Graduate Research School — université de BORDEAUX

Appel Contrat doctoral UBx / École doctorale SPI

Spécialité de thèse : • *Lasers, Matière, Nanosciences*

Année universitaire 2023-2024

DIRECTEUR DE THÈSE *(titulaire de l'HDR ou équivalence)* : **Lionel Canioni (HDR),**
Courriel : lionel.canioni@u-bordeaux.fr

CODIRECTEUR DE THÈSE *(titulaire de l'HDR ou équivalence)* :**Laurent Bechou (HDR), Laurent Oyhenart**
Courriel : laurent.bechou@u-bordeaux.fr

UNITÉ DE RECHERCHE : **ICMCB** *(UMR5026),* **IMS** *(UMR5218)*

TITRE DU SUJET DE THÈSE : **3D4PIC**

Etude et réalisation de dispositifs pour la photonique intégrée en utilisant la fabrication additive 3D multimateriaux assistée par laser femtoseconde : modélisation, fabrication et caractérisation

COLLABORATIONS SCIENTIFIQUES :

CRPP *(UMR 5031),* LN2 (*IRL-3463) (Université de Sherbrooke - Canada)*

RELATIONS INDUSTRIELLES :

Amplitude Systèmes, TECNALIA

CONTRAT :

Le contrat doctoral d'une durée de 3 ans (36 mois) est à pourvoir à partir du 1er septembre 2023. Le salaire mensuel est typiquement de 2044,12 € brut (en 2023, puis le salaire évoluera en fonction des arrêtés ministériels). Le contrat inclut la réalisation de 100 h de formation au sein de l'École Doctorale Sciences et Physique de l'Ingénieur (ED-SPI), 50 jours de congés annuels, et la possibilité (sous-conditions) d'effectuer une mission complémentaire (par exemple en enseignement)

Compétences requises

Titulaire d'un master (ou équivalent) en photonique, ou physique/physique-chimie depuis moins de deux ans. Motivé.e et talentueux.se, faisant preuve de dynamisme au sein d'une équipe et de curiosité scientifique, avec une bonne capacité d'organisation et de communication (orale et écrite) en français et/ou anglais Connaissance préalable souhaitée de l'optique physique, optique guidée, de l'optique non-linéaire. Réelle affinité pour les travaux expérimentaux.

Candidature et modalités d'admission

Les candidatures devront comporter : un Curriculum Vitae détaillé, un relevé des notes de Master ou équivalent, une Lettre décrivant votre motivation et vos expérience et qualifications pour les travaux proposés. Les candidat.e.s sont également invité.e.s à proposer au moins deux contacts ou à fournir deux lettres de recommandation. Les éléments demandés devront être adressés par mail à Lionel Canioni ou Laurent Bechou

DESCRIPTIF DU SUJET DE THÈSE :

