Contour-Mode Aluminum Nitride Vibrating RF Microsystems

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***Abstract*— Contour-mode aluminum nitride vibrating micromechanical resonators are presented as a new class of RF Microsystems capable of low-loss filtering and frequency synthesis for next generation wireless devices. Contour-mode piezoelectric resonators can span frequencies from 10 MHz up to few GHz on the same silicon chip offering high quality factors in air (1,000-4,000) and low motional resistance (25-500 Ω). Low loss electrically and mechanically coupled filters can be easily implemented using this resonator technology. A microsystems approach that takes advantage of massively arraying micromechanical vibrating resonators is presented as a solution for next generation cognitive radios based on low power transceivers that use frequency hopping, multi-band filtering and direct frequency synthesis.**

I. INTRODUCTION

Recent advancements in the field of wireless communications have dictated the need for new micromechanical RF components capable of multi-frequency low-loss filtering and frequency synthesis on the same silicon chip. The growing demand for newer functionalities and applications has crowded the frequency spectrum to the point that several RF bands are now closely spaced within a few MHz. These needs translate in performance requirements in terms of insertion losses, rejection, integration and quality factor that state-of-the-art resonator technologies such as SAW and FBAR can hardly meet altogether. A new class of vibrating RF MEMS resonators [1-4] has emerged as a potential solution for next generation wireless communications. These devices, either electrostatically or piezoelectrically transduced, are bulk acoustic wave resonators that have their fundamental frequency set by their in-plane dimensions and therefore dubbed contour-mode resonators. They have already demonstrated high quality factors (up to 10,000 at GHz), small size, good linearity, and especially the ability to span frequencies from few MHz up to GHz on the same silicon chip.

Amongst this new class of resonators, AlN contour-mode vibrating RF micromechanical devices (Fig. 1) constitute the most promising technology capable of immediately satisfying the emerging needs of the wireless industry. AlN contour-mode resonators are the only structures capable of spanning frequency from 10 MHz up to almost GHz (in their fundamental mode of operation) on the same silicon chip and demonstrating impedance values on par with existing technologies and therefore readily matched to 50 Ω RF systems.

This paper describes this new class of AlN contour-mode resonators and presents initial experimental results using these devices for circuit applications for band pass filtering. Furthermore, a microsystems approach that employs these vibrating RF MEMS components to enable new architectures for RF front-ends is presented. Large scale integration of these micromechanical devices will permit the realization of novel transceivers characterized by reduced power consumption and increased transmission capacity. The ability to batch fabricate filter banks at different frequencies will deliver compact and highly integrated analog spectral processors capable of frequency hopping and direct frequency synthesis in next generation cognitive radios.

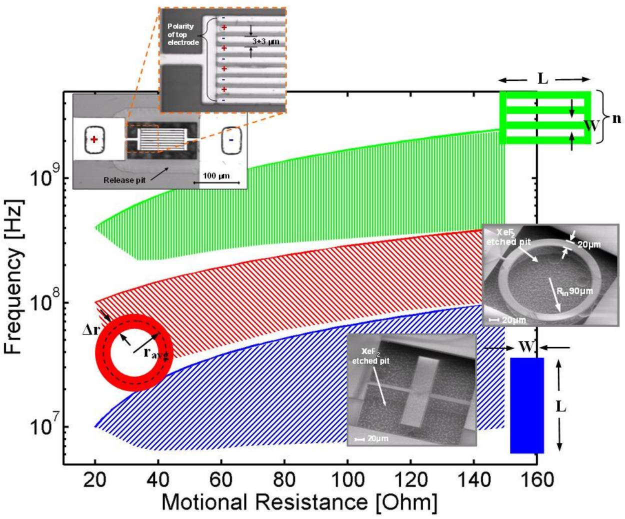


Figure 1. Schematic representation of the regions of operation (frequency vs. motional impedance) of the most promising contour-mode AlN resonator topologies. Fundamental geometrical parameters that can be defined at the CAD layout level are highlighted for each device. Futher technical details for each device can be found in [3, 5-7].

