Position Description

1. General Information

Name of the position	**Integrated nonlinear optics**
Foreseen date of enrolment	1 October 2023
Position is funded by	• COFUND, Marie Skłodowska-Curie Actions (MSCA), Horizon Europe, European Union • École Centrale de Lyon (EC Lyon) • Swinburne University of Technology (SUT)
Research Host	École Centrale de Lyon
PhD awarding institutions	École Centrale de Lyon & Swinburne University of Technology
Locations	Primary: Écully (Lyon), France Secondary: Hawthorn (Melbourne), Australia
Supervisors	Dr. Christian GRILLET (CNRS, INL), Pr. Christelle Monat (EC Lyon, INL) Pr. David Moss (SUT)
Group of discipline	Physics, Photonics, Nonlinear Optics

2. Research topics (only one of these projects will be funded)

Project 1: *Mid-IR Integrated Nonlinear Optics*

The Mid-infrared (Mid-IR) wavelength range - from 2.5 to 13 µm - is currently experiencing a huge surge of interest for an enormous range of applications that affect almost every aspect of our society, from compact and highly sensitive biological and chemical sensors, to imaging, defence and astronomy.

Despite their recognized potential, Mid-IR technologies are still limited in their range of applications, largely because of the bulky size of the Mid-IR devices and the prohibitive costs of the instruments used. Compact Mid-IR optical devices are indeed currently lacking and despite recent breakthroughs related to integrated mid-IR supercontinuum sources, compact and broadband sources in particular are critically missing.

Our strategy is therefore based on the development of an integrated hybrid Mid-IR platform, involving the miniaturization of optical components and their integration on a planar substrate made of materials with remarkable optical properties (particularly in terms of transparency and non-linearities) at MIR wavelengths like SiGe alloys, $LiNbO_3$ or emerging III-V semi-conductors like GaP.
The student's project will focus on one of the fundamental issues of integrated Mid-IR, namely efficient and broadband MIR sources and their integration into an optical circuit. In this thesis, we will exploit nonlinear-phenomena over an unprecedented wavelength range (from visible to Mid-IR). The aim will be to develop an on-chip supercontinuum (and potentially combs) that can cover a broad wavelength span, from the visible to the mid-IR.

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement № 101081465

There will be opportunities to travel and interact with our partners on a national and international level (both Europe/France and Australia) including European industry (CEA-LETI and others).

[1] F. K. Tittel, D. Richter, and A. Fried, "Mid-Infrared Laser Applications in Spectroscopy," in Solid-State Mid-Infrared Laser Sources, (Springer Berlin Heidelberg, 2003).
[2] M. Sinobad, et al., Optica 5, 360 (2018).
[3] M. Sinobad, et al., J. Opt. Soc. Am. B 36, A98 (2019).
[4] M. Sinobad, et al., Opt. Lett. 45, 5008 (2020).
[5] A. Della Torre, et al., "Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide," APL Photonics 6, 06102 (2021), https://doi.org/10.1063/5.0033070

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Research Fields: Photonics, Integrated Nonlinear Optics, Supercontinuum, Frequency COMBS

Project 2: *Mid-IR Frequency Microcombs*

Research conducted at the beginning of the millennium on optical frequency comb generation was crowned in 2005 by the Nobel Prize in Physics awarded to John Hall and Theodore Hansch. The need for more compact, robust, and energy efficient sources offering high repetition rates (> 1 GHz) has favored the emergence of a different approach to comb generation, based on nonlinear chip-based microresonators [1,2] that are manufactured by leveraging microelectronics processes and infrastructure. These "MicroCombs" have recently led to an explosion of record demonstrations, e.g. optical clocks on a chip [3], LIDAR [4], data transmission [5], neural networks [6], mostly using the Si3N4 or Hydex platform. INL/ CEA-Leti contributed to these efforts, with the development of Si3N4 dispersion engineered waveguides with very low loss [7], making possible the co-integration of combs with silicon optoelectronics [8] and the demonstration of an integrated Si3N4 comb source pumped by a butt-coupled DFB III-V laser (InGaAsP/InP) [9]. All these demonstrations are mainly centred around 1550 nm at telecom wavelength whereas many applications such as spectroscopy, gas detection, environmental surveillance, free space communication etc require combs in the mid-infrared (mid-IR - in the molecular fingerprint region beyond 3 um).

