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Microelectromechanical Devices for Wireless Communications

Clark T.-C. Nguyen

Center for Integrated Sensors and Circuits
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

ABSTRACT

An overview of recent progress in the research and development of microelectromechanical devices for use in wireless communication sub-systems is presented. Among the specific devices described are tunable micromachined capacitors, integrated high-*Q* inductors, low loss micromechanical switches, and micro-scale vibrating mechanical resonators with *Q*'s in the tens of thousands. Specific applications are reviewed for each of these components with emphasis on methods for miniaturization and performance enhancement of existing and future wireless transceivers.

I. INTRODUCTION

Vibrating mechanical tank components, such as crystal and SAW resonators, are widely used for frequency selection in communication sub-systems because of their high quality factor (*Q*'s in the tens of thousands) and exceptional stability against thermal variations and aging. In particular, the majority of heterodyning communication transceivers rely heavily upon the high *Q* of SAW and bulk acoustic mechanical resonators to achieve adequate frequency selection in their RF and IF filtering stages and to realize the required low phase noise and stability in their local oscillators. In addition, discrete inductors and variable capacitors are used to properly tune and couple the front end sense and power amplifiers. At present, the aforementioned mechanical resonator tanks and discrete elements are off-chip components, and so must interface with integrated electronics at the board level, often consuming a sizable portion of the total sub-system area. In this respect, these devices pose an important bottleneck against the ultimate miniaturization and portability of wireless transceivers. For this reason, many research efforts have been focused upon strategies for either miniaturizing these components [1-5] or eliminating the need for them altogether [6-8].

The rapid growth of IC-compatible micromachining technologies that yield micro-scale, high-*Q* tank components may now bring the first of the above strategies closer to reality. Specifically, the high-*Q* RF and IF filters, oscillators, and couplers, currently implemented via off-chip resonators and discrete passives may now potentially be realized on the micro-scale using micromachined equivalents based on a variety of novel devices, including high-*Q* on-chip mechanical resonators [9-11], voltage-tunable on-chip capacitors [12], isolated low-loss inductors [13-16], structures for high frequency isolation packaging [17], and low loss micromechanical switches [18]. Once these miniaturized filters and oscillators become available, the fundamental bases upon which communication systems are developed may also evolve, giving rise to new system architectures with possible power and bandwidth efficiency advantages.

This paper reviews recent progress in the research and development of microelectromechanical devices for use in communication sub-systems. It begins with a brief introduction into the needs of wireless communication transceivers, identifying specific functions that could greatly benefit from micromechanical implementation. Several specific devices will then be described, with particular emphasis on frequency-selective MEMS for high-*Q* oscillators and filters. The paper concludes by considering the impact that the discussed devices may have on future transceiver architectures.

II. MINIATURIZATION OF TRANSCEIVERS

To illustrate more concretely the specific transceiver functions that benefit from micromechanical implementation, Fig. 1 presents the system-level schematic for a typical super-heterodyne wireless transceiver. As implied in the figure, several of the constituent components can already be miniaturized using integrated circuit transistor technologies. These include the low noise amplifiers (LNA's) in the receive path, the solid-state power amplifier (SSPA) in the transmit path, synthesizer phase-locked loop (PLL) electronics, mixers, and lower frequency digital circuits for baseband signal demodulation. Due to noise, power, and frequency considerations, the SSPA (and sometimes the LNA's) are often implemented using compound semiconductor technologies (i.e., GaAs). Thus, they often occupy their own chips, separate from the other mentioned transistor-based components, which are normally realized using silicon-based bipolar and CMOS technologies. However, given the rate of improvement of silicon technologies (silicon-germanium included [19]), it is not implausible that all of the above functions could be integrated onto a single-chip in the foreseeable future.

Unfortunately, placing all of the above functions onto a single chip does very little towards decreasing the overall super-heterodyne transceiver size, which is dominated not by transistor-based components, but by the numerous passive components indicated in Fig. 1. The presence of so many frequency-selective passive components is easily justified when considering that communication systems designed to service large numbers of users require numerous communication channels, which in many implementations (e.g., TDMA) must have small bandwidths and must be separable by transceiver devices used by the system. The requirement for small channel bandwidths results in a requirement for extremely selective filtering devices for channel selection and extremely stable (noise free) local oscillators for frequency translation. For the vast majority of cellular and cordless standards, the required selectivity

