Micro-Loop-Gap Microwave Resonator Development for the LEMAC LTF-EPFL Miniature Atomic Clock

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***Abstract*—This paper discusses several evolved micro-loop-gap microwave resonator designs for chip-scale atomic clock applications. Two different schemes have been investigated to develop the LEMAC (LTF-EPFL Miniature Atomic Clock) based on the optical-microwave double resonance, aiming for improving the short-term and long-term stabilities of the counterpart. They show superior performance in terms of size reduction and magnetic field homogeneity for atom transition.**

Keywords—Atomic clock, magnetic field homogeneity, tunable microwave resonator, loop-gap resonator, loaded cavity, satellite navigation.

I. Introduction

Chip-scale atomic clock (CSAC) has been investigated as it has high potential in telecommunications, satellite navigation, remote sensing, underwater prospection, etc., as a replacement for GPS signals for synchronization. With a high frequency stability in the order of $\sigma(\tau) > 1\cdot10^{-11}\ \tau^{-1/2}$, miniature optical-microwave double-resonance atomic clocks have attracted more attention in the past decades. The double-resonance (DR) operation scheme that comprises a microwave frequency (e.g., at 6.835 GHz for rubidium atoms) and an optical frequency simultaneously is competitive because of its simple system architecture, high frequency stability, low fabrication cost, and compact size. Besides the specified peak resonance, such clocks require a homogenous magnetic field in parallel to the direction of the pumping light inside the microwave resonator in which a vapor cell is incorporated. The atoms are excited by the EM field in microwave band, leading to the transition between the ground-state hyperfine levels. To quantify this magnetic field purity, the field orientation factor (FOF) is identified as an essential metric of a microwave cavity for both theoretical and experimental uses [1] [2].

Loop-gap resonators, also named magnetron-type or slotted tube resonators, have been widely developed for the miniaturization purpose of DR atomic clock, since they feature compact sizes much small than the conventional waveguide-based cavities. The classical DR rubidium clock relies on glass-blown cell and metallic loop-gap microwave resonator. Recently, driven by the availability of micro-fabricated vapor cell, the microwave cavity creates new niche for the CSAC. In this frame, the size limitation, fabrication tolerance, manufacture cost, tuning capability, and magnetic field quality are the main challenges in the miniature microwave cavity design. This paper reports two different microwave resonator schemes to develop the LTF-EFPL miniature atomic clock (LEMAC) based on the optical-microwave DR, aiming for short-term and long-term stabilities in the order of $1\cdot10^{-11}\ \tau^{-1/2}$ and $1\cdot10^{-12}$ /day, respectively. Both microwave resonators derive from the basic micro-loop-gap resonator (µLGR) in [1]. Their performance is evidenced superior in terms of size reduction and magnetic field homogeneity for the miniature atomic clock.

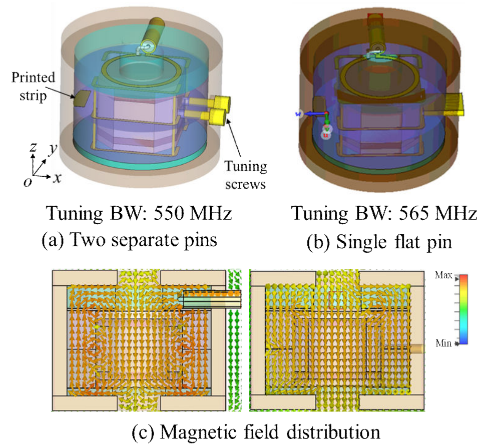


Fig. 1. Configuration and magnetic field distribution of the proposed wide-tuning µLGRs. Total volume is ~570 mm^3.

