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Operating a $^{171}Yb^{+}$ Microwave Ion Clock in a Continuous Mode

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***Abstract*—We are developing a highly miniaturized $^{171}Yb^{+}$ ion clock that operates in a continuous microwave-optical double-resonance mode by continuously probing the 12.6 GHz hyperfine transition in the $^{171}Yb^{+}$ ion. In the continuous mode, the clock will not require optical shutters and electrical switches, minimizing the components of the clock. Here, we demonstrate operating the ion clock with ions trapped in a permanently sealed, passively pumped vacuum package 3 cm^3 in volume. With resonant 369-nm light continuously illuminating the ions, the light shift is a substantial systematic shift of the hyperfine ground state that must to be well characterized and controlled. We present measurements of the light shift and demonstrate clock frequency instabilities below 1 × 10^{-12} at 100 s of averaging.**

Keywords—Microwave atomic clock; trapped ions; light shift;

I. Introduction

In the past two decades, there has been significant effort to miniaturize atomic microwave frequency standards. Drastic miniaturization has been demonstrated in vapor-cell-based atomic clocks [1, 2]. The long-term stability of the smallest vapor-cell clocks can be substantially degraded compared to their larger counterparts. To improve the long-term stability of a compact atomic clock, other approaches show promise such as laser cooled atoms [3-5], vapor-cell-based optical clocks [6, 7], and trapped ion clocks [8]. Miniaturizing a trapped $^{171}Yb^{+}$ ion clock [9, 10] has been the focus of our group. Our previous work demonstrated a miniaturized ion clock that operated in a pulsed mode where the microwave radiation and the 369-nm laser light are sequentially applied [11, 12]. The long-term fractional frequency instability of the miniaturized clock was below 10^{-13} [13], and recent work at Microsemi, Inc. has demonstrated a short-term stability of $1.6\times10^{-12}/\tau^{1/2}$, where τ is averaging time of the clock frequency [14]. To reduce the complexity of the compact ion clock, we operate the clock in a continuous mode where the laser light and microwave radiation are applied continuously. Advantages of the continuous mode are the elimination of the optical shutter, which can be an unreliable component, and the simplification of locking the laser directly to the ions. Continuous operation also allows an increase in bandwidth for locking a local oscillator to the Yb ions to relax the stability requirements of the local oscillator. A disadvantage of the continuous mode is that by applying the microwaves and 369-nm laser simultaneously, a light shift is introduced potentially degrading the long-term stability of the clock. To determine the impacts of the light shift, we developed a table-top testbed ion clock and measure the change in the frequency of the clock as a function of both the 369-nm laser power and frequency detuning. We then operate the continuous mode clock at two different linewidths of the microwave transition to observe how light shift effects the clock operation.

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II. Experimental System

In the $^{171}Yb^{+}$ ion clock, a local oscillator is stabilized to the 12.6-GHz ground-state hyperfine transition of the ion, in particular the $^2S_{1/2}$, $F = 0$, $m_F = 0$ to $F = 1$, $m_F = 0$ "clock" transition. The ions are contained in a 3-cm^3 vacuum package developed and constructed by the Jet Propulsion Laboratory and is described in [11, 13, 14]. The vacuum package is permanently sealed with a copper pinched-off and passively pumped with a nonevaporable getter. A linear quadrupole RF Paul trap contains the ions with 240 V_{rms} applied between adjacent rods of trap at 3.35 MHz and a potential difference of 20 V between the trap rods and the end caps, which are the body of the vacuum package. The vacuum package is filled with 4×10^{-6} Torr of neon, which provides buffer gas cooling of the ions. Microwave radiation is applied to the ions by coupling the microwave power into the package through the trap rods. A laser at 369 nm provides state detection and optical pumping light, and a 935-nm laser clears the low-lying $^2D_{3/2}$ state (Fig. 1). A commercial external cavity diode laser provides light at 369 nm, and a vertical cavity surface emitting laser (VCSEL) provides light at 935 nm. Fluorescence at 369 nm is collected with a photo multiplier tube. A 760-nm distributed feedback (DFB) laser is used to clear the $^2F_{7/2}$ state (not shown in Fig. 1). For the results shown in this paper, the 760-nm laser had little effect and is not required.