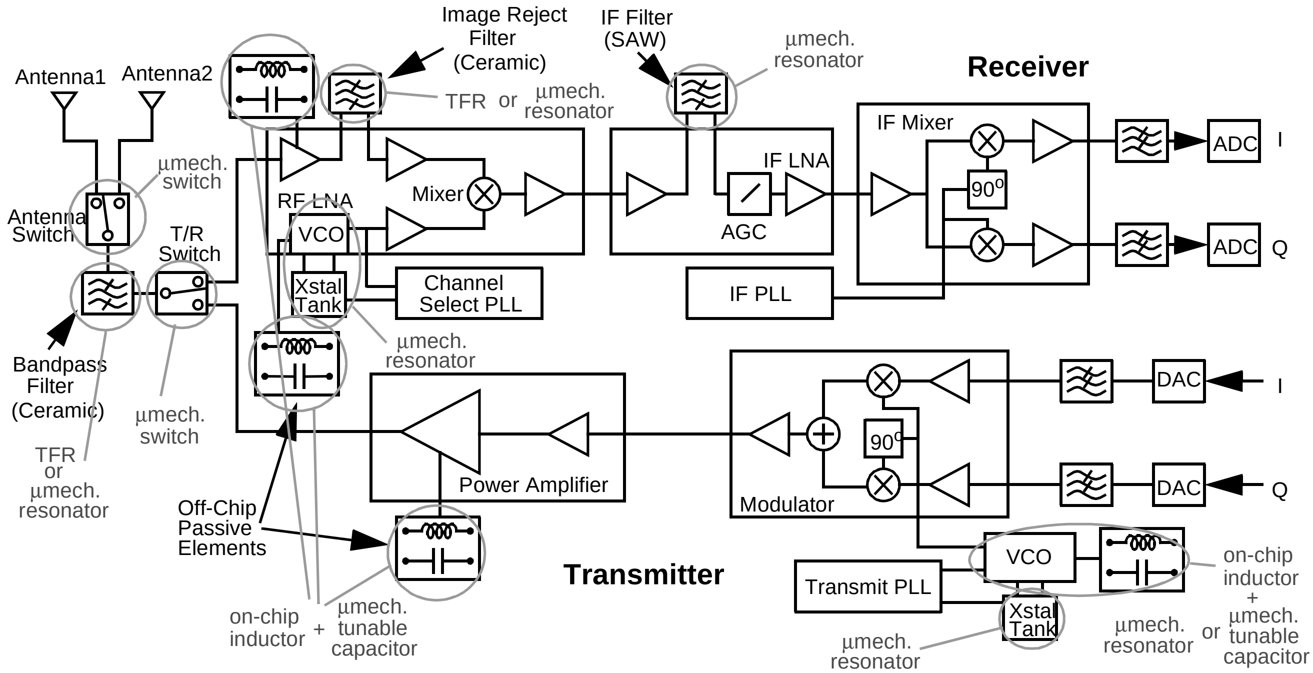

Fig. 1: System-level schematic detailing the front-end design for a typical wireless transceiver. The off-chip, high-*Q*, passive components targeted for replacement via micromechanical versions (suggestions in lighter ink) are indicated in the figure.

and stability can only be achieved using high-*Q* components, such as discrete inductors, discrete tunable capacitors (i.e., varactors), and SAW and quartz crystal resonators, all of which interface with IC components at the board level. The needed performance cannot be achieved using conventional IC technologies, because such technologies lack the required *Q*. It is for this reason that virtually all commercially available cellular or cordless phones contain numerous passive SAW and crystal components.

The Need for High Q in Oscillators.

For any communications application, the stability of the oscillator signals used for frequency translation, synchronization, or sampling, is of utmost importance. Oscillator frequencies must be stable against variations in temperature, against aging, and against any phenomena, such as noise or microphonics, that cause instantaneous fluctuations in phase and frequency. The single most important parameter that dictates oscillator stability is the *Q* of the frequency-setting tank (or of the effective tank for the case of ring oscillators). For a given application, and assuming a finite power budget, adequate long- and short-term stability of the oscillation frequency is insured only when the tank *Q* exceeds a certain threshold value.

