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Communications Applications of Microelectromechanical Systems

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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

The increasing demand for smaller and more capable portable phones, notebook computers, global positioning system (GPS) receivers, and remote sensors, has spawned an explosion of growth in wireless communications technology. As the volume of users increases, so does the requirement for more efficient use of the allocated spectral frequency ranges, and this in turn leads to increasingly stringent standards for transceiver components, requiring much more capable implementation technologies. From the consumer viewpoint, although the size of portable transceiver units has decreased substantially over the past few years down to the palm-sized, hand-held units commonly seen today, the demand for even smaller and cheaper devices—e.g., ones that can perhaps fit into the size of wristwatches—continues to drive much of today’s wireless research and development. In particular, miniaturized transceivers constructed using high volume planar integrated circuit (IC) technologies and perhaps fitting onto single silicon chips are of enormous interest.

At present, the ultimate miniaturization of super-heterodyne transceivers is limited mainly by the need for numerous off-chip, frequency-selective, passive components, many of which derive needed properties via mechanical operation (e.g., vibrating resonators, mechanical switches). Given the mechanical nature of these components, it makes logical sense to attempt to miniaturize these functions using micromechanical technologies that retain the needed mechanical properties, but implement them in orders of magnitude smaller size. For this purpose, micromechanical realizations of small percent bandwidth filters [1-3], highly stable and tunable oscillators [4-5], and low-loss switches [6-8] have all been investigated in recent research efforts with performance measures that equal or better those of their macroscopic counterparts.

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.

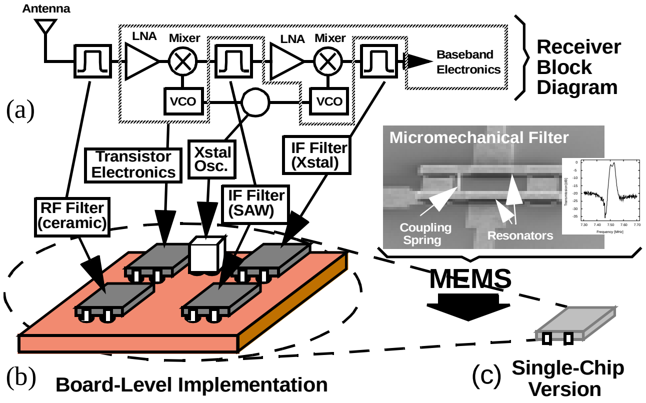

Fig. 1: (a) Simplified block diagram of a dual-conversion receiver. (b) Approximate physical implementation, emphasizing the board-level nature (many inductor and capacitor passives not shown). (c) Possible single-chip implementation using MEMS technology.

II. MINIATURIZATION OF TRANSCEIVERS

To illustrate more concretely the issues involved with miniaturization of transceivers, Fig. 1(a) presents the simplified block diagram for a wireless receiver, along with an approximate physical implementation in Fig. 1(b). As shown, many of the components in this system can already be miniaturized using conventional IC transistor technologies, including the low-noise amplifiers (LNA’s), mixers, synthesizer electronics, and baseband digital circuits that demodulate the incoming waveform, converting it to human-perceptible forms (e.g., audio, video). At present, although all of these functions are realized via transistor technologies, they generally do not occupy a single chip. In particular, due to a much higher frequency of operation, the first LNA is often implemented in a compound semiconductor technology, whereas the other transistor circuit components are realized in silicon. In addition, to maximize isolation between analog and digital functions, the baseband digital processing often also occupies its own chip. However, given the recent rapid advancements in bipolar and CMOS silicon (and SiGe [9]) technologies, and given recent micromachined isolation packaging technologies [10-11], it is not unreasonable that all of these transistor-based functions can occupy a single chip in the foreseeable future, and this is depicted in Fig. 1(b).