II. Wide-Tuning Scheme

Tunability is one of the useful methods to adjust the offset frequency, for example, adding variable capacitors, tuning screws, and perturbation pins. The configuration of the proposed wide-tuning µLGRs is demonstrated in Fig. 1, where a significant size reduction by a factor of ~2 is revealed, compared to the first µLGR that was presented in [1]. The overall volume of these two designs is merely 570 mm^3. Three main modifications are implemented in the new designs, as compared with the reference [1]. First, the number of stacked dielectric layers is reduced to two, associated with three printed conductive layers. Therefore, the improved µLGR symmetry along the longitudinal direction improves the magnetic field homogeneity inside the vapor cell, resulting in a larger FOF. The second is to position the tuning components in the middle electrode layer. This design will also improve the FOF in the longitudinal direction. The last and the most important one is to elaborate a printed strip on the left-hand side of the middle electrodes. Meanwhile, two lateral tuning screws or a single flat pin are inserting the µLGR from the right-hand side of the middle electrodes, constituting the entire tuning components for the improved µLGR structure. The mechanism using these tuning components to broaden the frequency tuning range has been comprehensively discussed in [2] using an

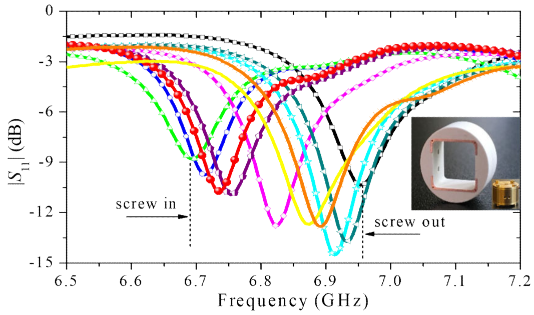


Fig. 2. Prototypes and measured frequency tuning range of the proposed wide-tuning μLGR with two separate screws.

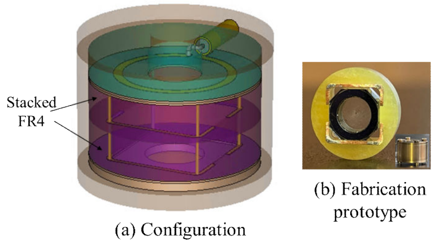
equivalent circuit model. Basically, they can increase the equivalent capacitor of the resonant frequency, hence reducing the lower end of the frequency tuning range. In addition, they help increase the electrical coupling to the upper excitation loop.

The magnetic field distribution of the proposed wide-tuning μLGR operating in TE_{011}-like mode is illustrated in Fig. 1(c). As can be seen, the magnetic field vectors inside the vapor cell are almost parallel to the vertical axis of the μLGR structure as well as the quantization axis of the clock. According to the FOF definition in [2], the theoretical FOF is derived as high as 0.906.

The measured resonance and tuning performance of the improved μLGR is depicted in Fig. 2, it shows that the exact rubidium resonance is obtained after the two lateral tuning screws are properly adjusted in the μLGR. The achieved loaded quality factor of ~40 can help suppress the cavity pulling effect. By totally tuning the screws in and out, the resonant frequency of the fabricated μLGR for the TE_{011}-like mode shifts from 6.694 GHz to 6.954 GHz, yielding a tuning range as wide as 260 MHz in the measurement, which is two times larger than the one in [1]. In summary, with high-thermal stability materials and the moderate loaded quality factor, the wide-tuning μLGRs are suitable to work in the customized high-performance scenarios with low power and good temperature stability for the long-term clock stability.

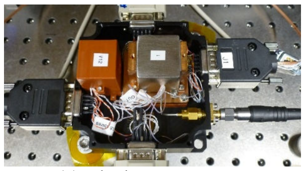
III. Tuning-Free Scheme

Another way to overcome the frequency shift is to broaden the operating bandwidth of the microwave resonator. This imposes the enhancement of two important bandwidths. One is the input impedance bandwidth and the other is the FOF bandwidth. The former ensures the impedance matching between different devices and the power transition; the latter guarantees the mode purity over frequency. In this section, we will show that the proposed tuning-free scheme can fulfill this requirement, thanks to the use of the FR4 substrate and a highly symmetric geometry [3]. Meanwhile, this alternate low-cost loading material can further reduce the fabrication cost of the entire clock, thus making the tuning-free scheme appropriate to the low-cost mass fabrication scenarios with excellent fabrication error tolerance.

