*PhD research proposal submitted in the frame of the **LIGHTinPARIS** cofund European project*
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Title : **"ERBIUM INTEGRATED LASERS IN SILICON PHOTONICS"**

PhD supervisors:

- *Supervisor*: **Eric Cassan** (https://minaphot.c2n.universite-paris-saclay.fr/en/), Full professor at Université Paris-Saclay, affiliated with the **EOBE doctoral school**, ORCID: https://orcid.org/0000-0003-2802-7689, eric.cassan@universite-paris-saclay.fr
- *Co-supervisor at Aalto University*: **Zhipei Sun** (https://research.aalto.fi/en/persons/zhipei-sun), Full professor, ORCID: https://orcid.org/0000-0002-9771-5293

Thesis research topic:

The research proposal lies in the field of silicon photonics **[1]**. The integration of various materials and the possibility of realising a wide range of functions through the advanced miniaturisation of guided wave optics offer very broad opportunities for a continuum of studies ranging from fundamental physics to applications. The compatibility with the silicon technological processes moreover opens up the perspectives to target large-scale applications. In this perspective, the development of integrated light sources compatible with this technological platform is of tremendous importance and has been the focus of intense research activities for years **[1]**. Light optical sources and amplifiers indeed represent a cornerstone for on-chip communications, on-chip optical metrology and sensing, the exploitation of nonlinear optical phenomena or quantum optical processes in integrated photonic circuits. The main approaches adopted so far are either based on the use of bulky external optical sources (e.g. fiber-based lasers) or III/V semiconductor laser dies heterogeneously integrated with silicon or silicon nitride waveguides. None of these two options meets the need of a straightforward integration of optical sources matching the silicon photonics technology. In this context, the **research proposal is focused on** the investigation of a specific class of **light sources exploiting rare earth materials directly integrated in hybrid optical silicon nitride waveguides for the realization of strongly miniaturized optical amplifiers and lasers on a chip**.

The exploited physical principle relies on the stimulated emission process in rare-earth doped materials. The approach to be developed is based on an ambition to push the miniaturisation of fibre optical amplifiers and lasers to the extreme with a view to their total integration in silicon photonics, which will lead to a dramatic reduction in the light/matter interaction lengths (from tens of meters to tens of hundreds of µm) and an increase of at least three orders of magnitude in the effective doping levels of the materials. Previous works from the collaborators (Université Paris-Saclay/C2N and Aalto University/Department of Electronics and Nanoengineering) have demonstrated the possible integration of Erbium-doped Al_2O_3 layer stacks with integrated silicin nitride waveguides **[2]**. This approach will be broadly extended to account for new possibilities of Erbium but also Erbium co-doping with Yttertium or Thulium rare-earth atoms through Atomic Layer Deposition (ALD). Combined with the possible realization of a large set of dielectric resonators (e.g. microring resonators, photonic crystal cavities, Bragg waveguide cavities), the different doping options of the active oxyde materials and the possible realization of dielectric high-quality factor resonators will give rise to a rich set of explored schemes. Optical pumping at 0.98µm will be the primary option, although other possibilities will be explored. Light emission exploiting optical transitions around 1.5µm wavelength will be the primary focus, but other transitions up to the mid-infrared up to 2µm and above will be also considered. In this view, silicon nitride optical waveguides will be retained due to low loss of Si_3N_4 waveguides (typically <0.1dB/cm at 1.55µm wavelength), the wide optical transparency of this material at the pump and emission wavelengths of interest, and its ultra-low two-photon absorption losses under light pumping.

The PhD candidate will explore the physics of the different possible approaches at the optical and material science levels in view of the realization of different integrated rare earth lasers.

<u>Objective 1</u>: Demonstration of net optical gain and realization of in-line integrated amplifiers pumped at 980nm wavelength

<u>Objective 2</u>: Integrated laser demonstration at 1.5µm wavelength and beyond, minimising optical pump power, demonstration of single-mode lasing, and maximising the emission power

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3-i dimension of the PhD research project:

The project brings the complementary expertise of two research teams from Université Paris-Saclay (**C2N CNRS/UPSaclay, Palaiseau, FRANCE**) and **Aalto University (Helsinki, FINLAND)**. The PhD candidate will be welcomed by Eric Cassan at C2N for his/her PhD project. He/she will visit Pr. Zhipei Sun's group in Helsinki for stays representing 12 months as a whole. Aalto university can cover the funding salary of the candidate for his/her research visits, making possible to extend the PhD project up to 4 years if needed as a whole. The international dimension of the research project stems from this arrangement, that will enable the implementation of an ambitious research agenda developed by the PhD candidate.

The two research teams definitely bring complementary expertise:
- The team at C2N has a broad expertise in **integrated photonics** from the design and fabrication of waveguide structures and **photonic circuits** to the realization of integrated functionalities on a chip and their optical characterization in various conditions (optical losses of waveguides, quality factors of resonators, proper schemes and experimental setups for light injection/extraction into/from photonic circuits, etc).
- The team at Aalto university has developed an in-depth expertise in **material science, the growth of nanomaterials (through CVD, ALD, etc), and their characterization**. They have developed so far a CMOS compatible process to realize thin oxide films through ALD (<1µm typically) highly doped with various rare-earth elements.

Among the experimental means available within the PhD project are:
- The clean room facilities at C2N/France (e-beam lithography, etching, and related morphological characterization: SEM, AFM, etc), and the whole modelling and experimental means and setups of the host team (FDTD and FEM optical simulation, optical benches with micrometer/nanometer position stages, etc).
- The experimental growth setups available at Aalto university (including ALD chambers) and the associated characterization setups (Raman, PL, etc).

<u>Additional inter-sectoral of the PhD project</u>:
In addition with the international dimension of the project, the PhD candidate will **navigate between photonics (the major theme) and material science**, bringing him/her skills in the two domains.

International expertise of the two supervisors:

- Eric Cassan has supervised/co-supervised more than 20 PhD projects and been involved in more than 25 funded French and European project in the last 20 years. His international network extends from Canada (NRC) and MIT/USA groups to European partners (Trento, Southampton, etc). He has already supervised 3 joint PhD theses ("Cotutelles de thèses"), among which one was with Pr. Zhipei Sun.
- Zhipei Sun has developed on his side links with a large set of European and international group. As a full professor at Aalto university, he has supervised many PhD projects in the recent years. A map of his international network can be seen here: https://research.aalto.fi/en/persons/zhipei-sun/network-map/

REFERENCES:

[1] "Roadmap on silicon photonics", D. Thomson, A. Zilkie, J. E Bowers, T. Komljenovic, G. T Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J.-M. Fédéli, et al., **Journal of Optics** 18 (7), 073003, https://iopscience.iop.org/article/10.1088/2040-8978/18/7/073003

[2] "Ultra-high on-chip optical gain in erbium-based hybrid slot waveguides", J. Rönn, W. Zhang, A. Autere, X. Le Roux, L. Pakarinen, C. Alonso-Ramos, A. Säynätjoki, H. Lipsanen, L. Vivien, E. Cassan, Z. Sun, **Nature Communications**, 10:432 (2019), https://doi.org/10.1038/s41467-019-08369-w

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