There are still, however, many functions in Fig. 1(a) that cannot be miniaturized using conventional IC transistor technologies. In particular, functions that require high frequency selectivity (with *Q*'s exceeding 30) cannot be implemented using conventional IC technologies, because the transistors, spiral inductors, and junction diode capacitors available through such processes are capable of *Q*'s on the order of only 5 or 6 at the frequencies of interest [12-14]. As a result, alternative off-chip technologies are used for the high-*Q* functions, including off-chip inductors, tunable capacitors, and vibrating mechanical and dielectric resonators. In particular, for cellular applications, the RF filters are often implemented using ceramic resonator technologies, the IF filters via quartz bulk acoustic and surface-acoustic (SAW) resonators, and the highly stable local oscillators by combinations of quartz and tunable LC tanks, all of which interface with transistor electronics at the board level, thus imposing a significant bottleneck against ultimate miniaturization of transceivers.

To date, many of the strategies for miniaturization of transceivers have been formulated on the premise that the above off-chip high-*Q* components cannot be miniaturized. Thus, the majority of research efforts aimed at miniaturizing transceivers have focused upon eradication of off-chip components using alternative transceiver architectures [15], such as direct conversion (zero-IF) [16], quasi-IF [17], and direct sub-sampling down-conversion [18], all of which attempt to eliminate the need for high-*Q* IF filters. Although attractive on paper, these alternative architectures have not achieved performance on par with super-heterodyne architectures, mainly due to practical issues in their operation. In particular, zero-IF designs are plagued by random dc-offsets that vary according to spatial movements of the transceiver; sub-sampling designs suffer from aliasing noise and jitter problems; and quasi-IF architectures, while partially suppressing the dc-offset problems of zero-IF, still provide inadequate dynamic range for many wireless applications. In addition, the above architectures do not achieve true single-chip implementations, since they all still require high-*Q* RF filters and reference oscillators. For these reasons, super-heterodyne architectures are still preferred by the vast majority of wireless transceiver manufacturers.

Fortunately, recent achievements in micromachining technologies now make possible a more direct approach to miniaturization, in which super-heterodyne architectures are retained and miniaturization is achieved by replacing off-chip macroscopic high-*Q* components with on-chip *micro*mechanical versions. In particular, planar IC-compatible micromachining technologies offer various approaches for achieving resonator tanks with *Q*'s from 30 to 100,000, or higher. By merging these technologies with those of planar IC transistors (via either full planar integration or bonding methods), single-chip transceivers that include RF filters and reference oscillators may be possible in the foreseeable future (Fig. 1(c)). As an added bonus, the size reductions afforded by these technologies, and their amenability to single-chip integration with transistor electronics, can potentially lead to large reductions in power consumption—a needed benefit considering the smaller battery size to be required by smaller transceiver units.

III. MICROELECTROMECHANICAL COMPONENTS FOR TRANSCEIVERS

Figure 2 shows a more complete block diagram schematic for both the transmit and receive paths in the front end of a typical super-heterodyne transceiver. Among the components targeted for replacement by micromechanical versions 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 [19]—not nearly adequate for GSM purposes. Furthermore, even slightly modified silicon CMOS and bipolar processes that include on-chip spiral inductors [20], or even bond wire inductors [21], 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 [22].

Recent demonstrations of voltage-tunable capacitors comprised of micromachined, movable, metal plates now offer substantial improvements over on-chip diode-based

