Microwave-Vacuum Integrated Cavity with a Low Temperature Sensitivity for Cs Fountain Clocks

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***Abstract*—A low temperature-sensitive microwave-vacuum integrated cavity (MVIC) for Ramsey interrogation in Cs fountain clocks is proposed and experimentally prepared. This cavity is a typical TE_{011} cylindrical microwave resonator (CMR), which is made of a titanium (Ti) tube with two oxygen-free copper (OFC) end caps. The quality factor *Q* of cavity is improved by thin layers of copper and gold coating on the inner surface of the tube. The cavity resonance frequency (RF) changes are compensated thanks to the different thermal expansion of the different parts. Each coupling hole is sealed with a ceramic window first and then covered by a rectangular waveguide. Thus, the MVIC itself can be functioned both as the microwave resonator and a part of the vacuum chamber of the clock physical package. In contrast to the design with a cavity installed inside a vacuum chamber, the physical package with this MVIC is more compact, and more convenient for assembling. Additionally, the RF of the MVIC can be finally tuned after vacuum baking. The design and preparation processes of this Cs MVIC are introduced. And the results show that, for this prepared Cs MVIC, the sensitivity of its RF to the temperature variation is measured to be -48.1 kHz/℃, 3.2 times superior to a traditional OFC cavity with the same sizes.**

Keywords—time and frequency metrology; cesium atomic fountain clocks; microwave cavity; low temperature sensitivity

I. INTRODUCTION

Cesium atomic fountain clocks have been used as the primary frequency standards to realize the definition of the second and to steer the International Atomic Time. At present, Cs atomic fountain clocks have achieved the uncertainties of a few parts in 10^{16} [1-4]. They have made considerable contributions to the fields such as time-keeping [5], precise timing and frequency comparation [6], and stringent tests of fundamental physics [7]. Many applications urgently demand these fountain clocks to be robust, transportable and having the capability of operating in a large range of ambient temperature. The Ramsey cavity is a key element where the atomic transition is excited [8]. And this cavity is also one of the key elements making the atomic fountain clock sensitive to the ambient temperature variations [9, 10], since its resonance frequency (RF) is determined by its geometric dimensions.

There are two ways to assemble a Ramsey cavity. One is that the Ramsey cavity made of oxygen-free copper (OFC) with its rigid microwave coaxial cables is arranged inside the vacuum chamber of the clock physical packages [11, 12]. Though the temperature-sensitivity of the resonance frequency (RF) of the cavity is slightly lowered in vacuum due to the temperature fluctuations are reduced, it makes the physical package large and heavy, and the cables difficult to be installed, and the microwave leakage unavoidable in the interrogation zone. Besides, the RF of the cavity cannot be finally tuned after the vacuum baking, which is more likely to shift the cavity resonance frequency by a few hundred kHz. Another layout is that the Ramsey cavity constructed of OFC also forms a vacuum tight structure, which can function both as the microwave resonator and a part of the vacuum chamber of the physical package [13-15]. Though it can overcome some drawbacks mentioned in the first design, the RF of the cavity is more sensitive to the temperature variations. A typical RF thermal-coefficient of a traditional cylindrical TE_{011} Ramsey cavity made from OFC for Cs fountain clocks reaches up to -150 kHz/℃ [16].

Previously, two main approaches are usually adopted to reduce the adverse effect of the temperature-sensitivity of Ramsey cavity on fountain clocks. The first is to reduce the *Q*-factor of Ramsey cavity, but it may result in a higher distributed cavity phase induced frequency shift. The second is that the temperature of Ramsey cavity is controlled, including the physical package of fountain clock is located in a room where the temperature is stabilized with air conditioning, the Ramsey interaction region is surrounded by heat pipe made of a thin layer of vacuum tube filled with pure water [17], and so on. However, these temperature control methods are impractical to achieve a best transportable-fountain clock. In particular, the optimum operating temperature of atomic fountain clocks is confined to a fairly small range.

In this paper, a low temperature-sensitive microwave-vacuum integrated cavity (MVIC) for Ramsey interrogation in Cs fountain clocks is proposed and experimentally prepared. This cavity is a typical TE_{011} cylindrical microwave resonator (CMR), which is made of a titanium (Ti) tube with two oxygen-free copper (OFC) end caps. The quality factor *Q* of cavity is improved by thin layers of copper and gold coating on the inner surface of the tube. The cavity resonance frequency (RF) changes can be compensated thanks to the different thermal expansion of the different parts. Each coupling hole is sealed with a ceramic window first and then covered by a rectangular waveguide. Thus, the MVIC itself can be functioned both as the microwave resonator and a part of the vacuum chamber of the clock physical package. The design and preparation processes of this Cs MVIC are introduced. And its RF sensitivity to temperature is also measured.

