Improving the stability and accuracy of the Yb optical lattice clock

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***Abstract*—We report results for improving the stability and uncertainty of the NIST ^{171}Yb lattice clock. The stability improvements derive from a significant reduction of the optical Dick effect, while the uncertainty improvements focus on improved understanding and constraint of the cold collision shift.**

I. INTRODUCTION

Optical lattice clocks have potential for achieving time and frequency measurement at unprecedented levels of accuracy and stability. However, to date these young systems are far from reaching this potential. Here, we describe efforts to mitigate effects which, left unresolved, pose significant obstacles to achieving these levels of performance. To improve the clock stability, we reduce the optical Dick effect. To improve the eventual accuracy of this system, we probe cold collisions between the lattice-confined atoms.

II. REDUCING THE OPTICAL DICK EFFECT

The fundamental limit to the instability of an atomic frequency standard is given by the quantum projection noise (QPN). For an optical atomic clock that probes a large ensemble of quantum absorbers, the QPN limit can be quite low. For example, for a Yb or Sr lattice clock with 10^5 atoms, a 1 Hz transition linewidth, and a cycle time of $T_c = 1$ second, the QPN instability limit is below 10^{-17} at 1 s. However, while such clocks have resolved optical transition linewidths approaching 1 Hz, the instability of these systems is much higher than indicated above. Instead, the fractional frequency instability is such that it would require significantly more than 10^4 seconds to reach the 10^{-17} level. This is because these systems are usually limited by the Dick effect [1], i.e. as the atoms are periodically interrogated by the local oscillator (LO) with a period of T_c and for a probe duration of T_p, the frequency noise of the LO is downsampled onto the transition spectrum and contaminates the clock stability. In this way, the frequency noise, the probe time T_p, and the cycle time T_c all influence the magnitude and downconverted Fourier frequency of the aliased noise and thus the stability degradation. The previous operating conditions for our Yb lattice clock were $T_p = 0.08$ s and $T_c > 0.5$ s. With a frequency noise of 0.5 Hz/$\sqrt{\text{Hz}}$ at a Fourier frequency of 1 Hz, this led to a Dick-limited instability of 1-2 × 10^{-15} at 1 s.

In order to reduce this limitation, several improvements could be made: reducing the LO frequency noise that is aliased, achieving a higher duty cycle with longer probe times or reduced dead time [2], or choosing a form of spectroscopy which is less sensitive to the aliasing process (e.g. short-pulse Ramsey spectroscopy). All of these are useful from a practical perspective. However, by improving the LO laser coherence and stability, we can achieve both reduction of the LO frequency noise and longer probe times. In order to improve the LO stability, the level of Brownian thermal noise in the optical cavities used for laser stabilization must be reduced. When stabilizing a laser to an optical cavity, the thermal-noise limited laser instability dominated by the cavity mirrors [3] is given by:

$$\sigma_{therm} = \sqrt{\ln 2 \frac{4k_bT}{\pi^{3/2}} \frac{1-\sigma^2}{Ew_0L^2} \left(\phi_{sub} + \phi_{coat} \frac{2}{\sqrt{\pi}} \frac{1-2\sigma}{1-\sigma} \frac{d}{w_0}\right)} \tag{1}$$

Here, σ, E and ϕ_{sub} are Poisson's ratio, Young's modulus and the mechanical loss for the mirror substrate, and ϕ_{coat} and d denote the mechanical loss and thickness of the thin-film reflective coating. w_0 is the laser beam size on the mirror, T is the mirror temperature (K), k_B is Boltzmann's constant and L is the cavity length. In order to improve laser stabilization by reducing the thermal noise, we designed a cavity with length $L = 29$ cm, fused silica substrates with low mechanical loss ($\phi_{sub} \approx 10^{-6}$) and a somewhat large beam size using mirrors with a somewhat longer radius of curvature ($R = 1$ m). For these parameters, the thermal-noise-limited fractional frequency instability is 1.4×10^{-16}.

To reduce acceleration-induced cavity length changes, the optical cavity sits horizontally on four symmetrically placed Viton hemispheres [4], [5]. The precise support position is optimized to reduce the vertical acceleration sensitivity. Figure 1 shows the vertical acceleration sensitivity as a function of support position, indicating both finite-element simulation results as well as experimentally measured sensitivities. Simulation results are also shown for cavity acceleration sensitivity offset from the cavity optical axis. The measured sensitivity reaches as low as 7 kHz/(ms^{-2}) at the laser wavelength of 578 nm. The experimental measurement also includes weak, incidental acceleration in the horizontal dimensions. During

