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ABSTRACT

The mid-term fractional frequency stability of miniaturized atomic clocks can be limited by light-shift effects. In this Letter, we demonstrate the implementation of a symmetric auto-balanced Ramsey (SABR) interrogation sequence in a microcell-based atomic clock based on coherent population trapping. Using this advanced protocol, the sensitivity of the clock frequency to laser power, microwave power, and laser frequency variations is reduced, at least by one order of magnitude, in comparison with continuous-wave or Ramsey interrogation schemes. Light-shift mitigation obtained with the SABR sequence benefits greatly to the clock Allan deviation for integration times between 10^2 and 10^5 s. These results demonstrate that such interrogation techniques are of interest to enhance the timekeeping performance of chip-scale atomic clocks.

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The development of low-SWaP (size-weight-power) frequency references with enhanced frequency stability is of crucial importance in a wide range of applications including timing, navigation, positioning, security, communications, or scientific systems.[1] In these domains, microwave chip-scale atomic clocks (CSACs)[2–6] based on coherent population trapping (CPT) have met a remarkable success by offering a daily drift about 100 times smaller than commonly used oven-controlled quartz oscillators.

Light-shifts are known to be an important contribution to the fractional frequency stability of miniaturized atomic clocks for integration times higher than 100 s. Multiple approaches have then been proposed to mitigate their detrimental impact. Some efforts were oriented toward the extraction of the actual laser or cell temperature, from the atomic response itself, in order to reduce the negative impact of temperature gradients between these key components and their respective temperature sensors.[2,5,7] Other sophisticated methods include the active stabilization of a specific laser microwave modulation index that reduces laser power-induced frequency instabilities,[3,5,8–10] possibly combined with the compensation for laser aging,[6] or the implementation of advanced tailored interrogation sequences using laser power modulation.[11] Deposition of gold micro-discs, used as privileged alkali condensation spots onto the cell windows was also shown to avoid the progressive obstruction of the transmitted laser light.[12]

An alternative and straightforward approach to mitigate light-shifts in CPT clocks is to probe the clock transition with Ramsey spectroscopy.[13,14] Mainly investigated in compact vapor cell clocks,[15] Ramsey-CPT spectroscopy has recently stimulated some research interest in miniaturized atomic clocks. The generation of robust Ramsey-CPT sequences with directly modulated lasers was demonstrated in Refs. 16 and 17, whereas spectroscopy, clock operation, and evidence of light-shift mitigation were reported with Ramsey-CPT in buffer-gas filled microfabricated vapor cells.[18,19]

Nevertheless, Ramsey-CPT spectroscopy suffers from a residual sensitivity to light-shifts, experienced by the atoms during the light pulses. Advanced Ramsey-based tailored interrogation protocols, based on two consecutive Ramsey sequences with different dark times, have then been proposed and demonstrated in various types of atomic clocks for enhanced light-shift mitigation.[20–27]

These protocols interleave two clock configurations with a different amount of light-shift, so that the light-shift can be retrieved and then compensated in real time. In standard vapor cell clocks, the same sample of atoms is probed at every iteration while the coherence

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lifetime is comparable to the pulse repetition period, yielding the atoms to keep a partial memory of past interactions. The atoms provide significantly different response, depending on the side (right or left) of the resonance probed before the dark time change, resulting in a bias in light-shift estimation and then reducing the efficiency of the protocol. In Ref. 23, it was demonstrated that by changing the aforementioned probing side, the sign of the bias changes as well, while its amount does not. In order to minimize the effect of the atomic memory, the clock sequence is repeated in a symmetric way, such that the two consecutive and opposite biases cancel each other.

However, the efficiency of this approach in microfabricated cells employed in CSACs is hardly predictable. Indeed, the shorter timescales of the light pulse sequence, imposed by the reduced CPT coherence lifetime, raise the question of a possible amplification of the atomic memory effect along with degradation of the signal-to-noise ratio in the estimation of the light shift, which depends on the difference between the short and long dark times.