II. PRINCIPLE AND PREPARATION

The Ramsey cavity uses a typical two or four azimuthally distributed feeds [13, 18]. The schematic diagram of MVIC and its layout on clock physical package is shown in Fig. 1.

This cavity is mainly a vertical CMR resonating in the TE_{011} mode at the hyperfine frequency of the atoms. The CMR is composed of a Ti cylindrical tube with two face-to-face coupling holes (C-holes) in its wall at the midplane, and the upper and bottom end caps (UEC and BEC) made of OFC, each with a cut-off waveguide along their central axis. In vacuum, the cavity RF is determined by the height and the radius of the CMR. Based on the cylindrical tube material Ti having a thermal expansion coefficient (TEC) lower than the end caps material OFC, the RF change of the CMR induced by the temperature-induced size variation of its radius can be self-compensated by that induced by its height, then this cavity can be immune to temperature fluctuations. By increasing the length of the caps extending into the tube, the cavity RF sensitivity to temperature can be reduced.

The C-holes are distributed symmetrically around the tube axis, and each of them is sealed with a ceramic window first, then covered by an OFC-based rectangular waveguide. The sealing part is shown in the enlarged view of Fig.1(b). The microwave radiation is coupled into the CMR through any of rectangular waveguides via ceramic windows. The Ramsey cavity itself can be functioned both as the microwave resonator and a part of the vacuum chamber of the clock physical package. Then, both the cables and the rectangular waveguide cavities are out of the vacuum chamber.

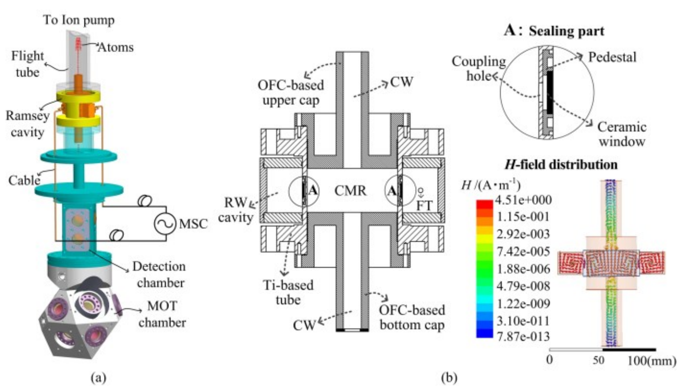

Fig.1. (a) Schematic diagram of MVIC and its layout on the clock physical package; (b) vertical section through the MVIC and its *H*-field distribution (TE_{011} mode). CMR, cylindrical microwave resonator; MSC, microwave synthesizer chain; MOT, magneto-optical trap; FT, feed-through. Individual parts are distinguished by different shading. Not shown are the screws for fastening one part to the others and details of the vacuum seals

The inner diameter of the tube is 2×24.2 mm, the height of the CMR is 34.01 mm, and the diameter of each C-hole is 4 mm. Both the lengths of the OFC-based UEC and BEC extending into the cylindrical tube is 20.4 mm. Both the cut-off waveguides with a length of 78 mm and a radius of 5.5 mm can not only be arranged for the atoms passing through, but also eliminate the microwave leakage from the CMR.

Due to the bulk conductivity of the Ti is 31 times smaller than that of the copper, the *Q*-factor of the Ramsey cavity with pure Ti tube is quite low and resulting in a higher distributed cavity phase induced frequency shift. As the bulk conductivity of gold is much larger than Ti, and its antioxidant property is much better than copper. A scheme that the surface of the Ti cylindrical wall coating with thin copper and gold films is proposed. The calculated skin depth of copper and gold under 9.19263 GHz is 0.68 mm and 0.79 μm, respectively. Considering the coating operation and the uniformity of layers, a scheme that the surface of the Ti cylindrical wall is coated by a copper layer with a thickness of 3 μm first and then a gold layer with a thickness of 0.2 μm on the top, is adopted eventually. Using a high vacuum ion beam sputtering technique, the Ti tube coating with films is obtained and its physical map is shown in Fig. 2(a). Sealing with a ceramic window on each C-hole, the cavity itself can be as a part of the vacuum chamber. As it belongs to a metal-non-metal seal, a twice-soldering way is used in order to diminish the thermal deformation of the tube wall. The metallization of the ceramic window is performed on the edge of its surface firstly. Then, the window is soldered on the pedestal in vacuum welding furnace. After that, this pedestal is soldered on the outer tube wall by laser welding. Eventually, the cylindrical tube coating with films and sealing by ceramic windows is performed and its photo is shown in Fig. 2(b).