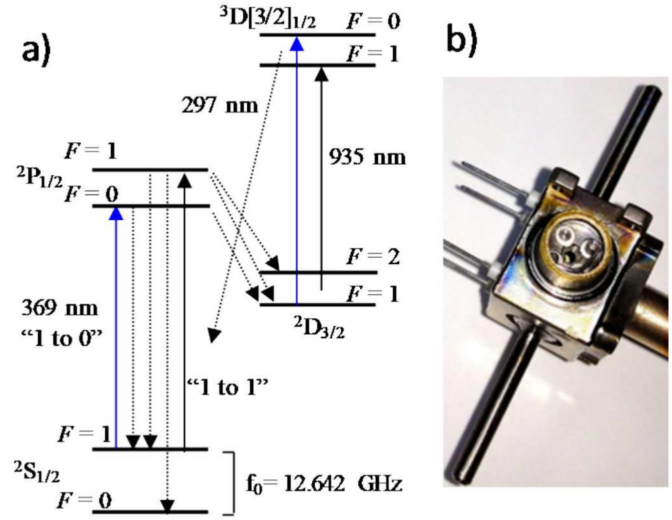

Fig. 1. (a) Simplified energy level diagram of the $^{171}Yb^+$ ion. The black arrows show the laser transitions used in the continuous-mode clock and the blue arrows show the transitions for the pulsed-mode clock. (b) Photograph of the 3 cm^3 vacuum package.

In our previous work, the clock was operated in the pulsed mode, and the 369-nm laser was tuned to the $^2S_{1/2}$ $F = 1$ to $^2P_{1/2}$ $F = 0$ transition (henceforth called the "1-to-0 transition") and the 935-nm laser was tuned to the $^2D_{3/2}$ $F = 1$ to $^3D[3/2]_{1/2}$ $F = 0$ transition. Fluorescence was collected at 297 nm from the $^3D[3/2]_{1/2}$ to the $^2S_{1/2}$ transition. The combination of these transitions creates a cycling transition where 300 – 500 photons are scattered at 369 nm and 1.5 – 2.5 photons are scattered at 297 nm per ion per microwave photon absorbed. In our compact clock, fluorescence collection was optimized in terms of signal-to-background ratio by collecting the 297-nm fluorescence because of significant 369-nm background in the compact fluorescence collection system. In the continuous mode, it is advantageous to shift the lasers to the $^2S_{1/2}$ $F = 1$ to $^2P_{1/2}$ $F = 1$ transition (called the "1-to-1 transition") for the 369-nm laser and ~100 MHz blue detuned from the $^2D_{3/2}$ $F = 2$ to $^3D[3/2]_{1/2}$ $F = 1$ transition for the 935-nm laser. The detuning of the 935-nm laser allows both hyperfine levels of the $^2D_{3/2}$ state to be depopulated. The primary reason for using the 1-to-1 transition for the 369-nm laser is to allow as-fast-as-possible interrogation of the clock transition. In the trapped ion microwave clock, coherence times of the clock transition is more than 100 s [15], and the full width at half maximum (*FWHM*) of the clock resonance is determined by optical and microwave power broadening,

$$FWHM = \frac{1}{\pi}\sqrt{\frac{\alpha}{2}\Omega^2 + \left(\frac{R_{369}}{2}\right)^2}, \quad (1)$$

where Ω is the microwave Rabi frequency, R_{369} is the optical pumping rate of the 369-nm laser, and α is the average number of photons scattered before optical pumping to the $^2S_{1/2}$, $F = 0$, $m_F = 0$ state. For the 1-to-1 transition, $\alpha = 3$, while for the 1-to-0 transition $\alpha = 300$ to 500, depending on the ion temperature. The instability of the clock is proportional to $1/(Q\ SNR)$, where Q is the quality factor of the clock transition and *SNR* is the signal-to-noise ratio. In the photon shot noise limit

