PARASITIC-IMMUNE REAL-TIME TRACKING OF A MEMS FREQUENCY REFERENCE

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ABSTRACT

In this paper, we introduce a new dual-tone frequency tracking scheme for electrostatic MEMS resonators that eliminates sensitivity to parasitic feedthrough and to drifts present within the supporting electronics. The approach is inspired by Pound-Drever-Hall (PDH) locking [1] that is used in photonics. We apply this scheme to a ~1 MHz double-ended tuning fork resonator, demonstrating real-time resonant frequency tracking in the presence of ambient temperature variations. Our approach is especially useful for electrostatic devices since it supports low input drive levels to help avoid amplitude-frequency (A-f) nonlinearity, enables very low bias voltages to reduce frequency sensitivity to bias voltages, and additionally eliminates parasitic feedthrough.

KEYWORDS

Real-Time frequency tracking, MEMS resonators, Parasitic cancellation.

INTRODUCTION

Micromechanical resonators have reached a level of stability that enables their wider use in frequency control and timing applications [2-4]. For such references, the real-time tracking of one or multiple mechanical modes [5-6] is of key importance. The dominant approaches for tracking frequency are to either produce a self-sustaining oscillator loop [5-6] or to lock an auxiliary oscillator (such as a voltage-controlled oscillator, or VCO) to the MEMS reference [3]. However, feedthrough mechanisms, such as the capacitance between the drive and sense electrodes in the MEMS resonator, can be inconvenient for implementing precise tracking. The additional phase shift induced by feedthrough also complicates the design of self-sustaining oscillator loop by making it difficult to meet Barkhausen's criteria. Self-sustaining oscillator loops also require large drive signals, which can induce frequency shifts within the MEMS due to amplitude-frequency (A-f) nonlinearity [7]. For electrostatic resonators, there is an additional concern with the well-known quadratic sensitivity of frequency to the dc bias voltages that are needed to obtain low motional impedance.

VCO-based tracking can be potentially superior since it allows the application of only small signals on the resonator and can work with only small bias applied to the resonator. Even so, VCO-based tracking is sensitive to drifts in the feedthrough [3], which can change the lock point and shift the output frequency. Even advanced measurement instruments such as digital lock-in amplifiers that are used for VCO-based tracking are particularly susceptible to the temperature-induced variations of analog front-ends and internal reference voltages. A more effective solution would be to bypass the need for any reference values or voltages altogether and simply lock at a "zero point" so that these issues can be circumvented.

The Pound-Drever-Hall (PDH) technique was originally introduced in 1983 as a tracking method for optical devices. This method, which is used very widely, tracks the frequency of a cavity resonator by generating a zero-value locking reference point for a laser while canceling out any feedthrough [1]. Our approach in this work is inspired by the original mathematics of the PDH scheme, but has been adapted for the unique electromechanics of electrostatic MEMS resonators.

METHODS

Our PDH-inspired system and its principle are described in Fig. 1, where the goal is to lock the VCO frequency to the resonance. First, two small-signal tones are derived symmetrically from the VCO by means of mixing with a local oscillator (LO) and are used for probing the MEMS resonator. A tone subtraction is performed after the resonator to eliminate the common mode parasitics through a second mixing step. Finally, the quadrature result is demodulated (by selecting a suitable VCO phase shift) to produce a baseband error signal. If demodulated correctly, this error signal is odd symmetric around the resonance and should be exactly zero only when the VCO is perfectly aligned to the MEMS resonance. Moreover, its monotonic slope can be used to lock the VCO via feedback without requiring any additional reference voltages. While the scale factor of the error signal is indeed dependent on the drive levels, the zero-error point always indicates the resonance position, and the slope is always monotonic, independent of the drive level or LO frequency.

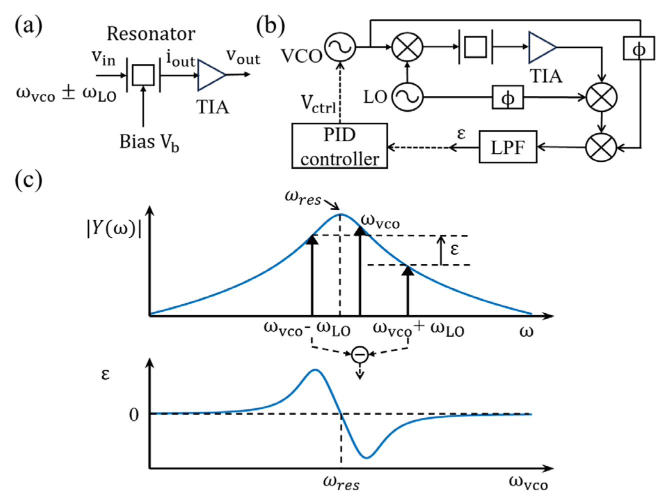

Figure 1: (a) Signal definitions around the resonator. (b) Schematic of the implementation of the frequency locking technique, with the final error signal ε. (c) General principle of operations relying on the sideband subtraction. $Y(\omega)$ is the electrical admittance of the resonator.