In this Letter, we study and demonstrate the implementation of a symmetric auto-balanced Ramsey (SABR) sequence in a CPT-based microcell atomic clock. For sake of simplicity and proof-of-concept demonstration, the pulsed optical sequence is applied with an external acousto-optical modulator (AOM). In comparison with the standard Rabi or Ramsey-CPT interrogation schemes, we demonstrate that the SABR method reduces the sensitivity of the clock frequency to laser power, microwave power, and laser frequency variations, by a factor higher than 10. Furthermore, we strengthen the importance of the sequence symmetry and its ability to annihilate the consequences of the atomic memory effect in mm-scale cells. We also show that the use of SABR improves the clock Allan deviation for integration times between 10^2 and 10^5 s, especially by reducing the impact of temperature-induced light-shift effects.

Figure 1 presents the CPT clock experimental setup. The heart of the clock is a pill-dispenser microfabricated Cs vapor cell[28,29] filled with about 90 Torr of Neon. The cell is temperature-stabilized at 70 °C. A static magnetic field of 10 μT is applied to raise the Zeeman degeneracy and isolate the 0–0 clock transition. Atoms in the cell interact with a dual-frequency optical field produced by direct microwave modulation of a vertical-cavity surface emitting laser (VCSEL),[30] tuned on the Cs D_1 line, and such that both first-order optical sidebands induce the CPT resonance. Except when willingly varied for tests, the microwave power that enters the VCSEL is about −2.3 dBm. At the output of the laser, an AOM, driven by a switchable radio frequency (RF) signal, is used to generate the pulsed optical sequence. Tuning the power of the RF signal permits control of the total laser power incident onto the cell. The 0.5-mm diameter laser beam is then sent through the Cs vapor microcell and detected at its output with a photodiode.

For this study, we have used a field-programmable gate array (FPGA)-based digital control electronics platform.[31] The latter allows fast computation and feedback to the experiment, such that the generated sequence is readjusted every clock cycle. In this ecosystem, the output 4.596 GHz signal that drives the VCSEL is obtained by mixing 4.3 GHz from a synthesizer and a 296 MHz signal generated by a direct digital synthesizer (DDS1). A second DDS (DDS2) delivers the 80 MHz RF signal that drives the AOM. This signal can be turned on and off with the help of embedded RF switches. All DDS are clocked with an ultra-pure 860 MHz signal obtained by frequency division by 5 of the synthesizer 4.3 GHz signal. The absolute phase noise of the output 4.596 GHz was measured to be −118 dBc/Hz at an offset frequency $f = 1$ kHz. This phase noise reduces the Dick effect contribution[32] to a negligible level for such a microcell-based clock. The microwave source is referenced to an active hydrogen maser. In the following, the optically carried 9.192 GHz signal of frequency ν_{LO}, used to probe the atomic transition, is named as the local oscillator (LO) signal. In clock operation, the value of ν_{LO} is changed by digitally changing the output frequency of DDS1. Corrections applied to DDS1 are then recorded and used as frequency data for analysis.

The tested SABR sequence, shown in Fig. 1, is similar to the one described in Ref. 23. It consists of two consecutive ABR sequences (ABR 1 and ABR 2). Each ABR sequence consists in turn of four consecutive Ramsey-CPT sequences with light pulses of length T_b. The two first Ramsey-CPT patterns use a short dark time T_S while the two following ones use a long dark time T_L. A $\pm\pi/2$ phase jump is applied onto the optically carried microwave interrogating signal during the dark times by acting on DDS1 in order to successively measure the transmitted signals on respective sides of the central fringe. This yields the extraction of error signals, noted ε_S (for the short dark time pattern) and ε_L (for the long dark time pattern). In the second ABR sequence (ABR 2), the light pulse pattern is identical while the LO phase modulation pattern is the mirror symmetric to the one used in the first ABR sequence (ABR 1). In vapor cell experiments, the use of a symmetric ABR sequence is of crucial importance to cancel memory effects of the atoms and then to improve the efficiency of the light-shift rejection.[23] Ultimately, two error signals are calculated, ensuring

