ENHANCED ELECTRICAL CHARACTERIZATION OF MEMS RESONATORS USING ON-CHIP PARASITIC FEEDTHROUGH SELF-CANCELLATION
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Abstract: We report a technique for the self-cancellation of parasitic capacitive feedthrough in microresonators by employing an identical pair of resonators, one of which is excited while the other functions as a matched negating compensation capacitor. This on-chip self-compensation scheme results in an enhancement in the resonance peak height of a wine glass mode disk resonator by an additional 18.8 dB

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INTRODUCTION

Electrically interfaced micromechanical resonators have been demonstrated as building blocks for a variety of sensor [1] and also signal processing [2] applications. However, electrical characterization of micromechanical resonators is increasingly complex as dimensions scale due to capacitive parasitics intrinsic to the process and device that often dominate the electrical measurements. The physical sources of this capacitive feedthrough parasitic include:

1. The direct overlap capacitance of the transducer,
2. Capacitive coupling through the substrate
3. Interconnects, and
4. The electrical package holding the chip

Although the estimated feedthrough capacitance is relatively small (typically 1-2 pF), for applications operating in the high frequency (HF) region and higher, the electrical path through this capacitor is significant and could potentially obscure any observable signal stemming from the motion of the structure.

As dimensions of structures are scaled down in order to achieve higher frequency by reducing the effective mass, the overlapping capacitance of the transducer is also decreased. This leads to poorer electromechanical coupling in the transducer, which results in increased motional resistance. A figure of merit may be defined by the ratio of the impedance of the parallel feedthrough capacitor at the resonant frequency to the motional resistance. To implement a Pierce oscillator, this figure of the merit has to be larger than 2. As a result, techniques for reducing feedthrough in electrically interfaced MEMS resonators are essential to both the design and realization of MEMS oscillators as well as the electrical characterization of resonators.

We have previously demonstrated a method and concept for feedthrough cancellation using tunable circuit components [3]. The concept is further developed in this paper, demonstrating the self-cancellation of parasitic feedthrough on-chip. The compensation element is integrated on the same chip with a disk resonator, and results in an enhancement in the resonance peak height of a wine glass mode disk resonator by an additional 18.8 dB and a full phase shift of -180°.

ANALYSIS AND CONCEPT

Fig. 1 provides a schematic of the most basic form for an equivalent circuit model that describes a typical electrically interfaced MEMS resonator. A more detailed model is described in [4]. As shown in Fig. 1, the resonator is modeled as a series LRC resonant circuit. These circuit model parameters are defined as follows:

\[ L_m = \frac{m}{(\xi V_p)^2} \]
\[ R_m = \frac{\sqrt{km}}{(\xi V_p) Q} \]
\[ C_m = \frac{(\xi V_p)^2}{k} \]

where \( m \) is the dynamic mass of the resonator, \( k \) is the effective spring stiffness, \( V_p \) is the applied DC bias, and \( \xi \) is the normalized electromechanical transduction coefficient, which is defined by the first partial derivative with respect to displacement of the overlapping capacitance \( (C_d) \) of the transducer when the structure is nominally stationary (ie \( x = 0 \)).
Fig. 1 shows that a feedthrough capacitor $C_0$ is located in parallel with the series resonant elements in the equivalent electrical model. The introduction of an AC drive voltage $V_{ac}$ at the input produces 2 output currents: a feedthrough current ($I_f$) and a motional current ($I_m$), which add up at the sense node to yield the measured current ($I_s$):

$$I_m + I_f = I_s$$

(3)

The net admittance between the input and sense node is then given by the ratio of this current to the input AC voltage:

$$Y_s = \frac{I_s}{V_{ac}} = \frac{I_m}{V_{ac}} + \frac{I_f}{V_{ac}}$$

(4)

Eq. (4) is simply the sum of the admittances for the feedthrough and motional electrical path:

$$Y_s(\omega) = \frac{j\omega C_m}{\left[1 - (\omega/\omega_0)^2\right] + j(\omega/\omega_0)/Q} + j\omega C_0$$

(5)

where $\omega_0$ is the resonant frequency of the structure and $Q$ is the quality factor. Eq. (5) shows that as the feedthrough capacitor ($C_0$) is increased, the admittance and thus current through it increases relative to the motional current. Thus a sufficiently large $C_0$ could potentially obscure any observable signal from the resonant circuit path.