The correlation between tank *Q* and oscillator stability can be illustrated heuristically by considering the simple oscillator circuit depicted in Fig. 2(a). Here, a series resonant oscillator is shown, comprised of a sustaining amplifier and an LC tank connected in a positive feedback loop. For proper start-up and steady-state operation, the total phase shift around the loop must sum to zero. Thus, if at the oscillation frequency the amplifier operates nominally with a 0^o phase shift from its input to its output, then the tank must also have a 0^o phase shift across its terminals. Given this, and referring to any one of the tank response spectra shown in Fig. 2(b) or (c), this oscillator is seen to operate nominally at the tank resonance frequency. If, however, an external stimulus (e.g., a noise spike, or a temperature fluctuation) generates a phase shift $-\Delta\theta$ across the terminals of the sustaining amplifier, the tank must respond with an equal and opposite phase shift $\Delta\theta$ for sustained oscillation. As dictated by the tank transfer functions of Fig. 2, any tank phase shift must be accompanied by a corresponding operating frequency shift Δf. The magnitude of Δf for a given $\Delta\theta$ is largely dependent on the *Q* of the resonator tank. Comparison of Fig. 2(b) with (c) clearly shows that a given phase shift incurs a much smaller frequency deviation on the tank with the higher *Q*. Thus, the higher the tank *Q*, the more stable the oscillator against phase-shifting phenomena.

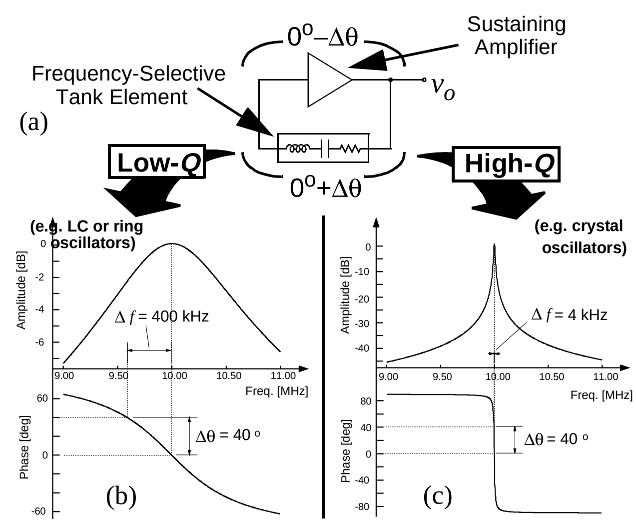

Fig. 2: (a) A simple series resonant oscillator schematic (b) Bode plot for a low *Q* tank, indicating the Δf for a given $\Delta\theta$. (c) Similar to (b), but for a high *Q* tank.

To help quantify the above heuristic concepts, one important figure of merit for oscillators is the phase noise power present at frequencies close to the carrier frequency. Typical phase noise requirements range from –100 dBc/Hz at 270

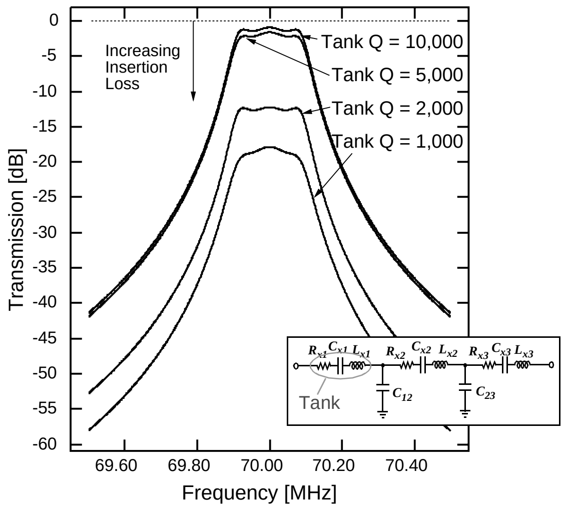

Fig. 3: Simulated frequency characteristics for a 0.3% bandwidth, 70 MHz bandpass filter under varying tank Q's.

kHz deviation from the carrier for the local oscillator in FDM/FM satellite communications networks [20] to –150 dBc/Hz at 67 kHz carrier deviations in Doppler-based radar systems [21]. Through a more rigorous analysis of Fig. 1 (assuming linear operation), the phase noise of a given oscillator can be described by the expression [20]:

$$\left(\frac{N_{op}}{C}\right)_{f_m} = \frac{FkT}{C}\frac{1}{8Q^2}\left(\frac{f_o}{f_m}\right)^2 \quad [\text{dBc/Hz}], \tag{1}$$

where $(N_{op}/C)_{fm}$ is the phase noise power density-to-carrier power ratio at a frequency f_m offset from the carrier frequency, F is the noise figure of the active device evaluated using the total oscillator power P, C is the carrier power delivered to the load, and f_o is the carrier frequency. From (1), phase noise is seen to be inversely proportional to the square of Q, and directly proportional to the amplifier noise figure F. Given that F can often be reduced by increasing the operating power P of the sustaining amplifier, (1) then can be interpreted as implying that power and Q can be traded to achieve a given phase noise specification. Given the need for low power in portable units, and given that the synthesizer (containing the reference and VCO oscillators) is often a dominant contributor to total transceiver power consumption, modern transceivers could benefit greatly from technologies that yield high Q tank components.

