A high stability optical frequency reference based on thermal calcium atoms

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***Abstract*—Here we report an imprecision below 10^{-14} with a simple, compact optical frequency standard based upon thermal calcium atoms. Using a Ramsey-Bordé spectrometer we excite features with linewidths < 5 kHz for the $^1S_0$-$^3P_1$ intercombination line at 657 nm. We have measured a fractional frequency instability below 6 x 10^{-15} at 1 s, with good prospects for still quieter performance. The key remaining issue for this standard is how well first- and second-order Doppler drifts can be suppressed. Due to its experimental simplicity such a system could find application as a less accurate, but high stability reference for commercial applications.**

I. INTRODUCTION

As optical atomic clock researchers have pushed towards the goals of creating clocks with absolute fractional uncertainties below 10^{-17} and fractional instabilities below 10^{-15} at 1 s, they have left in their wake a remarkable set of possibilities. That is, with some trade-offs between complexity and performance, clocks with a still remarkable level of precision seem possible for a variety of real-world (e.g., outside the standards labs) applications with comparatively simple, and realistically field-able instruments. In this direction, groups have been designing optical cavities that can serve as a reference for laser stabilization in noisy environments [1]. Here we report on an atomic transition-based optical frequency reference that uses a single diode-based laser system and can achieve stabilities well below 10^{-14} in 1 s averaging time. This is more than an order of magnitude below that of the best comparable microwave based systems and shows good prospects for still higher stability. Such a system could be ideal for optical-based ultra-low noise microwave generation applications that require longer averaging times and/or modest absolute frequency repeatability.

This research follows a direction first pointed out more than thirty years ago. In seminal research in 1979, Barger and Bergquist demonstrated high-resolution optical spectroscopy using a narrow intercombination line in neutral calcium [2]. Using the technique of optical Bordé-Ramsey spectroscopy [3], they obtained full-width half-maximum (FWHM) linewidths of several kHz, and pointed out the potential that this transition could have as an optical frequency standard. The $^1S_0$-$^3P_1$ transition at 657 nm in Ca has been the subject of many subsequent studies as its narrow natural linewidth (375 Hz) and visible wavelength made it ideal for atom interferometry [4,5,6]. However, this system's potential as an atomic frequency reference has yet to be fully evaluated. A Ca clock based on laser-cooled atoms showed an instability of 4 x10^{-15} at 1 s with an absolute frequency knowledge at the 10^{-14} level [7], while a more recent study used a blue laser system to enhance the signal-to-noise in a thermal beam-based system (9x10^{-14} instability at 1 s) [8]. Here we focus on trying to realize the full capability of a thermal beam system based on a single laser system. The instability for a generic atomic clock system limited by atom shot noise can be written [9]:

$$\sigma(\tau) \propto \frac{\delta\nu}{\nu_0}\frac{1}{\sqrt{N\tau}}, \qquad (1)$$

where $\delta\nu$ is the spectroscopic resolution, ν_0 is the clock frequency, N is the number of atoms detected in 1 second, and τ is the averaging time. Here we see the advantage of working at optical frequency and large atom number. Plugging reasonable values for the Ca thermal system into (1) yields possible clock instabilities of well below 10^{-15} at 1 s, although practical considerations would make fully reaching

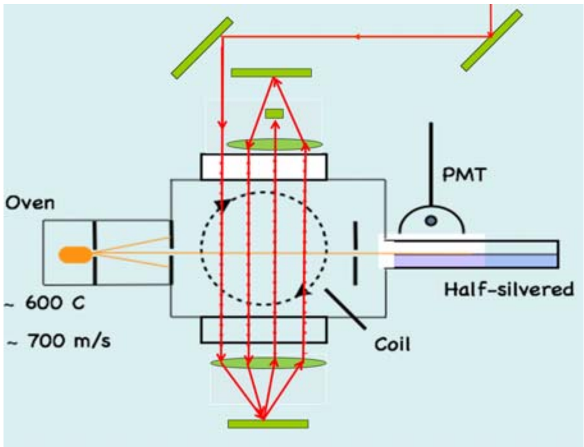

Figure 1: Calcium beam apparatus, including effusive oven, Ramsey-Bordé spectroscopy zone, and detection cell.

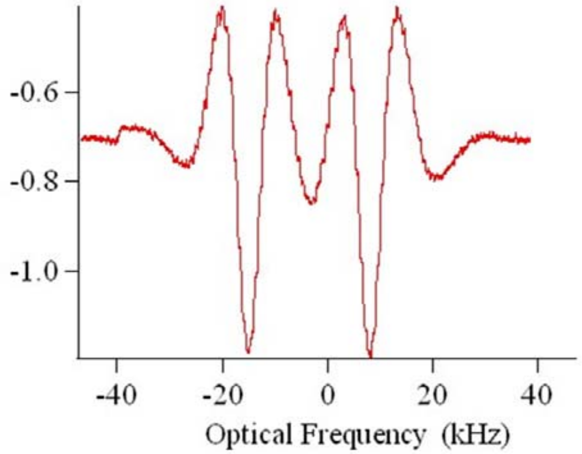

Figure 2: Ramsey-Bordé fringes, shown here with both recoil components. Fringe width is < 5 kHz (FWHM).

