CONTRATS DOCTORAUX 2025
PROJET QUANTEDU

Sujet de thèse – Laboratoire de Physique des Lasers

Title: **Quantum sensing of THz metamaterials with Rydberg atoms**
Thesis supervisor: Athanasios Laliotis
E-mail : laliotis@univ-paris13.fr

Atomic vapors confined in cells have proved to be extremely convenient platforms for the realization of compact quantum sensors, providing ultra-sensitive sensing of magnetic [1] as well as electric fields of frequencies up to the GHz range [2,3]. In particular, microwave and RF quantum sensors based on Rydberg atoms have been developed in a number of universities (Stuttgart, NIST, Ontario) but also quantum-technology start-ups (Rydberg technologies). More recently Rydberg sensing has been extended to the THz range [4,5], exploiting the conversion of absorbed far-field THz radiation into scattered photons in the visible range.

Fabricating efficient THz sensors is crucial, as this range of the spectrum offers significant potential for real-world applications, including wireless communications and gas sensing. The best way for creating THz devices such as modulators, sensors, and detectors has so far been metamaterial technology consisting of arrays of metallic resonators deposited on dielectric substrates. THz metamaterials are commonly characterized by far-field spectroscopy, however, such techniques are limited by diffraction and cannot provide mapping of the electric field in the vicinity of the resonators.

A possible route for overcoming such limitations is to extend Rydberg electrometry to the near-field and use atoms as local quantum probes of the THz near-field by interfacing atomic vapors with THz-metamaterials. The proposed project has the following pioneering goals:

1) Interface Rydberg atoms with metamaterials:
Fabricating cesium vapor cells that integrate metallic nanofabricated resonators, submerged into an atomic gas whose density is controlled by temperature. The metamaterials will be deposited and characterized by far-field time domain spectroscopy by the ODIN group of C2N.

2) Perform near-field characterization of the metamaterials using Rydberg probes:
When excited by an external THZ source, the resonators generate an intense electromagnetic response in the near-field. This field will induce dipole transitions on the surrounding vapor of Rydberg atoms (if the Rydberg state is chosen to be resonant) transferring population to adjacent energy levels from which they will decay by fluorescing visible photons. Visible light can be detected by ultra-sensitive cameras providing a mapping of the electric field in the vicinity of the resonators with a resolution that beats the diffraction limit by 3 orders of magnitude (ratio between THz and optical wavelengths). This will constitute a quantum technique for performing near-field optical microscopy.

3) Probe the Casimir-Polder interaction between Rydbergs and metamaterials:
Beyond quantum optical microscopy, interfacing THz resonators and Rydberg atoms can allow us to study the fundamental Casimir-Polder interaction between atoms and metamaterials. THz resonators modify the local density of states of the electromagnetic field, suggesting that a resonant coupling between Rydberg atoms and THz metamaterials could be used to tune Casimir-Polder interactions. To probe Rydberg-metamaterial interactions, we will use selective reflection spectroscopy, developed by the SAI group to probe atoms [6], at nanometric distances (typically ~100nm) above the active region of the resonator. To reach Rydberg states we will use a pump-probe scheme.

Perspectives:
Rydberg-metamaterial coupling and THz to visible conversion offers fascinating possibilities for extending quantum devices and performing quantum optics experiments in the THz regime. Additionally, fast tuning of the metamaterial properties can provide a unique tool to probe dynamical Casimir effects.

The SAI group of the LPL are specialists in Casimir-Polder spectroscopy of atoms and molecules close to interfaces. This project also includes a theory component that will be developed in collaboration with S. Scheel's group in the University of Rostock (Germany).

We are looking for a PhD student with good background in quantum physics, atomic physics and light-matter interactions to work on both experimental and theoretical aspects of this project and participate in the exchanges between the SAI group and its collaborators.

References

1. D. Budker et M. Romalis, ‘Optical magnetometry’, *Nat. Phys.*, 3, p. 227-234, (2007).
2. J. A. Sedlacek, A. Schwettmann, H. Kübler, R. Löw, T. Pfau, et J. P. Shaffer, ‘Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances’, *Nat. Phys.*, 8, p. 819-824, (2012).
3. D. A. Anderson, S. A. Miller, G. Raithel, J. A. Gordon, M. L. Butler, et C. L. Holloway, ‘Optical Measurements of Strong Microwave Fields with Rydberg Atoms in a Vapor Cell’, *Phys. Rev. Appl.*, 5, p. 034003, (2016).
4. Wade, C. G. *et al.* Real-time near-field terahertz imaging with atomic optical fluorescence. *Nat. Photonics* **11**, 40–43 (2017).
5. Downes, L. A. *et al.* Full-Field Terahertz Imaging at Kilohertz Frame Rates Using Atomic Vapor. *Phys. Rev. X* **10**, 011027 (2020).
6. A. Laliotis *et al.*, ‘Atom-surface physics: A review’, *AVS Quantum Science* **3**, 043501 (2021).