A 600kHz ELECTRICALLY-COUPLED MEMS BANDPASS FILTER

Siavash Pourkamali, Reza Abdolvand, and Farrokh Ayazi

School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0250, USA
Email: ayazi@ece.gatech.edu; Tel: 1-404-894-9496; Fax: 1-404-894-4700

ABSTRACT

This paper presents a 600kHz MEMS bandpass filter implemented using electrical coupling of single crystal silicon HARPSS micromechanical resonators. Passive and active filter synthesis approaches based on electrical coupling of capacitive MEMS resonators are introduced and discussed. A third order passive bandpass filter at the center frequency of 600kHz with a bandwidth of 125Hz, a stopband rejection of 48dB, and a 20dB-shape-factor of 2.1 is demonstrated. A quality factor (Q) enhancement technique based on active electrical cascading of the resonators is also presented. A 3-stage active cascade at 600kHz demonstrated a 2× increase in the effective Q.

1. INTRODUCTION

Over the past few years, extensive efforts have been devoted to replace off-chip frequency-selective components (i.e., frequency references and filters) in telecommunication systems with on-chip silicon-micromachined MEMS resonators. In order to achieve the desired selectivity, high order bandpass filters consisting of a number of coupled resonators are required. Mechanical coupling technique, traditionally used for implementation of high order filters from individual mechanical resonators [1], has been applied to micromechanical resonators for filter synthesis [2-6]. Electrically sensed and actuated MEMS filters up to the third order [3] with center frequencies up to 68MHz [4] as well as electrically actuated and optically sensed filters up to the 20th order at center frequencies of a few MHz [6] have been reported using the mechanical coupling technique.

This work presents a new filter synthesis approach based on the electrical coupling of individual MEMS resonators. In this method, capacitors are used to couple MEMS resonators to each other and provide a high order transfer function. The main advantage of electrical coupling approach in filter synthesis is its greater potential for extension into the UHF frequency range. In the UHF frequency range (0.3-3GHz) and above, which is the band of interest for many wireless applications, due to the very small size of the resonator element (<10μm), mechanical coupling will require sub-micron in size coupling elements (i.e., wires) that are difficult to fabricate using optical lithography. In addition, filter characteristics are sharply dependant on the positioning and dimensions of the coupling elements [7] and optimized design of a filter will require mechanical design expertise and specialized simulation tools. Filter synthesis using electrical coupling does not require mechanical design expertise and provides more design flexibility for electrical engineers.

In this paper, high-Q single crystal silicon capacitive resonators fabricated through the HARPSS process [8] are used as the building blocks for high order electrically-coupled MEMS bandpass filters. The concept of electrical coupling and its variations are discussed, and simulation and test results are presented.

2. ELECTRICALLY COUPLED MEMS FILTERS

Figure 1 shows the equivalent circuit model of a two-port capacitive micromechanical resonator, providing a second order bandpass transfer function with a pair of conjugate poles at its center frequency. The equivalent motional resistance of the device is determined by the area of the sense and drive electrodes, the capacitive gap size between the electrodes and the resonator, the applied DC polarization voltage and the Q of the resonator. The transformers at the terminations of the device (Fig. 1) account for any asymmetry between the sense and drive electrodes that may result in different input and output impedance levels. For a symmetric resonator, the equivalent circuit is reduced to a simple series RLC tank.
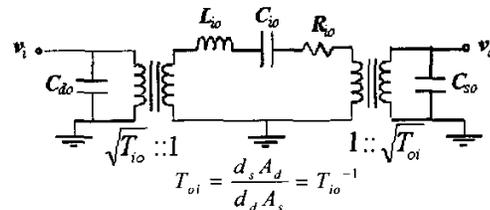

$$T_{oi} = \frac{d_s A_d}{d_d A_s} = T_{io}^{-1}$$

Figure 1. Electrical equivalent circuit of a two-port capacitive MEMS resonator. d_d, d_s, A_d and A_s are drive and sense electrode capacitive gaps and areas, respectively.

Two different schemes of the electrical coupling technique are proposed and used in this work for implementation of high order bandpass filters using individual two-port MEMS resonators: 1) capacitive coupling (passive); and, 2) electrical cascading (active).

