Status of a compact cold-atom CPT frequency standard

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***Abstract*—We describe the progress towards the realization of a cold-atom frequency standard based on coherent population trapping (CPT). We explain our particular CPT configuration and give details on the experimental setup.**

I. INTRODUCTION

The performance of atomic clocks based on coherent population trapping (CPT) has improved considerably over the last few years in terms of stability and reliability [1], [2], [3]. Frequency stabilities in the low $10^{-10}\ \tau^{-1/2}$ range are now realized within package volumes of a few tens of cubic centimeters [3]. Nevertheless, a significant frequency drift ($\geq 10^{-12}$/day) is observed in these devices. The use of wall coatings and buffer gases, which are required for high-contrast narrow-linewidth CPT resonances, degrades the long-term stability through cell aging and large temperature-dependent pressure shifts. Light shifts also contribute to the drift of CPT-based clocks.

To circumvent these issues, we began a study of a microwave CPT frequency standard based on laser-cooled atoms (CA-CPT). Cold atoms can provide good long-term performance, while the all-optical CPT interrogation enables good stability through narrow atomic resonances [1] and allows miniaturization of the physics package by eliminating the microwave cavity. This project aims at reaching a frequency stability of better than $10^{-11}\ \tau^{-1/2}$ and an accuracy of around 10^{-13} within a miniaturized physics package. Our work focuses both on the experimental realization and the metrological evaluation of a CA-CPT clock and on efficient ways of producing a cold atom sample in a millimetric volume (see [4]). Consideration of the expected systematics, including light shifts, second-order Zeeman effects and Doppler effects are given in [5].

II. CPT INTERROGATION

Many schemes and configurations with differing atom types, optical excitation lines, light polarization, etc., have been proposed to improve the metrological properties of a clock based on a CPT resonance [1]. Improvements can be made, for example, by use of a polarization configuration that does not involve so-called "trap states" (extreme m_F sublevels) [6], [7], [8], and by use of a larger intensity in the CPT beams to increase the pumping rate into the "dark state". However, this latter option has two major drawbacks. A large intensity broadens the resonance, so that the high contrast is quickly counter-balanced by a broader linewidth $\Delta\nu$; secondly, it increases the magnitude of the second-order Stark shift (light shift).

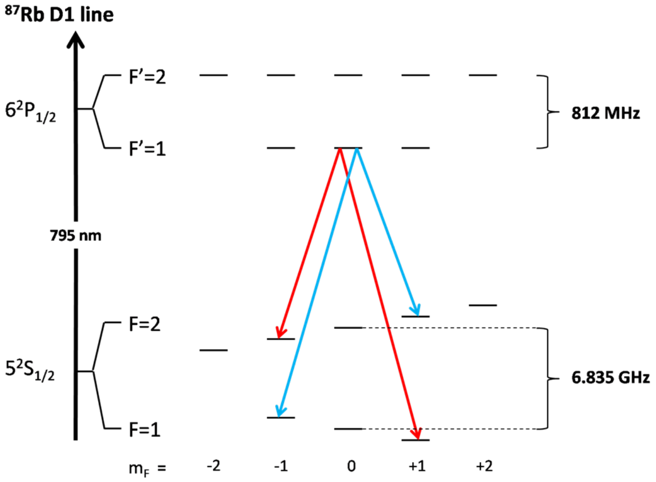

Fig. 1. Energy diagram of the ^{87}Rb D1 line at 795 nm and transitions involved in the $lin||lin$ configuration.

The sequence and configuration that we propose, a pulsed Ramsey-like sequence on a cold ^{87}Rb sample combined with a $lin||lin$ configuration [8], can achieve high contrast without being limited by power broadening and large light shifts. The advantages of this approach are described in the following.

A. *lin parallel lin configuration*

The $lin||lin$ configuration was first proposed and studied by Taichenachev *et al.* in [8] and then investigated further in [9], [10], [11], [12], [13]. The CPT resonance is the superposition of two Λ systems (see Fig. 1) connecting the ground state sublevels $|F=1, m_F=\pm 1\rangle$ and $|F=2, m_F=\mp 1\rangle$ through the excited level $|F'=1, m_F=0\rangle$. Because this configuration does not involve any "trap state" we expect an increased contrast. Indeed, contrasts of up to 40 % have been reported in [8] and of 25 % in [11]. From an experimental perspective, this scheme is well suited for a frequency modulated diode laser, as both beams have the same polarization.