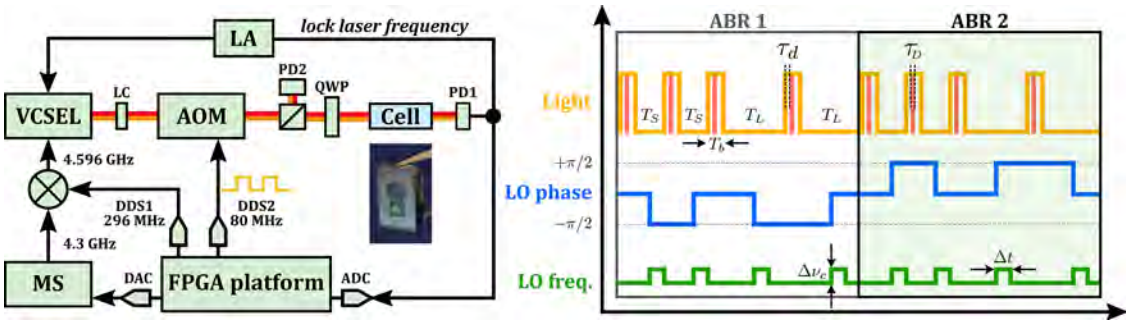

FIG. 1. Left: CPT clock setup and basic architecture of a SABR sequence. LC: collimation lens; QWP: quarter-wave plate; LA: lock-in amplifier; ADC: analog-to-digital converter; DAC: digital-to-analog converter; MS: microwave synthesizer. Right: simplified scheme for the SABR sequence.

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that information is extracted at all pulses for both correction signals and then preventing the negative impact of aliasing on the short-term stability.[23] The error signal $\varepsilon_+ = \varepsilon_S + \varepsilon_L$ is used to correct the LO frequency. The error signal $\varepsilon_- = \varepsilon_S - \varepsilon_L$ is extracted to correct the value of an additional phase jump φ_c, applied during dark times, that compensates for the light-induced phase shift built up during the previous light pulse. The phase jump φ_c is obtained by changing the LO frequency by the amount $\Delta\nu_c$ for a time Δt.

In all the tests reported in this Letter, the pulse length T_b is set to 183 μs, and the atomic signal is sampled after a delay τ_d of 33 μs to account for the delay induced by the anti-aliasing filter. The latter, a 25.6 kHz low-pass filter, averages the photodiode voltage over about 20 μs and is responsible of the actual duration τ_D of the detection window.

Figure 2(a) shows error signals ε_S, ε_L, and ε_+ extracted from a SABR sequence performed on the Cs-Ne microcell. It is clear that the initial error signal ε_S, extracted from the sequence with the shortest dark time T_S, is higher in amplitude and broader than the error signal ε_L obtained for the longest sequence. Their zero-crossings, mainly shifted from the natural Cs atom frequency because of the buffer-gas induced collisional shift, do not coincide due to the variation of the light-shift magnitude with the dark time value. The error signal $\varepsilon_+ = \varepsilon_S + \varepsilon_L$ benefits from a higher slope that justifies its use for stabilization of the LO frequency. The error signal $\varepsilon_- = \varepsilon_S - \varepsilon_L$, plotted in Fig. 2(b) vs the phase jump φ_c applied during the dark time, exhibits, in open-loop configuration, a zero-crossing point at a non-null value of φ_c ($\sim$0.3 rad), where the light-shift is compensated in closed loop.

Figure 3(a) shows the dependence of the clock frequency to laser power variations in the standard CW regime, the Ramsey-CPT case, the SABR case, and the non-symmetric ABR case. In the Ramsey-CPT case, the light-shift coefficient is 0.79 Hz/μW. In the SABR case, the latter is reduced by a factor of 26 and is 0.03 Hz/μW. This coefficient is 470 times smaller than the one measured in the standard CW scheme (14 Hz/μW). We have also performed the same measurement when the ABR clock sequence is reduced to the first part (ABR 1). In this non-symmetric case, the memory effect is responsible for a shift in

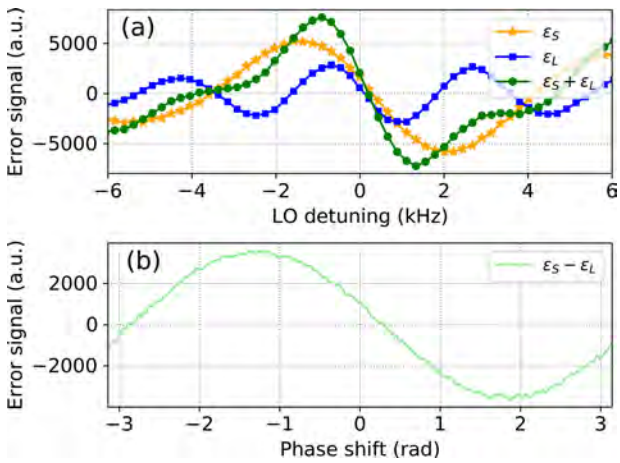

FIG. 2. (a) Error signals ε_S, ε_L, ε_+ as a function of the LO detuning from the value of 9 192 682 200 Hz and (b) error signal ε_- as a function of the phase jump φ_c during the dark time extracted from a SABR sequence.

