Miniaturized Microwave Cavity for Rubidium Atomic Frequency Standards

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***Abstract*—In view of mobile and battery-powered applications, there is an increasing demand for more radically miniaturized and low-power atomic frequency standards.**
For the miniaturization of a double-resonance Rubidium atomic clocks, the size reduction of the microwave cavity or microwave resonator (MWR) to well below the wavelength of the atomic transition (6.835 GHz in the case of ^{87}Rb) has been a long-standing issue.
In this paper we propose a new miniaturized MWR, the μ-LGR, that meets the requirements for the atomic clock application while the structure is very compact, and assembly can be performed using standard and potentially low-cost techniques.
Concept of the proposed device was proven through simulation and prototypes were successfully tested, showing the μ-LGR to be suitable for the integration in a miniaturized atomic clock.

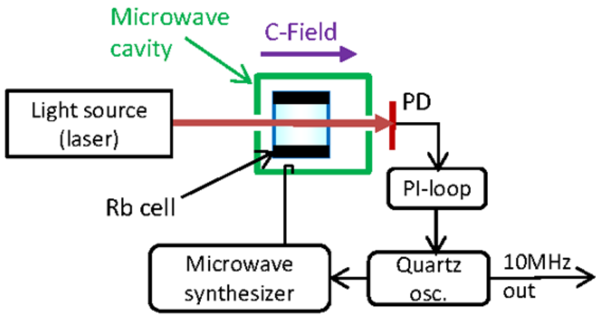

Fig. 1. Block scheme for a DR atomic clock.

I. Introduction

Atomic frequency standards (atomic clocks) achieve unmatched frequency stability over long periods of time by exploiting a well-defined atomic transition for steering the output frequency of a quartz oscillator [1], [2]. Very compact (0.5 to 2 liters volume) Rb-cell atomic clocks are based on atoms confined in small vapor-cells and have found a large number of applications, including digital communication, navigation systems, network synchronization, and others [1].
In view of mobile and battery-powered applications, there is an increasing demand for more radically miniaturized and low-power frequency standards.
The past decade has seen rapid progress in the development of chip-scale atomic clocks (CSAC), achieving clock integration in volumes of a few cm^3, and a total power consumption around 100 mW [2], [3], while showing a fractional frequency instability (Allan deviation) below 10^{-11} at 1 hour, i.e. several orders of magnitude better than a quartz oscillator of comparable size and power consumption.
Most approaches to CSAC were based on the CPT scheme [2], while the classical optical-microwave double-resonance (DR) scheme [1], [4] - although allowing for better clock stability - was only rarely studied [5], [6]. In the DR scheme using a ^{87}Rb cell (see Fig. 1), resonant light from a lamp or laser source optically pumps the atoms, and the $5^2S_{1/2}|F_g = 1, m_F = 0\rangle \rightarrow |F_g = 2, m_F = 0\rangle$ microwave "clock transition" is detected in the transmitted light intensity using a photodiode (PD), by coupling near-resonant microwave radiation to the atoms via a microwave cavity. A static magnetic field (C-field) is used to define a quantization axis and to isolate the clock transition.
For the miniaturization of a DR atomic clock, the size reduction of the microwave cavity or resonator (MWR) to well below the wavelength of the atomic transition (6.835 GHz in the case of ^{87}Rb) has been a long-standing issue. Solutions such as the magnetron-type MWR [7], miniature MWR using lumped LC elements [8], or slotted-tube MWR [9] were developed for Rb cells down to ≈1 cm size, but only few microwave structures for mm-scale cells are reported, based on strip-lines or micro coupling loops [6].
In this paper we present a miniature MWR, for use with 36 mm^3 micro-fabricated Rb cells [10]. The MWR is composed of a multi-layer stack of planar loop-gap resonator structures [11] printed onto substrates, and coupled to a coaxial fed strip-line. It has a total volume < 0.9 cm^3 and it will be referred to as μ-LGR in the following.
The loop-gap approach allows to meet the field requirements for Double Resonance atomic clocks (microwave magnetic field collinear to the laser beam, along the longitudinal direction z) - as explained more in detail in the section III-A - and the use of printed technology keeps the structure compact and suitable for low-cost batch fabrication using established techniques.

