Ultra-high Stability Optical Frequency Standard Based on Laser-Cooled Neutral Calcium

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Abstract: A beatnote between the Ca and Hg^+ optical frequency standards via a mode-locked fs-laser frequency comb demonstrates the highest frequency stability measured to date. The high stability accelerates evaluation of the Ca standard's systematic shifts.

OCIS Codes: (120.3940) Metrology; (300.6320) High-resolution spectroscopy; (140.3320) Laser cooling

1. Introduction

Optical frequency standards are experiencing a period of great growth due to tools developed over recent years. Because of their high oscillation frequencies, these standards have already achieved considerably higher stabilities than their microwave counterparts and ultimately should be more accurate as well. Among the neutral atom optical standards, the system based on the ${}^1S_0$-${}^3P_1$ intercombination line at 657 nm in Ca is one of the most mature [1]. This transition has a narrow natural linewidth (400 Hz), a nearly negligible collision shift, and is extremely insensitive to stray fields. Absolute frequency measurements of the transition in two different laboratories (NIST and PTB) agree with a fractional frequency uncertainty below 5×10^{-14}, within the stated uncertainties of the two standards. Moreover, the calcium standard has shown excellent stability, previously achieving a fractional uncertainty of 4×10^{-15} in 1 second of averaging time for freely expanding atoms at a temperature of 2 mK [2]. Reduction of the atomic temperature to 10 μK via second-stage laser cooling greatly reduces Doppler-related systematic effects [3,4], but requires much longer atom preparation time, thereby reducing the stability of the standard. Here we report new results with an improved probe laser and optimized measurement cycle, which have enabled us to improve the stability of the microkelvin Ca standard. Through comparison with the NIST Hg^+ standard via a mode-locked fs-laser-based frequency comb, we have measured an upper limit for the fractional frequency instability of 3×10^{-15} for 10 s and 2×10^{-16} for 2000 s averaging time, respectively. Additionally we have been able to use the high stability to identify and reduce several key systematic shifts, opening the door to accuracy measurements in the low 10^{-15} range. These improvements should accelerate the search for drifts in the values of fundamental constants.

2. The Ca apparatus

The NIST Ca standard has been described in detail in several publications, so here we outline the basic apparatus [5]. Using the strong cooling transition at 423 nm we load ~3×10^6 atoms from a beam into a magneto-optic trap in 15 ms with a resultant temperature of 2 mK, limited by width of the cooling transition. Roughly 25% of these atoms are transferred into a second-stage magneto-optic trap based on 657 nm light along with 552 nm quenching light to accelerate cooling on the clock transition [3]. This second stage trap has a residual temperature of only 10 μK (~ 4 cm/s), which leads to reduced Doppler shifts as well as higher signal contrast. With the cooling lasers extinguished, the clock transition is excited by a Bordé-Ramsey sequence [6], which enables ultra-high resolution spectroscopy while maintaining a high signal-to-noise ratio. The Bordé-Ramsey sequence consists of two pairs of counter-propagating pulses (3 μs duration) whose separation in time determines the spectral resolution. The probe laser is pre-stabilized on a narrow resonance ($\Delta\nu = 9$ kHz) of an environmentally-isolated Fabry-Perot cavity, yielding a laser linewidth of a few Hz on a one second time scale. A normalized shelving detection scheme, based on near-resonant light at 423 nm, is used to measure the fraction of atoms excited by the probe sequence and achieves nearly atom shot-noise performance.

Shown in Figure 1 is a low-resolution spectrum taken by continuously cycling the atom preparation/measurement sequence while slowly scanning the probe laser frequency over the clock resonance. The asymmetry in the fringe envelope is a direct result of atomic recoil effects, but should not limit the accuracy of the standard [7].

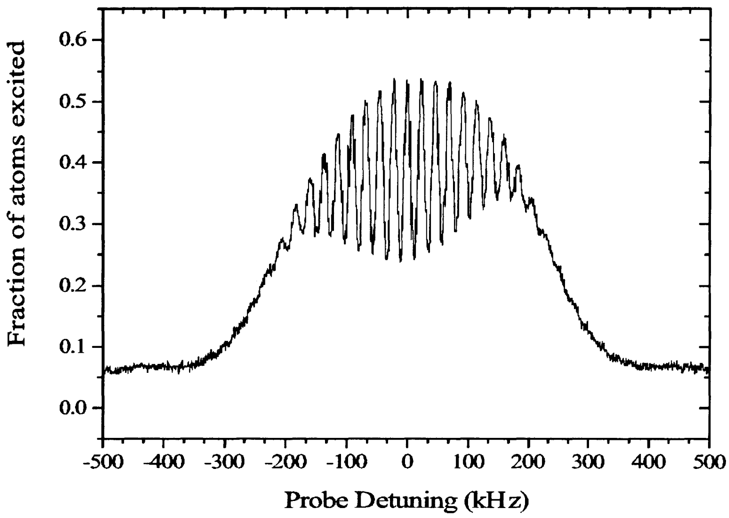

Figure 1. Low-resolution (11.55 kHz FWHM) scan of Optical Ramsey fringe pattern taken with 10 μK atoms. The data shown results from a single 25 s scan.