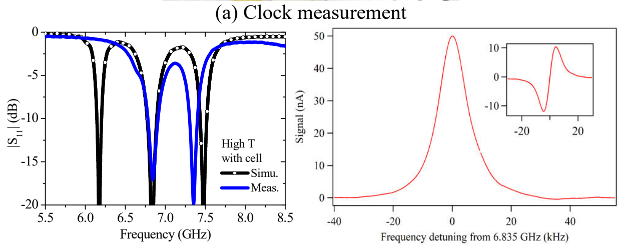


(a) Configuration (b) Fabrication prototype

Fig. 3. Configuration and fabrication prototype of the proposed tuning-free μ-LGR. Total volume is 648 mm^3.



(a) Clock measurement



(b) Measured results

Fig. 4. Measured results of the proposed tuning-free μLGR and the clock.

As depicted in Fig. 3, the tuning-free design removes all components in the middle layer for tuning purposes and replaces the Rogers TMM4 substrate with an FR4 substrate. According to our study on the accurate characterization of the FR4 substrate [4], the gradient slope of the permittivity variation over frequency in high working temperature is opposite to its gradient slope in room temperature, thus leading to the decrease of the side-mode frequency and a longer distance between the unwanted side mode and TE_{011}-like mode. In addition, based on the perturbation theory, we found that when removing the perturbation at the place of large magnetic field (i.e., removing the tuning components), the lower side-mode frequency can further shift down, while keeping TE_{011}-like mode at its high frequency position. Therefore, this side-mode suppression mechanism allows the desired TE_{011}-like mode to operate over an enhanced homogeneous field bandwidth. In conclusion, in addition to the appropriate FR4 loading, the higher symmetry enables the μLGR operating over a broad bandwidth with sufficient magnetic field strength. The slight frequency shift due to the fabrication errors and assembling errors is thus compensated.

The experimental results of the fabricated tuning-free μLGR and the entire clock are shown in Fig. 4. The resonance performance of the measured μLGR shows very good agreement with its simulated counterpart at the high temperature of 109°C, associating with an impedance bandwidth of 128 MHz. The preliminary measured short-term frequency stability of the subsequent designed double-resonance clock reaches $\sigma(\tau) \approx 2\times10^{-11}\ \tau^{-1/2}$, which is similar to the theoretical value of $1.5\times10^{-11}\ \tau^{-1/2}$ and close to the benchmark design using the first μLGR in [1], while a smaller volume retains.

Conclusion

We have proposed two different schemes to improve the SWaP and FOF performance of the micro-loop-gap resonator for double-resonance CSAC. These microwave resonators are particularly suitable to integrate micro-fabricated vapor cells. More µLGR evolutions are possible and could be our future work.

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References

[1] M. Violetti et al., "The micro-loop-gap resonator: A novel miniaturized microwave cavity for double-resonance Rubidium atomic clocks," *IEEE Sensors J.*, vol. 14, no. 9, pp. 3193–3200, Sep. 2014.

[2] Y. Su et al., "A wide-frequency-tuning micro-loop-gap resonator for miniature rubidium vapor-cell atomic frequency standards," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 12, pp. 5135–5146, Dec. 2023.

[3] Y. Su et al., "Mode suppression and homogeneous field bandwidth enhancement of a tuning-free micro-loop-gap resonator using FR4 for chip-scale rubidium clock", *IEEE Trans. Microw. Theory Techn.,* 2023, doi :10.1109/TMTT.2023.3326482.

[4] Y. Su, M. Pellaton, C. Affolderbach, G. Mileti, M. Veljovic and A. Skrivervik, "Characterization of microwave substrates for high accuracy and long-term stability using full-wave microstrip ring resonator method," *2021 51st European Microwave Conference (EuMC)*, 2022, pp. 421-424.