

Design and manufacture of a new microwave cavity assembly for use in cesium fountains at NIST

Gregory W. Hoth¹, Kurt Gibble^{1,2}, Vladislav Gerginov^{1,3}

¹Time and Frequency Division, NIST
Boulder, CO, USA

²Department of Physics, Penn State University
University Park, PA, USA

³Department of Mechanical Engineering, University of Colorado Boulder
Boulder, CO, USA
gregory.hoth@nist.gov

Summary—A new microwave cavity assembly has been designed and fabricated for use in the primary frequency standards at the National Institute of Standards and Technology (NIST). We will describe the design of the cavity and the manufacturing process. We will also present results from an initial study of the frequency bias due to the distributed cavity phase shift for this cavity design. The new cavity will be installed in NIST-F1.

Keywords—Primary frequency standard, cesium fountain, distributed cavity phase shift

I. INTRODUCTION

We are in the process of upgrading NIST-F1, a cesium fountain primary frequency standard [1]. In the last year, our investigation of the fountain's frequency biases led us to conclude that NIST-F1 had a bias due to a problem with the microwave cavity installed in the apparatus a few years ago [2]. Therefore, we have designed and fabricated a new microwave cavity structure.

Like many Cs fountains, the newly designed cavity for NIST-F1 makes use of the TE_{011} mode of a cylindrical cavity [3-6]. The TE_{011} mode is excited from four symmetric midplane cylindrical feeds (5 mm diameter). Each feed is excited by a TE_{010} rectangular filter cavity featuring an electric dipole antenna for symmetric H-field excitation to couple microwaves into the main cavity. The antenna is located at the midplane of the filter cavity. The filter cavities are dimensioned to be resonant at 9.192 GHz in the weak coupling regime. In practice, the filter cavities are strongly coupled to the pin antennas. The diameter of the feeds coupling the main cavity to the filter cavities is chosen to keep the main cavity in the weak coupling regime, resulting in a theoretical loaded quality factor Q of approximately 30,000 for TE_{011} in the main cylindrical cavity.

The body of the main cavity and the filter cavities were machined from a single piece of oxygen-free, high-conductivity copper. The main cavity (43 mm diameter) and the four filter cavities were cut out using an electrical discharge machining process. After machining, the parts were annealed in an H_2 atmosphere. Then, the inner surface of the main cavity was polished. The filter cavities were closed by rectangular lids. The central cavity was closed by two endcaps. Each endcap had an

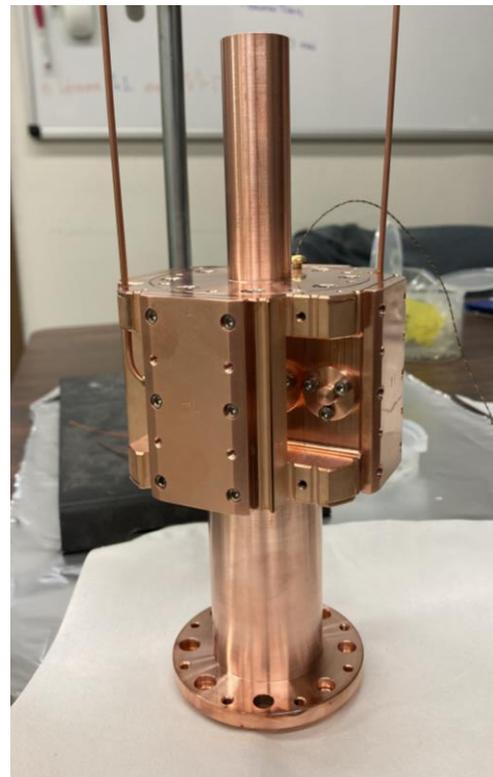


Figure 1. A photograph of one of the microwave cavity assemblies. The cavity was partially assembled to measure the resonance frequency and the cavity Q . The full assembly includes two identical cavities, one for state selection and one for Ramsey interrogation.

aperture with a diameter of 10.5 mm, allowing the cold atoms to enter and exit the cavity along its vertical axis. The outer edge of each endcap includes a 0.6 mm-wide and 5 mm-tall choke groove or mode filter [4-6] to detune the TM_{111} mode, which is degenerate with TE_{011} in a right cylindrical cavity. As a last step, the heights of the endcaps were fine-tuned and polished using a single-diamond tool to make the cavity resonant with the Cs clock transition in vacuum. The assembled cavity achieved a loaded Q of approximately 27,000. Figure 1 shows a photograph of the assembled cavity.