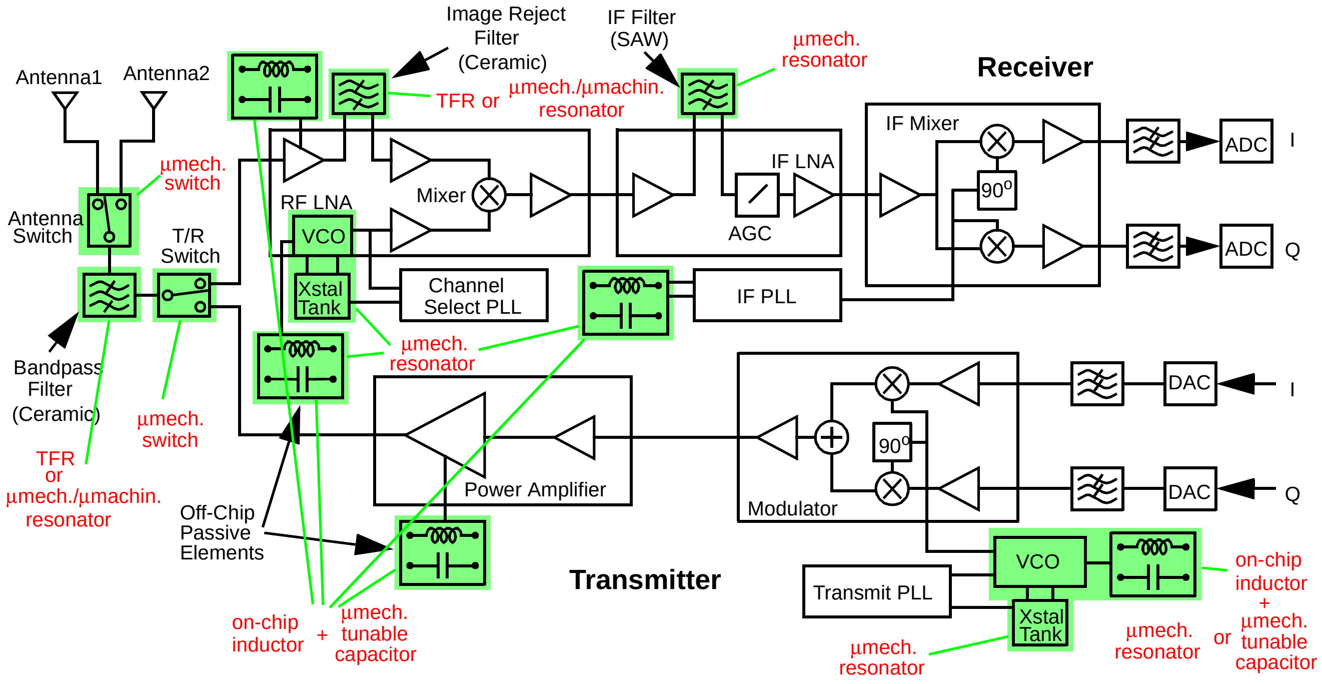

Fig. 2: System-level schematic detailing the front-end design for a typical wireless transceiver. The off-chip, high-Q, passive components targeted for replacement via micromechanical versions (suggestions in lighter ink) are indicated in the figure.

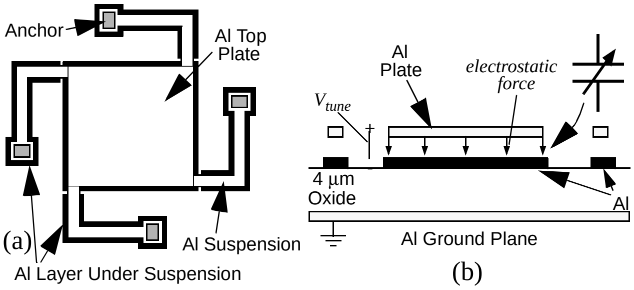

Fig. 3: (a) Overhead and (b) cross-sectional schematics of a voltage-tunable µmechanical capacitor [23].

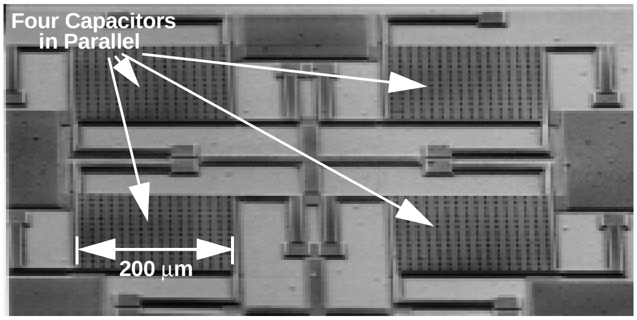

Fig. 4: SEM of a voltage-tunable µmechanical capacitor [23].

capacitors. Figure 3 presents the schematic of one such voltage-tunable micromachined capacitor [23], 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 by action of the underlying electrode. The SEM of a fabricated capacitor comprised of four of these plates hooked in parallel is shown in Fig. 4. This capacitor exhibited a tuning range of about 16% over 5.5V of applied bias, with capacitance values on the order of 2.2 pF and a Q of 62 at 1 GHz—all on par with off-chip varactor diodes [23].

