Hg^+ OPTICAL FREQUENCY STANDARD: RECENT PROGRESS*

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We report progress toward an optical frequency standard based on the 1.7 Hz linewidth ${}^2S_{1/2}\rightarrow{}^2D_{5/2}$ transition of a single trapped ${}^{199}Hg^+$ ion. We have constructed an isolated, high-finesse, Fabry-Pérot cavity for stabilization of the optical local oscillator. A 563 nm source frequency-locked to this cavity has a linewidth less than 0.16 Hz for averaging times up to 20 s. The measured fractional frequency instability is 3×10^{-16} at 1 s. A simple scheme allows the transport of this light through an optical fiber with negligible degradation of its spectral purity. We have constructed small cryogenic linear traps that are designed to provide confinement in the Lamb-Dicke regime for the optical transition.

1 Introduction

Neutral-atom and trapped-ion frequency standards based on microwave transitions have achieved fractional inaccuracies[1,2] near 10^{-15} and fractional frequency instabilities[1,3,4] near $4\times10^{-14}\tau^{-1/2}$, where τ is the measurement averaging time. Some of these microwave standards now have reached (or nearly reached) the theoretical performance limit set by quantum projection noise. For an atomic standard based on an ensemble of N uncorrelated atoms that are interrogated by Ramsey's separated oscillatory field method,[5] quantum projection noise limits the fractional frequency instability to[6]

$$\frac{\Delta\omega}{\omega_0} \approx \sigma_y(\tau) = \frac{1}{\omega_0\sqrt{NT_R\tau}}, \tag{1}$$

where $\sigma_y(\tau)$ is the two-sample Allan deviation, ω_0 is the frequency of the clock transition, and T_R is the Ramsey interrogation time.

The next major advance for frequency standards probably lies in the development of standards based on long-lived optical transitions. Because optical frequencies are $\approx10^5$ times higher than the 9.2 GHz microwave transition used in cesium standards, higher fractional stability can be achieved in a

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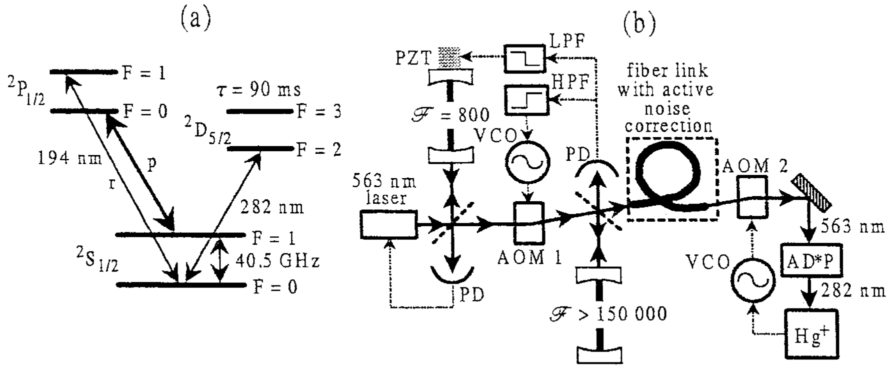


Figure 1. (a) Simplified energy-level diagram for $^{199}Hg^+$. We cool the ions using the $^2S_{1/2}{\rightarrow}^2P_{1/2}$ transitions at 194 nm. Transition p is a cycling transition. A second laser on transition r repumps atoms in $^2S_{1/2}$, F=0 back into $^2S_{1/2}$, F=1. The microwave clock transition is at 40.5 GHz, and the optical clock transition is at 282 nm. (b) Simplified schematic of the proposed optical frequency standard. A dye laser is prestabilized to a Fabry-Pérot cavity ($\mathcal{F}$ = 800). Further stabilization to a much higher finesse cavity ($\mathcal{F}$ > 150 000), and eventually to a narrow transition of a trapped Hg^+ ion should provide a highly stable frequency source. Solid lines denote optical paths and dotted lines represent electrical connections. AD*P, deuterated ammonium dihydrogen phosphate crystal for frequency doubling; AOM, acousto-optic modulator; $\mathcal{F}$, finesse; HPF, high-pass filter; LPF, low-pass filter; PD, photodiode; PZT, piezoelectric transducer; VCO, voltage-controlled oscillator.