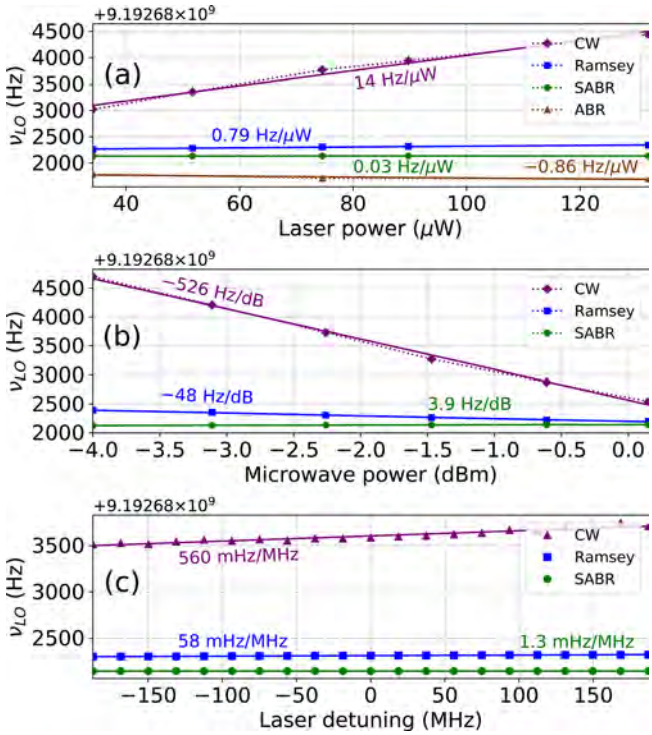

FIG. 3. Clock frequency vs (a) the laser power, (b) the microwave power, or (c) the laser carrier frequency in the standard CW, Ramsey-CPT, SABR, or ABR cases. Experimental data are fitted by linear functions, shown as solid lines, from which a linear light-shift coefficient is extracted. In (a) and (c), the microwave power is −2.3 dBm. In (b) and (c), the laser power is 72 μW.

the clock frequency by more than 250 Hz. Without symmetry, the ABR protocol does not give any significant advantage and even leads to a slight deterioration with respect to the Ramsey-CPT case in microcells. This result attests that the memory effect is strong in microcells, highlighting the importance of the sequence symmetry.

Variations of the microwave power that drives the VCSEL can also induce significant shifts of the CPT clock frequency.[3,8,9] We have then measured this sensitivity with the SABR sequence. Corresponding results are shown in Fig. 3(b), in comparison with those obtained with the CW or Ramsey-CPT schemes. In the SABR case, a sensitivity of +3.9 Hz/dB is measured to be compared with a slope of −48 Hz/dB and −526 Hz/dB in the Ramsey-CPT and CW cases, respectively.

Figure 3(c) depicts an additional sensitivity measurement with the laser frequency. Calibration of the laser frequency change was performed using absorption profiles detected at the cell output. Here again, we observe a strong reduction in the light-shift coefficient, reduced from 58 mHz/MHz in the Ramsey-CPT case and even 560 mHz/MHz in the CW regime down to 1.3 mHz/MHz in the SABR case.

Finally, frequency stability measurements of the microcell CPT clock operating with Ramsey-CPT or SABR-CPT sequences have been performed. These tests were conducted on the same setup with quasi-identical environment conditions. The total laser

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power at the cell input is about 72 μW. Allan deviations are shown in Fig. 4.

In the Ramsey-CPT case, the clock short-term stability is about $8.5 \times 10^{-11}\ \tau^{-1/2}$ until 60 s. We identified that the "bump" between 60 and 10^3 s was attributed to temperature fluctuations of the laboratory. For $\tau > 10^3$ s, a degradation is observed, yielding the level of 3×10^{-11} at 10^5 s.