II. Requirements

The homogeneity of intensity and orientation of the microwave field inside the MWR are essential to the performance of the atomic standard. The magnetic part of the microwave field should be parallel to the light beam and to the direction of the C-field, with a magnitude $|B| \simeq 10^{-8}$ Tesla.
To characterize the magnetic field distribution, we introduce the Field Orientation Factor (FOF) ξ, which can be used as a figure of merit in order to evaluate the part of the magnetic field energy inside the Rb cell which is useful for the atomic clock signal:

$$\xi = \frac{1}{V_{\text{cell}}} \frac{\left(\int_{V_{\text{cell}}} H_z dV\right)^2}{\int_{V_{\text{cell}}} H^2 dV} \tag{1}$$

where V_{cell} is the volume occupied by Rb atoms, and H_z is the component of the magnetic field along the direction of the C-field, z in our case. H_z should represent at least the 70% of the overall magnetic field energy, thus $\xi \geq 0.7$ is required.
The loaded Quality Factor (Q_L) of the microwave cavity should guarantee both a low power loss and a good coupling to the desired magnetic field mode. Design guideline values for the proposed μ-LGR are $Q_L \simeq 30$, injected power P_{in} on the μW level and power loss $P_{loss} \simeq 50$ nW.

III. Proposed Solution

A. Principle of Operation

The Loop-Gap Resonator (LGR), also referred to as the split ring resonator [12] or slotted tube cavity [13], can be represented, in its simplest model, by an LC circuit where the loop is an inductor and the gap is a capacitor. The electric fields, as shown in Fig. 2, are supported by the gap with the magnetic fields surrounding the loop [14]. When the dimensions of the resonator are sensibly smaller than the half-wavelength of the resonant microwave frequency, the lumped element model can be used and the electric and magnetic fields can be considered separated.
In a first order approximation represented by eq. 2, the resonance frequency of the resonator is defined by the geometry of the electrode structure, including the radius (r_o) and the thickness (W) of the electrodes, the width (t) and number (n) of gaps. Other versions of the formula, taking into account the fringing fields and the effect of the shield can be found in [11], [15].

$$C = \varepsilon \frac{WZ}{nt}, L = \mu \frac{\pi r_o^2}{Z} \rightarrow f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi}\sqrt{\frac{n}{\pi r_o^2 \varepsilon \mu} \frac{t}{W}} \tag{2}$$

A LGR can be coupled to external circuits both by capacitive or inductive means. In the first case a monopole probe is placed in proximity of the gap and it interacts with the gap's fringe electric fields. In the latter case, an inductive loop can be used for coupling to the magnetic fields at either end of the resonator.

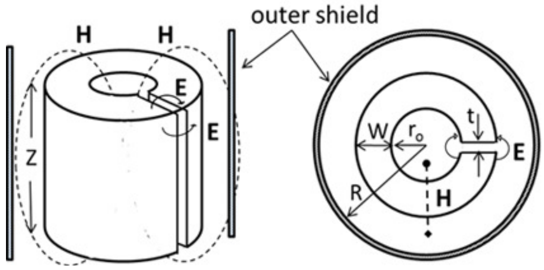

Fig. 2. The loop-gap resonator perspective and cut view, showing the principal components.

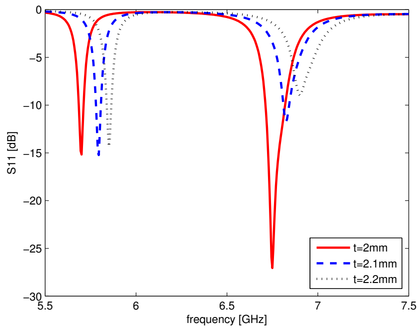

Fig. 3. Influence of gap size t on reflection coefficient. Resonance of interest is at 6.835 GHz (right), while the resonance at ~5.8 GHz (left) is a TM mode due to the cavity size.

In order to correct for inevitable manufacturing tolerances, fine tuning of the resonant frequency can be electronic or mechanical. Various solutions can be found in literature, based on a varactor to control the capacity of the gap [14], a tuning loop, a dielectric slab, a conductive plate [12] or a tuning screw [16].