Fig. 2 shows a circuit for reducing the effects of $C_0$. The input drive signal is passed through a single-to-differential driver, and it is split into two separate complimentary outputs. One output is applied to the resonator, while the other to an external tunable capacitor $C_{comp}$ located in parallel with the circuit, producing an output current of $I_c$. The resulting output currents finally all add up at the sense node:

$$I_m + I_f + I_c = I_s'$$

(6)

The net admittance between the input and sense node is now given by:

$$Y_s' = \frac{I_s'}{V_{ac}} = \frac{I_m}{V_{ac}} + \frac{I_f}{V_{ac}} - \frac{I_c}{V_{ac}}$$

(7)

$$Y_s'(\omega) = \frac{j\omega C_m}{\left[1 - (\omega/\omega_0)^2\right] + j(\omega/\omega_0)/Q} + j\omega(C_0 - C_{comp})$$

(8)

From eq. (8), the net feedthrough capacitance is now reduced to $C_0 - C_{comp}$. This means that if $C_{comp}$ is tuned to match the feedthrough capacitor $C_0$, the feedthrough effect of $C_0$ can be effectively negated.

The external compensation capacitor in Fig. 2 may be replaced by a dummy structure fabricated on the same chip as the resonator under test, as depicted in Fig. 3. In this scheme, two identical disk structures are fabricated on the same die, one being a duplicate “twin” of the other. Structure X is electrostatically excited in the wine glass bulk mode, while no DC bias is applied to its twin (structure Y). With no DC bias applied to structure Y, it remains static and thus effectively acts only as a feedthrough capacitor. Since both structures X and Y are nominally identical, the feedthrough capacitance between the input and output terminals for X and Y are closely matched. Structure Y can thus be used as the compensating capacitor $C_{comp}$ of Fig. 2. As the compensating capacitor is now integrated on the same chip as the resonator under test, no further tuning is required.

One of the outputs of the single-to-differential driver is coupled into the drive electrode of structure X, and the DC bias is introduced through a large resistor. The other output from the driver is applied to the drive electrode of the dummy structure Y. The structural node of both structures X and Y are electrically connected externally on a printed circuit board and interfaced to a transimpedance amplifier.

![Figure 2. Feedthrough compensation technique using an external tunable capacitor mounted on a circuit board](image)

![Figure 3. On-chip feedthrough cancellation scheme using a pair of disk resonators fabricated on the same chip](image)
IMPLEMENTATION

The on-chip feedthrough compensation technique has been implemented on disk resonators with a radius of 400 μm. The structures have been fabricated on 25 μm thick SOI using a foundry MEMS process by MEMSCAP with transduction gaps of 2 μm. Fig. 4 provides a cross-sectional view of the fabricated devices and Fig. 5 is an optical micrograph showing the two “twin” disk resonators. These twin structures differ from each other primarily in the shape of the connecting stem from the resonator to the anchor, but are otherwise identical to each other – a T-shaped stem has been used for the actuated disk while a straight stem was used for the static disk.

The electrical transmission of the uncompensated resonator alone was measured first with an Agilent 4396B network analyzer. The resonator was operated under vacuum and a DC bias of 60 V as applied to the electrodes. Fig. 6 and Fig. 7 show the measured magnitude and phase plot of the transmission response respectively. As may be seen from these transmission curves, the output signal is heavily buried in parasitic feedthrough. The resonant peak height is about 3.7 dB with a corresponding phase shift of just $57^\circ$ despite a high quality factor of 2 million.

The same disk resonator was excited in the wine glass mode but with the other kept stationary and used as a compensation capacitor. The same bias voltage and source power were applied to the resonator, while the environmental conditions were kept approximately the same. Fig. 8 and Fig. 9 show the measured electrical transmission. The magnitude plot in Fig. 8 shows a resonant peak height of 22.5 dB after using compensation, while a full phase shift of $180^\circ$ is may be observed from the phase plot shown in Fig. 9. This would correspond to an enhancement of 18.8 dB in the magnitude and an additional phase shift $123^\circ$ as a result of the on-chip feedthrough compensation.

The graphs indicate a slight over-compensation of the feedthrough arising from an overall capacitance mismatch. This may be deduced from the position of the anti-resonance relative to that of the series resonance. Fig. 8 shows that the anti-resonance occurs at a lower frequency from the series resonance, which suggests that the admittance of the compensation capacitor is larger than the feedthrough capacitor. Nonetheless, the degree of enhancement in the electrical transmission shows that the cancellation technique is still effective.
The transmission characteristic measured for the same disk resonator but using an external tunable capacitor is given in Fig. 10. This figure illustrates the case where the compensation capacitor has been fine-tuned to match the feedthrough capacitor more closely.

It may be observed that the resonant frequencies in the 2 sets of graphs (comparing Fig. 6 and 7 against Fig. 8 and 9) are different by about 200 Hz (approximately 36 ppm). This disparity is due to differences in the ambient temperature between the times when these 2 measurements were taken.

CONCLUSIONS

In this paper, we have demonstrated how the undesired presence of parasitic feedthrough could be compensated using an on-chip dummy twin structure. This compensation technique has been applied to disk resonators excited in the wine glass with a Q of 2 million. The proposed method of feedthrough cancellation has resulted in an enhancement of 18.8 dB in the height of the resonant peak and a full 180° shift in the phase.

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