Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 462–463

A-8-1 (Invited)

RF-MEMS for Low-Power Communications

Clark T.-C. Nguyen

Center for Wireless Integrated Microsystems
Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, Michigan 48109-2122
Phone: (734)764-1220, FAX: (734)763-9324, E-mail: ctnguyen@eecs.umich.edu

1. Introduction

Recent demonstrations of micro-scale high-Q passive components that utilize microelectromechanical systems (MEMS) technology to allow on-chip integration alongside transistor circuits have sparked a resurgence of research interest in communication architectures that emphasize the use of high-Q passive devices [1][2]. Among the most useful of these are vibrating micromechanical ("μmechanical") resonator circuits with frequencies approaching UHF and Q's in the tens of thousands [3][4][5]; tunable μmechanical capacitors with Q's up to 300 at 1GHz [6]; μmachined inductors with Q's up to 30 at 1GHz [7]; and μmechanical switches with insertion losses as low as 0.1dB [8]. Although much of the interest in these "RF MEMS" devices originally derived from their amenability to on-chip integration, it is actually their potential for enhancing robustness and reducing power consumption in alternative transceiver architectures that makes them so compelling.

2. Vibrating Micromechanical Signal Processors

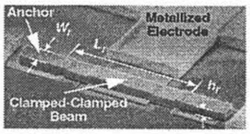
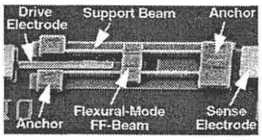
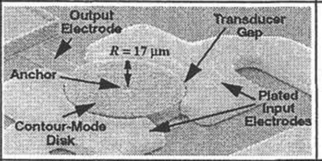
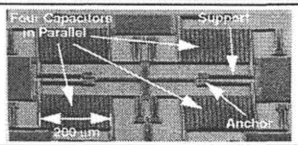
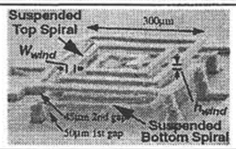
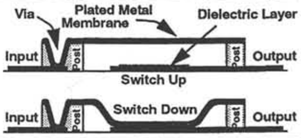
Table I summarizes the RF MEMS devices most useful for communications applications. Brief descriptions of each of these devices now follow.

High-Q Vibrating Micromechanical Resonators

Because mechanical resonances generally exhibit orders of magnitude higher Q than their electrical counterparts, vibrating mechanical resonators are essential components in communication circuits. With appropriate scaling via MEMS technology, such devices are expected to be able to vibrate over a very wide frequency range, from 1MHz to >1GHz, making them ideal for highly stable oscillator and low loss filtering functions at common transceiver frequencies.

The first three rows of Table I succinctly present the evolution of vibrating μmechanical resonator geometries over the past five years. As shown, clamped-clamped beam resonators, which are essentially guitar strings scaled down to μm dimensions to achieve VHF frequencies, can achieve on-chip

