PhD thesis offer

Ultra-stable Rb microcell optical frequency reference

Context and subject

With the contribution of **atomic spectroscopy, MEMS technologies** and **integrated photonics**, **miniaturized atomic clocks, sensors and instruments** have been developed for around 20 years [1]. This field of research, initiated in 2004 with the demonstration at NIST of the first **chip-scale atomic clock** (CSAC), has since experienced growing popularity, due to its strategic interest and the plethora of applications (GNSS, secure communications, PNT systems, etc.) it covers.

Current commercial CSACs lose about 1 microsecond per day, a hundred times less than quartz oscillators, within a comparable volume-consumption budget. However, the frequency noise of their laser (VCSEL) limits their short-term frequency stability while the presence of a buffer gas pressure in their cell induces a collisional shift that compromise their long-term stability.

Recent years have seen a relevant interest towards the development of new-generation **miniaturized optical atomic clocks**. In this domain, **sub-Doppler spectroscopy** techniques, based on the interaction of hot alkali atoms contained in a **microfabricated vapor cell** with **two counter-propagating laser beams**, constitute an attractive approach due to their simplicity and integration potential.

Among various methods, the **two-photon absorption spectroscopy** of the **Rb atom** at **778 nm** offers promising features. Using a Rb microcell and an external-cavity diode laser, NIST has demonstrated a compact optical reference with a fractional frequency stability of 1.8×10^{-13} at 1 s and approaching 10^{-14} at 100 s [2,3]. Competitive stability results of 3.5×10^{-13} at 1 s and 3×10^{-14} at 100 s have been reported at FEMTO-ST [4].

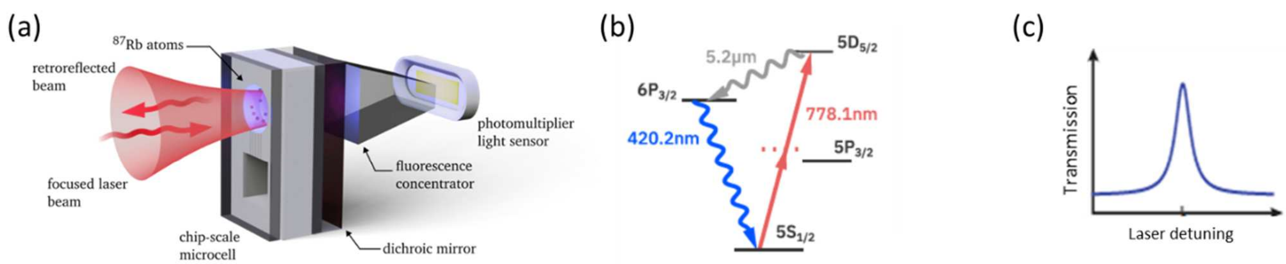

Figure 1: (a) Illustration of two-photon spectroscopy in Rb atom microcell (b) Involved energy levels in the atom-light interaction. (c) Resonance detected in a Rb MEMS cell.

In this context, based on the experience acquired at FEMTO-ST, the PhD thesis targets the **development, progress, and metrological characterization of an ultra-stable microcell optical reference based on two-photon transition of Rb atom at 778 nm**. Improved fractional frequency stability in the 10^{-14} range at 1 s and 1 hour integration time is targeted in a very simple laser system architecture. Such an optical reference might contribute to the **positioning or navigation** of GNSS-denied vehicles, **nano-satellites**, ships, and could find interest in the implementation of ambitious **space missions** that require precise timekeeping.

The short-term frequency stability of the FEMTO-ST Rb microcell reference is today limited by contributions from the two main blocks (laser and cell) : 1/ the **laser frequency noise**, which degrades the short-term stability of the atomic reference through a so-called intermodulation effect [5], 2/ the poor **signal-to-noise ratio** of the atomic resonance explained by the limited atom-field interaction length, the insufficient blue photon collection efficiency, and the limited number of Rb atoms involved in the atom-field interaction, as well as the presence of contaminants or residual gases in the microfabricated cell, which causes line broadening of the optical atomic resonance.

In order to improve the **short-term stability** of the reference, the candidate will actively contribute to:
1/ Implementation and characterization of a **new laser with ultra-low frequency noise** to reduce the intermodulation contribution
2/ Development of **original micro-fabricated cell architectures** offering increased atomic signal, reduced photon shot noise contribution (optimized fluorescence collection) and improved cell internal atmosphere purity, to access the detection of narrower optical resonances.

Efforts will then be pursued to improve the **long-term stability** of the reference. For optimized isolation of the atoms to their environment, the new cell will be implemented in a dedicated **specially-designed** small-size **physics package**, with optimized thermal, magnetic and mechanical stability. Also, **innovative interrogation sequences** will be implemented for **mitigation** of **light-shift** effects [6].

The metrological characterization of the Rb microcell two-photon optical reference stability will be obtained by comparing the laser output signal to a 778 nm reference signal generated from an optical frequency comb locked to an ultra-stable cavity laser, available at FEMTO-ST.

Bibliography
[1] J. Kitching, Appl. Phys. Rev. 5, 031302 (2018). https://doi.org/10.1063/1.5026238
[2] V. Maurice et al., Opt. Exp. 28, 17, 24708 (2020). https://doi.org/10.1364/OE.396296
[3] Z. L. Newman et al., Opt. Lett. 46, 18, 4702 (2021). https://doi.org/10.1364/OL.435603
[4] M. Callejo et al., J. Opt. Soc. Am. B (2025) https://arxiv.org/pdf/2407.00841
[5] C. Audoin et al., IEEE Trans. Instr. Meas. 40, 2, 121-125 (1991). https://ieeexplore.ieee.org/document/1032896
[6] V. Yudin et al., Phys. Rev. Applied **14**, 024001 (2020). https://doi.org/10.1103/PhysRevApplied.14.024001

Candidate Profile

The candidate should appreciate applied physics, for working in a highly-interdisciplinary subject that implies lasers, optics, quantum physics, CAD (physics package design), and electronics & instrumentation (Python preferred). The candidate should be attracted by high-precision metrology. Some experience with clean-room techniques might be a plus-value.

Environment and application

The PhD candidate will work at the interface between the **OHMS** and **MOSAIC groups** at **FEMTO-ST, Besançon, France**. The candidate will interact with researchers, engineers, technicians and will benefit from the support and skills of FEMTO-ST internal services (electronics/mechanics/computing), with access to a large park of **instruments** dedicated to **time-frequency metrology** and **microfabrication platform** (MIMENTO). The candidate will present his/her work in high-impact scientific journals and international conferences.

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