Microcell-CPT clock with reduced light-shift sensitivity using Ramsey-based sequences applied through direct modulation of the laser current

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***Summary*— This work introduces a coherent-population trapping (CPT) microcell atomic clock employing the symmetric auto-balanced Ramsey (SABR) interrogation sequence applied through direct current-based laser power modulation. This approach eliminates the need for external optical shutters, enabling seamless integration with compact clock architectures. Measurements demonstrate that SABR significantly reduces the clock frequency sensitivity to laser power, microwave power, or laser frequency, compared to continuous and Ramsey-CPT regimes. Importantly, a real-time tracking mechanism was implemented on the FPGA to address the thermal-induced jitter of the absorption profile within the detection window. This innovation stabilizes the detection process, enabling reliable light-shift measurements, and ensures robust clock performance. These advances might pave the way for the advent high-performance chip-scale CPT clocks based on Ramsey-based pulsed interrogation protocols.**

Keywords—Microwave clocks; microfabricated cells; digital electronics.

Chip-scale atomic clocks (CSACs) based on coherent-population trapping (CPT) have revolutionized precise timekeeping for portable applications in navigation, communication, and synchronization systems, by offering excellent fractional frequency stability within a low size, weight, and power (SWaP) budget [1]. These clocks operate by trapping alkali vapor atoms, confined in a microfabricated cell, in a quantum dark state, the CPT state, using an optically-carried microwave signal. This dark state is detected as a resonance peak (increased transmitted light) at the cell output, and is used to stabilize the microwave frequency of the local oscillator that drives the VCSEL.

Despite their success, the long-term performance of CSACs can be degraded by light-shift effects. Several methods have been developed to mitigate these light-shifts in continuous (CW)-regime CSACs [2-4]. Nevertheless, the latter techniques rely on experimentally determined quantities that are expected to change with time, from one device to another, possibly requiring intricate time-consuming calibration processes at the clock production level. Pulsed Ramsey-based interrogation protocols have been also demonstrated in microcell CPT clocks for light-shift mitigation. In some cases [5-6], studies involved the use of an external optical shutter, in general an acousto-optical modulator (AOM), to produce the pulsed sequence, jeopardizing the clock integration potential. In [7-9], Ramsey-like CPT sequences based on two-step pulses applied through direct modulation of the laser current were investigated. Nevertheless, these studies were performed in cm-scale glass-blown vapor cells, benefiting from longer CPT coherence lifetimes, while no closed loop clock operation was demonstrated.

In [10], we have demonstrated light-shift reduction and clock operation using a two-step pulse Ramsey-CPT interrogation sequence, within a buffer gas-filled Cs microfabricated cell, by directly modulating the laser current. If encouraging, Ramsey spectroscopy keeps a residual sensitivity to light-shifts such that exploring more advanced pulsed Ramsey-based interrogation protocols appeared as an exciting objective.

In this work, we demonstrate a CPT-based microcell atomic clock utilizing the symmetric auto-balanced Ramsey (SABR) interrogation sequence [11]. The sequence is applied through direct current modulation of a vertical-cavity surface-emitting laser (VCSEL), eliminating the need for external optical shutters and ensuring compatibility with fully integrated CSAC designs. The system, illustrated in Fig. 1, is fully managed by a Red Pitaya FPGA board, which oversees sequence generation, data acquisition, signal processing, and servo loop corrections.

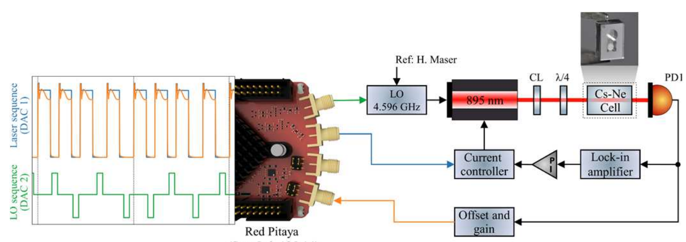

Fig. 1. Illustration of the CPT clock experiment with application of a SABR sequence by directly modulating the laser current.