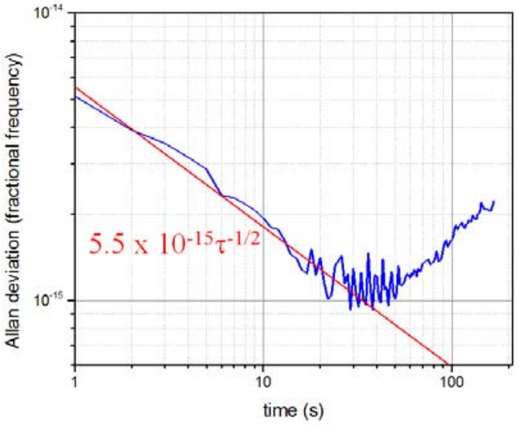

Figure 3: Instability versus time. Data shown in blue. Red solid line gives the white frequency noise asymptote.

this theoretical value difficult. Nonetheless, while such a system may not reach the stability attainable with an optical lattice clock, it would be significantly simpler and more compact. It has the additional benefit that the atom servo can have a bandwidth of 100's of Hz rather than the 1 Hz or less typically achieved by the highest performance systems. This increased servo bandwidth is one of the system aspects which considerably relaxes the stability requirements for the optical reference cavity required to pre-stabilize the clock laser.

II. THE CALCIUM THERMAL BEAM CLOCK

A. Apparatus

The apparatus is shown in Fig. 1. We pre-stabilize the diode laser at 657 nm (home-built in a Littman-Metcalf configuration) with a high-finesse Fabry-Perot resonator (linewidth ~ 9 kHz) to yield a laser linewidth of order 1 Hz on a 1 s timescale [7]. After using an optical fiber for spatial filtering, we send ~ 2 mW of the light to a four-beam Ramsey-Bordé spectrometer that excites the atoms in a thermal beam [3]. Atoms emerge from an aperture in the Ca oven, which we operate at temperatures ranging from 670-720°C, with a most probable velocity of about 640 m/s. Because of the long excited state lifetime (~ 400 μs), the excited state fluorescence is spread over more than 30 cm downstream of the excitation region. We detect a few percent of the total fluorescence, with a PMT centered 10 cm from the excitation region to reduce the background scattered light levels. As is standard with Ramsey-style excitation, the spectroscopic resolution is proportional to the separation of the excitation zones. For the present system our maximum available separation is 2D = 54 mm, which yields a FWHM resolution of just below 5 kHz.

As shown in Figure 2, there are actually two features, the well-known recoil doublet [2], separated by 23.1 kHz. We use a microcontroller+DDS system to modulate the laser (at a modulation frequency of 50 Hz) over one of these features to generate an error signal, and use a DDS-fed acousto-optic modulator between the laser and its reference cavity to keep the laser on resonance with the atomic transition. We have measured the stability of the locked system both internally (relative to our ultra-stable reference cavity) and externally (relative to an Yb lattice clock that has a stability of $<10^{-15}$ at 1 s [10]). In preliminary measurements, we have seen an instability (see Fig. 3) of $\sim 5 \times 10^{-15}$ at 1 s, which is, to our knowledge, the first time that a thermal atom-based system has reached below the 10^{-14} level in 1 s. We find that for high atom flux (achieved at oven temperatures above 660°C), the signal is atom-flux limited as is indicated in Figure 4 by the square root dependence of the clock stability on atom flux (see (1)).

III. FUTURE PROSPECTS

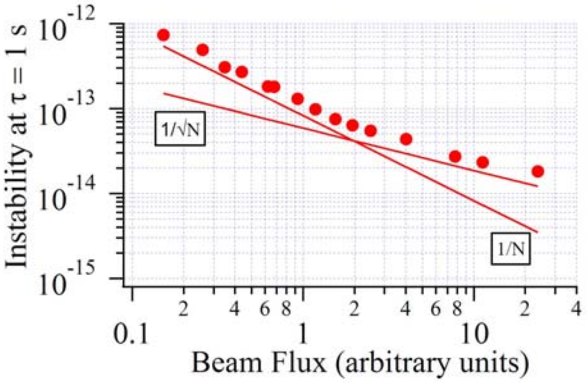

Figure 4: Measured instability at 1 second, as a function of beam flux. Data are shown as filled circles. The solid lines indicate N^{-1} and $N^{-1/2}$ asymptotes (N scales with beam flux).

Interestingly, we still see room for considerable reduction in the instability. We will soon be implementing new vacuum viewports that will enable separation of the Ramsey zones up to four times further, so we can approach the spectroscopic limit for this transition. Additionally we will add a high collimation nozzle to the oven source, which should increase the number of usable atoms and thus the signal-to-noise ratio. An important challenge for these systems will be to achieve adequate control of the Doppler shift. Even though the system is nominally Doppler-free, in fact it is sensitive to drifts in alignment, laser intensity, and oven temperature. As can be seen in Figure 3, the stability starts to degrade after 10 seconds, which is an indication of a drift in the system (fractionally, ~10^{-16}/s), most likely attributable to Doppler effects. We are presently investigating these effects and have devised several schemes for suppressing these drifts. Successful control of these effects would open the possibility for a portable high performance device suitable for a variety of real world applications.

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