For clock operation we usually work at much higher resolutions, typically around 700 Hz FWHM. Using frequency modulation techniques we lock the frequency of the probe laser to the central fringe by feeding back to a synthesizer-controlled acousto-optic modulator. Approximately 5 mW of the red light is sent through an optical fiber to the fs-laser measurement comb for evaluation of clock performance.

3. Measuring and Improving the Clock Stability

Since we have only one version of the Ca standard, we need to use other standards to evaluate its performance. Fortunately at NIST we have both the microwave-based NIST time scale, which is calibrated by a Cs fountain, and an extremely promising optical standard based on a transition at 282 nm in Hg^+ [8]. We compare these various standards with a mode-locked fs-laser measurement comb that spans a good portion of the visible spectrum as well as making a direct link to the microwave domain [8]. The comb can lock up tightly to one of the optical sources, thereby allowing direct comparisons between the high stability optical standards via simple beatnotes. In Figure 2 we show the Allan Deviation measured for the beat between the Ca and Hg^+ clocks taken with a 10 s gate time. On short time scales the frequency difference changes by a Hz or so shot-to-shot, and after averaging past a bump around 100 s of unknown origin, the difference averages down quite quickly to $< 2\times10^{-16}$ at 2000 s. Note that

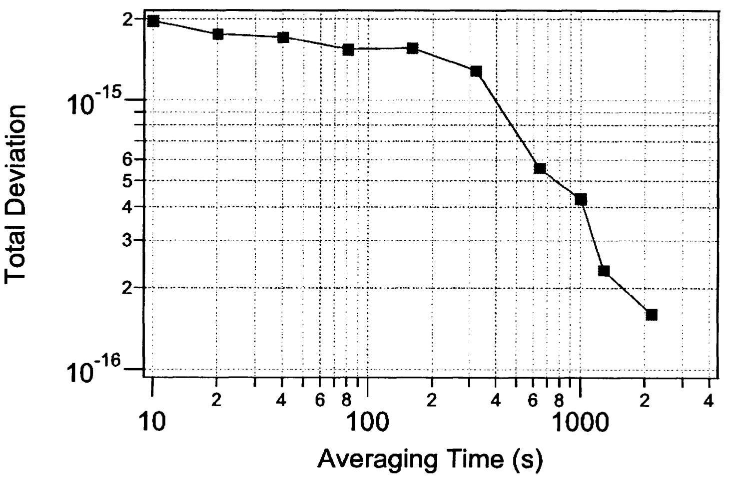

Figure 2. Total Allan Deviation as a function of averaging time for the beatnote between the Ca and Hg^+ optical frequency standards measured via the mode-locked fs-laser frequency comb.

because the signal contains contributions from both the Hg$^+$ and Ca clocks as well as the comb stabilization and two fiber links (with lengths of 200 m and 20 m) with Doppler cancellation, this result actually just sets an upper limit on any of the contributors, although the performance at short times is consistent with estimates of the Ca clock noise made relative to the Ca reference cavity.

The low noise level attained was made possible by two main improvements in the calcium apparatus. First, the pre-stabilized probe laser noise was reduced simply by moving all loud equipment (i.e. those with fans) away from the optical table and turning off all room fans. Second, the atom loading cycle was shortened from 60 ms to 22 ms, leading to a faster measurement rate (offset in part by a manageable loss in the number of atoms). Since the calcium stability is limited by the optical Dick Effect [9], which effectively aliases higher frequency noise into the spectroscopic signal, reducing the probe laser frequency noise and improving the measurement duty cycle both lead to improved signal to noise.

4. Evaluating Systematic Shifts and Future Prospects

The high stability of this system will enable a considerable acceleration in the evaluation of the systematic frequency shifts in the Ca clock. To this end, we have constructed an interlaced measurement scheme that allows us to evaluate various potential frequency shifts of this standard. By switching between two conditions (e.g. different drift velocities of the atomic cloud) on alternating measurement cycles we can effectively suppress the linear drift of our reference cavity and make precision measurements of systematic shifts. With the present system we can evaluate shifts at the hertz level in 100 s averaging time. The accuracy of this system has been verified by external measurements against the Hg$^+$ system. With all known physical effects (including residual Doppler effects) understood at the sub-hertz level, we are now able to expose and evaluate shifts due to technical issues at a similar level. In particular, shifts due to frequency chirps in the acousto-optic modulators are of considerable concern due to the brevity of our pulses (3 μs). With interlaced measurements taken at different probe resolutions, we can presently correct this shift with an uncertainty of ~2 Hz, although future work should reduce this considerably.

5. References

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