Saulius Juodkazis, Swinburne University of Technologies, Australia.
› Dr. Tetsuo Kishi, Assistant Professor, Tokyo Institute of Technology, Japan.
› Prof. Ya Cheng, Shanghai Institute of Optics and Fine Mechanics (SIOM), China.
› Prof. Jeff Squier, Colorado School of Mines, USA.

Collaborations
› Colorado School of Mines, USA.
› Tokyo Institute of Technology, Japan.
› Vilnius University, Lithuania.
› Heriot Watt University, Scotland, UK.
› Shanghai Institute of Optics and Fine Mechanics, China.
› University of Southampton, UK.

From left to right: Dr Benjamin McMillen, Pieter Vlugter, Dr Erica Block, Fathmah Ebrahim, Christos Athanasiou, Tao Yang, Jakub Drs, David Lambelet, Prof. Yves Bellouard and Matthieu Perrenoud
Christos Athanasiou (PhD student) received the best student presentation prize at the International Laser Processing Conference in Japan, 2015.

Tao Yang and Christos Athanasiou (PhD students) received respectively the 1st and 2nd prizes for the best student presentation, at the LASE conference part of the Photonics West conference, in San Francisco, USA, February 2016.

Tao Yang and Yves Bellouard received the 2016 Innovation in Optomechatronics Research Award from the LCA Forum (an informal assembly of presidents of eight startup companies, graduates of KAIST-LCA, Korea).

Prof. Yves Bellouard was designated Senior Member of the Optical Society of America (OSA).
PUBLICATIONS

Scientific journal publications

Invited & keynote talks at major conferences
› Glass and Optical Materials and Devices, Madison, USA, 2016.
› COLA 2015, Càrns, Australia, 2015.
› LAMP 2015, Fukuoka, Japan, May 2015.
› Photonics West, San Francisco, USA, February 2015.

Teaching activities
› Physics of Manufacturing, Bachelor 3rd year, Microengineering section EPFL.
› Design Project in a Team, Master 1st year, Microengineering section EPFL.
› GIAN courses, Indian Institute of Technology, Karaghpur, Dec. 2015.
› Head of the Doctoral School in Advanced Manufacturing (EDAM).

Editorial activities
› Editor-in-Chief, International Journal of Otpomechatronics, Taylor & Francis Ltd.
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