Letters

Measurement of Dynamic End-to-End Cavity Phase Shifts in Cesium-Fountain Frequency Standards

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***Abstract*—We have measured a previously unobserved systematic frequency shift in our cesium-fountain frequency standard, NIST-F1. This shift, predicted theoretically previously, mimics the well-known end-to-end phase shift in atomic beam standards when synchronous thermal transients are present. Detuning the microwave cavity several megahertz from resonance reduces this effect to the $\delta f/f = 10^{-16}$ level.**

I. Introduction

The temperature of the Ramsey microwave cavity and drift chamber in NIST-F1 is controlled in order to quantify and correct a systematic frequency offset known as the blackbody shift [1], [2]. As described in [3], small temperature fluctuations that are coherent with the interrogation cycle of a pulsed microwave clock can cause large frequency offsets.

II. Temperature Control

In NIST-F1 the temperature control is achieved by heating the TE_{011} mode microwave cavity and drift tube above room temperature with pulsed heaters driven with an alternating current (AC) excitation at about 25 kHz [2]. The heaters are on during the sample preparation stage and switched off during the free flight of the cesium atoms through the clock to avoid frequency offsets associated with heater operation (e.g., AC Zeeman effect). The on time of the heaters is typically 350 ms on, followed by 800 ms off. After a recent restructuring of the thermal control system of NIST-F1, a problem with this scheme was identified.

An accurate frequency measurement in a fountain frequency standard requires that the phase of the microwave field within the cavity be known (up to a constant) over the Ramsey time. As described in [3], the phase of the microwave field inside the cavity depends on the offset of the natural cavity frequency from the frequency of the drive field. This systematic frequency bias is related to the slope of the phase as a function of frequency and, in turn, to variations in the cavity temperature.

The pulsed heater causes a small temperature drift over the flight times of the atoms, which drift is synchronous with the fountain cycle. This small temperature fluctuation causes a small microwave-phase drift, synchronous with the Ramsey interrogation, within the cavity and thus a frequency error. This error is analogous to the end-to-end phase shift in a thermal beam and can be thought of as a "dynamic end-to-end phase shift" [3].

The following theory and estimate of the effect can be found discussed in more detail in [3]. If we denote the frequency of the drive field by ω_0 (nominally 9.19263177 GHz) and the natural frequency of the cavity by ω (also nominally 9.193 GHz), we can then write the phase of the microwave field (θ) within the cavity relative to the drive field phase as:

$$\theta = \tan^{-1}\left(\frac{Q}{\omega}\right)\left(\frac{\omega^2-\omega_0^2}{\omega}\right),$$

where Q is the (loaded) cavity quality factor (22500 in NIST-F1) defined in the traditional way so that the full width at half maximum, $\Delta\omega$, of the cavity response is given by $\Delta\omega = \omega/Q$.

Given the known thermal expansion coefficient of copper, $1.76 \times 10^{-5}\ \Delta l/l\mathrm{K}$, the cavity frequency versus temperature sensitivity can be deduced as being -160 kHz/K for the NIST-F1 cavity, which is constructed of oxygen-free (alloy 101) copper.

The phase shift between the first and second Ramsey interrogations then can be written as $\Delta\theta = \frac{d\theta}{d\omega}\frac{d\omega}{dT}\Delta T$, where T is the temperature of the Ramsey cavity and ΔT is the change in the temperature ($\Delta T \sim 250\ \mu\mathrm{K}$ inferred from the results obtained here). The frequency shift this induces on the output frequency of the cesium fountain is a function of the Ramsey time, with the shift being given by $\frac{\delta f}{f} = \frac{\Delta\theta}{\theta} = \frac{\Delta\theta}{\omega_0 T_R}$, where T_R is the Ramsey time of the cesium atoms.

