MICROWAVE MEMS TECHNOLOGY FOR NEXT-GENERATION WIRELESS COMMUNICATIONS - INVITED PAPER

Lawrence E. Larson

Center for Wireless Communications
University of California, San Diego
La Jolla, CA 92093

ABSTRACT

The use of MEMS technology for microwave applications promises to solve some of the most vexing problems still confronting the field of high-frequency technology for wireless communications. This paper provides a historical view of this field, surveys the state-of-the-art in recent performance, and outlines the research challenges ahead for MEMS to move into widespread use.

I. INTRODUCTION

The market for wireless personal communications devices has developed so dramatically in recent years that it is easy to forget that the fundamental *architecture* of radio transceivers has not significantly evolved from Armstrong's superheterodyne of the late 1920's. One reason for this is the elegance and simplicity of the "superhet" design, which discourages competitive approaches. However, another reason is the lack of fundamentally *new* high frequency devices that allow for alternative architectures to be considered. The widespread development of MEMS technologies promises one route for the development of new classes of transceivers for wireless applications. This potential has been realized in a dramatic fashion in recent years, with research on MEMS for RF applications increasing dramatically [1].

MEMS technology can be categorized in several different ways, and different types of MEMS devices can provide for differing types of functions. All MEMS devices provide for a certain amount of *mechanical* flexibility in the physical construction of the circuit, in addition to the traditional electronic functions. *Surface* micromachined devices provide mechanical machining of the thin surface layers on the semiconductor — typically the metalization and polysilicon layers. *Bulk* micromachined devices provide for mechanical structures through machining of the silicon or GaAs substrate. Both classes of MEMs devices have been proposed for microwave applications.

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Surface micromachining usually consists of the deposition and patterning of a variety of thin films — including polysilicon, various metals, SiO_2, Si_3N_4 and/or photoresist — on a Si or GaAs substrate using standard photolithographic techniques. Some of these films are "sacrificial" in the sense that they are selectively removed in subsequent processing, yielding free-standing structures of various shapes. In some cases, the structures are anchored at one or more position, and in other cases the structures are free to rotate around a pin joint [2].

A distinction is typically made between *passive* MEMS devices and *active* MEMS devices — often referred to as *actuators* — although the distinction between the two can be somewhat arbitrary. Passive devices include bulk micromachined transmission lines, filters and couplers. Active MEMS devices include switches, tuners, and variable capacitors. The electromotive force used to "move" the structures on the wafer surface is typically electrostatic attraction, although magnetic, thermal, and even gas-based micro-actuator structures have been developed.

Substantial progress has been made in recent years in the field of high-frequency acoustic resonant filters. These devices typically have center frequencies from 100 kHz to 100 MHz, with Q's ranging from 10,000 to 100, depending on the frequency. They have the possibility of realizing monolithic IF filters of comparable quality to external crystal and SAW devices.

II. MEMS ACTUATORS FOR MICROWAVE APPLICATIONS

The potential utility of MEMs technology for microwave and radio frequency *switching* and *tuning* applications was one of the first applications to be explored in this new field [3]. The genesis of the work in this area has several historical precedents, including initial development of bending beam micro-switches for high power applications [4], and some early work at various universities — particularly U.C. Berkeley and MIT — on electrostatic micro-motors [5].

One of the earliest applications of MEMS technology

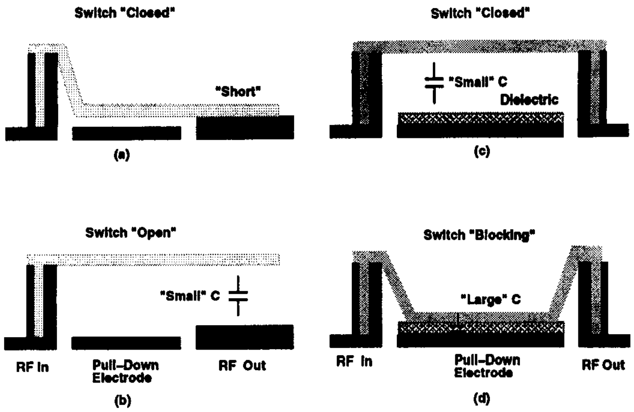

Figure 1: Micromachined switches employing electrostatic pull-down (a) Cantilever switch in "closed"-position (b) Cantilever switch in "open" position. (c) Air-bridge switch in "closed" position and (c) Air-Bridge switch in "blocking" position.

