Electrically Enhanced Readout System for a High-Frequency CMOS-MEMS Resonator

Arantxa Uranga, Jaume Verd, Joan Lluis Lopez, Jordi Teva, Francesc Torres,
Joan Josep Giner, Gonzalo Murillo, Gabriel Abadal, and Nuria Barniol

ABSTRACT—The design of a CMOS clamped-clamped beam resonator along with a full custom integrated differential amplifier, monolithically fabricated with a commercial 0.35 μm CMOS technology, is presented. The implemented amplifier, which minimizes the negative effect of the parasitic capacitance, enhances the electrical MEMS characterization, obtaining a 48×10^8 *resonant frequency-quality factor product (*$Q\times f_{res}$*) in air conditions, which is quite competitive in comparison with existing CMOS-MEMS resonators.*

Keywords—CMOS-MEMS, MEMS characterization, clamped-clamped beam resonator, differential readout amplifier.

I. Introduction

This letter focuses on the design of both a CMOS-MEMS resonator, in this case a clamped-clamped beam resonating structure [1], and an integrated CMOS differential amplifier which allows the MEMS characterization and improves the system electrical performance. In particular, it allows differential measurements to be carried out, opening new areas to work on, such as its behavior as a filter.

The clamped-clamped beam resonator basically consists of two electrodes, called excitation and readout electrodes, and a suspended structure, called a beam [1]. To electrically characterize the movement of the resonator, an electrostatic excitation and capacitive readout is performed. In particular, a DC voltage (V_{DC}) is applied to the suspended structure, while an AC excitation voltage (V_{AC}) is applied to the excitation electrode. The resulting electrostatic force induces the movement of the suspended structure at the excitation frequency. This oscillation generates a change in the capacitance constituted by the readout electrode and the suspended structure that can be quantified by measuring the induced output current:

$$I \cong V_{DC}\frac{\partial C_2}{\partial t} + C_0\frac{\partial V_{AC}}{\partial t}, \qquad (1)$$

where C_2 is the variable capacitance between the suspended structure and the readout electrode, and C_0 is the parasitic capacitance between the excitation and readout electrodes. The first term corresponds to the motional current, whereas the second term corresponds to the feedthrough or parasitic current.

The behavior of the MEMS configured as a two port (input and output ports) scheme can be modelled by an RLC equivalent circuit that models the motional current. At the same time, an additional capacitance (C_0) is added between the input and output ports to model the feedthrough currents. The presence of this parasitic current disturbs the characterization of the mechanical frequency resonance generating a parallel resonance at the frequency given by

$$f = f_0\sqrt{1 + C/C_0}, \qquad (2)$$

where f_0 corresponds to the RLC resonant frequency. Since C_0 is larger than C, the parallel resonance appears close to the series resonance, degrading its performance and impeding the MEMS measurement. The value of the motional admittance at the resonant frequency is 1/R, and the parasitic admittance is $\omega_0 C_0$. Therefore, in MEMS with a high resonance frequency, the corresponding value of this parasitic admittance should be

---

Manuscript received Nov. 25, 2008; revised May 13. 2009; accepted June 9, 2009.

Arantxa Uranga (phone: +34 93 5813218, email: arantxa.uranga@uab.es), Joan Lluis Lopez (email: jl.lopezmendez@gmail.com), Jordi Teva (email: jordi.teva@gmail.com), Francesc Torres (email: francesc.torres@uab.es), Joan Josep Giner (email: joanjosep.giner@uab.es), Gonzalo Murillo (email: gonzalo.murillo@uab.es), Gabriel Abadal (email: gabriel.abadal @uab.es), and Nuria Barniol (email: nuria.barniol@uab.es) are with the Department of Electrical Engineering, Universitat Autònoma de Barcelona, Barcelona, Spain.

Jaume Verd (email: jaume.verd@uib.es) is with the Electronic Systems Group, Universitat de les Illes Balears, Palma, Spain.

doi:10.4218/etrij.09.0208.0380

very large, compared with the motional admittance. As a consequence, the majority of the excitation signal goes through the parasitic capacitance and makes measurement of the resonator characteristics difficult. Therefore, some efforts have been reported to reduce the parasitic current caused by the parasitic capacitance that generates not only degradation of the measured electric quality factor of the MEMS (Q) but also a shift in the resonance frequency. Two main approaches have been proposed to overcome this problem: a) implementation of differential sensing using two identical MEMS resonators [2] and b) use of the MEMS as a mixer due to its quadratic dependence on the applied voltage [3]. In this mixing approach, the excitation/actuation of the MEMS is done by two AC signals, neither of which is at the resonance frequency of the resonator, but their sum or difference corresponds to the MEMS resonant frequency. This fact allows the removal of the effect of parasitic feedthrough, which separates the parasitic and motional current in the frequency domain as has been demonstrated [4].