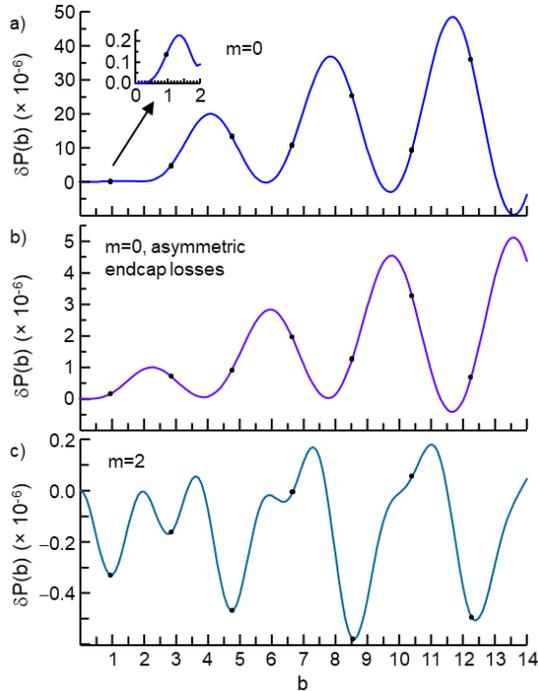


Figure 2. Calculated DCP errors, δP , for the new cavity design as a function of microwave amplitude, b , assuming typical cloud parameters for NIST-F1. All three plots use the same horizontal axis. The initial atomic distribution is modeled as a Gaussian density distribution with width $\sigma = 2$ mm and temperature $T = 1$ μ K. The distributed is centered on the fountain axis for the $m = 0$ calculations and offset by 1 mm from the axis for the $m = 2$ calculation. The black dots on each curve indicate microwave amplitudes where the Ramsey fringe contrast is at a maximum. The fountain typically operates at an amplitude corresponding to $b \approx 1$. The top panel shows the expected $m = 0$ DCP errors for symmetric endcap losses. The middle panel shows $m = 0$ DCP errors assuming a 20% asymmetry in the losses on the upper and lower endcaps. The bottom panel shows the expected $m = 2$ DCP error if the initial cloud is offset by 1 mm from the fountain axis. The detection is assumed to be homogenous.

II. DISTRIBUTED CAVITY PHASE

The accuracy of primary frequency standards based on the fountain geometry is presently limited by systematic frequency biases determined at the 1×10^{-16} level [7]. Among those are the frequency biases introduced by spatial variations in the phase of the microwave field interacting with the atomic clock transition [3,8,9], known as distributed cavity phase (DCP) errors. They are determined by the geometry of the Ramsey cavity and the distribution of the cold atoms during the fountain sequence.

An accurate model of the microwave field seen by the atoms is needed to quantify the DCP errors. The cavity field can be approximated as a short Fourier series in $\cos(m\theta)$ where m is an integer and θ is the angular variable in cylindrical coordinates [8,9]. This Fourier series also provides a natural decomposition of the DCP errors. Typically, only errors due to the $m = 0, 1, 2$ terms are relevant. The bias due to $m = 1$ phase variations can be measured experimentally and nulled by adjusting the relative phase and amplitude of opposing feeds

[3,10]. The bias due to the $m = 0$ and $m = 2$ phase variations is typically estimated from detailed modeling.

We have conducted an initial study of the DCP errors expected for the new cavity design. In Fig. 2, we plot the calculated DCP errors as a function of the microwave amplitude for $m = 0$ and $m = 2$, assuming a typical atom distribution for NIST-F1. The DCP error is quantified in terms of the shift in the transition probability induced by the spatial phase variations, δP [8,9]. In normal operating conditions, (microwave amplitude $b \approx 1$ in Fig. 2), the estimated $m = 0$ error is $\delta P \approx 0.13 \times 10^{-6}$, which corresponds to a fractional frequency bias of approximately 0.093×10^{-16} .

III. CONCLUSIONS

A new microwave cavity assembly has been designed and fabricated for NIST-F1. We are currently working to install the new cavity in the apparatus. After the upgrade is complete, the re-evaluation of the accuracy of NIST-F1 can proceed. The initial study of the distributed cavity phase bias for the new cavity shows that the DCP errors for this cavity should be tractable. At the conference, we will present more details of the cavity geometry, the manufacturing process, and the expected DCP errors for typical atomic distributions.

REFERENCES

- [1] S. R. Jefferts et al., "The accuracy evaluation of NIST-F1," *Metrologia*, vol. 39, pp. 321-336, Aug. 2002; T. P. Heavner, S. R. Jefferts, E. A. Donley, J. H. Shirley, and T. E. Parker, "NIST-F1: recent improvements and accuracy evaluations," *Metrologia* vol. 42, pp. 411-422, Sept. 2005.
- [2] G. W. Hoth, B. Patla, N. Ashby and V. Gerginov, "Initial Study of the Distributed Cavity Phase Shift for the New Microwave Cavities of Cs Fountains at NIST," 2022 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), Apr. 2022. doi: 10.1109/EFTF/IFCS54560.2022.9850867.
- [3] G. Vecchi and A. De Marchi "Spatial phase variations in a TE011 microwave cavity for use in a cesium fountain primary frequency standard," *IEEE Trans. Instr. Meas.* vol. 42, pp. 434-438, Apr. 1993.
- [4] R. Schroder, U. Hubner and D. Griebisch, "Design and realization of the microwave cavity in the PTB caesium atomic fountain clock CSF1," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 49, no. 3, pp. 383-392, Mar. 2002.
- [5] S. R. Jefferts, R. E. Drullinger, A. DeMarchi, "NIST cesium fountain microwave cavities," 1998 International Frequency Control Symposium, pp 6-9, May 1998.
- [6] K. Gibble, S. N. Lea and K. Szymaniec, "A microwave cavity designed to minimize distributed cavity phase errors in a primary cesium frequency standard," 2012 Conference on Precision Electromagnetic Measurements, 2012, pp. 700-701.
- [7] F. Riehle, "Towards a redefinition of the second based on optical atomic clocks", *C. R. Phys.* vol. 16, pp. 506-515, June 2015.
- [8] R. Li and K. Gibble, "Phase variations in microwave cavities for atomic clocks," *Metrologia* vol. 41, pp. 376-386, Oct. 2004.
- [9] R. Li and K. Gibble, "Evaluating and minimizing distributed cavity phase errors in atomic clocks," *Metrologia*, vol. 47, pp. 534-551, Aug. 2010.
- [10] J. Guéna, R. Li, K. Gibble, S. Bize, and A. Clairon, "Evaluation of Doppler Shifts to Improve the Accuracy of Primary Atomic Fountain Clocks," *Phys. Rev. Lett.*, vol. 106, pp. 130801, Apr. 2011.