Measurement of the ^{88}Sr^{+} reference transition frequency with a new probe laser system

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***Abstract*— We have designed and implemented a new 674 nm (445 THz) laser system for probing the ultranarrow $5s^2S_{1/2}$–$4d^2D_{5/2}$ reference (clock) transition of the trapped and laser-cooled ^{88}Sr^{+} ion. We describe briefly the double-stage probe laser system; linewidths of (50 ± 9) Hz FWHM were observed for the clock transition with this source. We also present results on the determination of the temperature of zero thermal expansion coefficient of the reference cavity. Our preliminary measurement of the absolute frequency of the ^{88}Sr^{+} clock transition frequency gives a frequency of $(444\,779\,044\,095\,472 \pm 15)$ Hz.**

I. INTRODUCTION

A single trapped and laser cooled ion holds the promise for unsurpassed frequency accuracy, predicted to reach levels of 10^{-17} to 10^{-18} once the small systematic shifts become well understood and controlled [1], [2]. The hertz or sub-hertz wide resonance of the clock transition (0.4 Hz FWHM for ^{88}Sr^{+}) helps in localizing the linecenter to a high accuracy. However, one weakness of these systems is the low data rate offered by the single ion; long interrogation times are required to derive an error signal for the probe frequency. The laser linewidth and the stability of the reference optical cavity are crucial in the successful probing of the ion resonance. In this paper, we present our first results in probing the ^{88}Sr^{+} ion clock transition with a new probe laser system.

II. PROBE LASER SYSTEM

The 674 nm source is a commercial extended-cavity (Littman configuration) diode laser. It is frequency-stabilized with a cascade of two Fabry-Perot resonators. The laser is first stabilized to a PZT-actuated resonator of 100 kHz FWHM linewidth. Its optical output is then locked to a second, ultra-stable, Fabry-Perot resonator of 3.7 kHz FWHM linewidth [3]. This two-stage servo provides a high gain for laser frequency narrowing and stabilization. Figure 1 shows a resonance profile of one of the Zeeman component of the ^{88}Sr^{+} clock transition measured with this probe laser. The (50 ± 9) Hz FWHM linewidth observed is attributed to broadening from mechanical noise on the resonator and to imperfections in the frequency lock.

The ultra-stable Fabry-Perot resonator is made of a ULE spacer onto which ULE mirrors are optically contacted. This Fabry-Perot is mounted inside a temperature-controlled vacuum chamber and is vibration-isolated with Viton O-ring supports. The vacuum chamber is itself enclosed in a temperature-controlled copper box. The whole probe laser setup is enclosed in a hut built inside the lab for further acoustic isolation from the environment.

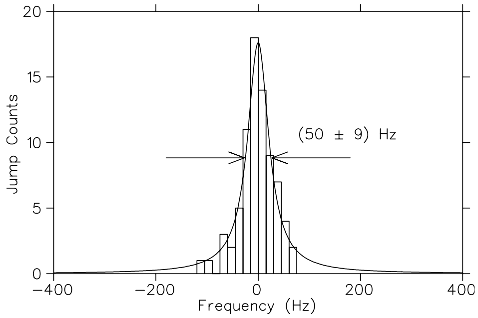

Fig. 1. Resonance profile of the $(m_{j''}, m_{j'}) = (1/2, 1/2)$ component of the ^{88}Sr^{+} clock transition. The probe duration in each measurement cycle was 40 ms, giving a Fourier transform limited linewidth of 22 Hz. The frequency steps were 15 Hz and the dwell time at each frequency was 60 s. The cavity drift of 0.16 Hz/s was accounted for in the lock algorithm.

For greatest long term stability, the vacuum chamber temperature is set at the temperature of zero thermal expansion coefficient of the ULE bar: $T_0 = 6.04$°C. To find this value, the vacuum chamber temperature was initially lowered below T_0. While a femto-comb laser was measuring the probe frequency locked to the reference Fabry-Perot, the temperature of the vacuum chamber was increased. As shown in Fig. 2, for temperatures below T_0 (times below $\approx$ 9500 s) the resonator frequency increases with temperature, and above T_0 it decreases. A simple thermal model was used to determine T_0 from the data. The observed frequency drift is caused by a slow shrinking of the ULE spacer.

III. CLOCK TRANSITION FREQUENCY MEASUREMENT

Figure 3(a) shows the data obtained during a measurement of the ^{88}Sr^{+} center frequency. This measurement is composed of two distinct parts: (1) the measurement of the probe laser frequency (ULE resonator) with the femto-comb laser chain, and (2) the offset frequency between the ULE resonator and the ion. This offset is provided by a synthesizer driving a double-pass acousto-optic modulator (AOM) and is determined by the lock of the probe laser to the ion [1]. The femto-comb laser and the synthesizer were referenced to an NRC maser corrected to TAI.