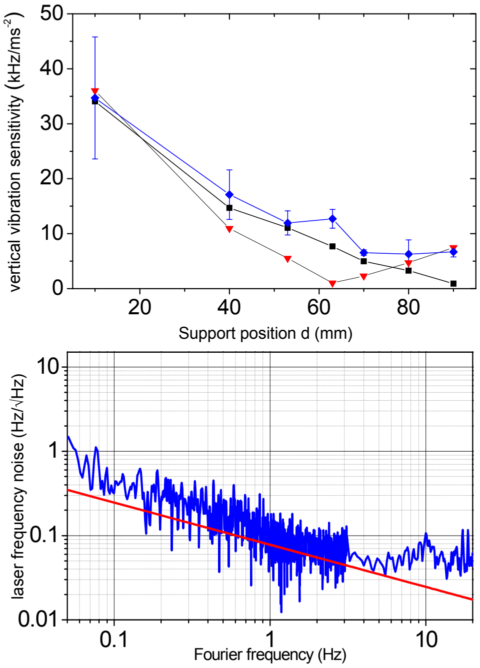

Fig. 1. top: Vertical acceleration sensitivity of the optical cavity. Experimental measurement (blue diamonds), simulation results (red triangles), simulation results for 250 μm removed from the cavity optical axis (black squares). The support position, d, is measured from where the cavity taper begins. bottom: Measured frequency noise spectrum for the laser locked to the fully-isolated cavity. The solid red line gives the theoretical prediction of the Brownian thermal noise.

normal operation, the reference cavities sat on vibration isolators.

While the use of fused silica mirrors helps reduce Brownian thermal-mechanical noise, it makes the cavity more susceptible to thermal expansion. However, a balance between the thermal expansion of the cavity components can be achieved, and we have been able to demonstrate operation of these cavities at the zero crossing of the coefficient of thermal expansion. This is done at a temperature conveniently just above ambient [6].

By comparing two independent cavity systems, we measured the frequency noise spectrum of the cavity-stabilized laser as shown in Figure 1. The red line is the thermal noise limit for each reference cavity. Up to several Hz, the laser frequency noise is close to the thermal noise limit. This low level of frequency noise in turn reduces the aliased noise contributing to the Dick effect. Furthermore, the reduced frequency noise spectrum yields laser coherence times which allow us to extend our clock probe time up to 1 second. For a more conservative operating condition of $T_p = 0.3$ s, the Dick instability is at $1.5 \times 10^{-16}/\sqrt{\tau}$, for measurement time τ. This constitutes an order of magnitude improvement over our previous Dick limit, and enables a significant improvement of the clock stability. By using the narrow atomic transition as a frequency discriminator, we have made measurements consistent with a clock instability at the $5 \times 10^{-16}/\sqrt{\tau}$ fractional frequency level [6].

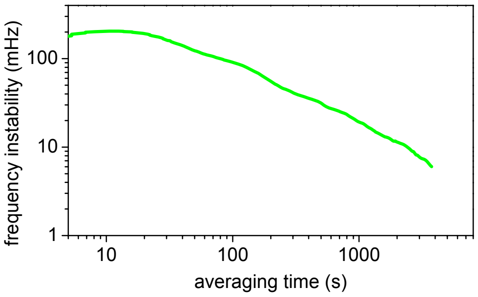

Fig. 2. Frequency instability from measurement of the cold collision shift, when the shift is cancelled to zero (see text).

III. COLD COLLISION SHIFT

While the presence of many atoms in the optical lattice is desirable for low clock instability due to quantum projection noise, another consequence of large atom number is high number density which can lead to significant interactions between the atoms. These interactions can shift the clock transition frequency and in so doing can potentially compromise the absolute uncertainty of the optical standard. Non-zero interactions in a ^{171}Yb optical lattice clock were first observed using one-pulse Rabi spectroscopy [7]. More recently, we have studied the resulting cold collision shift of the clock transition using two-pulse Ramsey spectroscopy, for atoms confined both in a one- and two-dimensional optical lattice. The choice of Ramsey spectroscopy was driven by simplification: the interactions yielding the collision shift occur primarily during the Ramsey dark time, when the atomic population is not simultaneously being driven by the probing laser field. By studying the collision shift as a function of excitation fraction, sample inhomogeneity, and Ramsey dark time, we have determined that the collisions responsible for the shift are dominated by p-wave interactions between a ground and excited state atom pair [8].

We have been able to identify regimes where the cold collision shift can be canceled, which is metrologically interesting for clock operation. One such case is given by controlling the excitation fraction just above 50%, where the shift on each clock state is the same. By operating at these conditions, the collision shift was measured to be consistent with zero at or below the 10^{-17} fractional frequency level. Figure 2 highlights such a measurement, showing the frequency instability of the measured collision shift. This data is taken by stabilizing the probe laser to interleaved samples of high and low atomic density, and measuring the frequency shift between the two cases. Due to the clock stability improvements described in section II, we are able to measure the shift at the 10^{-17} level with only several thousand seconds of measurement time. This measurement emphasizes the potential of the Yb lattice clock for very high measurement stability, as well as high accuracy through control of the cold collision shift.

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