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Resolution of phase difference and frequency measurements of mutually injection-locked oscillators for resonant sensing applications

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Abstract

Sensor architectures based on coupled resonators are receiving increased interest from the resonant sensing community. This is first motivated by the fact that such architectures can provide differential measurements of the physical quantity of interest, without being hampered by spurious couplings between the resonant elements. Furthermore, certain output metrics of such sensors have an increased sensitivity to the measurand, compared to conventional resonant sensors with frequency-modulated outputs. We have recently demonstrated that this gain in sensitivity did not necessarily entail a gain in sensor resolution. In this paper, we investigate this issue further, and provide a first experimental proof of our theoretical result, using CMOS-MEMS monolithically-integrated mutually injection-locked oscillators (MILOs).

I - Introduction

Because of their potentially high resolution, large bandwidth, low footprint, and the possibility of producing them with very large-scale integration processes, sensors based on MEMS resonators are used in several high-end applications such as mass sensing for gas or chemical sensors, inertial sensing for aerospace or military applications, pressure sensing for the oil industry, etc. In such applications, the natural frequency of the MEMS structure is designed to be sensitive to the quantity of interest; it is monitored by placing the resonator in an oscillator loop and comparing the oscillation frequency to that of a reference oscillator. If the reference oscillator has the same sensitivity to environmental drifts as the one used for sensing, a differential measurement of the quantity of interest can be obtained.

To avoid temperature gradients and the resulting measurement errors, the two oscillators must be placed as close to each other possible. Parasitic couplings (electrical, mechanical, electrostatic ...) between the oscillators are inevitable and result in unwanted signal injection, and frequency pulling or locking. Alternatively, one may seek to take advantage of existing couplings, or even enforce them, and take advantage of the parametric sensitivity of coupled resonators to implement differential sensors, with two or more resonators in close proximity.

Several approaches exist for coupling MEMS resonators: the coupling may be passive [1][2] (e.g. electrostatic or mechanical) or active, enforced through the actuation force [3][4]. The resonators may be operated in open-loop or closed-loop, at large or small oscillation amplitudes. Several output metrics may also be used to convey the information one seeks to measure, with different sensitivities, and different requirements on the interface electronics [3][5]. For example, mutually injection-locked oscillators (MILOs) based on matched MEMS resonators [3] can be used: in this closed-loop approach, an electronic mixer enforces the resonators into a synchronized oscillation state, in which the phase difference between the resonators becomes highly sensitive to any stiffness or mass mismatch. Similarly, approaches based on mode-localization can be used, in which the amplitude ratio

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between the motional amplitudes of two (or more) weakly-coupled resonators provides a high-sensitivity measurement of a physical quantity of interest [1].

Our theoretical work [3][5] shows that, in spite of their sensitivity several orders of magnitude larger than conventional resonant sensors with frequency-modulated outputs, these coupled sensors do not necessarily entail a gain in sensor resolution, regardless of which output metric is used, contrarily to what was suggested in previous work [6]. In this paper, we investigate this issue further, and provide a first experimental proof of our theoretical results, using a CMOS-MEMS monolithically-integrated MILO. The system is described in section II. Our experimental results are given and commented in section III. Section IV contains some concluding remarks and perspectives.

II – Description of the CMOS-MEMS MILO

II-1 Principle of operation and theoretical results

The core of the MILO consists in two resonators with nominally identical resonance frequency f_0 and quality factor Q . These resonators are placed in a feedback loop, which is designed so that they oscillate in quadrature ($\phi_0 = \pi/2$). If a small stiffness mismatch is induced between the resonators (e.g. electrostatically), the resonance frequencies of the resonators are no longer identical. The nonlinear mixer then ensures that the system remains in a phase-locked state, but with a phase difference which deviates from 90° . The deviation of the phase-difference from its nominal value then provides a high-sensitivity measurement of the stiffness mismatch between the resonators, and hence of the quantity of interest. On the other hand, if both resonators undergo the same stiffness variation (as would be the case if thermal drift affected both resonators), the phase difference is unchanged, whereas the oscillation frequency of the system drifts with the temperature. Thus, in our system, phase difference provides a differential measurement, whereas oscillation frequency does not (see [4][7] for more details on the drift-rejection capabilities of MILOs).