The approach proposed in this letter is based on the subtraction of the parasitic currents [2] provided by two MEMS resonators with the same physical dimensions taking advantage of the monolithical integration with an on-chip CMOS differential amplifier.

At the block level, the parts that constitute the full CMOS-MEMS system are two identical MEMS resonators, two current-to-voltage transimpedance amplifiers (TIAs), two cascode amplifier stages that increase the gain, and a differential voltage amplifier [5]. This architecture allows independent DC voltages to be applied in each resonator (V_{DC1} and V_{DC2}). Equation (1) shows how these DC voltages allow a MEMS output current to be obtained which corresponds to the sum of the parasitic current plus the motional current when a DC voltage is applied, whereas only the parasitic current is observed when V_{DC} is equal to 0 V.

The presence of the two current-to-voltage amplifiers generates two output voltage signals. These signals present a common mode signal, corresponding to the parasitic input current converted to voltage, and a differential mode signal, corresponding to the motional current converted to voltage. These two voltage signals are applied to the inputs of the differential amplifier. The design of the differential amplifier with a high common mode rejection ratio allows the effect of the MEMS parasitic current to be reduced; therefore, it is possible to obtain an electrical characterization of the MEMS closer to the intrinsic mechanical behavior.

II. Fabrication

1. Resonator

A polysilicon mechanical resonator, based on a 13 μm long, 0.35 μm wide, 0.28 μm thick clamped-clamped beam, and two electrodes (driver and readout electrodes), was used to study the proposed MEMS differential readout system. The device was implemented in a commercial 0.35 μm CMOS technology together with CMOS circuitry. A 150 nm gap spacing between the driver and the suspended structure was designed. The resonator structural layer and the driver and readout electrodes were defined using the polysilicon capacitance module available in the technology, while the sacrificial layers were the silicon oxide layers, which were removed after the CMOS process by means of a one-step maskless wet etching [1].

2. Differential Readout Amplifier

The proposed differential electrical readout scheme comprises three CMOS amplifier stages [5]. The first stage is a TIA which uses the intrinsic parasitic capacitance at the sense node (or readout node) to integrate the capacitive current generated by the MEMS resonator. The TIA structure is constituted by an inverting amplifier followed by a source-follower stage for bandwidth enhancing purposes. To polarize the sense node (amplifier input transistor gate), a PMOS pseudo-resistor with extremely high resistance was used. A cascode amplifier with cascode-load configuration was chosen and designed as the second stage to increase the final gain. This stage is self-polarized and AC-coupled with the first stage to assure the correct biasing of this amplifier. The differential amplifier is basically a conventional single-ended common emitter differential stage with active resistors as a load. The stage is self-polarized and AC-coupled with the previous stage. An output buffer is employed for testing purposes to load the 50 Ω impedance of the measurement instrumentation. As a result, a common mode rejection ratio of 43 dB at 20 MHz and a final gain of 87 dBΩ at 20 MHz are achieved with a power consumption of 16 mW, which corresponds to 80% of the total power consumption (12.8 mW) of the output buffer and cascode amplifier.

III. Experimental Results

Figure 1 shows an optical image of the proposed full system, comprising two identical clamped-clamped beam resonators and the readout differential amplifier. A scanning electron micrograph (SEM) of the two polysilicon resonators is shown in the inset of Fig. 1. Electrical characterization of the two resonators was performed using a network analyzer (Agilent E5100A). A DC voltage was applied to the suspended structure of the first MEMS resonator, while the second resonator was biased at 0 V DC. An AC voltage was applied to the excitation electrode of both resonators, whereas the two electrical readout signals were acquired from the readout electrodes and

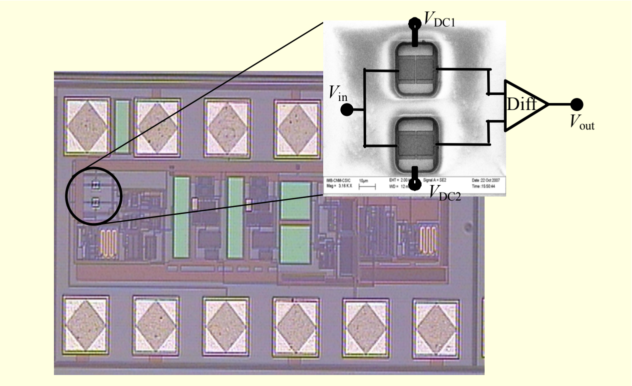

Fig. 1. Optical image of the differential MEMS system showing a scanning electron micrograph of the two identical released clamped-clamped beams.

