Cancellation of Doppler Shifts in a Cold-Atom CPT Clock

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***Abstract*— A compact cold-atom clock based on coherent population trapping (CPT) is being developed. Long-term goals for the clock include achieving a fractional frequency accuracy of 1×10^{-13} in a package of less than 10 cm^3 in volume. Here we present an overview of a prototype clock design, and a systematic evaluation of the first-order Doppler shift. We also introduce our second-generation physics package.**

Keywords- Atomic Clocks; Coherent Population Trapping; Doppler Shift; Laser Cooling; Ramsey Spectroscopy.

I. INTRODUCTION

A compact, cold-atom clock is under development. The clock is interrogated with light by use of coherent population trapping (CPT) in a lin ∥ lin polarization configuration [1]. This technique allows for excellent control of the phase of the interrogation fields on size scales much smaller than that of a microwave cavity, which is desirable for a small system. The use of cold atoms allows the system to achieve relatively long interrogation periods without requiring buffer gases, which introduce large, temperature-dependent shifts in clocks based on vapor cells.

The use of laser-cooled atoms eliminates the buffer-gas shift present in vapor-cell CPT clocks but in general introduces a 1^{st}-order Doppler shift, since the atom cloud expands and falls during interrogation and the atoms are therefore not in the Lamb-Dicke regime [2]. Atomic fountains also operate outside of the Lamb-Dicke regime, and the distributed-cavity phase shift is equivalent to the Doppler shift in fountain clocks. In fountains, this shift is made to be small by use of interrogation with a standing wave in a high-Q microwave cavity [3], but the shift can nevertheless contribute to the overall clock uncertainty at the 1×10^{-16} level [4].

The atoms are interrogated by use of a combination of CPT and Ramsey absorption spectroscopy in a scheme similar to the approach taken by Hemmer and colleagues [5], who used Ramsey CPT spectroscopy to interrogate Na atoms in an atomic beam. Our system differs from theirs in that it is based on laser-cooled ^{87}Rb atoms, so the Ramsey pulses are time-separated instead of spatially separated. The use of Ramsey spectroscopy reduces the light shift [6-8] and eliminates power broadening [9].

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The CPT scheme used here is a double-Lambda lin ∥ lin configuration [1], in which a higher contrast is achieved over conventional CPT spectroscopy owing to the elimination of trap states (for a review, see [10]). The linear polarization of the CPT light can be represented as a sum of σ^+ and σ^- circularly polarized light components, which results in probing the atoms with a superposition of two Lambda systems. The energy-level diagram for ^{87}Rb with the two clock Lambda systems is shown in Fig. 1. The frequencies of both of the resonances are sensitive to magnetic fields in first order, but the size of the first-order shift is equal and opposite. As long as the two Lambda systems have the same signal strength, the linear Zeeman shift will cause no net shift on the clock's frequency.

With the goal of making an atomic clock with a size of less than the microwave wavelength (44 mm for ^{87}Rb), we chose to use CPT interrogation with balanced counterpropagating beams to maintain good control of the CPT phase versus position in volumes that are much smaller than a microwave cavity. Early CPT clock work by Ezekiel and colleagues also pointed out that the CPT phase could be made uniform by use of counterpropagating beams [11].

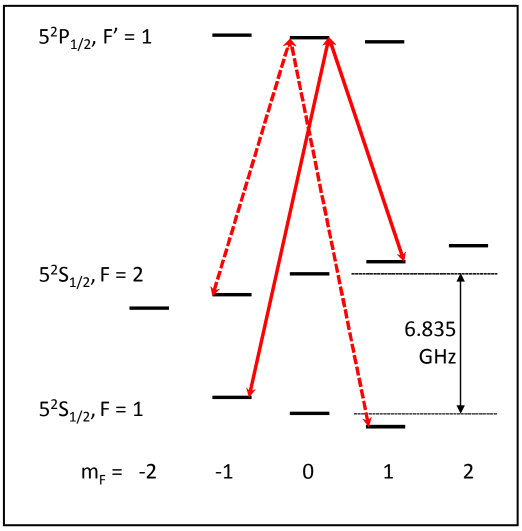

Figure 1. The energy-levels of ^{87}Rb probed with the double- Lambda lin ∥ lin technique. The two Lambda systems are shown. We use light resonant with the D1 transition at 795 nm.