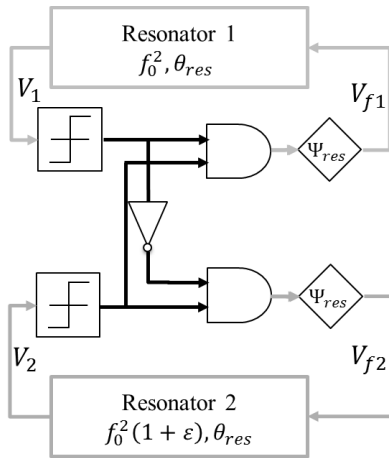


Fig. 1 – System-level view of a MILO, consisting of two resonators and their readouts, a digital mixer stage (comparators and logical gates) and distributed phase delay elements ψ_{res} (including the contributions of non-idealities, interconnects, etc.). For optimal operation at f_0 , one should have $\psi_{res} + \theta_{res} = \pi/4$, where θ_{res} is the phase delay at f_0 between the resonator inputs (V_{fi}) and readout outputs (V_i). The phase difference ϕ between V_1 and V_2 provides a high-sensitivity measurement of the relative natural stiffness mismatch ϵ .

In the particular case considered in this paper, the nonlinear mixer is designed to have maximal phase difference sensitivity to stiffness mismatch, as well as minimal fluctuations of the phase difference. The mixer consists of two comparators, which ensure that the Barkhausen gain criterion is met in both loops, and of a digital coupling stage (Fig. 1). The whole system must be designed so that the Barkhausen phase criterion is met at the resonance frequency of the resonators [7]. This requires a joint optimization of the resonators, their mixer, the resonator readouts, the mixer and the interconnections between these elements.

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Assuming the dynamics of the resonators are purely linear, one may show that [3]:

$$\phi \approx \phi_0 + Q\varepsilon, \quad f = f_0 \times (1 + \varepsilon/4), \quad (1)$$

where ε is the relative stiffness mismatch between the resonators, ϕ is the phase difference, and f the oscillation frequency. Furthermore, the fluctuations of ϕ and f induced by additive noise processes at the resonators inputs are governed by [3][5]:

$$\frac{\sigma_\phi}{\phi_0} = \frac{\sigma_f}{f_0} \times \frac{8Q}{\pi}. \quad (2)$$

Hence, the sensitivity enhancement of phase difference measurements compared to frequency measurements (1) is exactly compensated by an increase of the noise floor of the phase difference spectrum compared to that of the oscillation frequency spectrum. We have shown in [5] that similar results hold for several other coupled resonator architectures, such as mode-localized ones, whose resolution was wrongly thought to be intrinsically better than that of conventional resonant sensors [6].

