Internship proposal (2026-2027)

Laboratory: Centre de Nanosciences et de Nanotechnologies (UMR 9001, France) C2N's address: 10 Boulevard Thomas Gobert – 91120 Palaiseau, France	Centre de Nanosciences et de Nanotechnologies
Contact at UPSaclay: Éric CASSAN eric.cassan@universite-paris-saclay.fr https://minaphot.c2n.universite-paris-saclay.fr	

"Topological silicon photonic cavities incorporating 2D materials"

Research project description:

Context and Motivation

Silicon photonics has become the backbone of high-density photonic integration, enabling the mass fabrication of complex optical circuits on the same technology platform as microelectronics [1]. Its two fastest-growing frontiers now converge on the same requirement: **light–matter interaction that is stronger, more efficient, and above all more reliable**. On one side, the explosion of datacom traffic in AI-era datacenters demands on-chip lasers, modulators, and wavelength converters with ever-lower energy budgets. On the other side, on-chip quantum technologies — single-photon sources, entangled photon pair generation, quantum interconnects — call for extreme optical confinement and deterministic, well-controlled optical modes. Both roadmaps are bottlenecked by the same physical limitation: the inherently **weak optical nonlinearities of silicon and silicon nitride** [2].

A paradigm-shifting route to overcome this limit is to marry Si/SiN photonic structures with **disruptive materials possessing exceptional optoelectronic properties** — above all, two-dimensional (2D) atomic-layer crystals such as graphene and transition-metal dichalcogenides. These atomically thin materials exhibit giant optical nonlinearities, electrically tunable absorption, and natural compatibility with wafer-scale integration: they can be transferred or grown directly in or on silicon photonic structures, turning a passive cavity into an active, programmable one.

Yet hybrid integration brings a second, harder challenge: **robustness**. Conventional nanophotonic cavities (ring resonators, photonic-crystal defect cavities) are exquisitely sensitive to clean-room fabrication dispersion — a few nanometres of etching bias, sidewall roughness, or a slight recipe drift can shift resonances, degrade the quality factor, or even spoil the intended mode. What is needed are photonic structures whose essential optical properties are *guaranteed by design*, not by process control.

This is where **topological photonics** enters the game.

Why Topological Cavities?

Topological photonic cavities exploit the same mathematical machinery as topological insulators in condensed matter: the existence of an optical mode is dictated not by a delicately tuned geometry, but by a **topological invariant of the bulk band structure** — the Zak phase. The bulk–edge correspondence guarantees that whenever two periodic photonic structures with *different* Zak phases are interfaced, a confined interface mode *must* exist, and *only* it exists within the gap. The consequences are remarkable:

- **Deterministic single-mode operation.** The cavity formed at the interface of two photonic crystals with distinct Zak phases guarantees the existence of exactly one mode within its photonic bandgap — a property no conventional defect cavity can promise [3,4].
- **Robustness to fabrication imperfections.** Because the mode's existence is protected by topology, the hole shape and processing disorder do not critically affect the cavity mode as long as the topological bandgap remains open — the mode survives even when the patterned area is drastically reduced. This is exactly the tolerance to clean-room dispersion that silicon photonics needs.
- **Nanoscale confinement with high Q.** Topological nanocavity designs have demonstrated near-diffraction-limited mode volumes (down to ~0.23 $(\lambda/n)^3$, an order of magnitude below previous topological microcavities) together with Q factors approaching 60,000, enabling single-mode lasing with a spontaneous emission coupling factor orders of magnitude above conventional lasers (Ota *et al.*, 2018).
- **Rational, predictive design.** The rigorous relation established between the surface impedance of a 1D photonic crystal and the Zak phases of its bulk bands [3] means interface states can be engineered *on demand*, in prescribed bandgaps, from the bulk properties alone — a "bulk–interface correspondence" that turns cavity design from empirical guesswork into topology-driven engineering.