The main drawback with this type of capacitor has so far been its susceptibility to acceleration or microphonics. For this reason, research in this area focuses upon achieving similar mechanically tunable capacitors with greater resiliency against microphonics via use of stiffer springs or more rigid support and actuation mechanisms.

Micromachined Inductors.

For the needed VCO tank circuits, 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 [12-14]. Even those using bond wires as inductors fall short on Q for many applications [21]. The deficiencies of spiral inductors implemented using conventional IC technologies is perhaps best illustrated via the equivalent circuit for such an inductor, shown in Fig. 5. As shown, the equivalent circuit contains not only the desired inductance L_S, but also a series resistor R_S associated with resistance in the turns wires, as well as parasitic capacitance coupling the turns to each other and to the substrate. These parasitics both lower the Q of the inductor, making it insufficient for communications applications, and create a self-resonance frequency that limits the maximum frequency of operation of the inductor.

In order to improve inductor performance, more exotic technologies are required to increase the inductance per unit length of the turns and/or to reduce coupling to the sub-

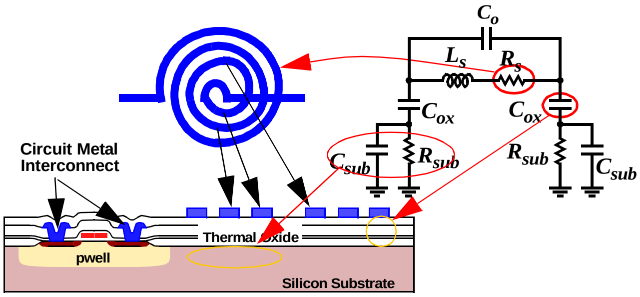

Fig. 5: Overhead and cross-sectional views of a typical spiral inductor implemented in a conventional IC technology, along with the corresponding equivalent circuit.

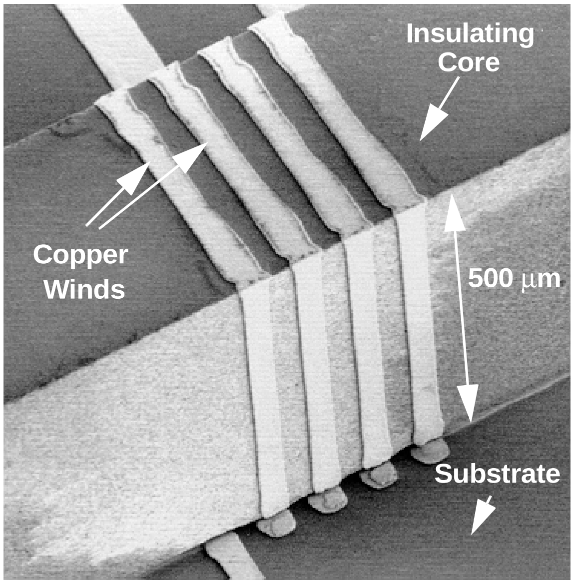

Fig. 6: 3-D inductor adhesively mounted miniature inductor coil [26].

strate. One strategy for realizing a larger inductance per unit length is to use a magnetic core underlying the spiral inductor [24]. This approach, however, is so far limited to low frequencies, since the permeabilities of the magnetic cores used to date have rolled off at higher frequencies.

For higher frequencies, strategies based on isolation of turns from the substrate have been more successful. Inductor values on the order of 115 nH have been achieved with Q's on the order of 22 at 270 MHz using EDP- or KOH-based substrate removal strategies [25]. A more recent miniaturized inductor, shown in Fig. 6, utilizes an exotic, maskless, three-dimensional, direct-write, laser lithography technology to pattern resist molds for metal winds around an insulating core, creating a miniature coil inductor, which both isolates the winds from the substrate, and increases the inductance per unit length in the winds without introducing significant self-resonance limitations [26]. Using a one-wind version in this technology, an inductance of 4.8 nH has been achieved with a Q of 30 at 1 GHz. This represents the best performance to date for a micro-scale inductor operating in the gigaHertz range, and is adequate for VCO purposes [26]. Whether this technology is conducive to high volume production remains an issue.