Unfortunately, the technique of varying the Ramsey time in order to detect a systematic is nonoptimal when searching for this effect. The total phase change in the Ramsey cavity is proportional to the temperature change between the two microwave pulses, which is, in turn, proportional (to first order) to the time the heaters have been turned off (which is essentially the Ramsey time). This first order dependence is, in fact, not sufficient to describe the system adequately in this case. The heaters being pulsed puts a thermal impulse on the system and, as a result, the (average) cavity temperature may actually rise during the Ramsey time, depending on the competing rates of heat flow into and out of the cavity. Also, this effect is inversely proportional to the thermal time constant of the microwave cavity. Previous attempts to measure this effect in NIST-F1 were unsuccessful; however, a recent restructuring of the NIST cesium-fountain thermal control

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system has markedly decreased the thermal time constant of the microwave cavity, unintentionally making the effect much larger than previously. In fact, the size of the effect depends on both the ratio and absolute values of several thermal time constants in the distributed thermal system and is nontrivial to fully analyze analytically. It also should also be mentioned that fountains using a Magneto-Optic Trap (MOT) may, depending on the details of the particular MOT coil design, suffer from an analogous effect. The MOT coils generally dissipate a great deal of energy and are pulsed on and off with the fountain cycle. If this pulsed heat source couples into the cavity temperature, the same effect as seen here occurs.

III. Dealing with Temperature Shifts

There are three obvious ways to deal with this shift [3]. First (and likely best), do not use a pulsed-heater system. It is the coherent nature of the temperature fluctuation in the cavity to the fountain operation cycle that causes the systematic bias to the output frequency. Incoherent temperature fluctuations, while causing frequency instability at the time scale of the temperature fluctuations, do not, in general, cause a systematic bias. In NIST-F1, the heaters are inside the magnetic shielding and, as a result, we currently use pulsed heaters absent a reconfiguration of the fountain. The continuous wave (CW) operation of the heaters would require a demonstration that the AC Zeeman shift is absent under CW operation. As noted above, however, use of a MOT also may inadvertently introduce a coherently pulsed source of heat into the Ramsey cavity. The NIST-F1 does not use a MOT.

Second, decrease the cavity Q in order to reduce the temperature sensitivity. This approach, as used in the Physikalisch Technische Bundestanstalt (PTB) fountain, has some advantages when the unloaded cavity Q is high and the reduction in (loaded) Q is imposed by the coupling of the cavity. However, it requires careful matching of the cavity coupling structure in order to avoid distributed cavity phase problems [4]. If the unloaded Q of the cavity is spoiled, by use of a low conductivity material for example, rather than the cavity being loaded to low Q, distributed cavity-phase effects almost are certain to occur.

Third, tune the cavity off-resonance so that the slope of the phase-temperature relationship is reduced. We have chosen the last option both for the reasons given in [3] and because it allows the fountain to operate without further redesign of the thermal control system. It also reduces the overall temperature sensitivity of the fountain.

In order to measure the size of this effect, we operated NIST-F1 with its Ramsey cavity tuned on-resonance and compared the frequency with that obtained with the cavity temperature tuned off-resonance by $2.7 * \Delta\omega$ (=1.1 MHz). The results of these measurements, after correction for the changed blackbody shift, give a fractional shift between on and off resonance of $\delta\omega/\omega = (5 \pm 1) \times 10^{-15}$, corresponding to an inferred temperature drift of 250 μK over the Ramsey time. We estimate that, before restructuring of the Ramsey cavity thermal control system, this effect was $\delta\omega/\omega \lesssim 1 \times 10^{-1}$, based on previous measurements and scaling of the old and new thermal time constants. With a cavity detuning of 1.1 MHz, the effect of the temperature change during the Ramsey time on the phase of the microwave field within the cavity is reduced by a factor of 27. Therefore, the off-resonance fractional frequency shift is less than 2×10^{-16}, with an uncertainty of less than 5×10^{-17}. This shift can be treated either as a corrected bias or be reduced below 10^{-16} by a further detuning of the cavity.

IV. Conclusions

Several other effects need to be considered when operating with the cavity detuned from resonance: cavity pulling effects, the presence of other cavity modes that may be excited by the increased microwave power required to run off resonance, and the sideband structure of the synthesizer which is now enhanced in a single-sideband way by the nonresonant cavity. These are not significant effects at the 10^{-16} level in NIST-F1, but are potential problems depending on the details of the frequency standard under consideration. Frequency shifts due to microwave leakage also are enhanced by the necessary increase in microwave power required to run off resonance. Presently in NIST-F1, this shift is less than 1.8×10^{-16}, limited by statistical uncertainty. We plan to decrease this uncertainty with further measurements.

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