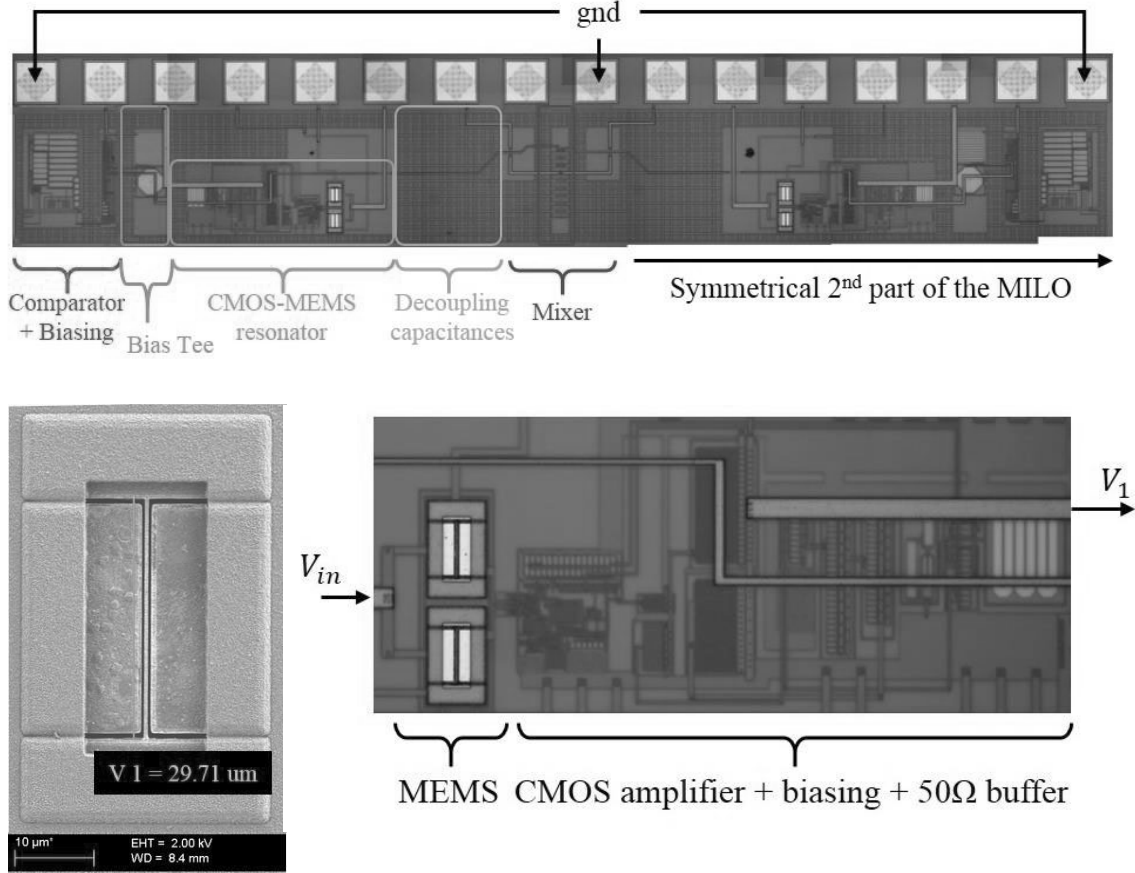


Fig. 2 – SEM view of the 2-port resonators (bottom left), and microscope views of monolithically-integrated MEMS and differential-input readout (bottom right) and of the whole system (top).

II-2 Fabrication and assembly

The clamped-clamped beam resonators (Fig. 2) are fabricated using a back-end wet HF release step [8] in the VIA3 layer of the AMS C35 standard process. Typical dimensions of the resonators are: 30mm

(length) \times 1.3mm (thickness) \times 0.5mm (width), with 380mm electrostatic gaps. The whole monolithically-integrated system is represented in Fig. 2. The chip is glued and wire-bonded to a PCB, connected to an excitation-level adaptation stage consisting of potentiometer bridges, and the loop is closed with SMA wires.

III – Experimental results

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In this section, we report typical experimental results obtained in the linear regime of operation of the resonators. The oscillation amplitude is chosen large enough to limit the impact of electronic non-idealities (such as comparator hysteresis), but below the critical Duffing amplitude, in order not to be affected by conversion of amplitude noise to frequency noise or phase-difference noise. This is achieved by working at an excitation level between 500mV and 1V (peak value), corresponding to an oscillation amplitude of 4%-8% of the gap, according to our model (Fig. 3).

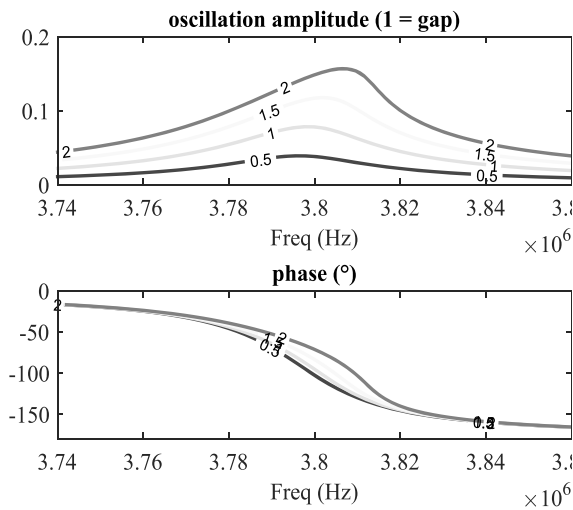


Fig. 3 - Simulated amplitude and phase response of a resonator ($Q=120$, $V_b=37.5V$) for different excitation voltages (colorscale, peak value in V).

Characterization shows that the resonance frequencies of the resonators are very close ($f_0 \approx 3.8\text{MHz}$ at 40V of bias voltage), as are their quality factors (with an average $Q \approx 100$ over all fabricated chips). Typical results concerning the sensitivity of our device are reported in detail in [7]: these are in very good agreement with our idealized models (1) and the remaining discrepancies are well explained by more elaborate modeling [3], as shown in Fig. 4.

In Fig. 5, the spectra of the frequency noise and phase difference noise are represented, along with the theoretical predictions derived from our model, assuming thermomechanical noise is the only source of fluctuations. As far as the noise floor is concerned, the experimental and theoretical results are in excellent agreement: this not only demonstrates that the resolution of our device is limited by thermomechanical phenomena, but also that (2) holds. Thus, the increased fluctuations of the phase difference (compared to those of the oscillation frequency) compensate the gain in sensitivity made by choosing this output metric (1).