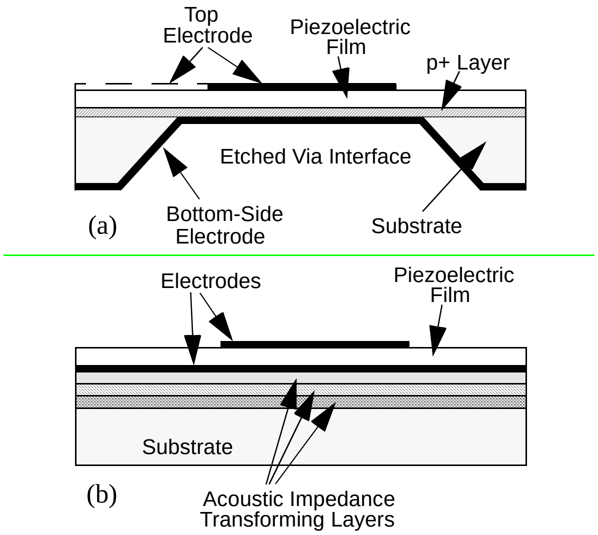

Fig. 7: Cross-sections of two thin-film bulk-acoustic resonators. (a) A membrane supported FBAR resonator [29]. (b) A solidly mounted resonator (SMR) [33].

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, 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 7(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 [29,30]. Although very promising, the device of Fig. 7(a) awaits improvements in process and trimming technologies. In addition, problems with the structural integrity of the supporting membrane have been reported [33].

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. 7(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 [33]. 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 [37], while Q's on the order of 20,000 have been achieved at 70 MHz (VHF) in SCREAM-processed single-crystal silicon material [38]. 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 [31,32].

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 [39] and switchability [32]; (2) an amenability to trimming [40]; (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.

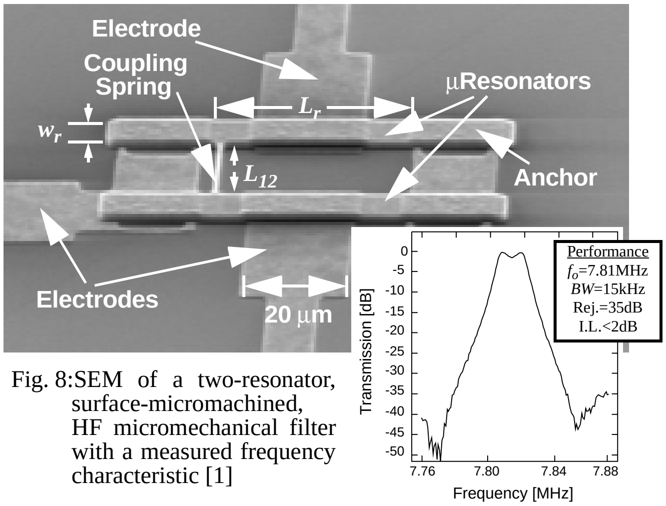

Fig. 8:SEM of a two-resonator, surface-micromachined, HF micromechanical filter with a measured frequency characteristic [1]

