Polarizability of an optical lattice clock at 20 ppm

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***Abstract*—Optical lattice clocks, which are based on highly-forbidden $^1S_0 \leftrightarrow {}^3P_0$ transitions of ultracold alkaline-earth atoms confined in standing-wave optical potentials [1], offer exquisite frequency stability and uncertainty. We leverage these advantages to determine the sensitivity of a ytterbium optical lattice clock to external electric fields at 20 part-per-million (ppm) accuracy [2]. We describe an electrode design compatible with various neutral optical atomic clocks and capable of absolute electric field generation at the ppm level. Importantly, the result bounds the uncertainty of the ytterbium clock frequency due to room-temperature blackbody radiation at the level of 3×10^{-17}.**

***Index Terms*—Atomic measurements, blackbody radiation, clocks, electric fields, precision measurements, polarizability, Stark effect**

I. Introduction

A low-lying atomic state $|i\rangle$ decreases in energy $-\frac{1}{2}\alpha_i E_{\mathrm{a}}^2$ when immersed in an electric field E_{a}. Here, α_i is called the state's static polarizability [3]. A ytterbium optical lattice clock is excited on the ultra-narrow $^1S_0 \leftrightarrow {}^3P_0$, 578 nm transition. The Stark shift on this transition frequency is

$$\Delta\nu = -\tfrac{1}{2}\alpha_{\mathrm{clock}} E_{\mathrm{a}}^2, \tag{1}$$

where $\alpha_{\mathrm{clock}} \equiv \alpha_{^3P_0} - \alpha_{^1S_0}$ is the net polarizability of the clock states, known theoretically to about 10% accuracy [4]. We reduce this uncertainty by a factor of 5000 by directly measuring $\Delta\nu$ with an accurately applied electric field E_{a}.

II. Interleaved optical atomic clock

A 578 nm laser system, described elsewhere [5], is locked using the Pound-Drever-Hall method to a thermally and vibrationally isolated high finesse optical cavity, reducing its linewidth to ~ 250 mHz and achieving a fractional frequency instability $\sigma_y < 4 \times 10^{-16}$ over 1 s–10 s. This laser is brought into resonance with 10^3–10^4 ytterbium atoms cooled to 10 μK and confined in a standing wave optical lattice at $\lambda_{\mathrm{m}} \approx 759$ nm. The so called 'magic wavelength' λ_{m} empirically results in no net ac-Stark shift ('light shift') of the clock transition [6]. The difference between the laser and atoms' transition frequency, cyclically measured with a shelving/fluorescence technique [7], drives a digital servo amplifier, removing drift of the stabilizing optical cavity.

To measure the clock's polarizability, α_{clock}, the atom/laser servo is operated in an interleaved locked fashion. After a period τ_v (nominally 2.9 s), voltage is either applied, reversed, or removed from a set of electrodes (described below) surrounding the atoms. Three independent digital servos steer

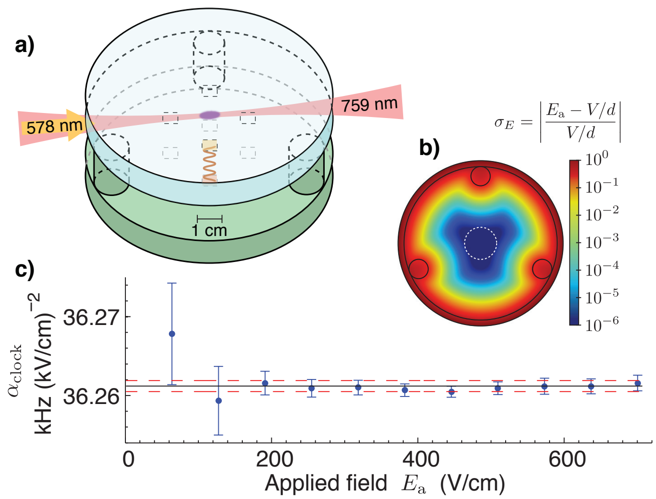

Fig. 1. (a) Sketch of the precision electrodes surrounding the one-dimensional lattice trap. (b) Finite-element model of field deviations from the infinite-planar capacitor prediction through the center plane of the electrodes. A dashed line highlights the central 2 cm. (c) Measured optical clock polarizability α_{clock} as a function of applied electric field E_{a}. Lines show the fitted mean and standard error range.

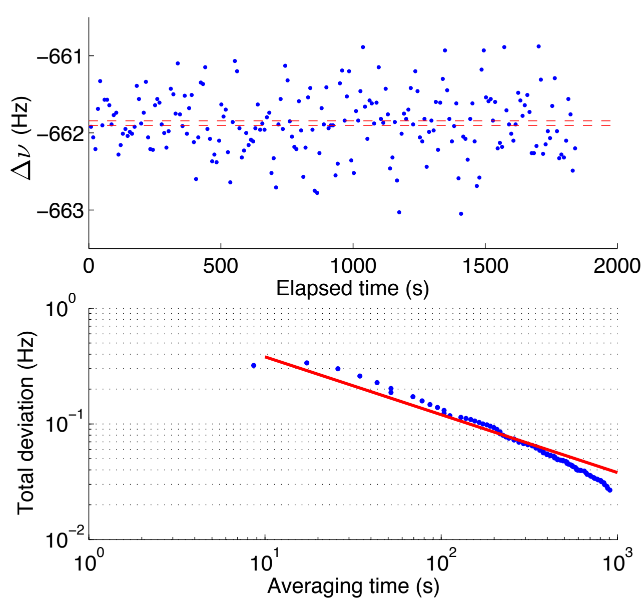

Fig. 2. An example time series (top) of the combination of integrated error signals yielding $\Delta\nu$ (see (2)) at $E_{\mathrm{a}} \approx 191.06$ V/cm. Red dashed lines illustrate the statistical (standard) error of the mean of the dataset (30 mHz) derived from the total deviation measure (bottom). Here, a solid red line serves as an eye guide of white noise $\sigma(\tau) = 1.2$ Hz $(\tau/1\ \mathrm{s})^{-1/2}$.

