Post-Doctoral opening
“Mid-IR ultra-fast polaritonic laser modulators”

Laboratoire : Centre de Nanosciences et de Nanotechnologies (UMR 9001)
Adresse : 10 boulevard Thomas Gobert, 91120 Palaiseau (Université Paris-Saclay)

Contact : Raffaele Colombelli
E-mail: raffaele.colombelli@c2n.upsaclay.fr
Web: https://odin.c2n.universite-paris-saclay.fr/en/activities/mir-thz-devices/
Pubs : http://www.mir-thz-devices.u-psud.fr/Publications/publications.htm

Applications relying on mid-infrared radiation (MIR, 3-12 μm) have progressed at a very rapid pace in recent years. MIR cameras have propelled the field of thermal imaging; the invention of the quantum cascade laser (QCL) was a milestone that made compact MIR laser sources commercially available for a wide range of applications. All recent advances have resulted from the development of revolutionary optical components.
A crucial feature for most photonic systems is the ability to electrically modulate the amplitude and / or phase of a beam at speeds of the order of GHz or higher. This is a valuable feature for a multitude of applications in MIR photonics, such as laser stabilization, coherent detection, spectroscopy and optical communications. In the visible / near-IR spectral ranges, the preferred approach consists in separating the functionalities: independent modulators, filters, interferometers are physically separated from the source. But in the mid-IR, this separate-functionality approach is lacking from the photonics toolbox.

A strategy to implement this vision is to develop active microcavity arrays whose optical properties can be modulated at ultra-fast (GHz) *via* an electrical input. **These so-called “patch” antennas are commonly used in the radio-wave regime, and the novelty here is the translation to optical wavelengths, mid-IR in this case.** In the case of modulators, it means developing a nano-structured surface that is capable of applying ultra-fast RadioFrequency (RF) modulation to a laser beam propagating in free space, whether in reflection or in transmission. **This approach does not require a specific integration of the source** and can in principle be applied to laser sources other than QCL, i.e. any type of MIR laser (CO_2 for example) opening the door to several scientific and industrial applications. An additional degree of freedom that can be exploited is the strength of the light-matter coupling. It is possible to operate such devices in the so called *strong coupling regime* (hence the name *polaritonic* microcavity arrays) between light and matter adding flexibility, and using a fundamental phenomenon for practical devices [1] [2] [3] [4].

We have developed a modulator demonstrator, following an idea that we have patented in France (Ref. FR 19 03211) and is now extended at the international level [4]. The principle of operation is schematically represented in Figure 1. A doped multiple quantum well structure is incorporated into the resonator of Fig. 1a, operating in strong light-matter coupling. The application of an external RF voltage **modulates the light-matter coupling strength** and thus the system reflectivity: an incoming laser beam will be amplitude modulated with high contrast. The normalized device response at different RF frequencies obtained from the sample with the setup in Fig. 1b, demonstrates the modulation of the incoming laser at least up to a modulation frequency of 1.5 GHz as shown in Fig.1c.

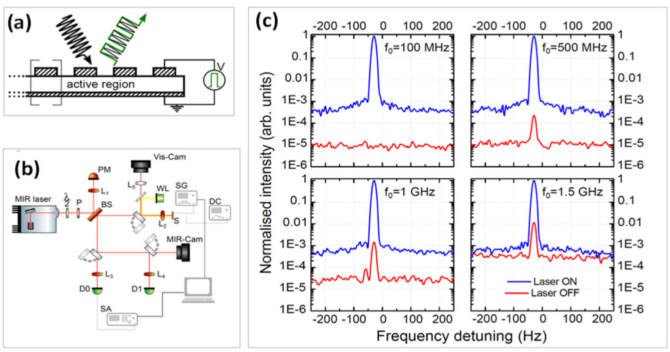

***Figure 1 – (a)** Sketch of the modulator geometry: the active region is embedded in a metal–metal structure. By applying an external bias, the amplitude of the reflected beam is modulated.*
***(b)** Sketch of the experimental setup to measure the modulator bandwidth. The sample is pumped with a commercial tunable mid-infrared QC laser.*
***(c)** Normalized “beat-note” spectra obtained when the sample undergoes modulation frequencies at 100 MHz, 500 MHz, 1 GHz, and 1.5 GHz from top left.*