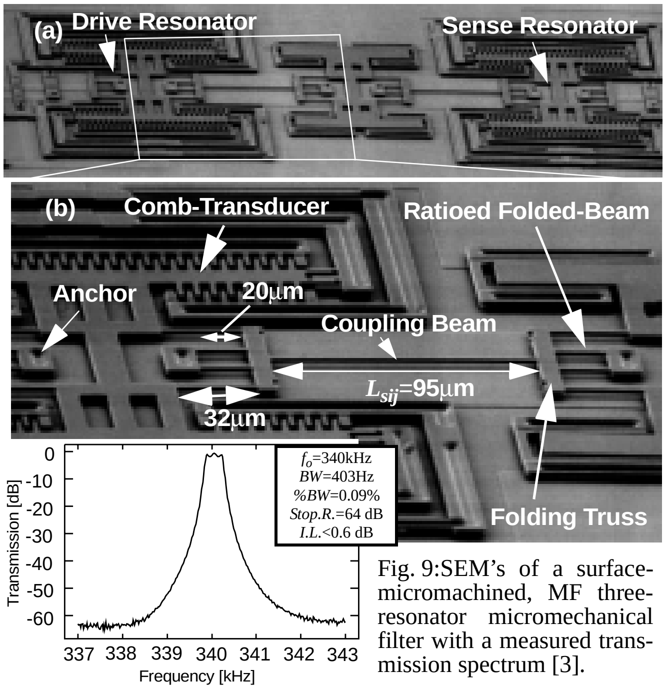

Fig. 9:SEM's of a surface-micromachined, MF three-resonator micromechanical filter with a measured transmission spectrum [3].

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. 8) have been demonstrated with frequencies up to 14.5 MHz, percent bandwidths on the order of 0.2%, and insertion losses less than 1 dB [1]. Higher-order three-resonator filters with frequencies near 455 kHz have also been achieved (Fig. 9), with equally impressive insertion losses for 0.09% bandwidths, and with more than 64 dB of passband rejection [2,3]. The filter of Fig. 9 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 10 presents the overhead view SEM of a 16.5 kHz prototype of such an oscillator [4]. Recent studies of similar fully-integrated oscillators have shown phase noise performance expected

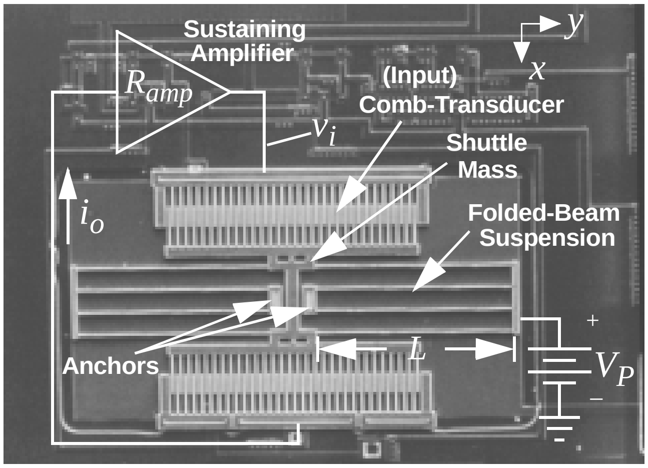

Fig. 10: SEM of the 16.5 kHz CMOS μresonator oscillator with schematics explicitly depicting circuit topology. The μresonator occupies 420×230 μm^2 [4].

of high-Q oscillator operation, but also show additional sources phase noise related to nonlinear amplitude perturbations caused by $1/f$ noise [5]. 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 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 [32] (not as good as quartz), and uncertainties concerning ultimate dynamic range and power handling capability [32]. 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 11 presents the cross-sectional schematic of a typical single-pole single-throw micromechanical switch. Such switches are now developed by several US industries [6-8]. As shown, the switch of Fig. 11 utilizes an air-bridge design, in which a bridge of conducting material is suspended 3-4 μm over a coplanar line. The top and bottom plates of this switch are constructed of evaporated or plated aluminum or gold. For the case of microwave/mm-wave switches, actual metal-to-metal contact is not necessary; rather, a step change in plate-to-plate capacitance also realizes switching. Thus, in high frequency applications, a protective nitride film (on the order of 1000 Å) often resides above the bottom electrode plate to prevent sticking when plates are pulled together. The dimensions of the top plate are around 300-400 μm-square for a 10-20 GHz switch, and 200 μm for 60 GHz designs.