given measurement time even for a smaller number of atoms. Single trapped and laser-cooled ions might be nearly ideal references for optical frequency and time standards.[7,8] High resolution is possible because perturbations can be made small and interrogation times long.[7,8,9,10] In addition, laser cooling considerably reduces first- and second-order Doppler shifts.[11] Several groups are developing optical frequency standards based on a variety of ions.[12] We are developing an optical frequency standard using $^{199}Hg^+$ ions, which are attractive because they offer both microwave and optical transitions suitable for frequency standards.[2,13] Figure 1(a) shows the $^{199}Hg^+$ electric dipole transitions at 194 nm used for laser cooling, optical pumping, and detection, and the 1.7 Hz linewidth electric quadrupole transition at 281.5 nm that is the reference for the optical frequency standard. For a single Hg^+ ion and $T_R = 30$ ms, Eq. (1) gives a quantum-projection-noise limit of $\sigma_y(\tau) \approx 10^{-15}\tau^{-1/2}$. Reaching such low instabilities requires a laser whose frequency fluctuations are $\lesssim$1 Hz during time intervals as long as a few seconds.

2 Overview of the Optical Frequency Standard

Figure 1(b) shows a simplified diagram of our proposed optical frequency standard.[13] A critical component is the high-finesse ($\mathcal{F} > 150\,000$) Fabry-Pérot cavity, which is described in Sec. 3.1. A dye laser at 563 nm is prestabilized to a cavity with a finesse $\mathcal{F} \approx 800$ using a Pound–Drever–Hall FM lock.[14] A feedback loop bandwidth of $\approx$2 MHz narrows the dye laser short-term (<1 s) linewidth to $\approx$1 kHz. An optical fiber (not shown) delivers light from the dye-laser table to a vibrationally isolated table that supports the high-finesse cavity. An acousto-optic modulator (AOM) mounted on the isolated table shifts the frequency of the incoming light to match a cavity resonance. A second FM lock performs corrections at frequencies as high as $\approx$90 kHz by varying the AOM drive frequency and at low frequencies by adjusting a PZT on the prestabilization cavity. With the lock enabled, the light entering the high-finesse cavity has a subhertz spectral width (see Sec. 3.2).

Finally, the frequency-stabilized light couples through an optical fiber to the table holding a cryogenic Hg^+ trap. A simple feedback loop actively reduces the frequency-noise contributions to the light from the fiber (see Sec. 3.3). The 563 nm radiation is frequency-doubled to 281.5 nm and is focused onto the trapped ion. AOM 2 in Fig. 1(b) shifts the frequency of the light to match the ion transition. We plan to interrogate the transition using the Ramsey technique[5] with a Ramsey time $T_R \approx 30$ ms. A digital servo loop will adjust the AOM frequency to step between both sides of the central fringe, and will periodically record the values of the center frequency.[13]

3 Laser Frequency Stabilization

The frequencies of several types of lasers have been locked to resonances of Fabry–Pérot cavities with imprecisions less than 0.1 Hz,[15] but the frequency instabilities of the cavity resonances were orders of magnitude greater. Previously, the narrowest published visible-laser linewidth was 10 Hz for a 1 s averaging time.[16] Recently we achieved a linewidth of 0.6 Hz for averaging times up to 32 s.[17] Here we report a linewidth <0.16 Hz for averaging times up to 20 s. These improvements arose chiefly from better isolation of the cavities from mechanical vibrations.

3.1 High-Finesse Reference Cavity

The high-finesse reference cavity should be insensitive to and/or well-protected from environmental perturbations.[17] The cavity spacer and mirror ıbstrates are composed of ULE,[18,19] a low-thermal-expansion material. The ıvity is supported inside an evacuated chamber by an aluminum V-block ·ith four Viton contact points. We protect the cavity from vibrational noise y mounting the vacuum chamber on a passively isolated optical table. Dash-ots filled with grease at each corner of the table provide viscous damping. 'o reduce the coupling of acoustic noise into the cavity, we enclose the optical ıble in a wooden box lined internally with lead foam.[20] Active servo control f the optical power transmitted through the cavity stabilizes the frequency ıift caused by mirror heating.