II. AlN CONTOUR-MODE RESONATOR TECHNOLOGY

Contour modes of vibration are excited in c-axis oriented aluminum nitride films via the d_{31} piezoelectric coefficient. By applying an alternating electric field across the film thickness, the AlN MEMS structure expands and contracts laterally and can be excited in resonant vibrations whose frequency is set by the in-plane dimensions of the device. The frequency of vibration is generally set by the width of the structure, whereas the second dimension can be employed to control the equivalent motional resistance and static capacitance of the device. Frequency setting via lithographic techniques enables the definition of multiple frequency devices on the same substrate and drastically reduces manufacturing tolerances on film thickness (by 10x) that are instead currently demanded by commercially available technologies such as FBARs and quartz shear resonators.

A. AlN Contour-Mode Resonators

Figure 1 schematically presents the range of operation for the three most promising device topologies developed for contour-mode AlN resonators. Rectangular plates, rings and higher-order contour-mode plates can be fabricated in the same process. According to experimental results, manufacturing considerations and theoretical observations (structural rigidity), and in order to achieve impedance levels that can be readily interfaced with 50 Ω RF systems:

- the rectangular plate geometry [5] can be effectively employed from 10 to approximately 100 MHz;
- the ring geometry [3] can be adopted between 100 and 400 MHz;
- the higher-order contour-mode rectangular geometry [7] can be used between 200 and 2,500 MHz.

Although based on preliminary results and subject to improvements through future research, these guidelines offer a good prospective of the status and range of applicability of the AlN contour-mode technology. As shown in Figure 2 these resonators are capable of Q as high as 4,300 in air, have motional resistances ranging from 25 to 500 Ω, figure of merit (FOM = $Q \cdot k_t^2$) ranging from 10 to 40 and can especially span a broad range of frequency from few MHz up to GHz on the same silicon chip.

B. AlN Contour-Mode Filters

AlN Contour-mode resonators have been demonstrated in circuit based applications for band pass filtering. Either electrically or mechanically coupled resonators have been employed to form VHF band pass filters. Table I summarizes the most significant experimental results that were obtained by arraying these resonators. Electrically coupled ladder structures are easily implemented and have proven highly reliable in the demonstration of high order filters (up to 8 resonators were coupled). Insertion loss (IL) as low as - 4 dB has been achieved at 93 MHz using 8 rectangular plates that occupy a fraction (~ 30x area saving) of the board space taken by existing IF SAW filters. Mechanical coupling of resonators has produced filters with the lowest IL level of - 1.5 dB and has the advantage of making possible the definition of the filter bandwidth directly at the lithography level. The bandwidth is in fact proportional to the ratio of the equivalent mechanical stiffness of the coupling beam and the resonator stiffness at the coupling location.

