Master (M2) internship in Paris (LNE-SYRTE/Observatoire de Paris) on

Sub-K Spectral Hole Burning for Quantum Metrology: from Ultra-stable Lasers to Quantum Correlations

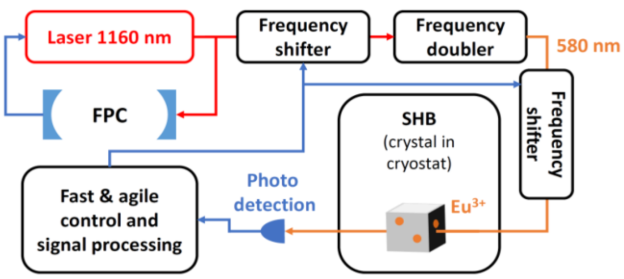
Background

Time and frequency metrology is one of the most successful fields of high accuracy measurement today. Microwave and optical frequency standards now realize accuracies in terms of fractional frequency in the 10^{-16} range, ensuring a vast variety of applications from **practical day-to-day time keepi**ng (realization of SI second, atomic international time, satellite navigation systems, timing and synchronization at various geographical scales, etc…) to the **most demanding fundamental research experiments (measurement of the drift of fundamental constants, tests of relativity, detection of gravitational waves, …)**. The future of time and frequency metrology lies in the optical domain: the second, the unit of time will soon (~2030) be defined via optical transitions in atoms; optical clocks around the world have reported unprecedented performance in both stability and accuracy; and optical fiber networks provide means of comparing distant clocks and disseminating frequency and time.

Yet, as of today, the lack of ultra-stable lasers with sufficient frequency stability to probe the atomic transitions without degradation hampers the search for ultimate performance. In short, the cold atom lattice clock devices could exhibit stability limited by their quantum projection noise if the interrogation lasers were to be substantially better than this limit. The lasers currently in use are based on stabilization to an ultra-stable Fabry-Perot Cavity (FPC) in extremely well controlled environment. Unfortunately, these systems are reaching their fundamental limits (due to thermodynamic noise at 300 K) at a few 10^{-16} stabilities, degrading the optical lattice clocks through noise aliasing. Although it is possible to fight against thermodynamic noise in Fabry-Perot cavities, the technological challenges are formidable, and we believe that a change of technological paradigm is more promising.

Project

Spectral hole burning in rare-earth ion doped crystals is a versatile system in quantum metrology. Narrow optical transitions of the dopant ions can serve as a frequency reference for laser stabilization. The presence of a large number of dopant ions not only ensures an excellent signal to noise ratio, but also provides a likely means to further reduce phase noise by exploiting classical and quantum correlations between them. The expected fractional frequency stability are thus orders of magnitude better than cavity-locked lasers at the state of the art.



At the SYRTE laboratory, an experimental setup using a Eu^{3+}:Y_2SiO_5 crystal has been constructed and the first demonstration of laser stabilization yields a fractional frequency stability at a few 10^{-15} around 1 s, limited by residual temperature fluctuations of the crystal [1]. Such a performance is compatible with that reported by NIST [2], whereas the technical noise floor is an order of magnitude lower [3]. Sensitivities to environmental factors such as stress field [4], electric field [5] and temperature [6] have also been characterized metrologically.

This project aims to improve the techniques of laser frequency stabilization, possibly down to the range of a few 10^{-18} at 1 s, and will explore the fundamental limits of such techniques, unknown for the time being.

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First, our cryostat is now equipped with a dilution stage, allowing for experiments at sub 1 K temperatures, where the sensitivities to temperature fluctuations are largely reduced [7]. Second, we have built and tested independently a new digital control and acquisition system with minimal time lag that allows for efficient and simultaneous probing of multiple spectral holes. These two aspects tackles the two limiting technological aspects since our last laser stabilization demonstration [1], and will most likely improve the frequency stability of a laser reference onto the spectral-hole structures. **This internship project aims to precisely achieve that by pushing to the limits the multi-heterodyne detection, currently implemented with 3 probe modes, and apply directly to laser frequency stabilization at dilution temperatures. Schemes to refresh the hyperfine levels will be studied and tested in order to overcome the need to thermally erase the spectral holes. There will be also room to explore theoretically classical and possibly quantum correlations (entanglement) between these classes of ions, in search for even better frequency stabilities.**

Eventually, these new lasers would not only enable optical clocks to reach their ultimate performance, but also facilitate advances in physics and quantum engineering: understanding matter-light interaction in the presence of a crystalline matrix, realizing quantum sensors taking advantage of the system's sensitivity to perturbing environmental factors, …

Scope and funding

The successful applicant will participate in all aspects of the experimental project, including but not limited to working on the experimental setup, data acquisition and analysis, and coordination with other experiments in the Optical Frequencies Group (e.g. frequency combs and optical clocks) for more involved measurements, etc. Various technical services (electronics, optical design and engineering, mechanics, and vacuum) within the SYRTE laboratory are available whenever necessary.

The internship can start from March 2024 onwards, for a duration of 4 months (remunerated, duration negotiable). The candidate is strongly encouraged to continue with a PhD programme on this experiment, and will be supported for PhD grant applications (e.g. EDPIF, DRIM QuanTiP, etc.).

The applicant

Serious, motivated and professional. Must have completed or is in the process of completing his/her master curriculum (besides the internship). Some experience in experimental physics (e.g. optics, electronics, signal processing and programming), as well as basic knowledge in quantum physics (quantum mechanics and atomic physics) are useful, but not a strict requirement. Given the collaborative nature and international context of the research project, communication in English must be practiced.

Application

Interested candidates should send a CV and a motivation letter to:

Dr. Bess Fang-Sortais : bess.fang@obspm.fr , and Dr. Yann Le Coq : yann.lecoq@obspm.fr .

Interviews will be arranged once the documents are examined.

References

[1] N. Galland *et al*, *Optics Letters **45** 1930 (2020)*.
[2] S. Cook *et al*, *Phys. Rev. Lett. **114** 253902 (2015)*.
[3] X. Lin *et al, Optics Express **31** 38475 (2023)*
[4] N. Galland *et al*, *Phys. Rev. Applied **13** 044022 (2020)*; S. Zhang *et al*, *Phys. Rev. Research **2** 013306 (2020)*.
[5] S. Zhang *et al*, *Appl. Phys. Lett. **117** 221102 (2020)*.
[6] S. Zhang *et al*, *Phys. Rev. A **107** 013518 (2023).*
[7] Manuscript in preparation.