2.1. Capacitive Coupling

In the capacitive coupling approach, as depicted in Fig. 2, micromechanical resonators are cascaded with a shunt capacitor to ground in between two adjacent resonators. The interaction of the coupling capacitors and the resonators equivalent RLC tank circuits results in several resonance modes in the system and consequently a multiple-order bandpass frequency response.
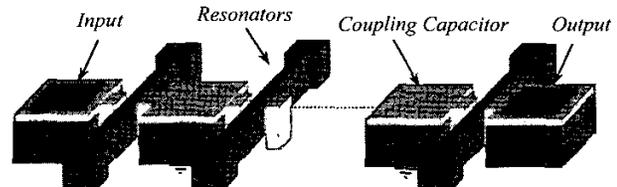

Figure 2. Schematic diagram of a capacitively-coupled microelectromechanical filter.

If we consider a two-resonator system, the capacitive coupling of two resonators with identical center frequencies (f_0), quality factors $(Q>1000)$, and motional resistances (R) results in a new pair of conjugate poles at the frequency of:

$$f_1 = f_0 \sqrt{\frac{1 + \pi f_0 C_c RQ}{\pi f_0 C_c RQ}} \qquad (1)$$

where C_c is the coupling capacitor. This will introduce a new resonance frequency in addition to the inherent resonance mode of the individual resonators at f_0. Looking at the frequency response of the two-resonator system, the first resonance occurs at the mechanical resonant frequency of the individual resonators. At the 1st resonance, as shown in Fig. 3a, the two resonators resonate in phase and the coupling capacitor has no contribution (while C_c is being charged by the first resonator, the other resonator is discharging it). At the 2nd resonance (f_1), the two resonators operate with a 180° phase difference and hence the coupling capacitor comes into the game (it is being charged and discharged at the same time by both resonators). Due to its symmetry, the system can be reduced to a half circuit with one resonator and a series capacitor $C_c/2$ to ground. The series capacitor reduces the total capacitance of the RLC tank, causing the second resonance mode. The case will be more complicated for a three-resonator system with two coupling capacitors, as shown in Fig. 3b.
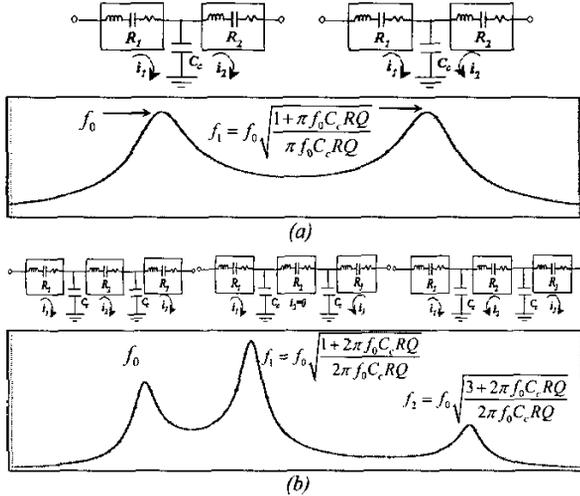

Figure 3. Electrical schematic diagrams of coupled resonators and their frequency response. a) 2nd order system; b) 3rd order system.

The asymmetry in the frequency response of the 3rd order filter is due to the fact that the end resonators have only one coupling capacitor attached to them but the one in the middle is terminated with two coupling capacitors at the two ends. This asymmetry can be compensated by slight frequency tuning of the end resonators of the chain with respect to the other resonators, but it can result in an increase in the insertion loss. A better solution to this problem is to use a closed chain of coupled resonators [6] to have complete symmetry for all the resonators.

Figure 4 illustrates simulation results of capacitively coupled electromechanical filters at 600kHz with different resonator quality factors, showing the dependence of the

insertion loss on the Q of individual resonators. The value of the coupling capacitors can be extracted from the resonators Q, the desired filter bandwidth, and the desired passband ripple. For the specific filter characteristics of Fig. 4, coupling capacitors of 0.2pF are required that can be easily fabricated on-chip.
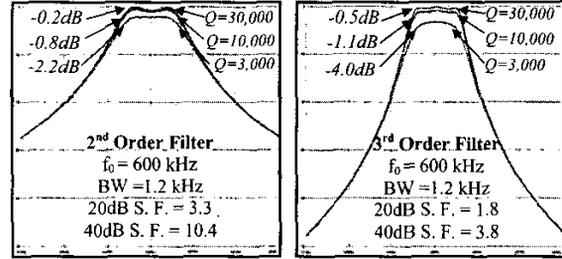

Figure 4: Simulation results for 600kHz capacitively-coupled 2nd & 3rd order filters. A higher resonator Q results in a lower insertion loss. Coupling cap: $C_c=0.15pF$ (2nd order); & $C_c=0.2pF$ (3rd order).