We now describe the principles of this approach through a basic mathematical derivation (scale factors are eliminated for simplicity). The first mixer (Fig. 1b) generates dual tones at $\omega_{vco} \pm \omega_{LO}$ by multiplying the VCO and LO. After passing through the resonator, the output current is shaped by the resonator transfer function as follows:

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$$Y(\omega_+)e^{j\omega_+ t} + Y(\omega_-)e^{j\omega_- t} + c.c. \quad (1)$$

where $Y(\omega)$ is the net admittance function including parasitics, and $\omega_\pm = \omega_{vco} \pm \omega_{LO}$. We now subtract these tones to reconstruct a signal at ω_{VCO} by mixing the output signal (second mixer) with a phase shifted version of the LO:

$$\left(Y(\omega_+)e^{j\omega_+ t} + Y(\omega_-)e^{j\omega_- t} + c.c.\right)\left(e^{j(\omega_{LO}t+\phi)} + c.c.\right) \quad (2)$$

which can be rewritten in the form:

$$Y(\omega_+)e^{j(\omega_{vco}t-\phi)} + Y(\omega_-)e^{j(\omega_{vco}t+\phi)} + c.c. \quad (3)$$

For $\phi = \frac{\pi}{2}$ we obtain a subtraction of the tones into a new term at frequency ω_{vco}:

$$j\left(Y(\omega_+) - Y(\omega_-)\right)e^{j\omega_{vco}t} + c.c. \quad (4)$$

which already carries all the information that we need to implement the proposed locking method. Based on symmetry arguments, this subtraction also eliminates any common-mode feedthrough contribution and is a function of only the resonator's admittance. Expanding into trigonometric form we can write this tone at ω_{vco} in terms of its quadrature:

$$\begin{aligned} &Real\{Y_{res}(\omega_-) - Y_{res}(\omega_+)\}\sin\omega_{vco}t \\ &+ Imag\{Y_{res}(\omega_-) - Y_{res}(\omega_+)\}\cos\omega_{vco}t \end{aligned} \quad (5)$$

where $Y_{res}(\omega)$ is now the true admittance of the resonator without the parasitics. Finally, we can obtain the baseband error signal

$$\varepsilon = Real\{Y_{res}(\omega_-) - Y_{res}(\omega_+)\} \quad (6)$$

by demodulating the suitable quadrature to a dc term. This is readily achieved by mixing the output after the second mixer with a phase-shifted version of the VCO and performing low-pass filtering. In our experiments we used a lock-in amplifier to perform this final demodulation and filtering operation.

RESULTS

For experimental validation of the proposed locking method, we used a 1.075 MHz wafer-level (Epi-Seal) encapsulated double-ended tuning fork (DETF) resonator [8] as shown in Fig 2. A traditional transfer function measurement of the resonator, performed via network analyzer (Fig. 3a), confirms that the phase response does not have the expected value of π on resonance. This occurs due to parasitics and indicates that the amplitude response will also be slightly shifted from the true resonance.

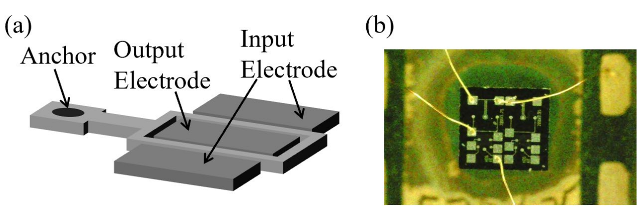

Figure 2: (a) Schematic of the encapsulated double-ended tuning fork (DETF) used in this work. (b) Photo of the wirebonded DETF.

For the locking method the LO frequency is a somewhat arbitrary choice, though it should be chosen within the resonator's half bandwidth to make sure that the sidebands fall within the response function for the resonator. For our experiments the resonator had Q factor around 10^4 implying bandwidth of ~100 Hz, leading to our choice of we set $\omega_{LO} = 50$ Hz. We used an HP 8648B signal generator as the VCO which has FM capability in response to dc input voltage. The first and second mixing operations were implemented using AD734 multipliers. The final quadrature demodulation and low-pass filtering were performed using a Zurich Instruments HF2LI lock-in amplifier, to produce a voltage corresponding to the baseband error signal ε (Fig. 3b). A custom op-amp based PID circuit was then used to act on the error signal and perform feedback locking to maintain the VCO at the zero-error point.