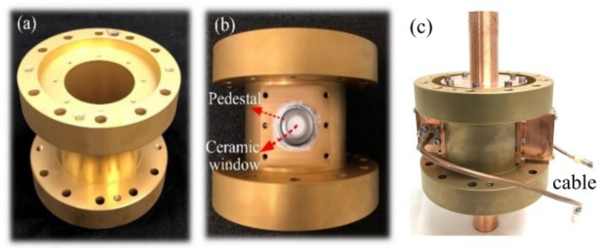

Fig. 2. Photos of Ti tube after (a) the coating and (b) sealing processes, and (c) prepared MVIC body

Before assembling the cavity, a high vacuum bake-out process is done for the cylindrical tube and the UEC (BEC) firstly. This process can not only facilitate the clock physical package with a high vacuum degree, but also enable the stress release, thereby the cavity RF will be stable and controllable. Next, the cavity RF is tuned closely to f_0=9.19263 GHz. The tuning method and processes are widely used and not given here. Then the two rectangular waveguides, UEC and BEC are tightly fixed on the cylindrical tube with titanium screws to form the assembled piece, before that with indium wires mounted among them as microwave seals, which are important measure to prevent microwave leakage. The photo of the assembled MVIC body is shown in Fig. 2(c). Following this piece will be mounted on the clock physical package. This piece is directly connected into the Ramsey interaction region as a part of the vacuum chamber, tightly fixed with titanium screws, and before that with indium wires mounted between them as vacuum seals. In order to lower the background pressure in vacuum chamber, the further bake-out of the fully assembled physical package is done for a few hours.

However, both the vacuum seals and the further bake-out processes shift the cavity RF slightly, so it has to be performed the final frequency tuning. The frequency mistuning amount between the RFs of the rectangular waveguide cavity and the CMR will affect the Ramsey cavity RF. Thus, the RF is tuned closely to Cs clock transition frequency by changing the RF of rectangular waveguide cavity. Note that, the influence coefficient of the RF of rectangular waveguide cavity on that of CMR is extracted with a value only about 0.005 in experiment, then the influence of the temperature-induced RF change of rectangular waveguide cavity on that of CMR is small. Eventually, the RF and Q-factor of this Ramsey cavity are measured by the Vector Network Analyzer (N5247A, Agilent Technologies Inc., USA), and the results are shown in Fig. 3. It shows the Q-factor is 10027 and the RF matches the Cs transition frequency within 31 kHz.

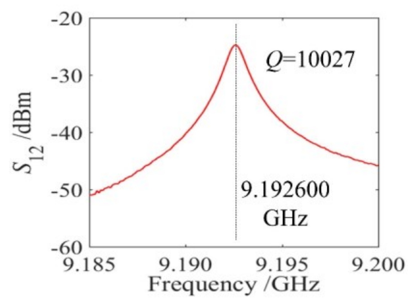

Fig. 3. Tested RF curve for the prepared MVIC

Notably, comparing to the traditional OFC-based Ramsey cavities, we found that the resonance frequency (RF) of this temperature-immune Ramsey cavity shifts slightly and stably during the vacuum-baking, vacuum seals and vacuumizing processes owing to the high-strength of Ti-based cylindrical tube. Additionally, the cavity RF can be final tuning after performed a further bake-out for the fully assembled physical package.

III. TEMPERATURE-SENSITIVITY MEASUREMENT AND DISCUSSION

In order to compare the RF temperature-sensitivities between this prepared MVIC (Ti&OFC-based cavity) and the traditional Ramsey cavity, an OFC-based Cs cavity is also prepared. Note that these two cavities are with the approximately same main dimensions, and the major difference between them is that the cylindrical tube of the OFC-based cavity is made of OFC.

Both these two cavities are put into the temperature-controlled copper boxes with a precision of 0.001 °C. The temperature is calibrated and set from the lab temperature T_0=22.27 °C to 34.27 °C with the temperature step of 3 °C, and the heat preservation times after each step is 72 hours to make the cavities sufficiently stable. After each heat preservation process, the RFs (f_T) of these two cavities are measured by the Vector Network Analyzer. And the measured curves (dotted lines) of the relative change of RF (f_T -f_{T0}) versus temperature T are shown in Fig. 4. f_{T0} is the measured RF at the lab temperature. The results show that, both the measured relative changes of RF are approximately linear to T for these two cavities. Extracted from their fitted curves, the RF thermal-coefficient is -48.1 kHz/°C and -154.4 kHz/°C for the Ti&OFC-based cavity and OFC-based cavity, respectively. And it shows the sensitivity of the RF to temperature for the Ti&OFC-based cavity is about 3.2 times lower than that for the OFC-based cavity.

