

Microfabricated vapor cell atomic clocks at FEMTO-ST

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Invited Talk, Abstract

SPIE Photonics West, San Francisco, 28-30 January 2025

Abstract

About 20 years ago was demonstrated at NIST the first chip-scale atomic clock [1]. This microwave clock, based on coherent population trapping (CPT), relying on the interaction of alkali atoms confined in a microfabricated vapor cell with an optically-carried microwave signal obtained by direct modulation of a vertical-cavity surface-emitting laser (VCSEL), achieved a fractional frequency stability of 2.5×10^{-10} at 1 s and 2×10^{-9} at 10 000 s. Definitely, this prototype has stimulated the emergence of a very active and intense research field targeting the deployment of low-power miniaturized atomic clocks. Intense research efforts are still pursued today in this domain by a large number of academic and industrial groups [2].

The stability of microcell-based CPT atomic clocks is often degraded after about 100 s by two main contributions, identified to be light-shifts and buffer-gas pressure collisional shifts. At FEMTO-ST, over the last years, we have invested numerous efforts to mitigate these contributions. For mitigation of light-shifts, we have implemented and demonstrated the efficiency of pulsed Ramsey-based interrogation sequences. With advanced Auto-Balanced Ramsey sequences, we have demonstrated a reduction of the clock frequency to all parameters of the light-field (laser power, microwave power, laser frequency) by more than two orders of magnitude, in comparison with the usual continuous interaction regime [3]. Recently, we have successfully implemented such protocols through direct modulation of the laser current, such that no external optical shutter or AOM is needed, confirming their compatibility to be used in fully-integrated CSACs [4]. In addition to light-shift mitigation techniques, we had to reduce buffer gas permeation issues through the cell glass windows. For this purpose, we have investigated the use of cells built with alumino-silicate glass (ASG) windows, instead of borosilicate glass [5]. We have also explored the possibility to use Al₂O₃ coatings on the cell windows. By combining ASG and 20-nm thick Al₂O₃ coatings, we have achieved a reduction of helium permeation rate by more than 3 orders of magnitude [5]. Studies were also performed to investigate the impact of the Al₂O₃ coating thickness on the gas permeation rate [6]. By combining pulsed Ramsey-based sequences and low permeation glass cells, we have demonstrated a microcell CPT clock with a fractional frequency stability of 7×10^{-11} at 1 s and averaging down below 2×10^{-12} at 1 day integration time [7]. Currently, some studies are in progress to increase the buffer-gas induced turnover temperature point of the microcell. These cells are planned to be obtained through the use of laser-actuated break-seal and make-seals reported in [8].

Over the last years, we have also started at FEMTO-ST the development of "new-generation" microcell optical frequency references. These references are based on sub-Doppler spectroscopy techniques, attractive due to their simple architecture (1 laser, 1 cell, no laser cooling), and high potential for

miniaturization with MEMS cells and integrated lasers/photonics. Two microcell optical references are in progress at FEMTO-ST. The first one is based on the excitation of the two-photon transition at 778 nm of the Rb atom. In this reference, atoms are promoted with an external-cavity diode laser to the $5D_{5/2}$ excited state and emit during their radiative decay blue fluorescence photons at 420 nm detected by a photomultiplier. Using this method, a frequency stability of 3×10^{-13} at 1 s and below 3×10^{-14} at 100 s has been achieved [9]. Limitations on the short-term stability and mid-term stability are well identified and some room for improvement does still exist. The second system is based on saturated absorption spectroscopy of the Cs atom $6S_{1/2} - 7P_{1/2}$ transition at 459 nm [10]. Two quasi-identical ECDLs, each stabilized onto a microcell, have been mounted. An encouraging preliminary short-term stability lower than 2×10^{-13} at 1 s for a single laser has been obtained.

Latest results will be presented at the conference and future perspectives will be discussed.

Note: This project has received funding from the European Defence Fund (EDF) under grant agreement 101103417 EDF-2021-DIS-RDIS-ADEQUADE. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

- [1] S. Knappe et al., Appl. Phys. Lett. 85, 1460 (2004).
- [2] J. Kitching, Appl. Phys. Rev. 5, 031302 (2018).
- [3] M. Abdel Hafiz et al., Appl. Phys. Lett. 120, 064101 (2002).
- [4] C. Rivera et al., Appl. Phys. Lett. 124, 114102 (2024).
- [5] C. Carlé et al., J. Appl. Phys. 133, 214501 (2023).
- [6] C. Carlé et al., J. Appl. Phys. 136, 085102 (2024).
- [7] C. Carlé et al., Opt. Express 31, 5, 8160 (2023).
- [8] V. Maurice et al., Nature Microsyst. Nanoeng. 8, 129 (2022).
- [9] M. Callejo et al., J. Opt. Soc. Am. B 42, 1, 151 (2025).
- [10] E. Klinger et al., Opt. Lett. 49, 8, 1953-1956 (2024).