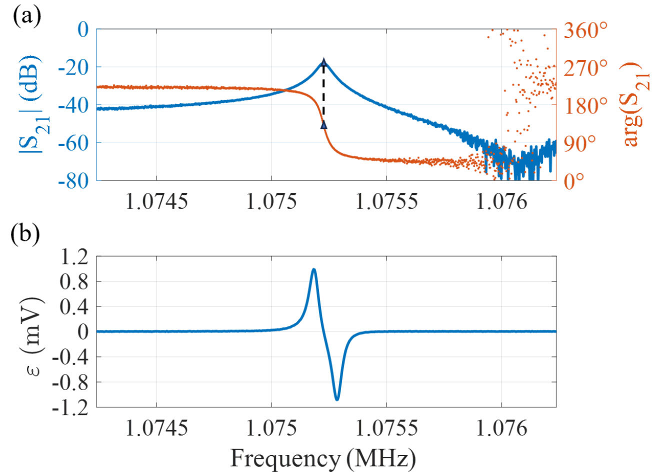

Figure 3: (a) Example S_{21} measurement of the resonator showing that the phase response is not the expected value due to feedthrough. (b) The error signal, ε generated through the approach in Fig. 1, provides a parasitic-immune zero crossing on resonance.

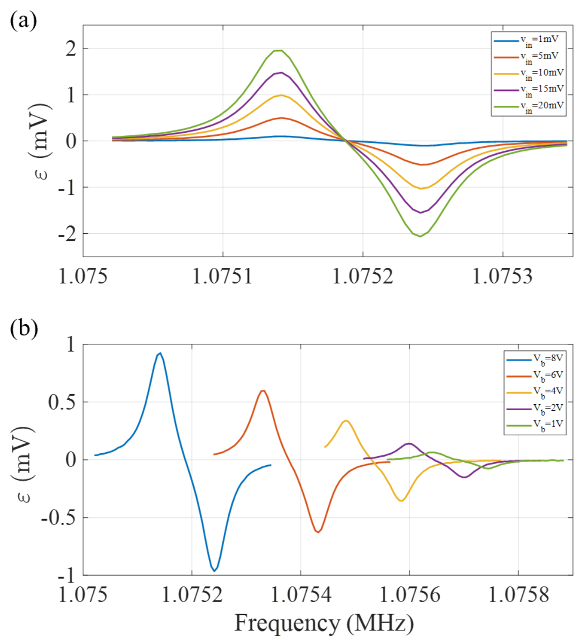

Figure 4: Experimental measurements of the error signal at (a) different input drive levels (fixed V_b=8 V, and v_{in} is the single tone amplitude value), and (b) different bias voltages (fixed v_{in}=10 mV). The error can be detected even with small input drive levels and bias voltages.

We further confirm (Fig. 4a) that the error signal is zero when the VCO is on resonance, irrespective of the drive amplitude, which allows us to use very small drive levels and circumvent the amplitude-frequency (A-f) nonlinearity. The error signal can also be acquired at very small dc bias (Fig. 4b), which significantly reduces the undesirable sensitivity for electrostatic resonators since the tuning due to electrostatic spring softening is a well-known quadratic function of the bias voltage.

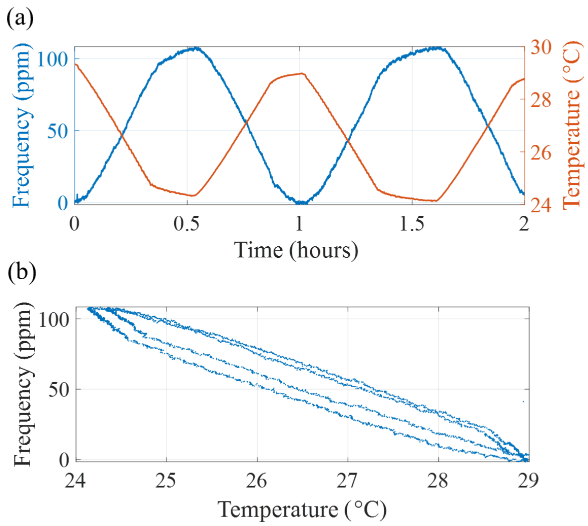

Figure 5: (a) Experimental results of real-time tracking of the DETF with a locked VCO, as the background temperature (measured using RTD) is varied. (b) The frequency vs temperature plot shows the negative temperature coeff. of the resonator, with expected hysteresis due to the mismatch between the RTD and the actual resonator temperature.

In Fig. 5 we present frequency measurements of the VCO successfully tracking the resonator frequency in real-time even as the ambient temperature varies. For this experiment the MEMS resonator was placed in a Test Equity 115A oven. Here we monitored the temperature via an RTD placed nearby, which is not at the exact temperature of the resonator, causing a hysteresis to appear in the frequency vs temperature plot. This experiment further confirms the importance of the dual mode "f1-f2" thermometry technique [3, 5] for performing thermal stabilization of mechanical references in real-time and will be implemented as our next major effort.

CONCLUSIONS

Our experimental results confirm that the proposed scheme can eliminate the feedthrough and generate an error signal that facilitates the locking of a VCO to a MEMS resonator, even at very small drive levels and small bias voltage. Another major feature of this approach is that the error-signal crosses zero at the resonance and thus does not require a value to serve as the locking point. We additionally achieved real-time frequency tracking using this method. Our approach can be widely employed for the real-time frequency tracking of MEMS resonators for both timing and sensor applications.

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