B. Model Validation

The proposed solution was validated through software simulation. In order to achieve the compact printed μ-LGR from the simpler n=1 LGR, the structure was optimized in several steps taking into account the Rb cell presence.
In particular, the influence of gap size (t) and width of electrodes (W) were investigated in order to get the desired resonance frequency.
As an example, Fig. 3 shows the simulated reflection coefficient for three different values of the gap size. The resonance shifts to higher frequencies as both L and C decrease, while the matching is also affected when t becomes too large.
Also, influence of cavity apertures and dielectric properties of different materials were studied in order to determine a package suitable for manufacturing.
Finally the influence of tuning screws was considered during the optimization of the electrodes structure, given their strong impact on both magnetic and electric fields.
For t = 2.0 mm, the magnetic field at resonance has the

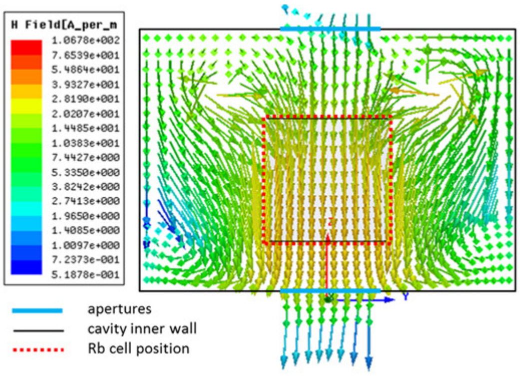

Fig. 4. Simulated magnetic field of the TE mode at 6.835GHz (t=2.0mm). The dotted red square indicates the position of the micro-fabricated Rb vapor cell.

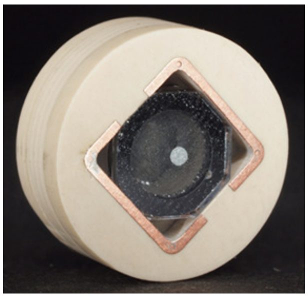

Fig. 5. The assembled μ-LGR (the outer diameter is 12 mm) containing the miniature Rb cell.

desired TE mode distribution shown in Fig.4, with $\xi = 0.9$.

C. Main Characteristics

A sealed miniature cell of the type described in [10], containing Rb atomic vapor, is positioned inside the resonator, as shown in Fig. 5. The resonator comprises a multi-layered structure of conductive electrodes separated by cylindrical dielectric layers, stacked along axial direction (z). The conductive electrodes are two-dimensional structures, formed by patterns of metal film printed onto the dielectric layers. The dielectric material composing the resonator layers has a temperature-compensated dielectric constant in the microwave region.

The electrodes are planar realizations of loop gap resonators, juxtaposed in pairs in order to obtain a series of stacked loops with 2 gaps (n=2) on each layer. The different layers of the electrode structure are electrically connected by means of metalized vias, but not in electrical contact with the outer metal enclosure.

Coupling to the microwave excitation is achieved by a loop-shaped strip-line fed by a coaxial line. The excitation loop is printed onto an additional thin dielectric layer, placed above the loop-gap multi-layered structure.

A metal outer shield consisting of a cylindrical brass box is placed around the multi-layer resonator structure, the

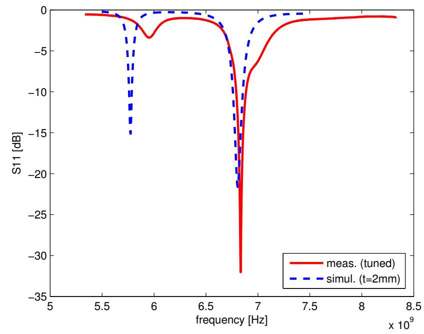

Fig. 6. Comparison between the reflection coefficient of one measured prototype (t=2.0 mm, tuned) and simulation of model t=2.0 mm with maximum insertion of the two screws. Frequency is higher in the measured prototype due to the presence of air inside the cavity.

coupling device and the Rb cell. The metal box is in contact with the outer jacket of the coaxial line and detached from the other parts of the cavity by means of dielectric spacing washer of appropriate size. The metal enclosure has apertures at its ends to allow for the laser beam to interact with the Rubidium atoms vapor.

The fine tuning of the resonance frequency is obtained by two tuning screws inserted into the cavity and manually controllable from the outside of the metal shield. The tips of the metal screws are able to perturb the electric field concentrated in the gap.