II. EXPERIMENT

The apparatus has been described in detail previously [12], and will be briefly reviewed here. The system is based on a compact vacuum system that has a two-chambered design, with 2D and 3D magneto-optical traps (MOTs).

The CPT light is generated by use of an optical phase-lock loop built from two megahertz-broad DFB and DBR laser diodes, which produces a relatively clean, two-component spectrum that is free from zero- and higher-order modulation sidebands that cause light shifts without contributing to the CPT signal. The master laser is locked to the F = 2 → F′ = 1 transition on the D1 line at 795 nm via saturated absorption, and the slave laser is locked to a frequency near the F = 1 → F′ = 1 transition by locking the beat-note frequency between the master and slave lasers to an accurate reference, which enables accurate absolute frequency measurements for the evaluation of systematic shifts. So far, about 75 % of the power is in the coherent carrier. Work is in progress to increase this percentage.

The Ramsey spectroscopy performed here is different from traditional Ramsey spectroscopy in that the pulses are not $\pi/2$ pulses. Instead, the first pulse, which is typically 400 µs long and has an intensity of 20 μW/cm^2 for each frequency component, prepares the atoms in the dark quantum superposition state. Then the quantum superposition state evolves during the Ramsey period. The second pulse, which is typically 50 µs long, probes the relative phase of the quantum superposition state with respect to the light after the dark state has evolved during the Ramsey period. The clock signals are derived from the ratio of the transmission of the second Ramsey pulse to that of the first Ramsey pulse.

The Ramsey period, T_R, is typically less than 10 ms. The short interrogation periods allow for efficient recapture of atoms from cycle to cycle with 3 mm MOT beams, enabling a typical laser cooling-stage duration of 45 ms for loading about 10^6 atoms. For longer Ramsey periods, the fringes also begin to wash out because of magnetic-field gradients in the unshielded system combined with thermal expansion of the atomic cloud.

We observe Fourier-limited Ramsey resonances with a transmission contrast of 55 % and a typical absorption of 7 %. To lock the clock to the hyperfine ground-state splitting, we alternately probe the central fringe on opposite sides of the line and steer the clock to the central fringe. The short-term fractional frequency stability is currently limited to $4\times10^{-11}\tau^{-1/2}$. The atom shot noise contribution is $1\times10^{-12}\tau^{-1/2}$. The long-term fractional frequency stability is limited by magnetic field drift in our unshielded system to 2×10^{-12} for a 1000 second averaging period.

III. DOPPLER SHIFT MEASUREMENT

When the atoms are illuminated by a CPT light field from a single direction, a Doppler shift arises from motion of the atoms along the direction of the CPT beams during the Ramsey period. The phase of the CPT interrogation field varies linearly with position, and the moving atoms are pumped into the dark state and probed in different positions. The resulting frequency shift is given by

$$2\pi\Delta\nu_D = \Delta\phi/T_R = k_{HF}\cdot dz/T_R\,, \qquad (1)$$

where dz is the change in position of the atom along the propagation axis during the Ramsey period and $k_{HF} = k_2 - k_1 = 2\pi/\lambda_{HF}$, where $k_i = 2\pi/\lambda_i$ are the wavenumbers for the two CPT frequencies, and λ_{HF} is the microwave wavelength. When the atoms are probed with travelling-wave CPT beams along the direction of gravity, the fractional frequency Doppler shift from free fall from Eq. (1) is 1×10^{-10} for a 10 ms Ramsey period. To substantially reduce the shift, the atoms are probed with standing waves by applying CPT beams symmetrically from above and below.

When counterpropagating fields are applied to the atoms, the phase of the dark state created from the up and down CPT interrogation fields varies linearly with position as $\pm k_{HF}\cdot z$ [13, 14]. The slopes are opposite for the up and down beams. The dark-state phase versus position is visualized in Fig. 2. When the beams have equal intensity, the dark state phase is the average of the phases created by the up and down beams and is constant versus position and equal to the phase at the point where dark states created by the up and down beams have equal phase – the "equiphase point". The dark-state amplitude is modulated due to interference of the dark states created from the up and down beams, with maximum amplitude at the equiphase point.