B. Pulsed interrogation

Ramsey-like pulsed interrogation with CPT interactions was first performed in the late eighties with a thermal sodium beam and spatially separated interactions [14], [15], [16]. More recently, several groups have used the technique in alkali vapor cells [7], [17] and on cold atoms [18] with two optical pulses separated in time by T_R. The first pulse pumps the atoms into the "dark state" (duration τ_p); then the atoms evolve freely for a period of T_R, after which the second pulse (duration τ_m) measures the accumulated phase. An absorption measurement gives rise to an interference pattern typical of Ramsey interrogation. In this scheme, because the atoms evolve most of the time in the dark, the linewidth $\Delta\nu$ no longer depends on the atomic saturation but is Fourier limited and scales as $1/(2T_R)$. For a miniaturized cold atom clock, the interrogation period is limited by the atomic free fall under gravity to about 10 ms duration (500 μm displacement), leading to a 50 Hz linewidth.

III. EXPERIMENTAL SETUP

The experimental apparatus has been fully assembled. This section presents some aspects of our designs and ideas concerning the vacuum chamber and the optical bench.

A. Vacuum chamber

We use a vacuum chamber produced by *Cold Quanta*[1] for atom-chip Bose-Einstein condensation experiments. The chamber is shown in Fig. 2 and described in detail in [19], [20]. The main chamber, where a 3D optical molasses is realized, is separated from a 2D-MOT zone containing a Rb dispenser by two pinholes of 1 mm diameter, ensuring differential pumping. The vacuum level in the main chamber is currently below 10^{-7} Pa, thanks to a 2 l/s ion pump and a getter pump.

The whole chamber is mounted horizontally to realize CPT interrogation parallel or perpendicular to gravity. A set of three pairs of Helmholtz coils is used to cancel the residual magnetic field and to define a proper quantization axis along the CPT beams.

B. Laser cooling setup

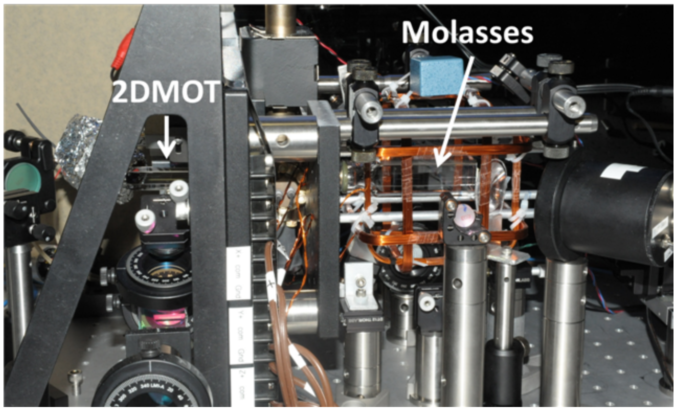

Fig. 2. Picture of the current apparatus.

We use a single diode laser to feed both the 2D-MOT and the 3D-optical molasses regions. We have about 16 mW of power after a double-pass AOM and fiber coupling. The light is tuned about 2 Γ below the $|F=2\rangle \rightarrow |F'=3\rangle$ transition of the ^{87}Rb D2-line, where Γ is the resonance linewidth. The 2D-MOT is generated by use of two elliptical retroreflected beams of area 12 × 25 mm^2 with 5 mW of power in each beam. The quadrupole field is produced by two permanent magnets (12 G/cm). A 1 mW push beam (1 cm diameter) provides a 2D$^+$-MOT geometry. For the optical molasses we use retro-reflected 3 mm beams (diameter @ $1/e^2$) with about 1.5 mW in each pair. With this setup, we are able to capture a few $\times 10^6$ atoms per second, which is currently limited by laser power. The fluorescence is collected with a fresnel lens (NA = 1) with an efficiency of about 4 % on a high-gain photodiode.