The Need for High Q in Filters.

Tank Q also greatly influences the ability to implement extremely selective IF and RF filters with small percent bandwidth, small shape factor, and low insertion loss. To illustrate, Fig. 3 presents simulated frequency characteristics under varying resonator tank Q's for a 0.3% bandwidth bandpass filter centered at 70 MHz, realized using the typical LC resonator ladder configuration shown in the insert. As shown, for a resonator tank Q of 10,000, very little insertion loss is observed. However, as tank Q decreases, insertion loss increases very quickly, to the point where a tank Q of 1,000 leads to 20 dB of insertion loss—too much even for IF filters, and absolutely unacceptable for RF filters. As with oscillators, high Q tanks are an outright requirement for RF and IF filters alike, although more so for the latter, since channel selection is done predominantly at the IF in super-heterodyne receivers.

III. MICROELECTROMECHANICAL COMPONENTS FOR TRANSCEIVERS

As shown in Fig. 1, the front-end of a super-heterodyne wireless transceiver typically contains a good number of off-chip, high-Q components that are potentially replaceable by micromechanical versions. Among the components targeted for replacement are RF filters, including image rejection filters, with center frequencies ranging from 800 MHz to 2.5 GHz; IF filters, with center frequencies ranging from 455 kHz to 254 MHz; high-Q, tunable, low phase noise oscillators, with frequency requirements in the 10 MHz to 2.5 GHz range; and switches for transmit/receive (T/R) selection, antenna selection, and multi-band configurability.

The following sub-sections now describe specific microelectromechanical components capable of both miniaturizing and improving the performance of the aforementioned functions.

Voltage-Tunable High-Q Capacitors.

One application presently under intense examination for possible miniaturization is that of the voltage-controlled oscillator (VCO) used in the synthesizer that generates the local oscillator signal. Currently, such VCO's are implemented using off-chip inductors (with Q's of at least 30) combined with off-chip voltage-tunable varactor diode capacitors (with Q's of at least 40). These relatively low Q values are justified for this VCO, because in the synthesizer this oscillator ends up slaved to a much more stable reference crystal oscillator, which cleans up the VCO's phase noise spectrum at small f_m's through the action of a PLL. As such, the phase noise specifications for this VCO are the easiest to satisfy in a given transceiver system, with numbers like –100 dBc/Hz at 10kHz offset from the carrier (for European GSM) being typical.

Even with this seemingly easy goal, however, attempts at miniaturization based on conventional IC technologies fall well short of this mark. In particular, CMOS ring or relaxation oscillators attain only –60 dBc/Hz at 10kHz offset [22]—not nearly adequate for GSM purposes. Furthermore, even slightly modified silicon CMOS and bipolar processes that include on-chip spiral inductors [23], or even bond wire inductors [24], yield LC VCO's with inadequate phase noise performance (~–85 dBc/Hz). A large part of the problem arises from the tunable capacitor implementation. Specifically, on-chip diodes used in place of previous off-chip varactor diodes exhibit excessive series resistance—much more than their off-chip varactor counterparts—and as a result, their Q's are severely lacking. In addition, the tuning range of such capacitors over available supply voltages is often limited to the point where trimming is required to set a starting capacitor value [25].

Recent demonstrations of voltage-tunable capacitors comprised of micromachined, movable, metal plates now offer substantial improvements over on-chip diode-based capacitors. Figure 4 presents the schematic of one such voltage-tunable micromachined capacitor [12], consisting of an aluminum top capacitor plate suspended by soft flexures above a bottom plate, in which the distance (and thus, capacitance) between the plates is electrostatically varied

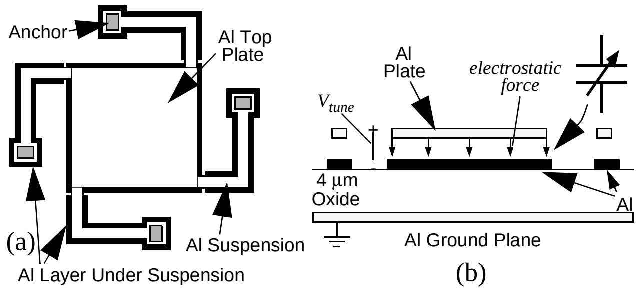

Fig. 4: (a) Overhead and (b) cross-sectional schematics of a voltage-tunable µmechanical capacitor [12].