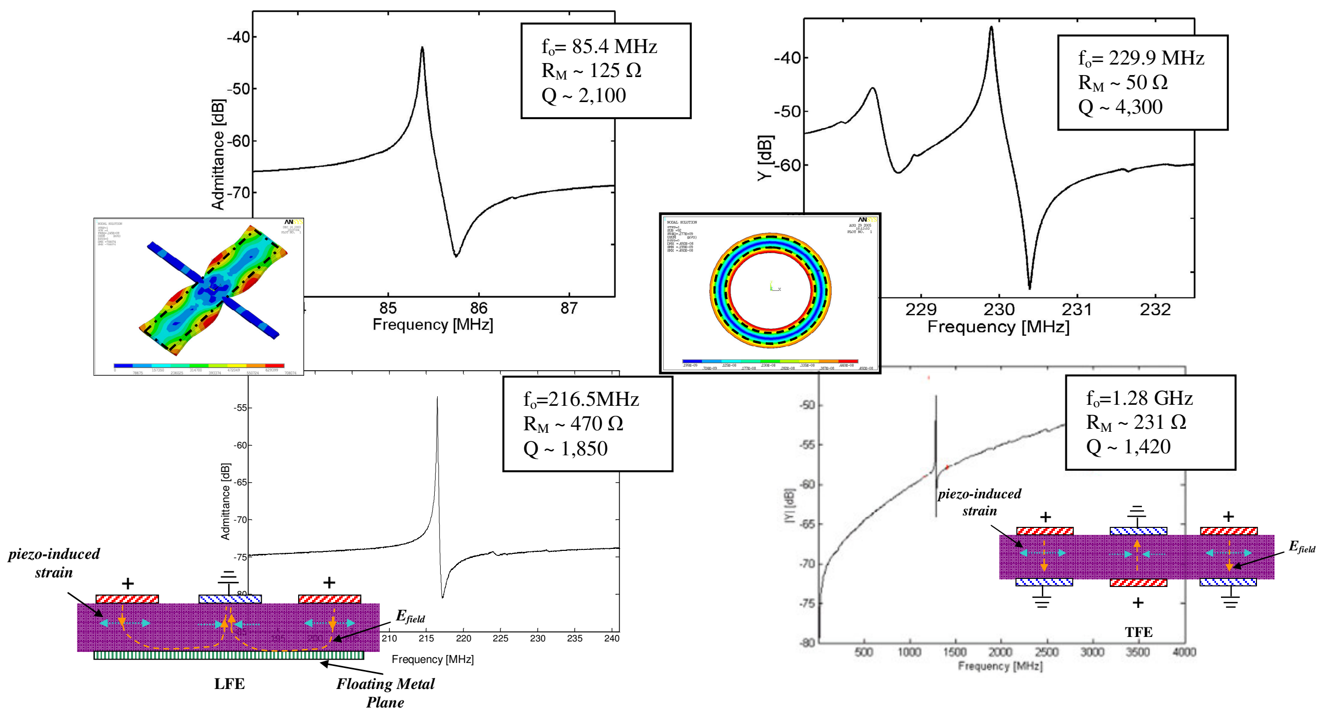
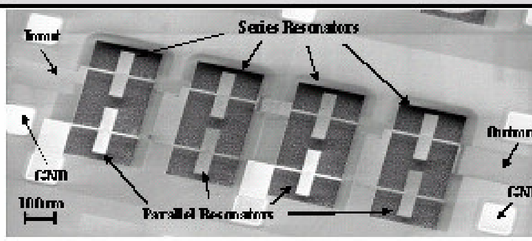
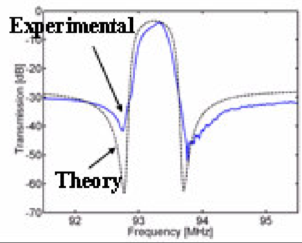
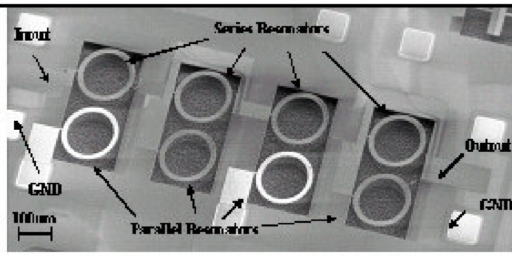
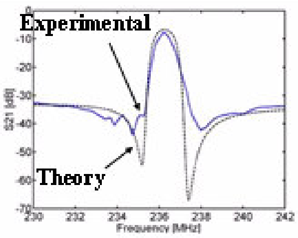
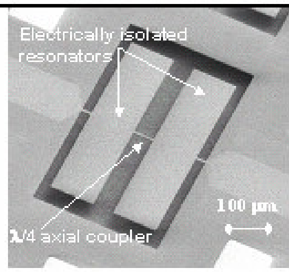
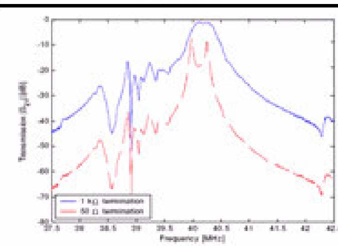
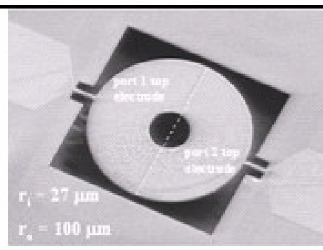
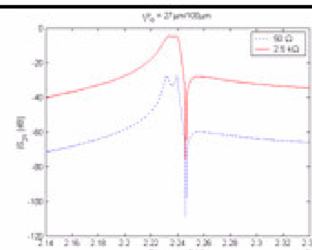
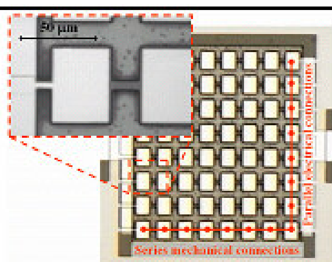
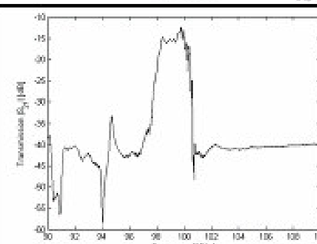


