A CPT-based Cs cell clock using the auto-balanced Ramsey interrogation protocol

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***Abstract*— We propose a preliminary theoretical investigation and demonstrate experimentally the application of the auto-balanced Ramsey (ABR) interrogation protocol onto a pulsed hot vapor Cs cell microwave atomic clock based on coherent population trapping (CPT). This approach, based on the alternation of two successive Ramsey-CPT sequences with unequal free-evolution times and the subsequent management of two interconnected phase and frequency servo loops, is found to allow a reduction of the clock frequency sensitivity to laser power variations. This approach, combined with the implementation of advanced electronics laser power stabilization systems, yields the demonstration of a CPT-based Cs cell clock with a fractional frequency stability at the level of 3.1 × 10^{-13} $\tau^{-1/2}$ and averaging down to the level of 7 ×10^{-15} at 2000 s integration time.**

Keywords—CPT clock, fractional frequency stability, auto-balanced Ramsey interrogation, vapor cell.

I. INTRODUCTION

Compact vapor cell microwave atomic clocks are attractive candidates in numerous applications due to their ability to exhibit small size, power consumption, and excellent fractional frequency stability. However, they often suffer on medium and long time scales from frequency instabilities, generally due to light-induced frequency shift effects.

The use of coherent population trapping (CPT) spectroscopy, is an interesting option for the development of high-performance compact vapor cell clocks. In particular, the Ramsey-CPT method offers the advantages to produce high contrast and narrow-linewidth Ramsey-CPT fringes. Moreover, this method is expected to reduce the contribution of light-shift effects by inducing resonant light shifts inversely proportional to the duration of the free-evolution time.

The application of the Ramsey-CPT method, combined with the use of an optimized CPT pumping scheme, has allowed recently the demonstration of a low drift cold atom CPT clock with an Allan deviation of 1.3×10^{-11} $\tau^{-1/2}$ averaging down to 2 × 10^{-13} after 40000 s [1,2]. At the opposite, the use of Ramsey spectroscopy has never demonstrated to date a significant improvement in the long-term clock stability of hot vapor cell CPT clocks [3,4].

The original Ramsey method is known to remain sensitive to perturbations from the interrogation field itself. Over the last decade, several robust interrogation protocols targeting to eliminate the contribution of the probing-field induced clock frequency shifts. This includes Hyper Ramsey spectroscopy techniques or synthetic frequency protocols [5-11]. More recently, the auto-balanced Ramsey (ABR) interrogation protocol, based on the combination of two successive Ramsey sequences with unequal free evolution times and the subsequent management of two phase and frequency servo loops, was proposed [12] and has stimulated a significant interest [13].

In FEMTO-ST, we have recently reported the development of a high-performance CPT-based Cs cell atomic clock, combining the use of an optimized pumping scheme named push-pull optical pumping (PPOP) [14,15] and a pulsed interrogation, with a short-term fractional frequency stability at the level of 2.3 10^{-13} $\tau^{-1/2}$ up to 100 s [4]. The clock combines a DFB laser tuned on the Cs D1 line, a Mach-Zehnder electro-optic modulator (EOM) driven a 4.596 GHz to produce the generation of CPT optical sidebands, an AOM to shift the laser frequency, apply the pulsed interrogation scheme and stabilize the laser power and a Michelson-like system to produce the PPOP scheme. The output 2-cm diameter light beam is sent into a Cs-N_2-Ar vapor cell and is detected at the output by a photodiode. The laser is frequency stabilized using a dual-frequency Doppler-free spectroscopy setup implemented at the output of the EOM [16].

II. EXPERIMENTS

In this work, we report the in-progress frequency stability performance of this CPT-based Cs cell atomic clock.

In a first step, advanced electronics dedicated to stabilize the laser power in the pulsed regime and improved thermal isolation of the experiment have been implemented, yielding a clock fractional frequency stability at the level of 1.4 10^{-13} $\tau^{-1/2}$ up to 200 s and 10^{-13} at 10 000 s.

In a second step, in order to improve the clock mid-term frequency stability, we demonstrate the possibility to probe the two-photon CPT resonance using the auto-balanced Ramsey (ABR) interrogation protocol. This original approach, based here on the alternation of two successive Ramsey-CPT sequences with unequal free-evolution times, was found to allow a reduction of the clock frequency sensitivity to laser power variations.

Using the ABR-CPT method, the preliminary clock short-term frequency stability is degraded by a factor 2, yielding 3.1×10^{-13} at 1 s, compared to the usual Ramsey-CPT case. This degradation comes from the fact that in this preliminary test, the error signal for the LO frequency correction was extracted from the cycle with a long free-evolution time (T=5.4 ms), compared to the optimal free-evolution time (T=2.7 ms), inducing a reduction of the Ramsey-CPT fringe signal due to the relaxation of the CPT coherence.

On the other hand, the Allan deviation of the clock is preliminary improved at the level of 6×10^{-15} at 2000 s averaging time using the ABR-CPT protocol. These performances at 2000 s are a factor 6.6 better than those obtained in the conventional Ramsey-CPT case, in correct agreement with the reduction of the clock frequency sensitivity to laser power. These results at 2000 s are a factor 33 better than those reported last year in EFTF-IFCS 2017. These results are encouraging towards the development of low-drift CPT-based atomic frequency standards but they need to be investigated further in detail.

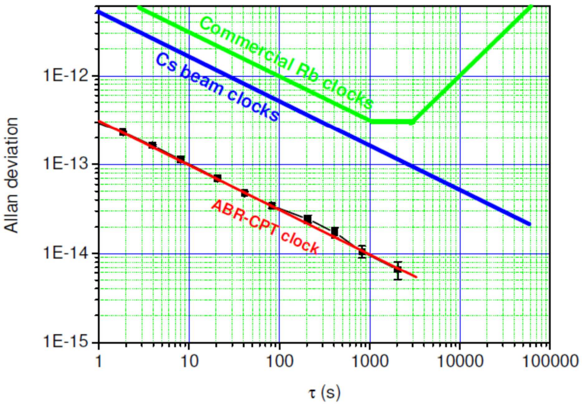

Figure: Allan deviation of the ABR-CPT Cs cell clock. For comparison, typical performances of a commercial Rb clock or a Cs beam clock are reported.

In a near future, a better understanding, characterization and application of the ABR-CPT method, combined with the implementation of advanced electronics, will be under investigation in order to try to improve further the short-term and mid-term frequency stability performances of this CPT clock.

For this purpose, we have recently implemented on this CPT clock an ultra-low phase noise microwave frequency synthesizer [17], combined with a high-performance FPGA-based electronics system [18], for full control of the clock. Moreover, optimization of the ABR-CPT sequence or some of its variants [14] reveals to be an attractive option for our future studies. Latest results will be shown at the conference.

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