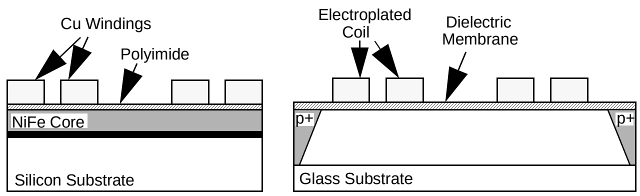

Fig. 5: Advanced integrated inductors utilizing micromachining processes. (a) Spiral inductor over a NiFe core. (b) Spiral inductor over an isolating platform. [13,14]

by action of the underlying electrode. The prototype capacitor of Fig. 4 exhibited a tuning range of about 16% over 5.5V of applied bias, with capacitance values on the order of 2.2 pF (achieved with four of these devices wired in parallel) and a Q of 62 at 1 GHz—all on par with off-chip varactor diodes [12].

Micromachined Inductors.

Obviously, implementation of a miniature tunable capacitor solves only part of the problem. To achieve resonator tanks with adequate Q (at least for VCO's), high Q inductors are required, as well. As mentioned above, numerous attempts to implement spiral inductors using conventional IC technologies have so far yielded inductors with insufficient Q [1-3]. Even those using bond wires as inductors fall short on Q for many applications [24].

For the above reasons, research aimed at improving on-chip inductor performance via more exotic micromachining technologies is currently underway. Among the strategies utilized for this purpose are (1) the use of magnetic cores to enhance coupling in inductive coils; and (2) removal of lossy substrates by fabricating inductors on suspended membranes, achieved via familiar backside etching techniques. Figure 5 presents two very recent applications of these methods. The inductor in Fig. 5(a) utilizes a NiFe core under a planar metal spiral to increase the achievable flux and attain 2.7 µH of inductance with a Q of 6.6 at 4 MHz [13]. This configuration was found to give the highest Q relative to three other topologies combining metal coils with magnetic cores.

Figure 5(b) presents the schematic of a miniature inductor fabricated on a substrate-isolating platform (or membrane) and achieving an overall inductance of 115 nH with a Q of 22 at 275 MHz. This inductor and others like it have achieved some of the highest Q values for on-chip inductors at their respective frequencies.

Despite the above promising results, the inductors of Fig. 5 are still inadequate for use in communication systems. In particular, both designs, even the one with substrate removed, suffer from parasitic self-resonance problems that

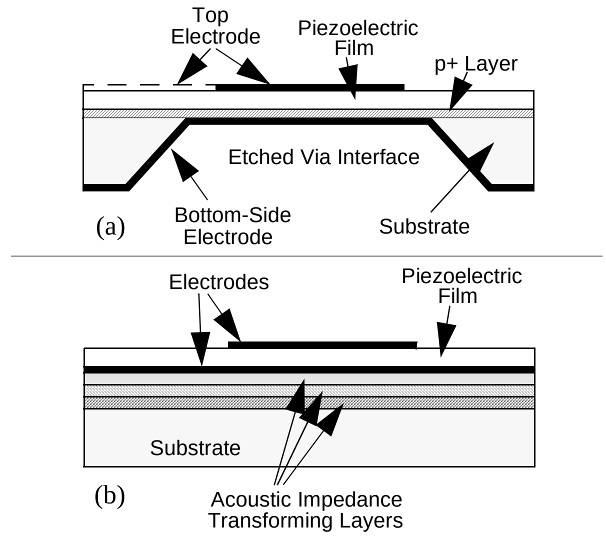

Fig. 6: Cross-sections of two thin-film bulk-acoustic resonators. (a) A membrane supported FBAR resonator [4]. (b) A solidly mounted resonator (SMR) [11].

limit their frequency range; secondly, for the case of Fig. 5(a) and for others based upon its design, the magnetic core only reacts up to a certain frequency range, beyond which its permeability drops to a useless value [16]. Research to solve these problems is ongoing.

Thin-Film Bulk Acoustic Resonators.

Assuming that Q's on the order of 40 can be achieved, the above tunable capacitors and on-chip inductors can potentially find use as resonator tanks for VCO's and low-Q RF filters, as well as elements for tunable couplers. However, given the present struggle to attain just these Q's, and with questions of susceptibility to microphonics and Brownian motion noise unanswered, it is unlikely that such elements could be utilized to replace the vibrating mechanical resonators (e.g., quartz crystals) used in the more demanding reference oscillator and channel-select filter functions. For these functions, as discussed in the context of Figs. 2 and 3, much higher Q's (in the thousands) are required.