Figure 3(b) shows the differences between the probe laser frequency locked to the ion and the straight line fit. These

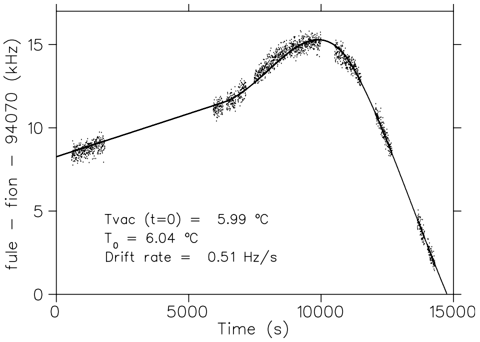

Fig. 2. Determination of the temperature (T_0) of zero thermal expansion coefficient of the ultra-high finesse Fabry-Perot ULE spacer. The vacuum chamber was kept at a constant temperature for the first 6000 s, then was heated. The dots are the femto-comb chain measurements of the probe laser frequency and the solid line is a simple model, fitted to the femto-comb data, describing the time evolution of Fabry-Perot frequency.

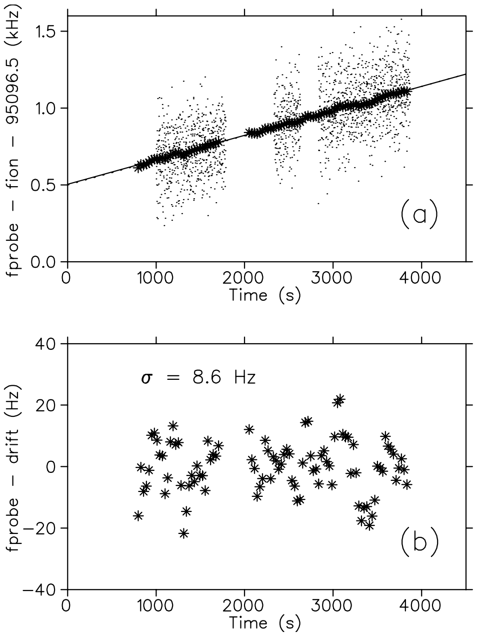

Fig. 3. Measurement of the ion frequency. (a) The dots are the femto-comb frequency chain measurements of the probe frequency, and the asterisk symbols ($*$) are the frequencies of the probe determined by the lock to the ion. The solid curve is a straight line fit to either data set. (b) The probe laser frequencies determined by the lock to the ion linecenter after subtraction of the straight line fit.

residuals show no observable deviation of the ULE resonator frequency from a linear drift.

Figure 4 summarizes the analysis of the ion frequency from the data shown in Fig. 3(a). The mean of these three measurements is $(444\,779\,044\,095\,472 \pm 15)$ Hz. The 15 Hz uncertainty was estimated by adding linearly the 5.7 Hz contribution from the data and the 9 Hz contribution from the maser reference signal. This preliminary result is based on a single measurement day and we have not investigated other sources or error. Recent values for the S-D transition center frequency are: $(444\,779\,044\,095\,520 \pm 100)$ Hz from the NPL [4] and $(444\,779\,044\,095\,510 \pm 50)$ Hz from our lab [1]. The new value reported here is lower, but in agreement with these more thorough measurements once the uncertainties are taken into account. The fourth run in Fig. 4 was a measurement of the ion frequency made while the 1092 nm radiation was illuminating the ion during the probe cycle. A light shift of (-33 ± 20) Hz was observed, in agreement with theoretical estimates [1].

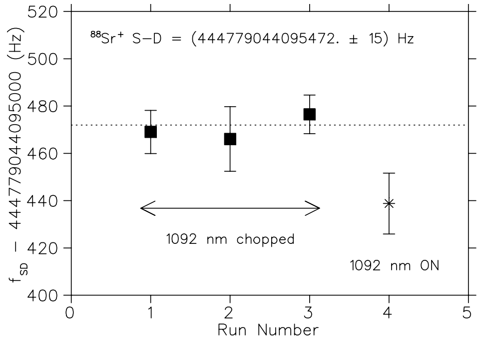

Fig. 4. Summary of the ion frequency measurements of January 12, 2004.

IV. CONCLUSION

We have observed (50 ± 9) Hz resonances with our new probe laser system. We have also presented our method used to find the temperature of zero thermal expansion coefficient of the reference Fabry-Perot resonator. The combination of a double-stage thermal control and the zero thermal expansion coefficient eliminates the effect of any remaining drift on the servo system. Assuming a linear drift, the frequency of the ULE resonator could be predicted to better than 10 Hz over the period of one hour.

We obtained a preliminary measurement of the $5s^2S_{1/2}$–$4d^2D_{5/2}$ transition frequency of the $^{88}\mathrm{Sr}^+$ ion with the new probe laser system. A more thorough determination of the ion frequency will be presented at the conference.

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