.2 *Measurement of Cavity Stability*

'o characterize the cavity's stability, we constructed a second cavity and ıounted it on a second, independent, vibrationally isolated table.[17] A laser ıeam is frequency-locked to each of the cavities. Some light from one of hese beams propagates from one isolated platform to the other. There, it ıeterodynes with light from the beam that is stabilized to the second cavity, ıroviding a measure of the relative frequency deviations between the two avities. We mix the beat note ($\nu \approx 400$ MHz) with a linearly swept rf source, vhich translates the beat-note frequency lower to facilitate high-resolution ınalysis and removes a fairly uniform frequency drift ($\lesssim$2 Hz/s). We also can emove Doppler-shifts of the beat frequency caused by relative motion of the solated platforms,[13,17] but that correction is usually unnecessary.

In the frequency domain, a fast Fourier transform (FFT) spectrum ana-yzer measures the spectrum of the beat note, as shown in Fig. 2. The width ›f the spectrum at its half-power point is 0.22 Hz (20 s averaging time). The).19 Hz resolution bandwidth of the spectrum analyzer makes a sizable contri-›ution to this frequency width. However, we conservatively estimate the laser inewidth by omitting the bandwidth correction. We infer that at least one ›f the beams has a linewidth <0.16 Hz at 563 nm for averaging times up to ?0 s. This fractional linewidth of 3×10^{-16} is nearly two orders of magnitude ;maller than published results for other stabilized lasers, and may represent ;he smallest fractional linewidth ever measured in the optical regime.

For time-domain analysis, we first frequency-divide the beat signal by a 'actor of 20, and then mix the signal down to dc.[17] The frequency division ›ermits a simple conversion from mixer output amplitude to relative laser ›hase $\Delta\phi$ by allowing the in-quadrature condition $(\Delta\phi/20 - \pi/2) \ll 1$ to ›ersist for several seconds. From a time record of $\Delta\phi$ we compute $\sigma_y(\tau)$ for $\tau \leq 2.5$ s. For $\tau \geq 0.5$ s, we perform time-domain measurements using an ıutomated dual-mixer time-difference measurement system.[21] Figure 3 shows

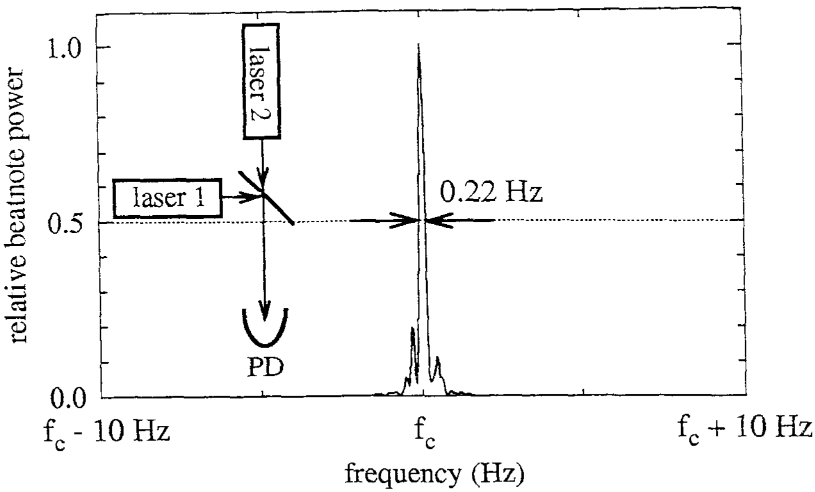


Figure 2. Power spectrum of the beat note between two 563 nm laser beams stabilized to two independent cavities. The dashed line shows the -3 dB level. The resolution bandwidth of the spectrum analyzer is 0.19 Hz, and the averaging time is 20 s. A nearly uniform relative cavity drift of 0.4 Hz/s is suppressed by mixing the beat note with a swept frequency synthesizer. PD, photodiode.

the Allan deviations determined using these two measurement techniques, alongside the reported $\sigma_y(\tau)$ for other stable laser systems. For 30 ms $< \tau <$ 100 s, the Allan deviation of our laser is approximately an order of magnitude less than that of any other stable lasers.

3.3 Reduction of Optical Fiber Noise

Optical fibers are convenient for transporting light and avoiding alignment instabilities. Unfortunately, fibers add considerable frequency noise to the light.[27] A high-performance fiber-noise cancellation scheme using two AOMs has been demonstrated.[27] Since we need multiple fiber links with limited table space and wish to conserve optical power, we implemented a simpler scheme using a single AOM, as shown in Fig. 4.