With the knowledge that such Q's are already attainable using macroscopic vibrating mechanical tanks (e.g., quartz crystals, SAW's), much initial research had focused on developing exotic thin-film technologies to yield miniature versions of vibrating mechanical resonators operating under principles similar to their macroscopic counterparts. Figure 6(a) presents the schematic of one such thin-film bulk acoustic mode, piezoelectric resonator (FBAR), comprised of deposited piezoelectric films sandwiched between conductors in a similar fashion to quartz crystals, all suspended on a thin membrane, and so acoustically isolated from the substrate. Such resonators constructed using aluminum nitride piezoelectric films have been demonstrated with Q's of over 1000 and resonance frequencies from 1.5 GHz to 7.5 GHz [4,5]. Although very promising, the device of Fig. 6(a) awaits improvements in process and trimming technologies. In addition, problems with the structural integrity of the supporting membrane have been reported [11].

One promising solution to the above drawbacks dispenses with the fragile membrane support and allows construction of the thin-film resonator directly over a solid substrate, as shown in Fig. 6(b). In this scheme, energy loss to the substrate (which would greatly attenuate the Q) is avoided by acoustically isolating the substrate from the piezoelectric resonator materials using impedance transformations obtained through strategic selection of the number and thickness of layers separating the two media [11]. Although the implementation of such a solidly mounted resonator (SMR) requires more careful deposition of layers, it promises to greatly improve the resiliency of thin-film bulk acoustic resonators.

As with other novel technologies discussed here, thin-film bulk acoustic resonators, with all of their advantages, still have several important drawbacks that presently hinder their use. First, a convenient and effective means for trimming and tuning these resonators is not yet available. Such a trimming technology is vitally important, especially if groups of these resonators are to be used to implement small percent bandwidth filters with small shape factors. Second, these filters are presently most appropriate for the high UHF and S-Band frequency ranges, becoming overly thick and cumbersome at lower frequencies.

Micromechanical Resonators and Filters.

For lower frequency applications, planar IC-compatible micromachining processes have now realized flexural-mode micromechanical resonators in a variety of structural materials, and (so far) in a range of frequencies from LF to VHF. Q's exceeding 80,000 in vacuum have been measured for LF flexural-mode resonators constructed in surface-micromachined polysilicon [26], while Q's on the order of 20,000 have been achieved at 70 MHz (VHF) in SCREAM-processed single-crystal silicon material [27]. Since the use of this technology for high frequency applications is quite recent, its ultimate frequency limit is as yet unknown. Operating frequencies into the gigaHertz range, however, are not unreasonable [9,10].

In addition to their enormous Q values and wide applicable frequency range, micromechanical resonators are extremely flexible from a design perspective, having several features that greatly simplify the design and implementation of complex resonator systems. Among their most attractive features are (1) an inherent voltage-controlled frequency tunability [28] and switchability [10]; (2) a conduciveness to trimming [29]; (3) wide flexibility in available geometries (leading to a seemingly limitless range of possible designs); (4) flexibility in the choice of structural materials used; and (5) flexibility in the type of transduction used (electrostatic, piezoelectric, and magnetostrictive have all been utilized in the past). On top of all of this, successful construction of devices using such resonators is relatively straightforward, since critical features are usually defined by a single masking step, which itself is part of a planar process largely compatible with conventional IC processes.

The above features, in particular those associated with tuning and design flexibility, have greatly accelerated the rate at which more complex oscillator and filtering applications of the technology have been realized. Specifically, micromechanical filters comprised of multiple resonators coupled by soft mechanical springs have recently been implemented with performance attributes comparable to some of the best high-Q filters available. To date, two-resonator micromechanical bandpass filters (Fig. 7) have been demonstrated with frequencies up to 14.5 MHz, percent