Topological cavities therefore offer the rare combination of *robustness* (clean-room tolerance), *determinism* (guaranteed mode spectrum), and *extreme confinement* (strong light–matter interaction) — the ideal playground to host low-dimensional materials and to unlock efficient nonlinear photonics on silicon.

Subject of the Internship

The internship is devoted to pushing these topological cavities from a robust curiosity to a **functional nonlinear photonic platform**. Specifically, the candidate will:

- **Explore the unusual physical properties** of topological nanocavities implemented in Si/SiN — mode chirality, field profiles at the interface, and their tolerance to fabrication disorder, in direct dialogue with the Zak-phase design principles **[3,4]**.
- **Extend their behaviour to multimode operation**, by designing multi-interface or cascaded topological structures hosting several phase-locked modes — a key step towards broadband nonlinear processes and mode-multiplexed photonic circuits.
- **Hybridize the cavities with 2D materials** (graphene, TMDs) transferred on top, and characterize the linear and nonlinear optical response of the loaded hybrid cavities: electro-optic tuning, saturable behaviour, and enhancement of effective nonlinearities.
- **Investigate four-wave-mixing (FWM) mechanisms** in the designed and realized topological cavities — degenerate and non-degenerate FWM, parametric amplification, and, looking forward, correlated photon-pair generation for on-chip quantum applications.

The ambition is that topology-protected modes and 2D-material giant nonlinearities will mutually reinforce each other: the cavity boosts the weak response, while the material makes the robust cavity functional.

Activities

- **Optical modelling and design**: electromagnetic simulation of photonic structures with Maxwell solvers (FDTD, plane-wave expansion, eigenmode solvers); computation of Zak phases, band structures, Q factors, and mode volumes; design of topological cavity layouts and their multimode extensions.
- **Mask design for clean-room fabrication**: layout of photomasks/e-beam lithography patterns, including test structures and design-of-experiments for fabrication dispersion.
- **Clean-room fabrication**: hands-on follow-up (and, depending on progress, active participation) of the process flow — lithography, etching, and 2D-material transfer onto the fabricated cavities.
- **Experimental characterization**: optical measurement of the fabricated devices on dedicated nanophotonic setups — resonant transmission/reflection spectroscopy, Q-factor and dispersion extraction, nonlinear measurements (four-wave mixing, pump-probe), and tuning of hybrid cavities.

Profile and Practical Information

- **Target**: Master student (M2 or equivalent) in photonics, physics, micro/nanoelectronics, or applied physics.
- **Skills**: solid background in electromagnetism/optics; interest in condensed-matter topology a plus; prior experience with numerical simulation, clean-room practice, or optical benches appreciated but not mandatory.
- **Duration**: 6 months, full-time.
- **Environment**: a research group combining clean-room nanofabrication facilities, top-tier nanophotonic characterization setups, and strong expertise in silicon photonics and 2D-material integration; the internship can naturally pave the way to a PhD.

References:

[1] **"Roadmap on silicon photonics"**

David Thomson, Aaron Zilkie, John E Bowers, Tin Komljenovic, Graham T Reed, Laurent Vivien, Delphine Marris-Morini, Eric Cassan, Léopold Virot, Jean-Marc Fédéli, et al.

Journal of Optics 18 (7), 073003, https://iopscience.iop.org/article/10.1088/2040-8978/18/7/073003

[2] **"Hybrid integration of 2D materials for on-chip nonlinear photonics"**

Vincent Pelgrin, Hoon Hahn Yoon, Eric Cassan, Zhipei Sun

Light: Advanced Manufacturing (2023), 4:14 - https://doi.org/10.37188/lam.2023.014

[3] **"Surface impedance and bulk band geometric phases in one-dimensional systems"**, M. Xiao, Z. Q. Zhang, C. T. Chan, Physical Review X **4**, 021017 (2014).

[4] **"Topological photonic crystal nanocavity laser"**, Y. Ota, R. Katsumi, K. Watanabe, S. Iwamoto, Y. Arakawa, Communications Physics **1**, 86 (2018).