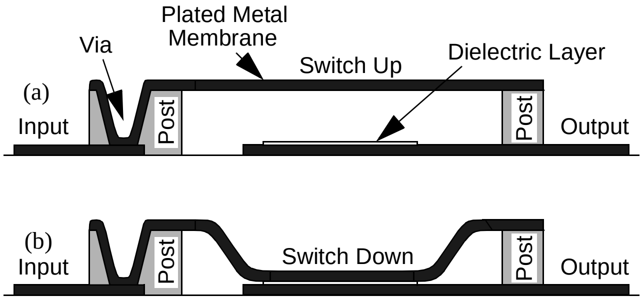

Fig. 11: Cross-sectional schematics of a typical micromechanical switch: (a) Switch up. (b) Switch down [6].

Micromechanical switches have been fabricated in both series and shunt (to ground) configurations. The insertion loss of a typical shunt switch in the “on-state” position (bridge is up and capacitance is low) is around 0.1 dB at 10 GHz and increases linearly with frequency to 0.6 dB at 60 GHz. The isolation of a micromechanical switch in the “off-state” position (bridge is low and capacitance is high) is directly proportional to the bridge area and can be designed to be -20 to -25 dB at 20 GHz, at 40 GHz, or at 60 GHz [6]. To date, metal-to-metal series switches which have shown impressive “off-state” (bridge is up and capacitance is low) isolation at 1-4 GHz (-60 to -50 dB), with a very low “on-state” (bridge is down and metal to-metal contact is achieved) insertion loss (-0.1 dB), have been demonstrated [7]. Currently, most shunt switches can safely handle 0.5-2 W of RF power in the “on-state” position before hot-switching becomes a problem, a phenomena where the RF voltage under the switch in the “on-state” position develops enough of a voltage to actually pull the micromechanical bridge down.

Micromechanical switches, such as shown in Fig. 11, normally outperform those implemented with PIN diodes or GaAs FETs in “on-state” insertion loss and “off-state” isolation. They also consume zero power when activated, unlike their solid-state counterparts which sink a finite amount of current when activated. However, most are much slower than PIN or FET diode switches (4-20 μs vs. 1-40 ns), and they so far require relatively high actuation voltages (20-60 V vs. 3-5 V). Micromechanical switches are also prone to stiction problems in a metal-to-metal switch and dielectric charging problems in case of a nitride film between the electrodes, and research is still being conducted to evaluate their ultimate lifetimes (now at billions of cycles). However, there is one aspect of micromechanical switches that makes them extremely favorable for communication systems: Micromechanical switches are extremely linear devices. A 2 GHz switch in a two-tone experiment resulted in unmeasured intermodulation products and an extrapolated IP3 of 66 dBm (4000 W).

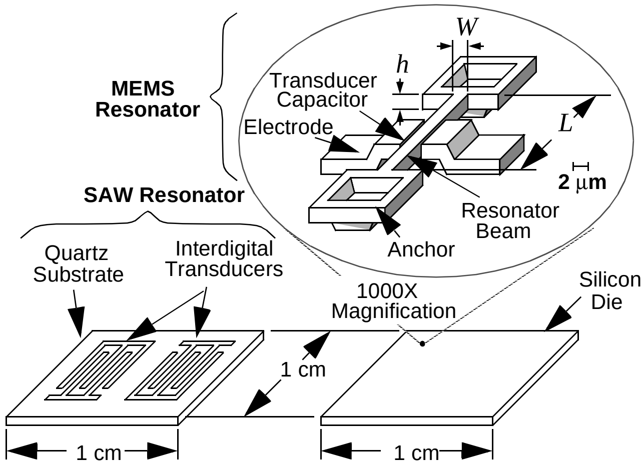

Fig. 12: Size comparison between present-day SAW resonator technology and the described high-Q μmechanical resonator technology.

Micromechanical switches are particularly attractive in low-power RF/microwave/mm-wave communication systems because of their low distortion characteristics, and for active antenna applications (phased arrays, power combining, etc.) because of their very low insertion loss (which eliminates the need for loss-recovering power amplifiers) and near-zero DC power consumption (which allows substantial power savings). Research on micromechanical switches continues, and new versions with all of the above advantages, but with much smaller actuation voltage requirements and much faster response times, are presently under investigation [8].