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the clock laser; each is updated and active only during its matching voltage state. Cavity drift is largely common to the three integrated error signals $\Delta\nu_{A,B,C}$ corresponding to the grounded and high voltage polarity conditions, respectively. After 2000 s of averaging, the Stark shift

$$\Delta\nu = \tfrac{1}{2}(\Delta\nu_B + \Delta\nu_C) - \Delta\nu_A \tag{2}$$

is resolved to 30 mHz–80 mHz (see Fig. 2). The effect of a stray static electric field is canceled in (2). Stray components parallel to $\vec{E}_{\mathrm{a}}$ are precisely measurable and proportional to $(\Delta\nu_B - \Delta\nu_C)$; we typically found 0.1 V/cm static strays.

III. Electrodes

A. Design

It is essential that the applied electric field at the site of the trapped atoms be accurately known. Following [8], we sought to approximate an infinite-planar capacitor design (see Fig. 1a) so an applied voltage V to electrodes spaced by d creates a nearly uniform field $E_{\mathrm{a}} = V/d$. Each transparent electrode is a 12.7 mm thick fused silica disk, 101.6 mm in diameter, and polished to better than $\lambda/10$ flatness. One surface is made conducting with a thin ($<$ 1 nm) coating of indium tin oxide (ITO). The other surface receives an anti-reflection coating for all cooling/trapping wavelengths. The electrodes are rigidly spaced apart by three fused silica cylinders 12.7 mm in diameter and 15 mm long. The spacers were sawed from the same flat substrate and polished together so their lengths are nearly identical. By bonding the electrodes and spacers together using KOH-catalysis [9], the resulting electrode wedging was found to be $\theta_{\mathrm{wedge}} < 7$ μrad.

Finite element simulations (e.g. Fig. 1b) verify that the electric field in the central region of the electrodes deviates from the infinite-planar result below the 1 ppm level due to the electrode's finite size, at the 1 ppm level due to the dielectric spacer rods, and at the 2 ppm level due to θ_{wedge}. A complete uncertainty budget is detailed in [2].

B. Measurement

The electrode separation $d = 15.03686(8)$ mm is measured interferometrically, *in situ*. On top of the conductive ITO surfaces, 2 nm of chromium and 33 nm of gold were evaporated in square patterns to form four planar Fabry-Perot etalons. The measured finesse $\mathcal{F} \approx 20$ is consistent with the gold reflectivity ($\sim 90\%$), electrode wedging, and surface-figure error. The frequency between N etalon transmission peaks is approximately N times the free-spectral range ν_{fsr},

$$\nu_{N+i} - \nu_i = \frac{c}{2d}\left(N + \frac{\phi(\nu_{N+i}) - \phi(\nu_i)}{2\pi}\right) \approx N\nu_{\mathrm{fsr}}, \tag{3}$$

since the metal mirror phase shifts $\phi(\nu_{N+i}) - \phi(\nu_i) \approx 1°$. Errors made determining the frequencies of fringe peaks (systematic wavemeter error, line-pulling of parasitic etalons, center-finding error) are all averaged down by N. An external cavity diode laser centered at 766 nm had a tuning range of 17 THz, allowing $N \approx 1700$, and a 5 ppm measurement of d. Measurement of different gold pad pairs yields θ_{wedge}.

Regulated high voltage, stable to 1 ppm over 1000 s, is created by amplifying a buried diode reference. An opto-coupled network of high voltage reed relays mediates the voltage state of both electrodes independently. Two calibrated commercial voltmeters directly measure the applied high voltage at 8 ppm absolute accuracy, constituting the dominant source of measurement uncertainty.

IV. Conclusions

The optical clock transition polarizability is found to be $\alpha_{\mathrm{clock}} = 36.2612(7)$ kHz (kV/cm)$^{-2}$ (Fig. 1c). A field of 0.1 V/cm shifts the clock transition -0.18 mHz, though a properly designed conductive shield can guarantee this, or smaller static fields. Viewed another way, the lattice clock is a sensitive and accurate meter of moderate electric fields.

Because blackbody radiation is a source of electric field intensity $\langle E_T^2\rangle \approx (8.319$ V/cm$)^2(T/300$ K$)^4$ which is quasi-static compared to relevant atomic transition frequencies, the blackbody Stark shift $\Delta\nu_{\mathrm{BBR}} = -\frac{1}{2}\alpha_{\mathrm{clock}}\langle E_T^2\rangle(1 + \eta_{\mathrm{clock}})$ receives a small 'dynamic correction' calculated to be $\eta_{\mathrm{clock}} = 0.0145(15)$ [10] at room temperature. With the present value of α_{clock}, knowledge of the blackbody environment sets the uncertainty in $\Delta\nu_{\mathrm{BBR}}$. An effective 1 K temperature uncertainty results in a fractional frequency uncertainty of 3×10^{-17}.

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