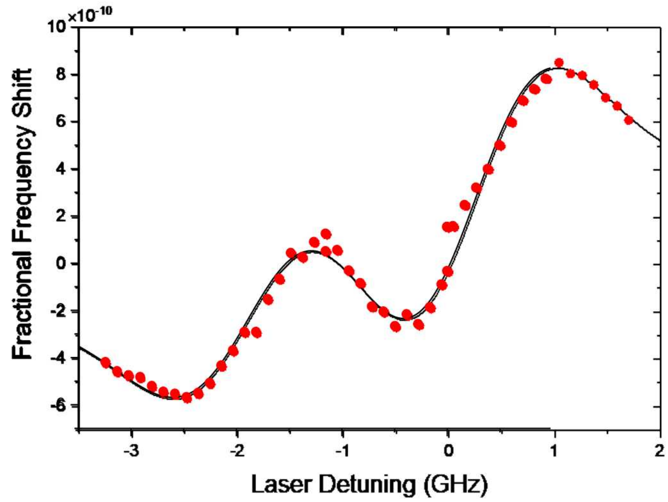

Fig. 2. Plot of the light shift (fractional frequency shift in parts in 10^{-10}) as a function of the 369-nm laser frequency detuning at a fixed optical power. The nominal linewidth for this data is 30 Hz. The line is a calculation of the light shift that has been manually adjusted to the fit the data. The zero of the horizontal and vertical axes are set approximately at the zero light-shift point for the 1-to-1 transition.

for a chosen linewidth of the clock transition, the instability is optimized when $\Omega = (3/(2\alpha))^{1/2}R_{369}$. In this case, the time to optically pump the ions from the upper clock state to the lower state is $\alpha/(\pi\, FWHM)$. Thus, the 1-to-1 transition can be used to interrogate clock transition much faster than the 1-to-0 transition. However, in the continuous mode many fewer photons are scattered per microwave photon absorbed compared to the pulsed mode. Therefore, fluorescence is collected at 369 nm. For the tabletop experiments described here, we use a 15-cm long imaging system to reject background scatter. For a fully integrated and miniaturized clock, careful design is required to reject background scatter during fluorescence collection at 369 nm.

III. Light Shift

In continuous-mode operation, a systematic shift is introduced that is not present in pulsed-mode operation; the AC Stark Effect from the 369-nm laser shifts the levels of the hyperfine ground state causing the so-called light shift.

A. AC Stark Effect Calculations

The clock resonance frequency can be shifted by changing the 369-nm laser intensity, optical detuning, and optical polarization. We have established a numerical model using the methods described in [16]. In our numerical model, we have included all $^2S_{1/2}$ ground-state hyperfine sublevels and $^2P_{1/2}$ excited state hyperfine sublevels. Based on the oscillator strength data of $^{171}Yb^+$ ion D1 transition, we are able to calculate the optical polarizability of all the relevant optical transitions between the ground-state and the excited-state sublevels. We can therefore acquire the energy shifts of the ground-state sublevels with a given 369-nm intensity, detuning, and polarization. The light shift of the clock resonance frequency is therefore equal to the difference of the energy shifts of the two clock states. For trapped ions, each ion is not