Our first objective is to demonstrate **the first "Micro-comb" on a CMOS compatible platform to cover the actual mid-IR region.** We will exploit the SiGe and Ge platform to create highly nonlinear resonators in the mid-IR with high Q-factor, suitable dispersion and repetition rate (from tens GHz to few GHz FSR as required for direct gas sensing). The initial focus will be to determine the best trade-off architecture, in terms of nonlinear enhancement, dispersion engineering, coupling strategy and loss reduction.

Our **second objective** is to demonstrate an on-chip dual-comb spectrometer operating in the mid-IR. We will aim at demonstrating the usefulness of these compact spectrometers for sensing applications such as pollution monitoring, breath analysis.

There will be opportunities to travel and interact with our partners on a national and international level (both Europe/France and Australia) including European industry (CEA-LETI and others).

1. L. Razzari, et al. "CMOS-compatible integrated optical hyper-parametric oscillator," Nat. Photonics 4, 41-45 (2010).
2. T. J. Kippemberg, R. Holzwarth and S.A. Diddams, "Microresonators-based optical frequency combs," Science 332, 555-559 (2011)
3. S. A. Diddams, K. Vahala, T. Udem, *Science*, vol. 369, p. 267, 2020.
4.J. Riemensberger, A. Lukashchuk, M. Karpov, W. Weng, E. Lucas, J. Liu, T. J.Kippenberg, *Nature*, vol. 581, p. 164, 2020.
5.B. Corcoran, et al., *Nat. Commun.*, vol. 11, p. 2568, 2020.
6. X. Xu, et al., *Nature*, vol. 589, p. 44, 2021.
7. H. El Dirani, et al. Opt. Express 27, 30726-30740 (2019)
8.H. El Dirani, et al., Appl. Phys. Lett. 113, 081102 (2018); https://doi.org/10.1063/1.5038795
9. Sylvain Boust, Houssein El Dirani, et al., J. Lightwave Technol. 38, 5517-5525 (2020)

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Project 3: *Integrated nonlinear optics with 2D materials*

Chip-based nonlinear optical devices at around 1,55um wavelength have been successfully developed in the past two decades using silicon photonics, so as to open new technologies for all-optical signal processing devices that could sustain, for example, a new generation of fast and compact optolectronic routing devices for datacom/ telecom applications. Yet, silicon is intrinsically limited at telecom wavelenths, since this material is plagued by two-photon absorption and free carrier penalty, which both restrict the speed and power consumption of the resulting devices. With the advent of graphene and other 2D materials late 2010, hybrid integration of material platforms appears as a new and promising solution for creating more efficient nonlinear devices, with both compact size and low power consumption, while still benefiting from the mature fabrication of the underlying dielectric material platform. Following this route, several demonstrations of graphene and graphene oxide hybrid devices with enhanced nonlinear properties have been reported in the last few years [1-5].

The goal of the present PhD topic will be to move beyond the simple integration of 2D materials and Si or SiN waveguides that have been mainly reported so far, so as to create more efficient nonlinear devices. Resonant structures, for instance, will be designed and fabricated, so as to increase the interaction between light and 2D material deposited on top. Additionally, novel functionalities such as frequency comb generation or broadband supercontinuum will be demonstrated with hybrid devices coated with 2D materials. The unique properties of the 2D material (graphene, graphene oxide…) will be adjusted to provide the best trade-off in terms of their nonlinear properties, so as to achieve optimized nonlinear devices.

There will be opportunities to travel and interact with our partners on a national and international level (both Europe/France and Australia) including European industry (CEA-LETI and others).