To verify the effectiveness of this self-compensating theoretical model, the relative changes of RF (f_T-f_{T0}) versus temperature T for the Ti&OFC-based, and OFC-based Ramsey cavities are simulated with the referenced TEC values (α_{Ti}=8.5×10^{-6}/K, α_{OFC}=16.8×10^{-6}/K) [19, 20], and the simulated curves (solid lines) are also shown in Fig. 4. The f_{T0} is the RF of the cavities when T_0=22.27 °C. Note that the main dimensions of the OFC-based Ramsey cavity are approximately same as those of the Ti&OFC-based cavity. Form these two simulated curves, each the relative change of RF is linearly related to temperature. And the extracted thermal-coefficient is -44.1 kHz/°C and -154.4 kHz/°C for the Ti&OFC-based and OFC-based cavities, respectively. The experimental and simulated results show that the prepared MVIC has an obvious self-compensating effect on the temperature-induced RF change.

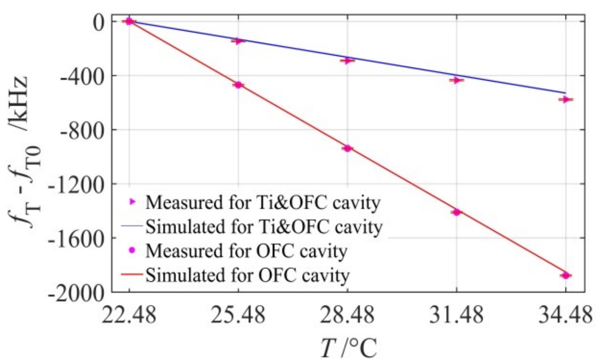

Fig. 4. Relative changes of RF versus T for two cavities with same sizes. Ti&OFC cavity represents the prepared MVIC

Though the prepared MVIC shows an obvious self-compensating effect, there is a deviation of RF thermal-coefficient about 4 kHz/°C between the simulated and measured results shown in Fig. 4. The main reasons inducing this may include that, the actual TEC values of the materials (Ti and OFC) using in our system deviate from the referenced ones. And the influence of the mutual coupling interaction among CMR, rectangular waveguides, cut-off waveguides and C-holes on the RF thermal-coefficient is not considered when the temperature increases.

IV. CONCLUSIONS

A low temperature-sensitive microwave-vacuum integrated cavity (MVIC) using for Cs atomic fountain clocks is proposed and experimentally demonstrated. Utilizing the cylindrical tube material Ti has a thermal expansion coefficient (TEC) lower than the end caps material OFC, a total self-compensating effect can be achieved to yield a zero thermal-coefficient of the RF value of Ramsey cavity. Thus, the Ramsey cavity can be immune to temperature fluctuations. The Q-factor of the cavity can be improved by using thin copper and gold films coating on the surface of the Ti cylindrical wall. Owing to the high-strength of the tube, the RF of the cavity will be shifted slightly and stably during the vacuum-baking and vacuumizing processes compared to the traditional OFC-based Ramsey cavity.

For the constructed Cs MVIC with a Q-factor of ~10000, the measured RF thermal-coefficient is -48.1 kHz/°C, 3.2 times superior to a traditional OFC cavity with the same sizes. This temperature-immune microwave cavity can strongly promote the development of transportable atomic fountain clocks commercially available, and significantly improve their tolerance of ambient temperature range. For the next work, the temperature-immune Ramsey cavity with a near zero thermal-coefficient will be prepared, and its performance improvements on fountain clocks will be also evaluated and analyzed.

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REFERENCES

[1] V. Gerginov, N. Nemitz, S. Weyers, R. Schröder, D. Griebsch and R. Wynands, "Uncertainty evaluation of the caesium fountain clock PTB-CSF2," *Metrologia*, vol. 47, no. 1, pp. 65-79, 2010.

[2] S. Beattie, B. Jian, J. Alcock, M. Gertsvolf, R. Hendricks, K. Szymaniec and K. Gibble, "First accuracy evaluation of the NRC-FCs2 primary frequency standard," *Metrologia,* vol. 57, no. 3, p. 035010, 2020.