Having balanced beams minimizes Doppler shifts when the signals from both the up and down beams are averaged during detection. In the experimental configuration described here, the absorption signals are detected independently and averaged. In a more elegant retroreflected configuration that we are currently using, the averaging is done automatically and only one signal is measured.

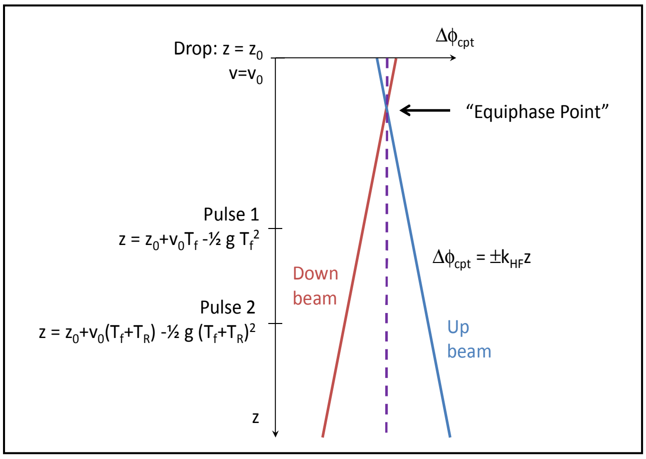

Figure 2. Phase versus height for dark states created by the up and down beams. The average phase for balanced up/down interrogation is shown as the dashed line. The atom position versus time after the drop is marked on the vertical axis. z_0 and v_0 are the atoms' mean initial position with respect to the "equiphase point" and the atoms' initial average velocity. The Doppler shift resulting from measuring the absorption signal on only one of the beams can be found from Eq. 1 and the position of the atoms during the second CPT pulse.

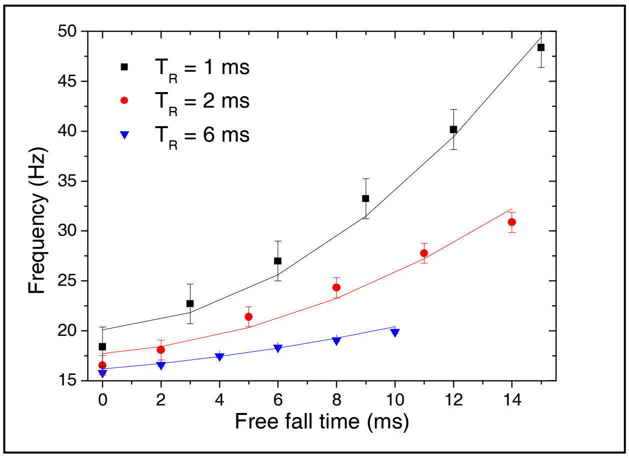

Figure 3. Clock frequency versus extra free-fall period for different Ramsey periods compared to the basic kinematic model for the Doppler shift. Only the signal from the downward beam was used to lock the clock, which maximizes the shift. The offset frequency is the only fit parameter. The three curves are slightly offset from each other because the Zeeman and light shifts were slightly different for the measurements with different Ramsey periods. The full scale (35 Hz) corresponds to a fractional frequency shift of 5×10^{-9}.

For our evaluation of the Doppler shift, independent up and down beams are simultaneously applied to the atoms, and absorption signals are measured for the up and down beams individually. The individual signals are then used to lock the clock to either the up beam signal only, the down beam signal only, or the average of the up and down signals. A variable extra period of free fall, T_f, is also inserted before the first Ramsey pulse to enlarge the shift so that it can be easily compared to a basic model.

Measurements of frequency shift versus free-fall period, Ramsey period, and probe direction show very good agreement with a simple kinematic model for the atoms' average position and velocity. Measurements of frequency shift versus free-fall period are shown in Fig. 3 for three different Ramsey periods when only the down beam signal was used to lock the clock. Detailed results from these studies are presented in a separate publication [15]. When the atoms are probed symmetrically along the direction of gravity, the total shift for the clock's typical Ramsey period of 6 ms is consistent with zero and has a current fractional frequency uncertainty of 1×10^{-11}. The shift magnitude should be more than an order of magnitude smaller when the probe direction is within 5° of a direction perpendicular to gravity.

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