Table I: Micromechanical RF Devices Most Useful for Communications

Device	Photo/Schematic	Performance	Applications	Research Issues
CC-Beam Resonator [3]		Demonstrated: Q ~8,000 @ 10MHz Q ~300 @ 70MHz (anchor diss.) Q drop w/ freq. limits freq. range Series Resistance, R_x ~50-5000Ω	Reference Oscillator HF-VHF Filter HF-VHF Mixer-Filter (arrays of above)	power handling thermal/aging stability impedance vacuum packaging
FF-Beam Resonator [4]		Demonstrated: Q ~8,000 from 10-100MHz No drop in Q with freq. Freq. Range: >1GHz; unlimited w/ scaling and use of higher modes Series Resistance, R_x ~50-5000Ω	Reference Oscillator HF-UHF Filter HF-UHF Mixer-Filter Ka-Band? (arrays of above)	freq. extension power handling thermal/aging stability impedance vacuum packaging
Contour-Mode Disk Res. [5]		Demonstrated: Q ~10,000 @ 156MHz Balanced design; no anchor diss. Freq. Range: >1GHz; unlimited w/ scaling and use of higher modes Series Resistance, R_x ~50-5000Ω	Reference Oscillator VHF-S-Band Filter VHF-S-Band Mxr-Filter Ka-Band? (arrays of above)	freq. extension power handling thermal/aging stability impedance vacuum packaging
Tunable Capacitor [6]		Demonstrated: Q ~300 @ 1GHz using movable dielectric Q lower w/ movable metal plate Capacitance: 1-4pF	>UHF VCO's Tunable Biasing Tunable Matching Multi-Band RF Filter	tuning range stress control packaging microphonics
μMachined Inductor [7]		Demonstrated: Q ~30 @ 1GHz W_{wind}=30μm, h_{wind}=15μm, L~1-4nH using suspended, thick copper Q Range: can it get to 300?	>UHF VCO's Biasing/Matching Multi-Band RF Filter?	Q must increase to 300 for multi-band filter microphonics
μMech. Switch [8]		Demonstrated: IL ~ 0.1dB, IIP_3 ~66dBm Switching Voltage: >20V Switching Time: ~5μs trade switching voltage vs. power handling	Tunable Biasing Tunable Matching Phase Array Antennas Multi-Band RF Filter?	reliability switching voltage switching speed hot switching

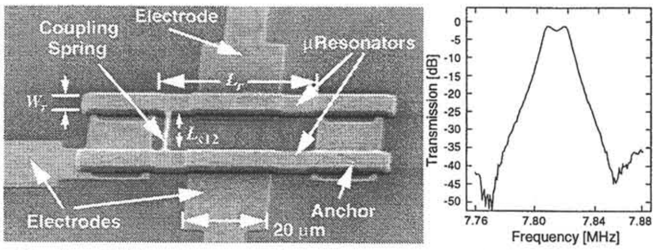


Fig. 1: SEM and measured frequency characteristic for a three-link, 7.81-MHz polysilicon µmechanical filter [3].

Q's ~8,000 for oscillator and filtering functions in the HF range. However, anchor losses in this specific structure begin to limit the achievable Q at higher VHF frequencies, limiting the practical range of this structure to <100MHz when using µm-scale dimensions. To achieve higher frequency while retaining Q's in the thousands and without the need for sub-µm- dimensions, more balanced structures that eliminate anchor losses can be used, such as the free-free beam or contour-mode disk resonators in rows 2 and 3 of Table I. These resonators are expected to be able to operate at and beyond GHz frequencies when properly scaled.

Although stand-alone vibrating µmechanical resonators are themselves applicable to local oscillator synthesizer applications in transceivers, their application range can be greatly extended by using them in circuit networks. In particular, by interlinking mechanical elements in specific networks, a variety of low-loss circuit functions are available, from bandpass filters [3] to mixers [9] to gain devices [9]. Figure 1 presents the scanning electron micrograph (SEM) and measured frequency characteristic for a 7.81-MHz µmechanical filter, showing only 1 dB of insertion loss for a 0.22% bandwidth, attained with zero dc power consumption.

High-Q Tunable Capacitors

Tunable µmechanical capacitors, summarized in row 4 of Table I, consist of metal plates that can be electrostatically moved with respect to one another, allowing voltage-control of the capacitance between the two plates. Because metal materials can be used in their construction, Q's as high as 300 can be attained—much higher than attainable by lossy semiconductor pn diodes offered by conventional IC technology. Paired with medium-Q inductors, µmechanical capacitors can enhance the performance of low noise VCO's. Also, if inductors could be achieved with Q's as high as 300, tunable RF pre-select filters might be achievable that could greatly simplify the implementation of multi-band transceivers.