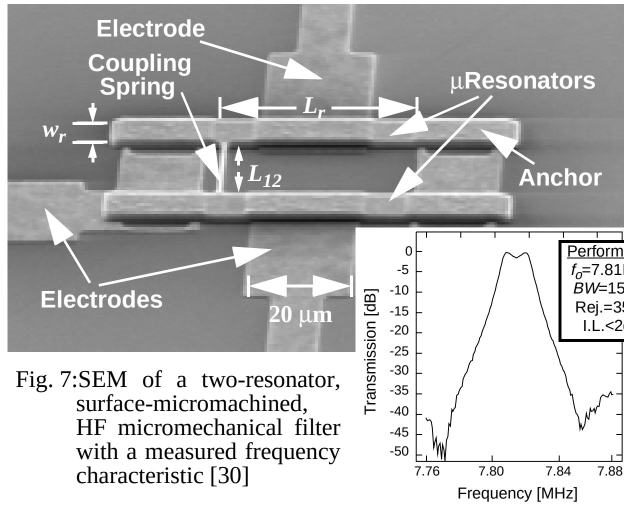

Fig. 7:SEM of a two-resonator, surface-micromachined, HF micromechanical filter with a measured frequency characteristic [30]

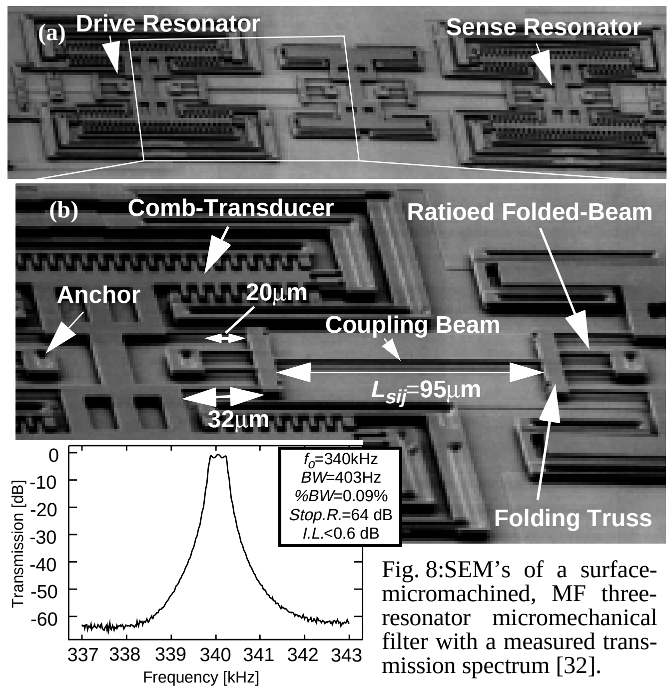

Fig. 8:SEM's of a surface-micromachined, MF three-resonator micromechanical filter with a measured transmission spectrum [32].

bandwidths on the order of 0.2%, and insertion losses less than 1 dB [30]. Higher-order three-resonator filters with frequencies near 455 kHz have also been achieved (Fig. 8), with equally impressive insertion losses for 0.09% bandwidths, and with more than 64 dB of passband rejection [31,32]. The filter of Fig. 8 features balanced comb-transduction for feedthrough suppression, low velocity coupling, and frequency tuning electrodes, adeptly illustrating the complexity and flexibility achievable using this technology.

In addition to filters, LF high-Q oscillators, fully-integrated with sustaining CMOS electronics, have also already been demonstrated in this technology. Figure 9 presents the overhead view SEM of a 16.5 kHz prototype of such an oscillator [33]. Recent studies of similar fully-integrated oscillators have shown phase noise performance expected of high-Q oscillator operation, but also show additional sources phase noise related to nonlinear amplitude perturbations caused by $1/f$ noise [34]. Thus, much work is still needed to attain optimal performance of micromechanical resonator oscillators. Research is also currently underway to extend the frequency of this oscillator to the popular 10

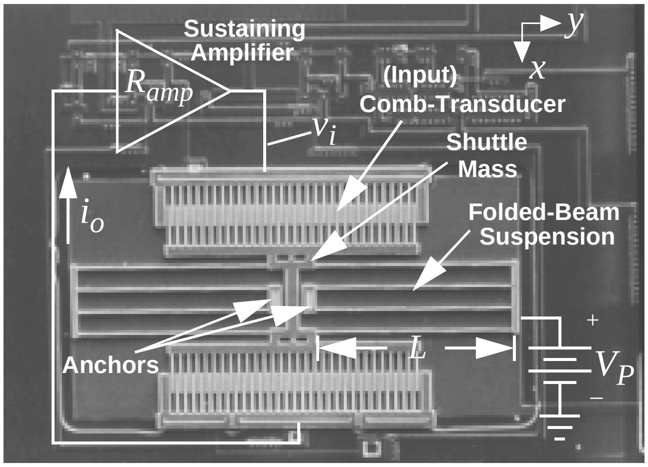

Fig. 9: SEM of the 16.5 kHz CMOS μresonator oscillator with schematics explicitly depicting circuit topology. The μresonator occupies $420 \times 230\ \mu m^2$ [33].