for microwave applications has been in the area of surface micromachined actuators [6] for the realization of microwave switches with very high linearity, low dc standby power and low insertion loss. In this case, the switch design was the classic "bending beam" design, where electrostatic attraction was employed to "pull" the switch into position. In this case, the force pulling the beam down is the gradient of the stored energy in the parallel-plate capacitor, i.e.

$$F = \epsilon_0 A V^2 / 2t^2 \tag{1}$$

where ϵ_0 is the free-space dielectric, A is the plate area, V is the applied voltage, and t is the plate-to-plate spacing.

This force is counterbalanced by the mechanical upward restoring force on the beam. The advantage of this approach is that the bending beam switch can be designed to present a nearly 50Ω impedance across a broad range of frequencies, yet is nearly an open circuit when there is no connection. Since, that time, several new switch architectures have been presented, the most promising of which is the air-bridge structure [7] [8]; both switch types are shown in cross-section in Fig. 1. The air-bridge structure utilizes a very high capacitance variation of approximately 150:1 to achieve the switching action. Most of these schemes suffer from relatively high switching voltage requirements — in excess of 10 V — although the dc power dissipation of the switch is essentially zero.

The cantilever design has the intrinsic advantage of higher loss in the "open" state, especially at lower frequencies due to the very small fringing capacitance, although it suffers from the well-known lifetime limitation of "stiction," where the two contacting metal surfaces "self-weld" during contact. The air-bridge structure minimizes the stiction limitation, at the expense of a slightly lower loss at low- frequencies. By comparison, the cantilever switch and air-bridge switch both exhibit less than 1 dB loss from dc to 50 GHz in the "closed" state, but the cantilever design has superior insertion loss at *low* frequencies (less than 15 GHz) [9].

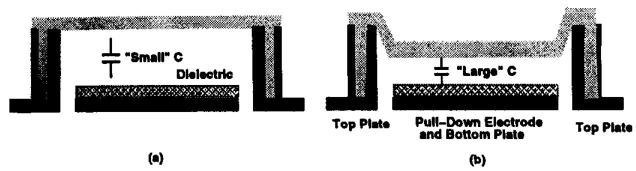

Figure 2: Micromachined capacitor (a) low-capacitance and (b) high capacitance.

Another creative use of MEMs technology for RF applications is in the area of variable capacitors, as a replacement for varactor diodes for tuning [10], [11]. In this case, there are two commonly employed approaches, one employing lateral capacitance variation, and the other employing parallel plate capacitance variation. The parallel plate version is shown schematically in Fig. 2. The capacitance variation of these structures is impressive — over 3:1 — making them very attractive for wide-band tuning of monolithic VCOs. The measured quality factor is over 30 at 2 GHz. The major limitation of these variable capacitance circuits is the low-frequency mechanical resonance of the structure, which creates spectral sidebands for many oscillator applications.

III. BULK MICROMACHINED FILTER AND ANTENNA STRUCTURES

A substantial amount of progress has been made in recent years on bulk micromachined transmission lines, filters, couplers and resonators [12] [13]. In this case, the intrinsic limitations of transmission line structures implemented on Si, GaAs, or InP substrates are overcome through the use of selective removal of material near the transmission lines through the use of bulk micromachining. A cross-sectional view of two common alternative bulk-micromachined transmission line structures is shown in Fig. 3.