Context of the proposal

In recent years, there has been an incredible surge of technological advancement in additive manufacturing (3D printing). This has enabled rapid automated one-step fabrication of elements otherwise requiring multi-step processes by highly skilled specialists. This geometrical freedom allows great design flexibility, enabling new forms not possible with other techniques, as well as the combination of a variety of materials in the same process, permitting complex functionalities. Many of these technologies have made it to the consumer market and are widely used by start-ups and established companies in industries.
While multiple printing approaches have been already commercialized, the field continues to grow rapidly, advancing to tackle issues in several key areas: form precision and roughness (especially for large scale components), availability of optical materials, limitations of the number of materials available in the same process and system versus component level prototyping *(a)*.
This doctoral proposal is part of an ambitious national initiative EQUIPEX+ ADD4P aiming to develop additive manufacturing of optical devices. This project will allow photonic achievements that current methods cannot do as brilliantly demonstrated by additive metal fabrication in other fields with the following advantages: performance gain, weight reduction, increase in mechanical and thermal resistance of parts, original design of new functions, freedom of design, rapid prototyping, reduction in development and manufacturing costs, waste reduction, multi-material projects, implementation of the industry 4.0 concept. It opens up all possible areas to the imagination of researchers and engineers, whether for research and innovation or for news ways for industrial productions. The applications are very broad : process monitoring, sensors production for severe or harsh environments, in situ control of object parts produced in 3D metal printing, health monitoring, for medicine of the future, integration of PICS (photonic-integrated-circuits).... Due to the required high resolution (classically submicronic but also nanometric), the development of glass-based devices with a sufficient optical quality by additive manufacturing is very difficult and faces many bottlenecks in order to develop additive engineering for photonics : transparency, no scratches, roughness of surfaces close to a few nanometers, flatness of λ / 20, homogeneity / control of the refractive index, different spectral transmission bands, chemical and geometrical structuration in 3D geometries, etc.
This ambitious project intends to overcome most of these bottlenecks by developing new raw materials, new additive printing methods incorporating in-situ control, artificial intelligence and for some applications resolution down to 100nm suitable materials such as : silica, silicon, phosphate, germanate, tellurite, chalcogenide.
Numerous demonstrations have been already reported based on organic polymers using Multi Photon Stereolithography. This can be a good solution for short life time components and Lab-made demonstrators. However, these organic materials suffer from multiple drawbacks: low temperature resistance, strong optical absorption, low laser damage thresholds, performance degradation by ageing in operating conditions, etc. Therefore, we will focus on multimaterial devices based on glasses to improve reliability and to optimize performances and design. Printing of optical devices on the top or at the edge of PICs has recently been demonstrated using polymers. It has been performed using direct writing by two photon polymerization and polymer materials (b). Besides, detailed modeling of various beam shaping components has also been published in 2018 by Dietrich et al. (c). It highlights the diversity of approaches that can be addressed by direct-printed optical components on chips.

This PhD research work will take benefit from a joint effort between ICMCB and IMS Labs from Université de Bordeaux collaborating on the development of PIC platform for sensing of pollutants (metallic ions) in water based on optical ring resonator. Since 2015, IMS has successfully designed and fabricated such devices based on polymer materials (PMMA) deposited on porous silica by classical lithography techniques enabling to detect specific molecules in demineralized water with a state-of-the-art sensitivity in the visible range. Such an optical micro-resonator relies on the label-free interaction between the evanescent part of the wave and the specific molecules to be detected. *(d,e)*.
This PhD work will aim to participate to this national project by demonstrating the ability to develop a PIC platform for sensing pollutants with optimized additive manufacturing process of optical building blocks that could clearly tackle part of this challenge. In this frame, the PhD effort will focus on fabrication of some building blocks (waveguides and optical ring resonators) with submicronic resolution by addressing the study of the laser-material interactions as well as the fabrication of the final device using 3D printing. Performance will be assessed through dedicated optical test setup and compared to the performance of devices fabricated by photolithography process conventionally used in microelectronics.

Methodology

- **New recipes for glass: silica, silicon and soft glass (ICMCB)**

The development of new recipes based on silicon powder and two photon 3D printing will be privileged. We will focus on specialty glasses, mainly phosphate and germanate for which solgel or coacervate chemistry is available, to take advantage either of the rare earth solubility, the nonlinear optical properties or the transmission window. Considering that shrinkage is a central deterrent to successful 3D printing of inorganic glass optics, replacing the organic solvent with a low viscosity, liquid, inorganic resin would permit high resolution printing with minimal shrinkage *(e)*. The formulation of inorganic liquid resins suitable for multicomponent photonics components is one aspect of the research collaboration between ICMCB, CRPP.

- **3D printing fabrication process (ICMCB/IMS)**

Super-resolved laser structuring with dimensions at the mesoscale (100 nm and below) will be developed. To do so, special care will be paid to the management of localized laser energy deposition and cumulative effects. Moreover, the use of structured light (combination of structured light and/or of dual-color irradiation schemes, optical vortices with unique phase/polarization distributions) will offer the possibility to get super-resolution for material processing. Preliminary and pioneering results have been obtained at CELIA *(f, g)*. To reduce the processing time for practical application, multi-spot irradiation in the same or distinct focusing planes will be developed. The effort will be devoted to both spatial and polarization handling experimental scheme and multi-spot irradiation.