The insertion loss of capacitively coupled filters (assuming ideal lossless coupling capacitors) is determined by the Q of the individual resonators, the order of the filter and the termination resistors added to flatten the passband:

$$Insertion - Loss(dB) = 20\log\left(\frac{nR_r + 2R_{term}}{2R_{term}}\right) \qquad (2)$$

where n is the order of the filter, R_r is the equivalent motional resistance of the resonators $(R_r \propto 1/Q)$, and R_{term} is the termination resistor. Figure 5 shows the simulation results with non-ideal (lossy) coupling capacitors. The finite Q of the coupling capacitors does not have a significant effect on the first resonance peak but its attenuation effect becomes more pronounced in higher resonance modes.
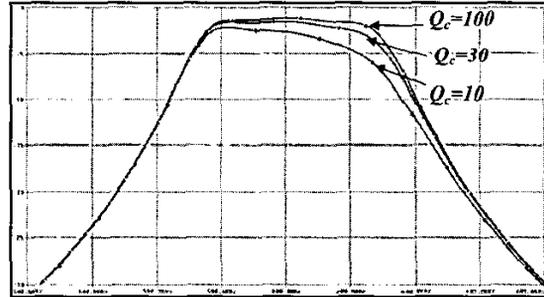

Figure 5. Effect of the finite Q of the coupling capacitors on the frequency response of a third order capacitively coupled filter.

2.1.1 Implementation and Results

Single crystal silicon (SCS) capacitive HARPSS resonators [8,9] were used to implement 2nd and 3rd order electrically-coupled MEMS filters. In these in-plane resonators, as shown in Fig. 6, the resonating element is made out of SCS, and the electrodes are made out of polysilicon. The capacitive transduction gaps are defined in a self-aligned process step by the thickness of a sacrificial oxide layer and can be scaled down to tens of nanometer. Figure 7 shows cross-sectional and top views of 80nm capacitive gaps of the fabricated resonators. The 600kHz SCS clamped-clamped beam HARPSS resonators used in this work had a high Q of ~10,000.
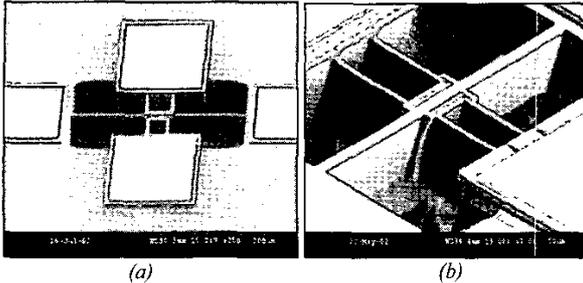
Figure 6. 300μm long, 7μm wide, and 20μm thick HARPSS SCS beam resonator (f_0=600kHz). (a) top view, and, (b) close-up view.
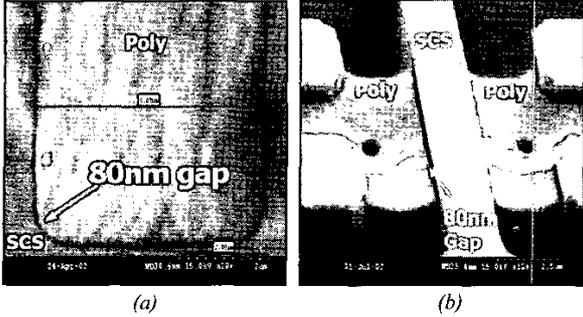

Figure 7. SEM views of the 80nm capacitive gap. (a) Cross-sectional view, at the bottom of a 20μm deep trench. (b) Close-up view of the electrode area of a SCS beam resonator.

In order to implement a 2ⁿᵈ order filter, two 600kHz HARPSS resonators were mounted and wire-bonded on a PCB containing a low noise JFET-input amplifier to sense the output signal of the filter. The PCB was placed in a custom vacuum system, which kept the pressure below 1mTorr. The output port of the first resonator was directly connected to the second resonator through wirebonds and the metal track on the PCB and the frequency response of the filter was measured using an Agilent 4395A network analyzer. The parasitic capacitances introduced by the wire-bonds and the PCB in addition to the large pad capacitors of the resonators (~1pF) resulted in a total coupling capacitor of ~3pF. With such a large coupling capacitor, separation of the two resonance peaks was less than the bandwidth of the individual resonators. The large capacitor attenuated the signal, resulting in a larger insertion loss as shown in Fig. 8a. To obtain a larger bandwidth, the two resonance peaks were separated by adjusting the applied DC polarization voltages, which resulted in an increased insertion loss as shown in Fig. 8b. Contribution of the 3pF parasitic capacitance in increasing the insertion loss of the filter was confirmed by simulation, as shown in Fig. 8c. On-chip implementation of the coupling capacitors will reduce the insertion loss of the filter to less than 2dB.