In the SABR case, the clock short-term stability is slightly degraded with the level of 1.1×10^{-10} at 1 s. At the opposite, the clock performance is clearly improved in the 10^2–10^5 s range. We observed with SABR a significant suppression of the correlation of the clock frequency with temperature variations of the laboratory, benefiting greatly to the clock Allan deviation that averages down until 2000 s at the level of 3×10^{-12}. It is also interesting to note that, with SABR, a correlation was observed between the lab temperature and the routinely measured phase jump φ_c. These results confirm further that the SABR method efficiently mitigates light-shifts in microcells and improves the mid-term stability of miniaturized clocks without any significant deterioration of the short-term stability.

For $\tau > 3000$ s, the Allan deviation remains degraded, reaching the level of about 2.5×10^{-11} at 10^5 s. However, several arguments tend to exonerate light-shift effects. From Fig. 3, we calculate that this stability level should be explained by fluctuations at 1 day of the laser power and laser frequency, such that $\Delta P = 7.6\,\mu$W ($\Delta P/P = 10.6\%$) and $\Delta f = 177$ MHz ($\Delta f/f = 5.2 \times 10^{-7}$), respectively. These values are high in comparison with those reported in the literature.[3,29,33] Variations $\Delta P_{\mu W}$ of the microwave power of only 0.06 dB at 1 day might be more suspected[3,6,29] to justify the stability limitation. However, this assumption is counterbalanced by two observations. First, Allan deviation results obtained at 1 day are comparable for SABR and Ramsey-CPT cases whereas light-shift coefficients in the Ramsey case are at least one order of magnitude higher. Second, in both Ramsey and SABR cases, we observed that the clock frequency constantly drifted with a negative slope. This similar frequency drift sign, observed in both regimes, is contradictory with the fact that light-shift coefficients reported in Fig. 3(b), obtained in Ramsey and SABR cases, exhibit opposite signs. We have also checked that the

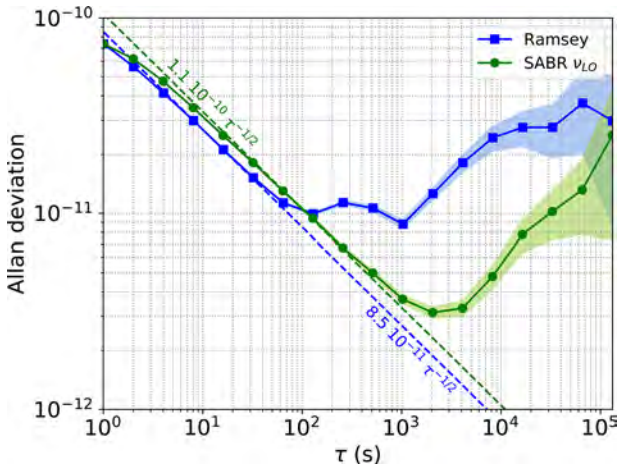

FIG. 4. Allan deviation of the clock frequency in Ramsey-CPT and SABR-CPT regimes. The laser and microwave powers are 72 μW and −2.3 dBm, respectively.

temperature dependence of the buffer gas collisional shift,[34,35] the Zeeman shift, barometric effects,[36] or alkali condensation on the cell windows[12] could not explain the measured stability level at 1 day. To date, the clock stability limitation at 1 day on this setup is suspected to come from a possible unstable cell inner atmosphere. This could be related to Ne buffer gas permeation through the glass windows,[37] materials degassing, or dispenser pollution.[38]

In conclusion, we have explored the implementation of auto-balanced Ramsey (ABR) spectroscopy for light-shift mitigation in a microcell-based atomic clock. Despite the use of patterns with optical pulses and dark time durations of only a few hundreds of microseconds, this technique, provided that symmetry of the pattern is well applied, reduces the dependence of the clock frequency to laser field parameter variations by more than two orders of magnitude with respect to the standard CW-regime approach, commonly used in commercial CSACs. We have also demonstrated that SABR improves the clock Allan deviation of a microcell CPT clock between 10^2 and 10^5 s, where light-shifts are predominant. One of the next steps consists in the implementation of SABR in a microcell without the use of an external AOM in order to remain compatible with a CSAC architecture. Several approaches might be explored for this purpose.[16,17,39]

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AUTHOR DECLARATIONS

Conflict of Interest

The authors state that there is no conflict of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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