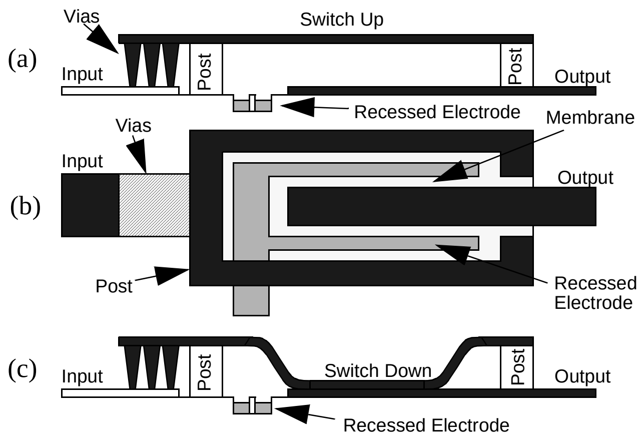

Fig. 10: Cross-sectional schematics of a typical micromechanical switch: (a) Switch up. (b) Overhead view. (c) Switch down [18].

MHz frequency of reference oscillators used in many transceivers, and to do so in a fashion that reduces the overall temperature coefficient of the oscillator.

Again, as with the other technologies, micromechanical resonator devices are not without their drawbacks. Among the more disturbing of them are the need for vacuum to attain high Q, an unaided temperature coefficient of -10 ppm/^{o}C [10] (not as good as quartz), and uncertainties concerning ultimate dynamic range and power handling capability [10]. Research on micromechanical resonators and their applications is ongoing.

Micromechanical Switches.

In addition to the filter and oscillator research described above, a good amount of research effort has focused on the implementation of micromechanical switches for antenna or filter-path selection in multi-band communication systems, and for deployment of phased-array antennas in higher frequency systems operating past Ka-band (where antennas become small enough for arrays). Such switches are often characterized by metrics describing switching speed and off/on impedance. So far, the majority of switches for communications have operated via electrostatic actuation.

Figure 10 presents the schematic of a single-pole, single-throw micromechanical switch developed by Texas Instruments [18]. The top and bottom electrodes of this switch are constructed of plated metal, and the actuating electrode is recessed to prevent shorting to the top electrode. For the case of high frequency switches, actual metal-to-metal contact is not necessary for switching; rather, a step change in plate-to-plate capacitance also realizes switching. Thus, in high frequency applications, a protective nitride film often resides above the bottom electrode plate to prevent sticking.

Switches such as shown in Fig. 10 normally outperform those implemented using pin diodes in "on-state" insertion loss and "off-state" isolation. They also consume zero power when activated, unlike their pin diode counterparts, which sink a finite amount of current in the "on-state". However, they are often slower than pin diode switches, they so far require relatively high actuation voltages, and research is still being conducted to evaluate their ultimate lifetimes. Aside from these drawbacks, however, micromechanical switches show great promise for substantially improving the performance of beam-steerable phased array antennas. Micromechanical switches are particularly attractive for such applications because their low insertion loss (which eliminates the need for loss-recovering PA's) and zero power consumption allows a substantial power savings when realizing phased array antennas.

IV. CONCLUSIONS

Due to the need for Q values beyond the capabilities of conventional IC technologies, board-level passive components continue to occupy a substantial portion of the overall area in super-heterodyne transceivers, presenting a key bottleneck against further miniaturization. Although there have been many research efforts aimed at replacing super-heterodyne architectures with alternatives that use higher levels of transistor integration to eliminate the need for off-chip passive elements, none of these new approaches has yet been able to match, let alone improve, the performance of existing systems.

Micromechanical resonators and micromachined passives, on the other hand, offer an alternative set of strategies for transceiver miniaturization and improvement, the simplest of which may merely retain proven super-heterodyne architectures, the boldest of which may revolutionize the way future transceivers are designed. In particular, the availability of high-Q micromechanical filters, with their tiny size and zero dc power dissipation, may encourage future architectures that take advantage of large arrays of such filters to yield novel transceivers with multi-band capability and enhanced security against jamming or interception. In combination with low clock-rate sub-sampling down-converters [8], such an array architecture might also provide substantial power savings over previous systems, especially when used in frequency hopping scenarios. Needless to say, research on micromechanical devices for communications continues on both device and system levels, with quiet promises to greatly influence wireless communications in the near future.

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