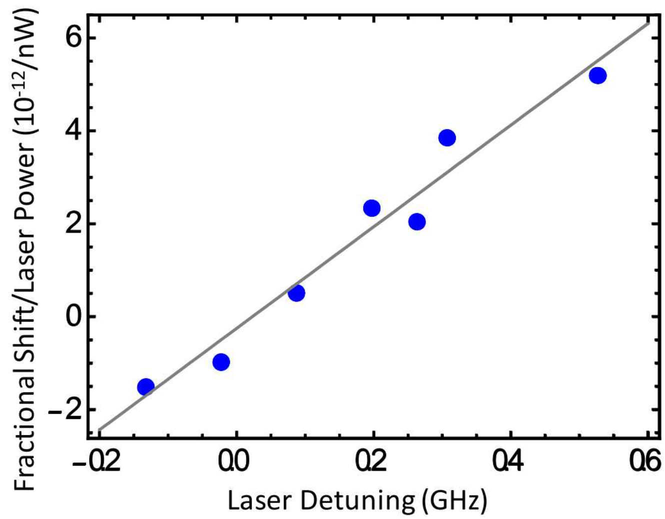

Fig. 3. Plot of the slope of the light shift with 369-nm laser power as a function the frequency of the 369-nm laser. The line through the data is a fit giving a slope of of 1.09×10^{-11}/(GHz nW).

stationary but moving all the time due to the finite temperature of ions (usually around 1000 K in our ion trap). Therefore, the Doppler effect is added into the calculation by convolving the optical-detuning-dependent light-shift curve with a Doppler profile of a corresponding ion temperature. For example, the line in Fig. 2 is the calculated light-shift curve for $^{171}Yb^{+}$ ions at 1050 K and a 30-Hz clock resonance linewidth.

B. Light Shift Measurements

To characterize the light shift, we measure the frequency shift of the clock as a function of both the frequency detuning and the power of the 369-nm laser. In Fig. 2, the detuning of the 369-nm laser is scanned across both the 1-to-1 and 1-to-0 transitions. The measured temperature of the ions is 1140 K. Near the center of each transition, the light shift is approximately linear passing through a point where changes in the optical power do not affect the clock frequency, or a zero-light shift point. Fig. 3 shows a characterization of the light shift around the 1-to-1 transition in terms of both power and detuning. At each detuning the laser power is scanned, and a linear fit extracts the slope of the clock shift as a function of power. We find that the fractional frequency shifts as 1.09×10^{-11}/(GHz nW). The 369-nm laser is focused through the long axis of the trapped ions and has a $1/e^2$ diameter of 0.1 mm giving an averaging intensity of 0.025 mW/cm^2 with 2 nW of optical power. However, the beam's diameter is somewhat smaller than that of the ion cloud, and the effective intensity experience by the ions is reduced.

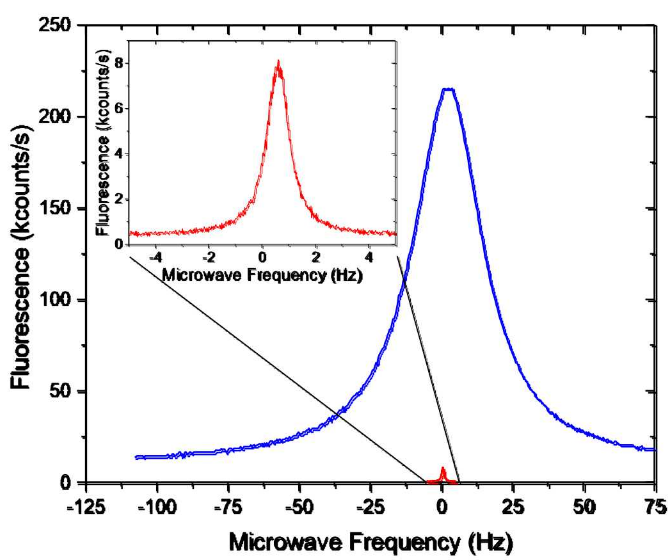

Fig. 4. Plot of the clock resonances at 30 Hz linewidth (blue line) and 1 Hz linewidth (red line). The inset shows the 1 Hz linewidth expanded to show its detail.