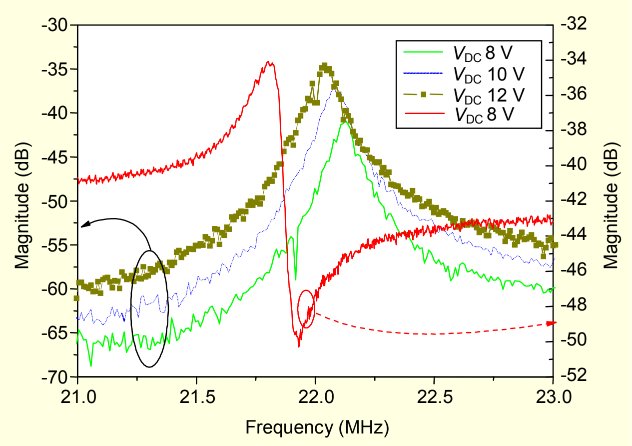

Fig. 2. Frequency response obtained with the differential amplifier configuration when a DC voltage of 0 V is applied to the beam of one MEMS while the other beam is biased with various DC voltages. Red line shows measurement of a clamped-clamped beam device using the 2-port characterization.

conditioned with the implemented amplifier circuit. Figure 2 shows the experimental frequency response obtained in air conditions for DC voltages of 8 V, 10 V, and 12 V applied to the first MEMS resonator, while the second resonator was biased at 0 V. We compared the operation of the full system with result obtained using a conventional 2-port characterization on a different clamped-clamped beam MEMS in Fig. 2. The measurement setups in the resonance frequency and the transmission amplitude at the resonance frequency differ because the MEMS devices belong to different chips and use different amplifiers. Clearly, the implemented differential readout scheme eliminates the effect of the parasitic capacitance because the parallel resonance is not present, and only a resonant frequency of around 22 MHz is shown. The spring softening effect due to the electrostatic excitation of the mechanical structure can also be observed. An electrical quality factor of 218 is obtained for a bias polarization voltage of 12 V. A higher value of the quality factor is expected to be achieved under vacuum conditions. Finally, the resonance frequency-quality factor product ($Q\times f_{res}$) was calculated, obtaining a value as high as 48×10^8 in air conditions.

IV. Conclusion

We presented a CMOS-MEMS resonator with a new CMOS readout amplifier circuit that allows the characterization of MEMS in a very simple manner, eliminating the parasitic current that masks the motional current. Experimental results corroborate the viability to eliminate the negative effects of the parasitic capacitance on electrical measurements. The implemented solution for the technological realization of the monolithic CMOS-MEMS eases the design of two identical resonators; thus, our approach works without the need of a gain tuning to assure identical feed-through signals. The 48×10^8 resonant frequency-quality factor product obtained in air conditions is absolutely competitive compared with existing CMOS-MEMS resonators [6].

Although the subtraction of the parasitic current can be performed using a network analyzer with only one resonator device and by turning on and off the bias voltage, we want to point out that the implemented system is an example of integration of a MEMS resonator into CMOS integrated circuits manufacturing. Moreover, the use of the two MEMS along with the designed differential amplifier is a promising means to implement tuneable bandwidth filters.

References

[1] J. Teva et al., “VHF CMOS-MEMS Resonator Monolithically Integrated in a Standard 0.35 µm CMOS Technology,” *Proc. MEMS*, 2007, pp. 779-782.

[2] P. Rantakari et al., “Reducing the Effect of Parasitic Capacitance on MEMS Measurements,” *Proc. Transducers/Eurosensors XV*, June 2001, pp. 1156-1159.

[3] J.R. Clark et al., “High-Q UHF Micromechanical Radial Contour Mode Disk Resonators,” *J. Microelectromech. Syst.*, vol. 14, no. 6, 2005, pp. 1298-1310.

[4] A. Uranga et al., “Fully Integrated MIXLER Based on VHF CMOS-MEMS Clamped-Clamped Beam Resonator,” *IEE Electron. Lett.*, vol. 43, 2007, pp. 452-454.

[5] J.L. Lopez et al., “High Q CMOS-MEMS Resonators and Its Applications as RF Tunable Band-Pass Filters,” *Proc. Transducers*, June 2009, pp. 557-560.

[6] C.-C. Lo et al., “On-Chip High Quality Factor CMOS-MEMS Silicon-Fin Resonators,” *Proc. Transducers,* June 2007, pp. 2449-2452.