Once implemented, our initial motivation was to measure light-shift coefficients under the SABR-CPT and Ramsey-CPT regimes. Sensitivity coefficients of 2.5 mHz/MHz (SABR) versus −10 mHz/MHz (Ramsey) for laser detuning −0.06 Hz/μW (SABR) versus 0.4 Hz/µW (Ramsey) for laser power, and 2.8Hz/dB (SABR) versus −80.4Hz/dB (Ramsey) for microwave power demonstrate that SABR reduces the clock frequency dependence to variations of the light-field parameters. These results confirm the efficiency of the SABR-CPT interrogation sequence, applied here through direct modulation of the laser current, in mitigating light-shifts.

A key challenge identified during the experiment was the jitter of the VCSEL laser frequency caused by abrupt current pulses, which lead to jitter of the absorption profile (about +/- 80 ns), subsequent shifts of the clock frequency, and invalidating early measurements. To address this issue, we have implemented a real-time detection window tracking mechanism on the FPGA board, which dynamically compensates for these fluctuations by extracting the signal of interest around the bottom of the absorption profile. Light-shift coefficients in absolute value of 6.8 mHz/ns (Ramsey) and 23.35 mHz/ns (SABR) due to this phenomenon were measured. Furthermore, optimal observation offset positions were identified, where the dependence of the clock frequency on the absorption profile position is minimized.

This work highlights the potential of SABR-based interrogation sequences combined with advanced real-time feedback mechanisms to reduce light-shifts in microcell CPT clocks, paving the way for high-performance, fully integrated chip-scale atomic clocks. Latest results, including clock stability performances, will be reported at the conference.

REFERENCES

[1] J. Kitching, Chip-scale atomic devices, Appl. Phys. Rev. 5, 031302 (2018).

[2] M Zhu and L. S. Cutler, Theoretical and experimental study of light-shift in a CPT-based Rb vapor cell frequency standard, 32nd Annual Precise Time and Time Interval (PTTI) Meeting, 311-324 (2000).

[3] V. Shah, V. Gerginov, P. D. D. Schwindt, S. Knappe, L. Hollberg, and J. Kitching, "Continuous light-shift correction in modulated coherent population trapping clocks", Appl. Phys. Lett. 89, 151124 (2006).

[4] S. Yanagimachi, K. Harasaka, R. Suzuki, M. Suzuki, and S. Goka, "Reducing frequency drift caused by light shift in coherent population trapping-based low-power atomic clocks", Appl. Phys. Lett. 116, 104102 (2020).

[5] M. Abdel Hafiz, C. Carlé, N. Passilly, J. M. Danet, C. E. Calosso and R. Boudot, Light-shift mitigation in a microcell-based atomic clock with Symmetric Auto-Balanced Ramsey spectroscopy, Appl. Phys. Lett. 120, 064101 (2022).

[6] C. Carlé, M. Abdel Hafiz, S. Keshavarzi, R. Vicarini, N. Passilly, and R. Boudot, A pulsed-CPT Cs-Ne microcell atomic clock with frequency stability below $2x10^{-12}$ at 10^5 s, Opt. Express 31, 5, 8160-8169 (2023).

[7] T. Ide, S. Goka, and Y. Yano, "CPT pulse excitation method based on VCSEL current modulation for miniature atomic clocks," in Proceedings of the IEEE International Frequency Control Symposium—European Frequency and Time Forum Joint Meeting (IEEE, 2015).

[8] M. Fukuoka, S. Goka, M. Kajita, and Y. Yano, "Light shift of Ramsey-coherent population trapping resonance using drive current modulation," Jpn. J. Appl. Phys. 62, 122005 (2023).

[9] M. Fukuoka and S. Goka, "Simultaneous observation of semi-continuous and Ramsey-coherent population trapping resonances using the Ramsey pulse sequence with drive current modulation," Jpn. J. Appl. Phys. 63, 012005 (2023).

[10] C. M. Rivera-Aguilar, M. Callejo, A. Mursa, R. Vicarini, M. Abdel Hafiz, N. Passilly, J-M. Friedt, and R. Boudot, Operation of a Ramsey-CPT microcell atomic clock with driving current-based power modulation of a vertical-cavity surface-emitting laser, Appl. Phys. Lett. 124, 114102 (2024).

[11] M. Abdel Hafiz, G. Coget, M. Petersen, C. E. Calosso, S. Guérandel, E. de Clercq, and R. Boudot, "Symmetric autobalanced Ramsey interrogation for high-performance coherent-population-trapping vapor-cell atomic clock", Appl. Phys. Lett. 112, 244102 (2018).