The project

The **goal of the project,** is to bring to maturity this idea. At the device level, this means optimizing the device modulation speed up to several GHz integrating RF technology to the devices. Crucially, the activity implies judicious quantum design of the active region, based on semiconductor heterostructures, using design techniques similar to the ones employed for quantum cascade lasers, as well as electromagnetic design of the microcavity array (an array of metal-insulator-metal resonators) to optimize the optical properties. Once the devices operate at reasonably high performance, we can move to demonstrate specific applications, namely high-resolution *fast* spectroscopy by sideband generationand electronic generation of MIR frequency combs [5] [6].

The project benefits from collaborations with two French laboratories IEMN (Univ. Lille/CNRS) and LPL (Univ. Sorbonne Paris-Nord/CNRS), as the host team closely collaborates with them on a nearby topic, namely *integrated waveguide* mid-IR modulators. The perspective candidate will benefit from this existing collaboration.

Perspective candidate

From the description, it is evident that the research project is experimental, involving device fabrication in cleanroom, optical and RF characterizations, and characterization of the final modulators. However, an important effort will be also devoted to quantum/electromagnetic numerical modeling towards device design and development. The successful applicant will be an energetic individual with interest in semiconductor device physics, and will have completed a graduate program in a related topic (Physics, Optics or Engineering).

The research activity is rich: it will include device RF design and cleanroom fabrication, optical/RF testing, use of ultra-fast detectors [7], optical setup building and integration of optical components. Experience in a majority of these domains, but not necessarily all (as the CV will be evaluated globally), is important.

The project is funded for 18 months (24 months negotiable), that covers the salary and epitaxy/cleanroom costs. The typical gross salary, that will be commensurate with experience, lies in the 3000/3800 Euros/month. The perspective candidate will be part of the host team (*Mid-IR and THz quantum devices team*) at C2N, and she/he will benefit from constant interactions with the team members, and of course full access to the existing experimental setups.

References

1. P.-B. Vigneron, S. Pirotta, I. Carusotto, N.-L. Tran, G. Biasiol, J.-M. Manceau, A. Bousseksou, and R. Colombelli, "Quantum well infrared photo-detectors operating in the strong light-matter coupling regime," Appl. Phys. Lett. **114**, 131104 (2019).
2. M. Jeannin, J. M. Manceau, and R. Colombelli, "Unified Description of Saturation and Bistability of Intersubband Transitions in the Weak and Strong Light-Matter Coupling Regimes," Phys. Rev. Lett. **127**, 187401 (2021).
3. M. Lagrée, M. Jeannin, G. Quinchard, O. Ouznali, A. Evirgen, V. Trinité, R. Colombelli, and A. Delga, "Direct polariton-to-electron tunneling in quantum cascade detectors operating in the strong light-matter coupling regime," Phys. Rev. Appl. **17**, 44021 (2021).
4. S. Pirotta, N.-L. Tran, A. Jollivet, G. Biasiol, P. Crozat, J.-M. Manceau, A. Bousseksou, and R. Colombelli, "Fast amplitude modulation up to 1.5 GHz of mid-IR free-space beams at room-temperature," Nat. Commun. **12**, 799 (2021).
5. A. Schliesser, N. Picqué, and T. W. Hänsch, "Mid-infrared frequency combs," Nat. Photonics **6**, 440–449 (2012).
6. A. Parriaux, K. Hammani, and G. Millot, "Electro-optic frequency combs," Adv. Opt. Photonics **12**, 223 (2020).
7. M. Hakl, Q. Y. Lin, S. Lepillet, M. Billet, J.-F. Lampin, S. Pirotta, R. Colombelli, W. J. Wan, J. C. Cao, H. Li, E. Peytavit, and S. Barbieri, "Ultra-fast quantum-well infared photodetectors operating at 10{\mu}m with flat response up to 70GHz at room temperature," (2020).