2.2. Electrical Cascading

The other approach used for implementation of high order MEMS filters is the electrical cascading of resonators using active components. The electrical cascading of resonators with buffers or amplifiers in between (to eliminate the loading effect) results in multiplication of the transfer functions and an overall higher order transfer function with several pairs of conjugate poles.
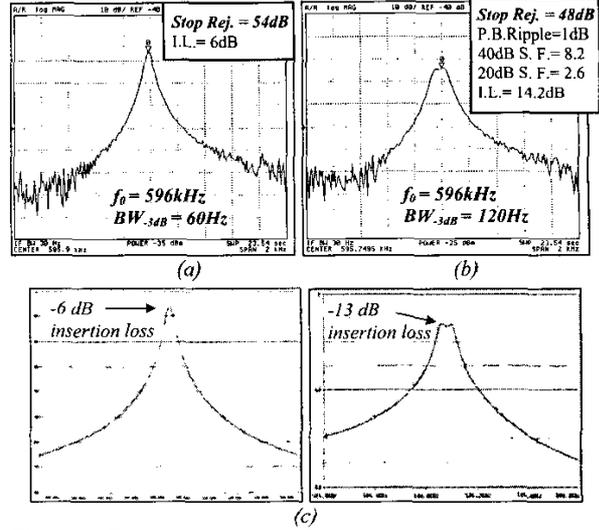

Figure 8. Frequency response of capacitively coupled resonators with off-chip interconnections a) equal center frequencies; b) separated center frequencies; c) simulation results for both cases.

When all the stages have equal center frequencies, cascading will result in order multiplication of poles, which can be interpreted as an overall higher equivalent quality factor. Mathematically, it can be shown that if n identical 2ⁿᵈ order resonators with individual quality factors of Q_i are cascaded, the resultant Q factor of the cascade is equal to:

$$Q_{total} = \frac{Q_i}{\sqrt{10^{0.3/n} - 1}} \quad \rightarrow \quad Q_{total} \cong 1.2\sqrt{n}Q_i \quad if \ n >> 1 \quad (3)$$

This concept can be used to increase the equivalent quality factor of MEMS resonators for filtering or frequency synthesis applications, in case their intrinsic Q is not high enough. In addition, according to the following equation, shape factor for the cascaded resonators is determined only by the order of the system, independent of the quality factor:

$$S.F_{40dB} = \sqrt{\frac{10^{4/n} - 1}{10^{0.3/n} - 1}} \quad \rightarrow \quad 1 \quad as \ n \ becomes \ large \quad (4)$$

Figure 9a illustrates simulation results of cascaded resonators with different orders showing the overall Q amplification by increasing the order of the system. The comparison between cascaded resonators with different number of stages but identical overall Q (Fig. 9b) confirms that despite having equal quality factors, higher order cascades provide sharper roll-off and better selectivity.
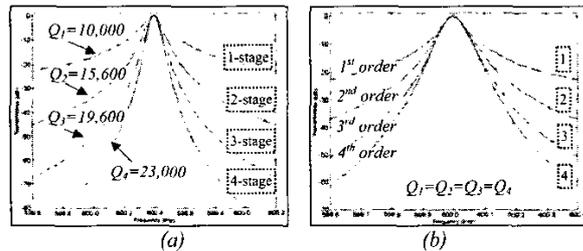

Figure 9. (a) Simulation results of cascaded resonators with individual Q=10,000 (600kHz). (b) Simulation results of cascaded resonators with identical overall quality factors & different orders.

To achieve larger bandwidths without sacrificing the sidewall sharpness in electrically cascaded micromechanical filters, one can take advantage of the frequency tuning characteristics of capacitive resonators. Introducing a slight mismatch between the center frequencies of cascaded resonators results in separation of poles and hence a wider bandwidth. However, center frequencies of cascaded devices should be close enough to avoid extra attenuation of each stage by the other stages.