1. P. Demongodin et al. APL Photonics 4, 076102 (2019)
2. J. Wu, L. Jia, Y. Zhang, Y. Qu, B. Jia, and D. J. Moss, "Graphene Oxide for Integrated Photonics and Flat Optics," Advanced Materials, Vol. 33 (3) 2006415 (2021).
3. Y. Yang, J. Wu, X. Xu, Y. Liang, S. T. Chu, B. E. Little, R. Morandotti, B. Jia, and D. J. Moss, "Enhanced four-wave mixing in waveguides integrated with graphene oxide," APL Photonics, vol. 3, no. 12, pp. 120803, 2018/12/01, 2018
4. Y. Zhang, J. Wu, Y. Yang, Y. Qu, L. Jia, T. Moein, B. Jia, and D. J. Moss, "Enhanced Kerr Nonlinearity and Nonlinear Figure of Merit in Silicon Nanowires Integrated with 2D Graphene Oxide Films," ACS Applied Materials & Interfaces, vol. 12, no. 29, pp. 33094-33103, 2020/07/22, 2020.
5. Y. Qu, J. Wu, Y. Yang, Y. Zhang, Y. Liang, H. El Dirani, R. Crochemore, P. Demongodin, C. Sciancalepore, C. Grillet, C. Monat, B. Jia, and D. J. Moss, "Enhanced Four-Wave Mixing in Silicon Nitride Waveguides Integrated with 2D Layered Graphene Oxide Films," Advanced Optical Materials, Vol. 8 (21) 2001048, 2020. DOI: 10.1002/adom.202001048.

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3. Employment Benefits and Conditions

École Centrale de Lyon offers a 36-months full-time work contract (with the option to extend up to a maximum of 42 months). The employment contract includes a probation period of one month, which may be renewed once for a period not exceeding the initial duration. The total working hours per week is 35h.

The remuneration, in line with the European Commission's rules for Marie Skłodowska-Curie fellows, will consist of a gross monthly salary of EUR 2,044 in 2023. Of this amount, the estimated net salary to be received by the researcher is EUR 1,640 per month. However, the final amount to be received by the Researcher is subject to national tax legislation (approximately EUR 100 / month). This salary will increase during the thesis and should reach, on average, EUR 2,340 gross (i.e. EUR 1,870 net) per month.

Benefits include

- Access to all the necessary facilities and laboratories at EC Lyon (INL) and RMIT University.
- Tuition fees exemption at both PhD awarding institutions.
- Yearly travel allowance to cover flights and accommodation for participating in AUFRANDE events.
- 10,000 EUR allowance to cover flights and living expenses for up to 12 months in Australia.
- 27 days paid holiday leave.
- Sick leave.
- Parental leave.

4. PhD enrolment

Successful candidates for this position will be enrolled by the following institutions and must comply with their specific entry requirements, in addition to AUFRANDE's conditions.

EC Lyon

To be admitted in a Doctorate program, Applicants must hold a Master's degree (foreign degrees are examined by the doctoral schools to determine whether they are equivalent to a Master's).

More information: https://www.ec-lyon.fr/en/research/doctorate/admission-enrolment-doctorate

Important: the authorisation of the Defence Security Officer may be required before admission. In case of denial, the enrolment will not be carried out.

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Swinburne University of Technology

Applicants must have completed at least four years (or equivalent) of tertiary education studies in a relevant discipline at a high level of achievement, and must have been approved for the award of the degree(s) for which they studied.

A high level of achievement is defined as the equivalent of a four year Swinburne Honours degree that includes a significant research component in the fourth year, leading to an Honours degree class 1 (average grade between 80-100) or class 2A (average grade between 70-79) level.

Four years of tertiary studies can be demonstrated by the completion of any of the combinations of qualifications below, at the required standard of achievement:

- a bachelor degree (three or four years) and a Masters by Research; or
- a bachelor degree (three or four years) and an Honours year; or
- a bachelor degree (three or four years) and a Masters by Coursework; or
- a bachelor degree (three or four years) and a postgraduate diploma in Psychology; or
- a bachelor degree (four years) in an approved discipline.

International applicants must also provide evidence of one of the following English language requirements:

- minimum IELTS overall band of 6.5 (Academic Module) with no individual band below 6.0 or a TOEFL iBT (internet-based) minimum score of 79 (with a reading band no less than 18 and writing band no less than 20); or Pearson (PTE) 58 (no communicative skills less than 50) no longer than 24 months before submitting your application;
- satisfactory completion of Swinburne's English for Academic Purposes (EAP) Advanced level certificate at the postgraduate level (EAP 5: PG-70%);
- successful completion of a total of 24 months (full time equivalent) of formal study where the language of instruction and assessment was English at AQF level 7 or above (or equivalent) at an approved university no longer than 60 months before submitting your application;
- successful completion of a degree where the language of instruction and assessment was English at AQF level 8 or above (or equivalent) at an approved university no more than 60 months prior to submitting their application for candidature.

More information: https://www.swinburne.edu.au/courses/applying/how-to-apply-research-degree/entry-requirements/#required-standards-of-achievement-research-experience

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