The stabilized light propagates through the optical fiber and then an AOM. Some of this light retroreflects back through the AOM and the fiber, where it heterodynes with a sample of the input light. A phase-locked loop servos the AOM deflection frequency so that the beat signal is phase-coherent with a stable rf reference signal at 160 MHz. Thus, the phase-locked loop

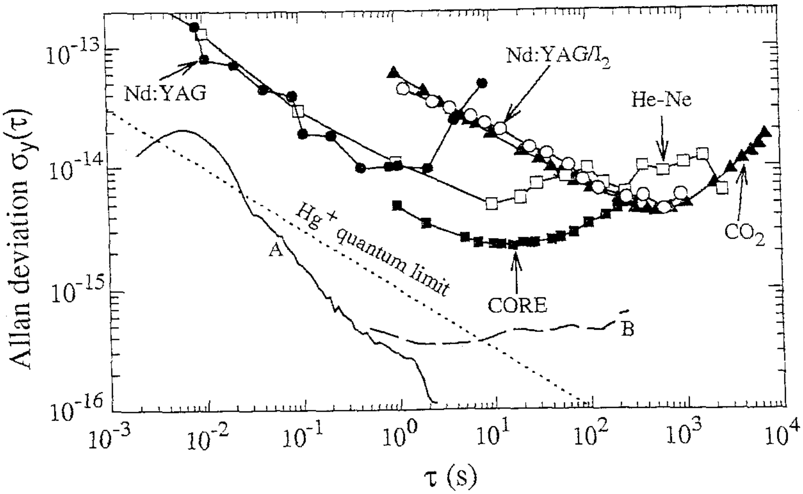


Figure 3. Allan deviation curves for stabilized lasers. We calculate $\sigma_y(\tau)$ for one of our sources from an analog-to-digital sample of the beat signal (curve A) and using a dual-mixer measurement system (curve B). (We remove a linear relative cavity drift of 2.4 Hz/s.) The dotted line shows the quantum noise limit for a Hg^+ optical frequency standard ($N = 1$ and $T_R = 30$ ms). Results for other stabilized lasers: (Nd:YAG) Nd:YAG lasers locked to Fabry–Pérot cavities[22]; (Nd:YAG/I_2) iodine-stabilized Nd:YAG lasers[23]; (He–Ne) methane-stabilized He–Ne lasers[24]; (CO_2) CO_2 lasers[25] locked to OsO_4; (CORE) Nd:YAG lasers locked to cryogenic resonator oscillators.[26]

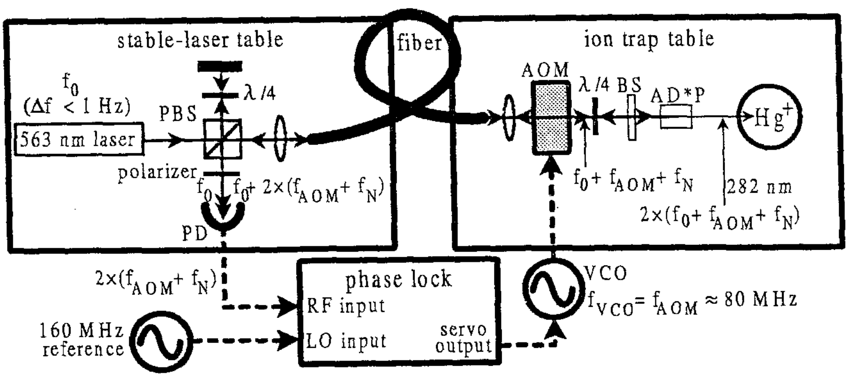


Figure 4. Fiber-noise cancellation scheme. A phase-locked loop controls the deflection frequency f_{AOM} of an AOM to suppress the frequency noise f_N on the light caused by the optical fiber. BS, beam splitter; PBS, polarizing beam splitter.

impresses noise on the AOM frequency that nearly cancels the noise put on the light by the fiber. Consequently, light that only single-passes both the fiber and the AOM has a frequency precisely 80 MHz different from the incident light, maintaining its high spectral purity.