IV. FUTURE TRANSCEIVERS USING MEMS

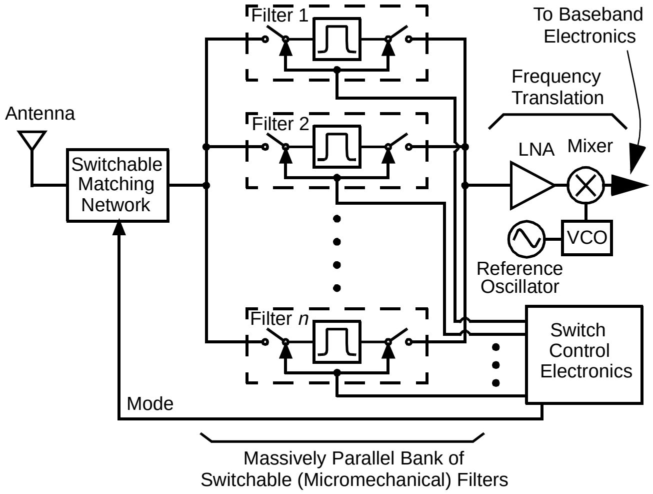

Fig. 13: Possible front-end receiver architecture utilizing a parallel bank of switchable micromechanical filters for a first stage of channel selection. Note that it is also possible to replace the frequency translation blocks with a low clock-rate sub-sampling down-converter.

From a component perspective, the above micromechanical devices offer tremendous size reduction when used to replace existing macroscopic counterparts. To emphasize the substantial size difference, Fig. 12 compares a typical SAW resonator with a clamped-clamped beam micromechanical resonator of comparable frequency. The particular μresonator shown is a variation to those previously shown, this one designed to vibrate in a direction parallel to the substrate with a frequency determined by material properties, geometric dimensions, and stress in the material. Typical dimensions for a 100 MHz micromechanical resonator are $L \approx 12.9$ μm, $W=2$ μm, and $h=2$ μm. With electrodes and anchors, this device occupies an area of 420 μm^2 = 0.00042 mm^2. Compared with the several mm^2 required for a typical VHF range SAW resonator, this represents several orders of magnitude in size reduction. In addition, as mentioned previously in Section II, integration with transistor electronics is also possible for the majority of these technologies, and this results in additional transceiver size reduction. Perhaps, however, the most important benefit is in power consumption, since such a fully integrated transceiver eliminates the need to drive board-level capacitors and allows a certain amount of impedance tailoring for passive devices, resulting in significant power savings over board-level implementations. Such power reduction is essential, since transceiver size reduction must also be accompanied by battery size reduction.

Perhaps the most revolutionary impact offered via micromechanical implementation will prove to be architectural. In particular, although both miniaturization and power reduction are attainable via mere substitution of micromechanical components for their macroscopic counterparts in the system of Fig. 2, even more power savings may be possible by taking advantage of new flexibilities. In particular, when using micromechanical components, architectures are no longer limited to just a handful of high-Q components. For the case of micromechanical filters, hundreds, perhaps thousands of them can now be used, with little size penalty (thousands will still require less space than a single one of today's macroscopic filters) and—given the passive nature of micromechanical resonators—no additional power consumption.

Thus, rather than use a single tunable filter to select one of several channels over a large frequency range, a massively parallel bank of switchable, micromechanical filters can be utilized, in which desired frequency bands can be switched in, as needed. The simplified block diagram for such a front-end architecture is illustrated in Fig. 13, where each filter switch combination corresponds to a single micromechanical filter, with input and output switches activated by the mere application or removal of dc-bias voltages (V_P) from the resonator elements. By further exploiting the switching flexibility of such a system, some very resilient frequency-hopping spread spectrum transceiver architectures can be envisioned that take advantage of simultaneous switching of high-Q micromechanical filters and oscillators. If resonator Q's are high enough ($>$ 10,000), channel selection may be possible directly at RF, followed by direct conversion using a low clock rate sub-sampling A/D converter [18] with relaxed dynamic range requirements, and thus, further power savings.

V. 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 [18], 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 promises to greatly influence wireless communications in the near future.

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