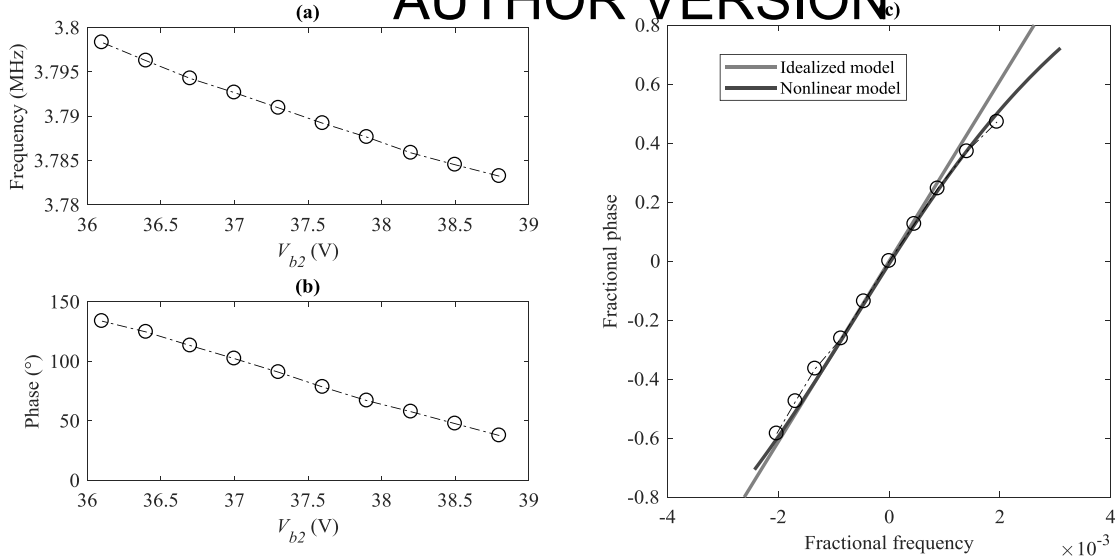


Fig. 4 – Evolution of oscillation frequency (a) and phase difference (b) with the bias voltage of resonator 2. Comparison of experimental measurements (circles) with linear and nonlinear models (full lines) derived from [3] (c).

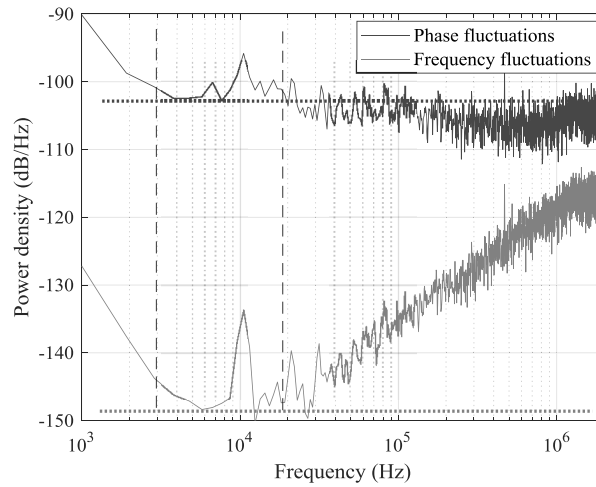


Fig. 5 – Power spectra of relative frequency fluctuations (red curve) and phase difference fluctuations (blue curve). The dotted horizontal lines correspond to the theoretical predictions of the thermomechanical noise floors. The dashed vertical lines delimit the bandwidth over which thermomechanical noise dominates.

IV – Conclusion

“There are two sides to every coin”, as the saying goes. Our theoretical and experimental results show that this is indeed the case, as far as the much vaunted sensitivity of sensor architectures based on coupled resonators goes. However, this is no reason to “throw out the baby with the bath water” either: first of all, coupled architectures such as ours are intrinsically differential, and they are an efficient solution to reduce the impact of drift on resonant measurements of a physical quantity of interest. It is our opinion that research in this domain should in fact be more focused on the minimization of drift

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(through system-level, mechanical or electronic design, choice of output metric, and control of fabrication inaccuracies) rather than on the maximization of sensitivity. Moreover, coupled oscillator architectures can be designed to minimize the impact of electronic noise [9], which can be a real advantage compared to conventional, single-resonator architectures, when (as often) thermomechanical effects are not the dominant noise mechanisms. Finally, it must be pointed out that the nonlinear operation of these coupled architectures is also a largely unexplored and very promising field, in which several of the results established so far, such as the proportionate increase of sensitivity and fluctuations discussed in this paper, may be questioned.

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