2.2.1 Implementation and Results

Frequency response of the active cascade was investigated using a test setup comprised of cascaded HARPSS resonators (600kHz) with off-chip amplifiers in between. Second and third order bandpass filters were achieved using two and three cascaded resonator stages, respectively, as shown in Fig. 10. A passband gain can be achieved in this case because of the amplifiers. Figure 11 shows the frequency response of up to 3 stages of cascaded resonators with equal center frequencies (600kHz). An overall Q of 19,300 was achieved by cascading three resonators with individual Q of 10,000. Table 1 summarizes the measurement results of Q amplification via active cascading of the resonators at several center frequencies.
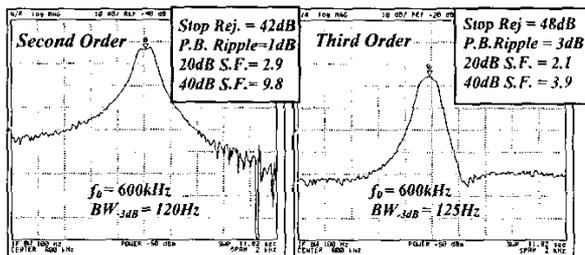

Figure 10. Frequency response of 2nd and 3rd order bandpass filters achieved by active electrical cascading of HARPSS resonators.

Table 1. Calculated and measured overall and individual Q's for cascaded resonators.

f_0	Q_1 1st stg	Q_2 2nd stg	Q_3 3rd stg	$Q_{cascade}$ Theory	$Q_{cascade}$ Measured
60.5kHz	17,500	16,300	-	26,300	28,100
449kHz	10,000	18,900	-	22,900	23,800
599kHz	9,800	10,600	-	15,900	15,600
599kHz	9,800	10,600	9,000	19,100	19,300
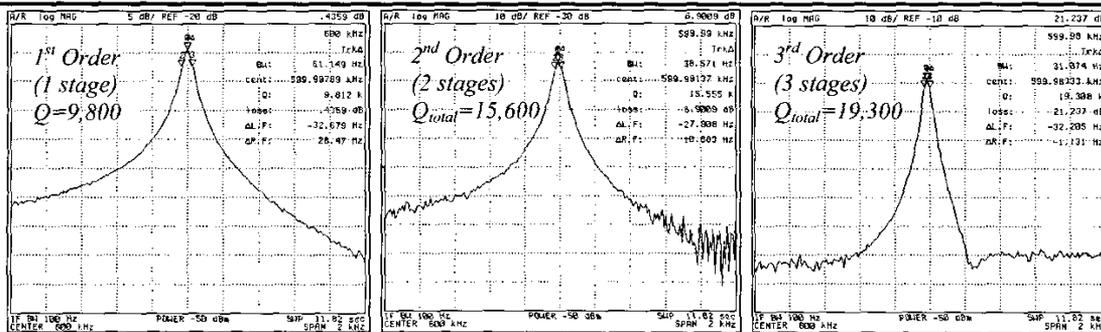
3. CONCLUSIONS

A MEMS filter synthesis approach based on the electrical coupling of capacitive microelectromechanical resonators was introduced and two variations of this approach were discussed. Single crystal silicon HARPSS capacitive resonators were used as building blocks for 2nd and 3rd order electrically-coupled filters. Measurement results of capacitively coupled (passive) filters show large insertion loss as a result of off-chip interconnections and large pad capacitors. Simulation results confirm that on-chip integration of coupling capacitors will reduce insertion loss of such filters to less than 1dB. A Q-enhancement technique based on active electrical cascading of the resonators was also presented, showing doubling of the Q in a 3-stage cascade.

ACKNOWLEDGMENTS

REFERENCES

[1] R. A. Johnson, "Mechnical filters in electronics", A Wiley-interscience publication.
[2] F. D. Bannon, et al, "High frequency micromechanical IF filters", IEDM 96, pp. 773-776.
[3] K. Wang, et al, "High-order medium frequency micromechanical electronic filters", JMEMS 8(4), 534, (1999).
[4] A.-C. Wong, et al, "Anneal-activated, tunable, 68MHz micromechanical filters", Sensors and Actuators 99, pp 1390-1393.
[5] L. Lin, et al, "Microelectromechanical Filters for Signal Processing", JMEMS 7(3), 286, (1998).
[6] D. S. Greywall, et al, "Coupled micromechanical drumhead resonators with practical applications as electromechanical bandpass filters", J. Micromech. Microeng. 12 (2002), pp 925-938.
[7] K. Wang, et al, "Q-Enhancement of microelectromechanical filters via low velocity spring coupling", IEEE Ultrasonics symposium, 1997, pp. 323-327.
[8] S. Y. No, et al, "Single crystal silicon HARPSS capacitive resonators with submicron gap spacings", proceedings, Hilton Head 2002, pp. 281-284.
[9] F. Ayazi and K. Najafi, "High Aspect-Ratio Combined Poly and Single-Crystal Silicon (HARPSS) MEMS Technology", JMEMS, 9(3), pp. 288-294, (2000).

Figure 11. Measured frequency response of cascaded resonators demonstrating Q amplification.