

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

Q 's $\sim 8,000$ 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 <100 MHz when using μ m-scale dimensions. To achieve higher frequency while retaining Q 's in the thousands and without the need for sub- μ m- 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 μ mechanical 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 μ mechanical filter, showing only 1 dB of insertion loss for a 0.22% bandwidth, attained with zero dc power consumption.

High- Q Tunable Capacitors

Tunable μ mechanical 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, μ mechanical 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 μ mechanical 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 $Q \sim 300$ needed for multi-band tunable RF filters, this $Q \sim 30$, when paired with a μ mechanical capacitor, should allow the implementation of low noise VCO's with lower power consumption than those using conventional IC technology. Tunable bias/matching networks

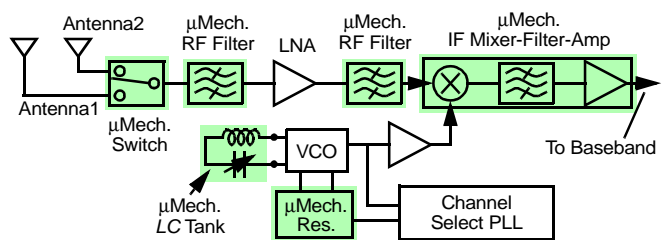


Fig. 2: System block diagram of a super-heterodyne receiver architecture showing potential replacements via MEMS-based components. (On-chip μ mechanics are shaded.)

that can reduce power consumption in power amplifiers should also be feasible.

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, μ mechanical 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 >66 dBm. 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 μ mechanical 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 μ mechanical 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 μ mechanical 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 μ mechanical filters is utilized to select channels right up at RF, greatly enhancing robustness and simplifying the design of subsequent stages.

References

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