The transmission line technology used to implement these devices has a number of advantages over standard planar transmission line techniques: the transmission lines are essentially "floating in air," possess negligible dielectric loss, and exhibit minimal radiation and dispersion. Relatively standard silicon bulk micromachining technology can be employed to realize the structures, and they can be easily co-integrated with other silicon microwave integrated circuits [14]. Results in this technology include Monolithic W-band filters with 1.4 dB insertion loss and 17% bandwidth [15], and a 10-60 GHz directional coupler [16].

IV. MECHANICAL BANDPASS MEMS FILTERS

Although they operate at relatively low frequencies for microwave applications, *mechanically* resonant MEMS structures have demonstrated tremendous recent progress in the 10 kHz to 10 MHz regime recently, making them potentially ideal for IF filtering applications, and extension into the higher VHF and UHF ranges is the subject of intensive research [17]. MEMS mechanically resonant filters have historically employed electrostatic "comb" drives, but these result in relatively low frequencies for communications applications; instead, a "clamped-beam" design is typically employed for applications from 5-50 MHz. From a geometrical perspective, a clamped beam design is capable of operating into the GHz regime for dimensions on the order of several microns. However, the impedance required to match into these high-frequency structures, their achievable Q, and matching tolerances are all beyond the level of today's microelectronic technology. More research is required to extend these filters into the microwave region.

In addition, their dynamic range is limited somewhat by the linearity of the transducer, and decreases as the *square* of the interelectrode gap, rendering a reduced dynamic range as the frequency of the filter increases. Linearization techniques for these filters are another area of active research.

V. THE IMPACT OF MEMS TECHNOLOGY ON FULLY INTEGRATED RADIO FREQUENCY TRANSCEIVER ARCHITECTURES

At the beginning of this paper, I alluded to the fact that widespread application of MEMs technology may yield some profound changes in the standard heterodyne frequency conversion architecture. What might some of those changes be?

First of all, MEMs technology promises to provide dramatically improved switching and filtering capabilities at the front end of radio receivers. At typical cellular telephone or PCS frequencies, the isolation of a MEMs switch can exceed 60 dB, and its insertion loss when "closed" is less than 0.3 dB. In addition, the intermodulation and distortion of these devices is virtually nonexistent, rendering their dynamic range more than adequate for the most demanding receiver applications. A MEMS tunable bandpass filter, as shown in Fig. 4 could serve partial channel selection as well as "roofing" functions for a typical receiver, dramatically lowering the IF and improving the integrability of portable wireless receivers. At these low IF frequencies, the aforementioned mechanical resonant filters could serve as a final channel selection and IF filter, making the goals of a wide dynamic range fully integrated radio receiver a reality.

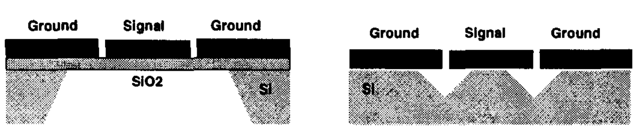

Figure 3: Bulk micromachined transmission line structures (a) Coplanar line suspended on a thin dielectric membrane — also known as a "microshield line" [13] (b) finite ground coplanar waveguide (FGC) structure [12]

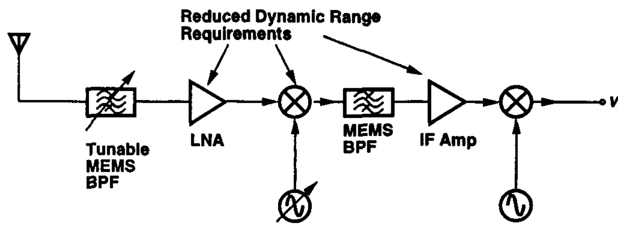

Figure 4: Proposed MEMS-based receiver employing tunable front-end filter.