A preliminary development of a basic 3D printing system equipped with a machine learning approach able to extract the best lighting conditions (i.e. best laser characteristics) to perform stereolithography microscopic elements will be investigate. Investigations will be realized by using a real time identification of matter constitution changes during stereolithography (Raman spectroscopy - Infrared spectroscopy and LIBS) versus characteristics of the pulse delivered by the laser source. Machine Learning will be developed in close collaboration with ICMCB and IMS.

- **PIC-based fiber sensing systems and packaging issues (ICMCB/IMS)**

The optical performances of PIC systems will be evaluated using different optical techniques (near and far field characterizations, imaging, ...) in the visible and infrared range. A performance comparison will permit to study the drawbacks and advantages of each fabrication technique (3D printing fabrication process versus photolithography techniques on planar surfaces). The performance of the structures to act as sensitive transducers will be addressed by measuring the resonant responses using a fine-tuning DFB laser. This will rely on measurement of the micro-resonator resonant response variation induced by sulfo-cyanine solutions bring with microfluidics systems.

Fiber to chip interfaces is also a fundamental challenge requiring complex approaches and components such as active alignment techniques, fiber ribbon, tapers, mode field adapters to cope with the various 2D mode profiles of PIC waveguides and singlemode fiber. This clearly limits the scalability of PIC systems and their demonstration capabilities in operating conditions. Additive manufacturing of optical components to ease the light coupling between fiber sensing arrays and PIC circuits would clearly tackle part of this challenge. The PhD student will take part to these coupling issues by proposing specific development for single-mode fiber pigtailization.

Facilities and equipment for the project

Equipment for the micro and nano-fabrication by multiphoton absorption

For this doctoral project, a new system is set at Université de Bordeaux. It will consist of four beam lines all equipped for a dedicated additive manufacturing process or combined laser writing and additive manufacturing. An agile femtosecond laser source allowing a repetition rate from 100kHz to 40 MHz and burst mode in pulse-to-pulse pulse control, and delivering energies up to 500µj, corresponding to about 100W of continuous power; The system could generate pulses adjustable from 1 ps to 60 fs. The system integrates a spatial shaping (Programmable phase mask), the control of the polarization for the optimization of the processes. Two chambers for 3D printing in reactive atmosphere equipped with high precision translation stage and optical diagnostic for in situ characterizations.

Equipment for the Micro and nano-fabrication by photolithography/e-beam lithography and complete characterization of the optical structures

LN2-IRL located in Sherbrooke, Canada has 500 m² of class 100 clean rooms with high-precision photolithography and e-beam lithography equipment.

IMS Lab: Optical setup for complete characterization of the devices equipped with spectrometer, polarization controller, detector, cameras, multiple LASER sources from 532 nm to 1550 nm, microfluidics systems (OPERAS platform) and usual micro spectroscopy devices (Luminescence, Raman, SHG, LIBS, …).

Doctoral student's work

Main expected contributions:

- Large investigation of the literature in the field and proposal of materials to be investigated for laser-assisted 3D printing considering submicronic resolution.
- Investigations on laser-material interactions and implementation of fs 3D printing experiments to optimize a process fabrication. Development of a fabrication flow-chart of waveguides and sensitive optical ring resonators including fiber to chip interfaces.
- Characterization of photonic devices already fabricated structures by photolithography at LN2 and the ones fabricated by optimized laser-assisted additive manufacturing from ICMCB-IMS partnership.

References

a) G. Berglund et al. Optica 9, 623-638 (2022)
b) SPIE 3D Printed Optics and Additive Photonic Manufacturing II (2020)
c) P.L. Dietrich et al., Nature Photon 12, 241–247 (2018)
d) P. Girault et al, J. Light. Technol. 41, 1571 - 1581 (2022)
e) F. Meziane et al. Sensors and actuators B. 209, 1049-1056 (2015)
f) Z. Hong et al., Optica 8, 904-910 (2021)
g) K. Mishchik et al., Opt. Lett. 40, 201 (2015)
h) E. Lee et al., Opt. Expr. 25(9), 10565-10573 (2017).