C. Optical PLL setup

In many cases, the bichromatic laser field needed for excitation of the CPT resonances is generated by modulating the injection current of a diode laser. This produces a comb of optical frequencies of varying amplitudes. The unwanted residual sidebands degrade the clock performance by contributing to detection noise and the AC Stark shift, but they do not contribute to the CPT signal.

To avoid spurious sidebands in the CPT light we use two independent phase-locked diode lasers. We phase-lock two commercial DFB/DBR lasers at 795 nm with measured Lorentzian linewidths of 1 MHz and 0.6 MHz respectively. The optical beat note is realized around the ^{87}Rb hyperfine splitting at 6.8 GHz. The design of the optical phase lock loop is shown in Fig. 3. The amplified optical beat note is mixed with a 6.65 GHz signal coming from a microwave synthesizer (referenced to a 10 MHz H-Maser signal), filtered, amplified, and compared with a 150 MHz signal coming from a direct digital synthesizer inside a digital phase frequency detector (DPFD AD9901). This DPFD provides an error signal that is filtered and fed back on the slave laser's current. By use of high-speed electronics and through careful measurement of the FM response of both lasers to determine the best master/slave combination, we are able to achieve phase-locked operation with a bandwidth of about 8 MHz. We measured the fractional power in the coherent carrier to be about 70 %, which corresponds to a phase error variance of $0.35\ \mathrm{rad}^2$ over a 20 MHz integration bandwith. We measured the phase noise of the optically generated signal by comparing it to an external RF synthesizer, as shown in Fig. 3. The results are shown in

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[1] Products or companies named here are cited only in the interest of complete scientific description, and neither constitute nor imply endorsement by NIST or by the US government. Other products may be found to serve equally as well.

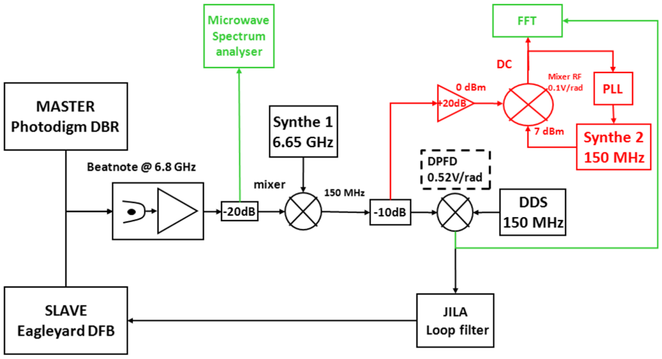

Fig. 3. Optical phase-lock-loop design

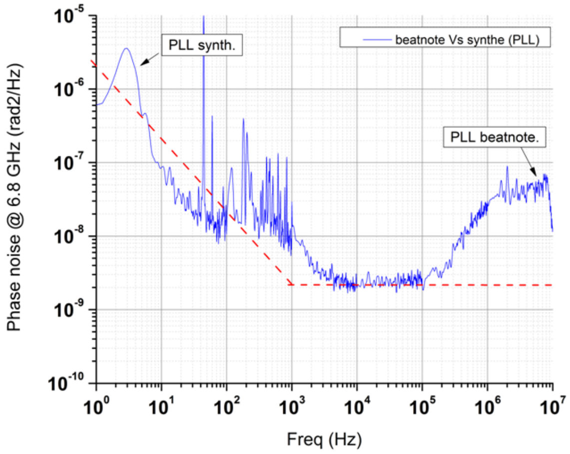

Fig. 4. Measured phase noise of the optically carried 6.8 GHz signal. The small bump around a few hertz is an artifact due to the very narrow band PLL used in the phase noise measurement.

Fig. 4. Out to several kilohertz, the phase noise is determined by joint contribution of the DDS and Synth2, and then we observe a noise floor corresponding to the PLL residual noise. Above 100 kHz the increase in the noise spectrum is due to the loss of PLL gain. With such phase noise, we estimate that the Dick effect will degrade the clock stability at a level of $5 \times 10^{-12}\tau^{-1/2}$. Because the sensitivity function of a pulsed CPT interrogation has yet to be derived, we used the appropriate function for a standard microwave Ramsey interrogation. The parameters used are a cycle duration of 100 ms, $T_R = 10$ ms and $\tau_m = \tau_p = 50$ μs.

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