A second benefit of the highly integrated MEMS mechanical filters is that many of them can be integrated on a single integrated circuit die, making the possibility of an IF channel selection bank of filters possible with a relatively high first IF frequency. This would allow the widespread use of a *fixed* (non-tuned) first LO frequency in a receiver. The resulting downconverted signal can be passed to a channel selection bank of filters, and the desired channel selected from the final output, as shown in Fig. 5. This architecture eliminates the requirement of tuning the first local oscillator, with the simultaneous problem of fast switching speed and low phase-noise at very high oscillator frequencies. The switching speed and bandwidth burden is then placed on the second — lower frequency — local oscillator, where the goals of fast switching speed and low phase noise are much easier to achieve.

Under normal circumstances, the use of this proposed architecture would appear to be absurdly impractical; all of the filters would be prohibitively expensive and require an enormous amount of board space. However, in this case, the use of MEMs technology allows the filters and switches to be implemented monolithically almost "for free", and the dynamic range burden on the active mixer and channel filter is greatly reduced by the filtering action of the monolithic elements. In essence, the dynamic range requirements on the *active* devices are moved onto the *passive* devices — a very beneficial tradeoff!

On the transmitter side, the use of MEMs technology may allow for the realization of high-quality on-chip matching networks at the output of power amplifiers. It is this critical area that often limits the performance of power amplifiers, which is why power amplifiers have historically been

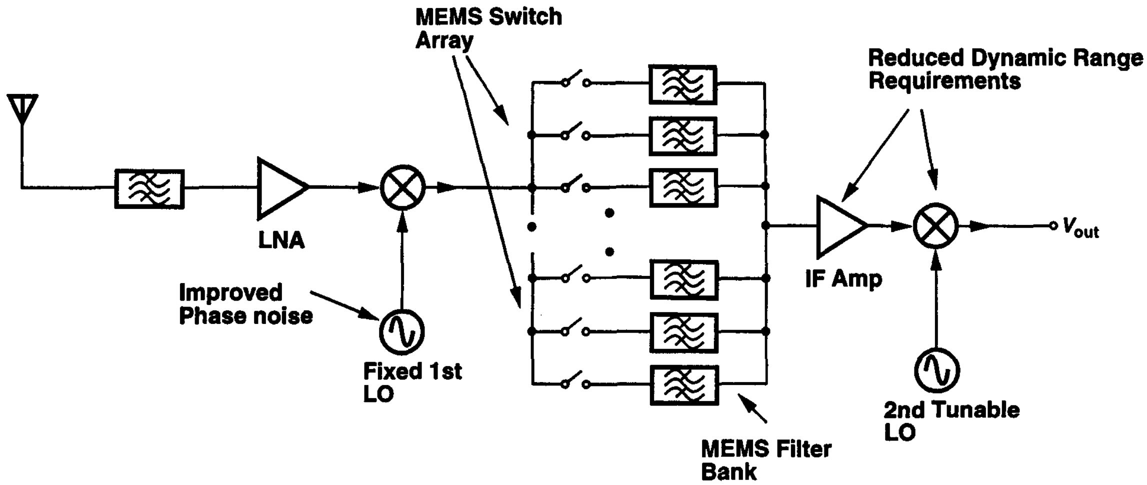

Figure 5: Proposed MEMS-based receiver with acoustic resonant IF filter banks.

implemented with off-chip power matching networks. Furthermore, the use of MEMS devices for mmW filtering and coupling can completely eliminate the need for expensive and bulky waveguide components, making the realization of low-cost mmW systems possible for the first time.

VI. CONCLUSIONS

The use of MEMS technology for RF and microwave applications promises to solve several technological limitations that have plagued the high-frequency electronics field for decades. In particular, MEMS can provide for low-loss switching and tuning of microwave circuits, with higher dynamic range, lower cost, and greater flexibility than competing techniques. Filters, couplers, and resonators implemented with bulk micromachining techniques will allow low-cost implementations of mmW systems without sacrificing performance.

VII. REFERENCES

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