[3] J. Guéna, M. Abgrall, D. Rovera, P. Laurent, B. Chupin, M. Lours, G. Santarelli, P. Rosenbusch, M. E. Tobar, R. Li, K. Gibble, A. Clairon and S. Bize, "Progress in atomic fountains at LNE-SYRTE," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 3, pp. 391-409, 2012.

[4] T. P. Heavner, E. A. Donley, F. Levi, G. Costanzo, T. E. Parker, J. H. Shirley, N. Ashby, S. Barlow and S. R. Jefferts, "First accuracy evaluation of NIST-F2," *Metrologia,,* vol. 51, no. 3, pp. 174-182, 2014.

[5] A. Bauch A, S. Weyers, D. Piester, E. Staliuniene, W. Yang W, "Generation of UTC(PTB) as a fountain-clock based time scale," *Metrologia,,* vol. 49, no. 3, pp. 180-188, 2012.

[6] W. F. McGrew, X. Zhang, H. Leopardi, R. J. Fasano, D. Nicolodi, K. Beloy, J. Yao, J. A. Sherman, S. A. Schäffer, J. Savory, R. C. Brown, S. Römisch, C. W. Oates, T. E. Parker, T. M. Fortier and A. D. Ludlow, "Towards the optical second: Verifying optical clocks at the SI limit," *Optica,* vol. 6, no. 4, p. 448, 2019.

[7] P. Wolf, F. Chapelet, S. Bize and A. Clairon, "Cold Atom Clock Test of Lorentz Invariance in the Matter Sector," *Phys. Rev. Lett.,* vol. 96, no. 6, p. 060801, 2006.

[8] R. Schröder, U. Hubner and D. Griebsch, "Design and realization of the microwave cavity in the PTB caesium atomic fountain clock CSF1," *Ultrasonics Ferroelectrics & Frequency Control IEEE Transactions on*, vol. 49, no. 3, pp. 383-392, 2002.

[9] S. R. Jefferts, R. E. Drullinger and A. Demarchi, "NIST cesium fountain microwave cavities," in *Frequency Control Symposium, 1998. Proceedings of the 1998 IEEE International. IEEE*, 1998.

[10] N. Ashby, S. Romisch and S. R. Jefferts, "Endcaps for TE01 cavities in fountain frequency standards" in *Proc. IEEE Intl. Freq. Cont. Symp* (Tampa), pp. 1076-1083, 2003.

[11] F. Fang, M. S. Li, P. W. Lin, et al., "NIM5 Cs fountain clock and its evaluation," *Metrologia,* vol. 52, no. 4, pp. 454-468, 2015.

[12] S. Weyers, V. Gerginov, M. Kazda, et al., "Advances in the accuracy, stability, and reliability of the PTB primary fountain clocks," *Metrologia*, vol. 55, no. 6, pp. 789-805, 2018.

[13] S. R. Jefferts, R. E. Drullinger and A. DeMarchi, "NIST cesium fountain microwave cavities," in *Proc. IEEE Freq. Control Symp.* (Pasadena) pp. 6–8, 1998.

[14] A. D. Marchi and G. A. Costanzo, "Accuracy Evaluation of NIST F-1," *Metrologia,* vol. 53, no. 1, p. 174, 2002.

[15] A. Takamizawa, S. Yanagimachi, T. Tanabe, K. Hagimoto and I. Hirano, "Preliminary Evaluation of the Cesium Fountain Primary Frequency Standard NMIJ-F2," *IEEE T. Instrum. Meas.,* vol. 64, no. 9, p. 2504, 2015.

[16] M. Kumagai, H. Ito, M. Kajita and M. Hosokawa, "Evaluation of caesium atomic fountain NICT-CsF1," *Metrologia,* vol. 45, no. 2, pp. 139-148, 2008.

[17] F. Fang, K. Liu, X. K. Yan, R. Suo, W. L. Chen, N. F. Liu, Y. Zhang and T. C. Li, "Reducing the blackbody radiation shift in the NIM new fountain design," in *Proc. EFTF-IFC* (Prague), pp. 232-234, 2014.

[18] R. X. Li and K. Gibble, "Evaluating and Minimizing Distributed Cavity Phase Errors in Atomic Clocks," *Metrologia,* vol. 47, no. 5, pp. 534-551, 2010.

[19] N. J. Simon, E. S. Drexler and R. P. Reed, "Properties of copper and copper alloys at cryogenic temperatures. Final report," NIST Monograph Report No. 177, Government Printing Office, p 257, 1992.

[20] P. Hidnert, "Thermal expansion of titanium,", *Journal of the Franklin Institute*, vol. 235, no. 3, p. 288, 1943.

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