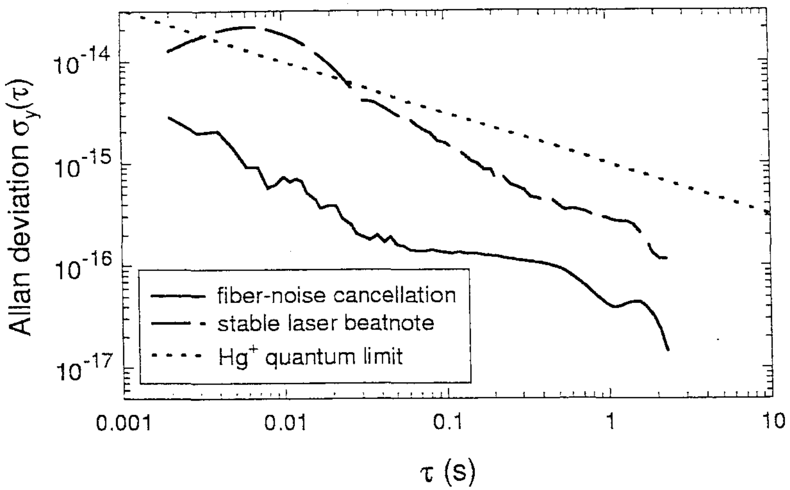
Unfortunately, the $\approx$80 MHz AOM also amplitude-modulates the light at a frequency nearly degenerate with our 160 MHz signal. This modulation component, which is about 24 dB below the signal power, limits the fiber-noise cancellation. Additionally, we retroreflect light through the fiber using linear polarization orthogonal to the incident light polarization, rather than identical linear polarization. This conserves optical power, but there may be a difference between the noise contributions on the two passes through the fiber, again limiting the accuracy of the noise cancellation.

We test the capability of our scheme to transport light without significant spectral broadening by using a fiber link similar to that in Fig. 4, except that both fiber ends are mounted on a single optical table. We verify the noise correction by heterodyning the single-passed light with some incident light. The spectral purity of the 80 MHz beat signal indicates the accuracy of the fiber-noise cancellation. When the phase lock is disabled, the frequency excursions of the beat note are $\approx$20 kHz; when enabled, the phase lock largely eliminates the fiber noise. We perform time-domain characterization of the 80 MHz beat signal as described in Sec. 3.2. The Allan deviation corresponding to the residual fiber noise (see Fig. 5) is $\approx$10 times less than $\sigma_y(\tau)$ for the laser light.

4 Single-Ion Frequency Reference

The high vapor pressure of Hg^+ at room temperature combined with our desire for ion storage times of several days has guided us toward cryogenic traps. Cryogenic operation introduces a host of challenges, most prominently the accumulation and "freezing out" of patches of charge on the trap electrodes during the loading process. The resulting stray electric fields can add enough additional bias to prevent the trapping of ions. Therefore, heaters must be incorporated into the trap structure so that its temperature may be elevated enough to permit the dissipation of any charge accumulated during the time the Hg oven and ionizing electron beam are activated. After loading, the trap is returned to cryogenic operation without further evidence of fluctuating bias fields.

We are experimenting with a number of heated trap structures, which, so far, are all variations of a linear rf Paul trap geometry.[28] For use in the optical frequency standard, it is critical that the trap provide tight confine-



gure 5. Fractional frequency instability introduced by our fiber link with fiber-noise can- llation. The Allan deviation measured for the incident laser light is ≈10 times larger than e instability introduced by the actively corrected fiber link.

ent satisfying the Lamb-Dicke criterion that the ion's maximum excursions ιr| $< \lambda/2\pi \approx 45$ nm.[29,30] Otherwise, the transition strength of the optical ırrier sensitively depends on the vibrational amplitude of the trapped ion, ıd fluctuations in transition strength result when the mean excitation num- ɜr of the harmonic motion is large or changing. Presently, we have trapped ıd cooled ions to crystallization in one trap that does not satisfy the Lamb- icke criterion. We recently constructed a smaller trap that should yield ronger confinement. In the future, we may employ lithographic traps sim- ar to those used in our group for quantum-state engineering investigations, ut modified for cryogenic operation.

Conclusions

/e have demonstrated a laser suitable for precision spectroscopy and for ptical frequency standards. It has a linewidth of less than 0.16 Hz at 563 nm ›r averaging times up to 20 s. Its fractional frequency instability is 3×10^{-16} t 1 s. We have assembled a new cryogenic Hg^+ trap that should provide amb-Dicke confinement. When tight confinement is demonstrated, we will ·equency-lock our stable laser to the ion.[13] If a simple frequency synthesis scheme connecting the optical transition to microwave frequencies[31,32] proves feasible, we anticipate a time standard with an inaccuracy near 10^{-18}, and stability surpassing the best present-day clocks.

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