Figure 2. Examples of the electrical response of AlN contour-mode resonators. From left to righ and top to bottomt:admittance plot and mode shape of a 200x50 µm rectangular plate; admittance plot and mode shape for a 20 µm wide circular ring with 100 µm average radius; admittance plot and excitation scheme for a lateral field excited (LFE) 200x60 µm higher-order contour-mode plate; admittance plot and excitation scheme for a thickness field excited (TFE) 100x40 µm higher-order contour-mode plate

Table I. Performance summary of electrically and mechanically coupled IF filters realized using AlN contour-mode micromechanical resonators.

	Filter Photograph	Data	Performance
Electrically Coupled Ladder [8]			f_0 ~ 93.2 MHz BW_{3dB} ~ 305 kHz % BW_{3dB} ~ 0.33% BW_{20dB} ~ 671 kHz I.L. ~ -4 dB Rejection ~ 27 dB R_{term} ~ 2 kΩ
Electrically Coupled Ladder [8]			f_0 ~ 236.2 MHz BW_{3dB} ~ 605 kHz % BW_{3dB} ~ 0.26% BW_{20dB} ~ 1.8 MHz I.L. ~ -7.9 dB Rejection ~ 26 dB R_{term} ~ 1 kΩ
Mechanically Coupled Array [9]			f_0 ~ 40 MHz BW_{3dB} ~ 392 kHz % BW_{3dB} ~ 0.98 % BW_{20dB} ~ 1.1 MHz I.L. ~ -1.5 dB Rejection ~ 20 dB R_{term} ~ 1 kΩ
Dual Mode Resonator [10]			f_0 ~ 22.4 MHz BW_{3dB} ~ 112 kHz % BW_{3dB} ~ 0.5 % BW_{20dB} ~ 358 kHz I.L. ~ - 4.8 dB Rejection ~ 30 dB R_{term} ~ 2.5 kΩ
Hybrid Array [11]			f_0 ~ 99 MHz BW_{3dB} ~ 1.98 MHz % BW_{3dB} ~2 % BW_{20dB} ~ 2.5 MHz I.L. ~ - 12 dB Rejection ~ 29 dB R_{term} ~ 1 kΩ

These parameters can be defined at the CAD layout level, differently from the case of electrical coupling for which the bandwidth is instead set by material properties (k_t^2). Hybrid approaches based on arrays of mechanically coupled filters electrically connected in parallel have also been demonstrated. Preliminary results on arrays of 64 resonators have shown IL of ~ - 12 dB at 99 MHz. Lower IL can easily be achieved if smaller anchors are employed and higher resonator Q (> 1,000) is demonstrated in these smaller structures. The implementation of IF filters via AlN contour-mode resonators not only shows the possibility to bring back into fashion low-power super-heterodyne architectures based on IF filter stages, but also sets the path for realizing new classes of on-chip RF front-ends based on large scale integration of micromechanical components.