IV. CLOCK FREQUENCY INSTABILITY

The frequency instability of the clock is measured under two different conditions. By setting to optical and microwave power, the linewidth of the microwave transition is set to 1 Hz and 30 Hz. The 369-nm optical power for the 1-Hz (30-Hz) linewidth is 2 nW (220 nW). We would expect the optical power at 30-Hz linewidth to be 30 times larger than the power at 1-Hz linewidth rather than the measured factor of 110; we attribute this to poor optical alignment in the 30-Hz case. The ion cloud does not overlap well with the laser beam, and the ion cloud is not exactly at the laser beam focus. The measured clock resonances are shown in Fig. 4, showing both the width of the transition as well as the number of fluorescence photons collected per second. A narrower linewidth offers better stability and reduced light shift while a broader linewidth allows a faster attack time on the local oscillator. Additionally, in a compact clock, the lasers may need to be locked to the ion fluorescence signal, and a broader linewidth would allow a faster lock to for the lasers as well.

The frequency instability of the Yb ion clock is shown in Fig. 5 while the laser is tuned to the zero light-shift point. The frequency reference to which we compare the Yb ion clock is a Microsemi 4145C quartz oscillator locked to a Microsemi

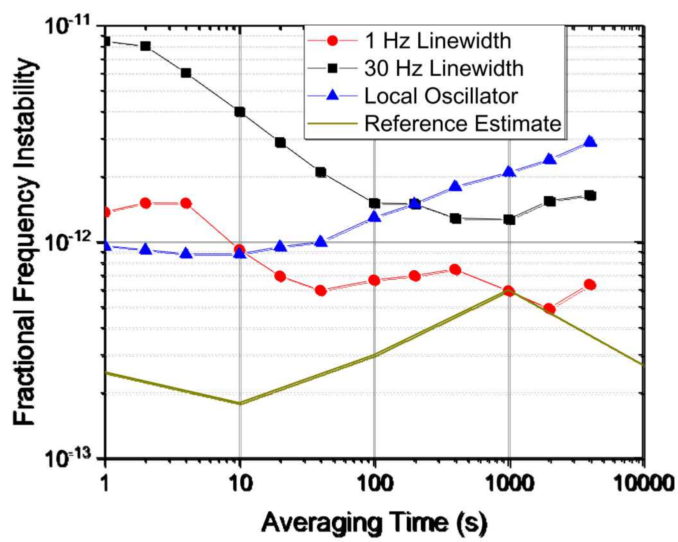

Fig. 5. Allan deviation of the Yb ion clock under different conditions. The Local Oscillator data is the local oscillator's free-running performance without feedback from the Yb ions, and the Reference Estimate is the estimated performance of the frequency reference to which we compare the Yb ion clock based on manufacturer specifications.

CsIII Cs beam clock. The local oscillator of the ion clock is an SC10 quartz oscillator from Stanford Research Systems. With the local oscillator stabilized to the Yb ions with a 1-Hz linewidth, the stability of the Yb ion clock quickly surpasses that of the local oscillator alone and approaches the stability of the reference. With a 30-Hz linewidth, the short-term stability of the Yb ion clock is degraded, while at integration times near 1,000 s the stability is likely limited due to the light shift from the frequency instability of the 369-nm laser.

V. Conclusion

To operate an ion clock in the continuous mode, the light shift must be well controlled. To reach a stability below 10^{-13} when the laser is tuned to the zero-light-shift point, the laser must have a stability below 4.5 MHz for the 1-Hz microwave linewidth and 150 kHz for the 30-Hz linewidth. Such a stability is achievable with modern laser locking techniques, and we are currently evaluating techniques for implementation into a compact clock. Our results show that a compact ion clock operating in the continuous mode can achieve a stability better than 10^{-12} at an averaging time longer than 10 s, and the microwave linewidth can be adjusted to balance clock performance with the required attack time on the local oscillator.

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