The structure is fully demountable in case the vapor cell or other parts of the cavity need to be removed or changed.

IV. Tests on Prototype

Several prototypes were built and successfully tested. Considering the influence of the gap width on resonance frequency, the prototypes present different values of t (from 1.9 to 2.3 mm, with a step of 0.1 mm). The built resonators were measured and tuned, giving promising results. In Fig. 6 the simulated model of one of the prototypes (t=2.0 mm) is compared to the equivalent measured resonator. Results show good agreement and the small frequency shift is due to the presence of air inside the real assembled device. Loaded quality factor Q_L is $\simeq$26.

The two tuning screws were proven to be an efficient means to achieve the desired Rb resonance frequency at 6.835 GHz. The average tuning capability is 140 MHz for the built prototypes. The tuning of one prototype (t=2.0 mm) is shown in Fig. 7.

The μ-LGR was used for observing the DR signal of the ^{87}Rb clock transition. Laser light resonant with the Rb D2-line (780 nm) is sent through the μ-LGR containing a 4 mm-thick micro-fabricated Rb vapor cell [4], [10] (both held at 82°C). The light intensity transmitted through the cell is detected on the photodiode as a function of the microwave frequency injected into the μ-LGR, see Fig. 8 (injected microwave power is -20 dBm). The observed signal has the typical signature of a DR signal and proves the suitability of the μ-LGR for operation of

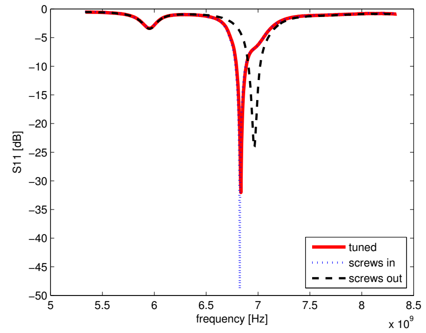

Fig. 7. Tuning of the μ-LGR prototype (t=2.0 mm) at 6.835 GHz.

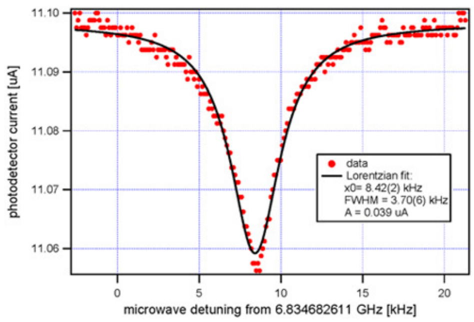

Fig. 8. DR signal with the μ-LGR.

a miniature atomic clock. In particular the signal line-width of 3.7 kHz is only 2 times larger than the limit calculated from the cell properties, due to line broadening from the optical and microwave radiation, and can still be optimized.

The resonance frequency of the μ-LGR was measured as a function of temperature from 20°C (room temperature) to 100°C, in order to evaluate its impact on the performance of the atomic clock at its temperature of operation of 80°C. Results show an overall frequency shift of $\sim$ 30 MHz which can be corrected for by means of the fine tuning screws. The reflection coefficient remains $\leq$-30 dB. Fig. 9 shows the measured prototype inside the thermally regulated enclosure.

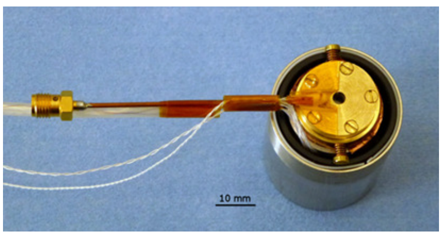

Fig. 9. μ-LGR inside the thermally regulated enclosure used for measurements. The outer metal shield of the cavity with the inserted tuning screws is visible.

V. Conclusion

The μ-LGR was proven to be suitable for atomic clock applications. The principle of operation was proven and optimized through software simulations. In particular, the influence of relevant geometrical features, the presence of the Rb cell and the influence of the cavity apertures were investigated. Measurements were in agreement with simulated results, showing that the prototypes could be easily tuned at the desired Rb resonance frequency of 6.835 GHz.

The μ-LGR was successfully used for observing the DR signal of the ^{87}Rb clock transition. Also measurements towards a large temperature variation were carried out, yielding an expected frequency shift which is largely acceptable for the application.

Acknowledgment

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