III. MEMS-BASED RF FRONT-ENDS

As already stated, AlN contour-mode resonators will have a tremendous impact on the wireless industry by providing smaller size and lower power RF components that can directly replace bulky and unintegrable (non silicon based) legacy technologies such as SAW and quartz crystals.

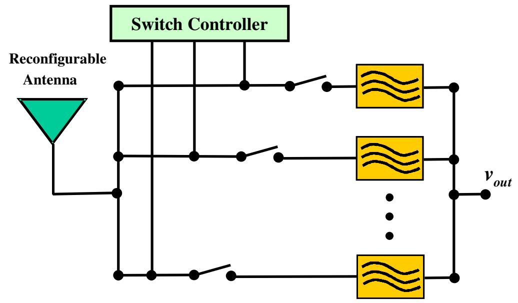


Figure 3. Next generation single-Chip RF front-end that uses closely spaced filter banks. Frequency hoping spread spectrum communication will be possible over a broad range of frequency.

Significantly more performance gains are to be achieved by large scale integration of multiple frequency micromechanical devices on the same substrate. By massively arraying banks of closely spaced (in frequency) band pass filters it is possible to easily implement frequency hopping spread spectrum (FHSS) transceivers (Fig. 3) for future reconfigurable radios. The implementation of such RF Microsystems will go beyond currently available FHSS transmission standards by spanning ultra wide bandwidth (as wide as 1 GHz) and occupying a very small board area (would instead occupy an impractically large area with current multi-package SAW or FBAR technology). This solution will provide improved SNR and lower power consumption levels and at the same time will increase transmission capacity and security.

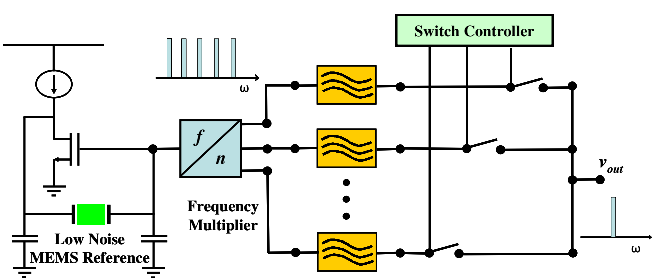


Figure 4. Direct frequency synthesis via arrays of switched narrow band filters. A low noise MEMS reference source is used to generate a single-tone signal. A train of pulses is then produced and processed by a bank of filters.

Narrow bandwidth filters can also be employed for direct frequency synthesis in spread spectrum applications. Instead of using power-hungry tunable PLL, frequencies are produced by generating a train of pulses from a low-noise reference source and selecting among signals processed through banks of filters (Fig. 4). In this manner faster switching speed and lower power consumption level than using indirect frequency synthesis methods based on PLL can be achieved. Direct frequency synthesis could also be pursued more aggressively by using switched banks of high Q (Q ≥ 10,000) and high frequency resonators.

IV. CONCLUSION

AlN contour-mode vibrating RF MEMS have been presented as a new class of resonator technology that will offer unprecedented performance gains in next generation wireless communications. These piezoelectric contour-mode devices have already been demonstrated over a frequency range from few MHz up to GHz, with high Q factors (1,000-4,000) and low motional resistance (25-500 Ω) and can potentially substitute existing bulky RF components. Despite these substantial improvements, true advantages will be gained by massively integrating multiple frequency micromechanical resonators and filters on the same silicon chip and making possible the realization of low power and large capacity frequency hopping spread spectrum wireless communication devices.

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