Medium-Q Micromachined Inductors

As mentioned above, tunable µmechanical capacitors must be paired with inductors with Q >20 to be useful in communication circuits. Unfortunately, due to excessive series resistance and substrate losses, conventional IC technology can only provide spiral inductors with Q's no higher than 7. Using MEMS technologies to both thicken metal turns (reducing series resistance) and suspend the inductor turns away from the substrate (reducing substrate losses), inductors with Q's as high as 30 at 1GHz have been demonstrated (c.f., row 5 of Table I). Although not the Q ~300 needed for multi-band tunable RF filters, this Q ~30, when paired with a µmechanical capacitor, should allow the implementation of low noise VCO's with lower power consumption than those using conventional IC technology. Tunable bias/matching networks that can reduce power consumption in power amplifiers should also be feasible.

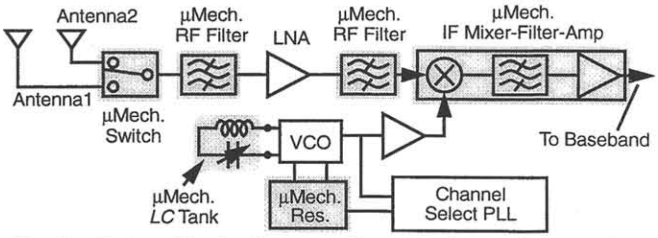


Fig. 2: System block diagram of a super-heterodyne receiver architecture showing potential replacements via MEMS-based components. (On-chip µmechanics are shaded.)

Micromechanical Switches

Micromechanical switches have essentially the same structure as the clamped-clamped beam resonators of row 1 in Table I, but are operated in a binary fashion: when the beam is up, the switch is open; when the beam is pulled down (e.g., by an electrostatic force), the switch is closed. Again, due to their metal construction made possible by MEMS technology, µmechanical switches post much smaller insertion losses than their FET-based counterparts (0.1dB versus 2dB) and are many times more linear, with IIP_3's >66dBm. Although their switching times are much slower than that of FETs, they are still adequate for antenna switching, switchable filter, and phased array antenna applications, provided their high switching voltage levels can be reduced or accommodated. If achievable, the above applications are desirable for multi-band reconfigurability in handsets and for diversity against multi-path fading. At present, the industry awaits improvements in the reliability of µmechanical switches.

3. Conclusions: MEMS-Based Transceiver Architectures

Perhaps the most direct way to harness RF MEMS devices is via direct replacement of off-chip components, as shown in Fig. 2. Due mostly to the higher Q attainable by on-chip µmechanical vibrating resonators relative to off-chip counterparts, analyses before and after replacement by MEMS in a super-heterodyne architecture often show dramatic improvements in receiver noise figure, e.g., from 8.8dB to 2.8dB.

Although beneficial, the performance gains afforded by mere direct replacement by MEMS are quite limited when compared to more aggressive uses of MEMS technology. To fully harness the advantages of µmechanical circuits, one should take advantage of their micro-scale size and zero dc power consumption, and use them in massive quantities to enhance robustness and trade Q for power consumption. The RF channel-select architecture proposed in [1] is one good example of this approach, where a bank of high-Q µmechanical filters is utilized to select channels right up at RF, greatly enhancing robustness and simplifying the design of subsequent stages.

References

[1] C. T.-C. Nguyen, *BCTM 2000*, pp. 142-149.
[2] C. T.-C. Nguyen, *et al.*, *Proc.IEEE*, pp. 1756-1768, Aug. 1998.
[3] F. D. Bannon III, *et al.*, *IEEE JSSC*, pp. 512-526, April 2000.
[4] K. Wang, *et al.*, *IEEE/ASME JMEMS*, pp. 347-360, Sept. 2000.
[5] J. R. Clark, *et al.*, *IEDM 2000*, pp. 493-496.
[6] D. J. Young, *et al.*, *Hilton Head Conf. 1996*, pp. 86-89.
[7] J. B. Yoon, *et al.*, *IEDM 1999*, pp. 753-756.
[8] Z. J. Yao, *et al.*, *IEEE/ASME JMEMS*, pp. 129-134, June 1999.
[9] A.-C. Wong, *et al.*, *IEDM 1998*, pp. 471-474.