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VIBRATING RF MEMS TECHNOLOGY: FUEL FOR AN INTEGRATED MICROMECHANICAL CIRCUIT REVOLUTION?

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Abstract—Having produced devices with sufficient *Q*, thermal stability, and manufacturability, for component-level use in present-day wireless handsets, vibrating RF MEMS technology is now poised to take its next logical steps: higher levels of circuit complexity and integration. In particular, as vibrating RF MEMS devices are perceived more as circuit building blocks than as stand-alone devices, and as the frequency processing circuits they enable become larger and more complex, the makings of an integrated micromechanical circuit technology begin to take shape, perhaps with a functional breadth to rival that of integrated transistor circuits. This paper suggests the mechanical circuit element properties that insure a broad functional range for integrated micromechanical circuits.

Keywords: resonator, LSI, VLSI, quality factor, micromechanical circuit, RF MEMS, wireless communications

1. INTRODUCTION

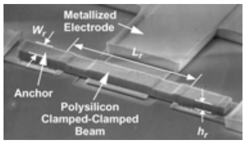
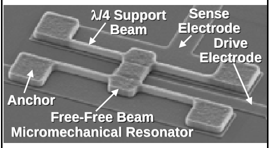
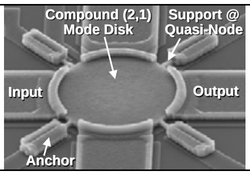
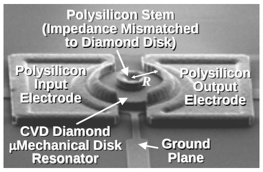
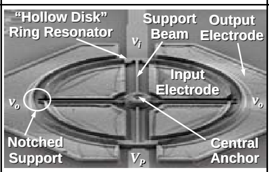
Recent advances in vibrating RF MEMS technology [1] have yielded micromechanical resonators with *Q*'s greater than 10,000 at GHz frequencies [2]-[4], thermal stabilities down to 18 ppm over 27-107°C [5], impressive aging characteristics [6], and antenna-matchable impedances [7]. Indeed, with some of the above attributes superior to those attainable by macroscopic counterparts, the technical argument for the use of vibrating RF MEMS as high-*Q* replacement components in existing wireless sub-systems is already quite strong. Indeed, piezoelectric thin-film bulk acoustic resonators (FBAR's) [8][9], composed of deposited piezoelectric materials sandwiched between metal electrodes that drive them into extensional vibration, have already become a successful high volume MEMS product in the wireless handset arena.

But the benefits afforded by vibrating RF MEMS technology go far beyond mere component replacement. In fact, the extent to which they offer performance and economic benefits grows exponentially as researchers begin to perceive these devices more as on-chip building blocks than as discrete stand-alone devices. In particular, by mechanically linking vibrating mechanical structures into more general networks, "integrated micromechanical circuits" can be conceived capable of implementing virtually any signal processing function presently realizable via transistor circuits, and with potential power and linearity advantages, especially for functions that involve frequency processing. In essence, micromechanical linkages might form the basis for an integrated micromechanical circuit technology with a breadth of functionality to rival that of transistor integrated circuits. This paper muses over this possibility and attempts to suggest the MEMS technologies and attributes most suitable to enabling an integrated micromechanical circuit platform.

2. MICROMECHANICAL RESONATORS

Table 1 presents a semi-historical summary of the vibrating RF MEMS devices with the highest frequency-*Q* products in their class. Frequency-*Q* product is often the most important performance metric when designing oscillators and filters for communications. In particular, oscillator phase noise is often inversely proportional to

Table 1: High Frequency-*Q* Product Vibrating RF MEMS Devices

	Photo	Performance
CC-Beam Resonator [8]		Demo'ed: *Q* ~8,000 @ 10MHz (vac) *Q* ~50 @ 10MHz (air) *Q* ~300 @ 70MHz (anchor diss.) *Q* drop w/ freq. limits freq. range Series Resistance, R_x ~5-5,000Ω
FF-Beam Resonator [11]		Demo: *Q* ~ 28,000 @10-200MHz (vac) *Q* ~2,000 @ 90 MHz (air) No drop in *Q* with freq. Freq. Range: >1GHz; unlimited w/ scaling and use of higher modes Series Resistance, R_x ~5-5,000Ω
Wine-Glass Disk Res. [12]		Demo'ed: *Q* ~156,000 @ 60 MHz (vac) *Q* ~8,000 @ 98 MHz (air) Perimeter support design nulls anchor loss to allow extremely high *Q* Freq. Range: >1GHz w/ scaling Series Resistance, R_x ~5-5,000Ω
Contour-Mode Disk Res. [2][3]		Demo'ed: *Q* ~11,555 @ 1.5 GHz (vac) *Q* ~10,100 @ 1.5 GHz (air) Balanced design and material mismatching anchor-disk design nulls anchor loss Freq. Range: >1GHz; unlimited w/ scaling and use of higher modes Series Resistance, R_x ~50-50,000Ω
Hollow Disk Ring Res. [4]		Demo'ed: *Q* ~15,248 @ 1.46 GHz (vac) *Q* ~10,165 @ 1.464 GHz (air) λ/4 notched support nulls anchor loss Freq. Range: >1GHz; unlimited w/ scaling and use of higher modes Series Resistance, R_x ~50-5,000Ω

the square of *Q*, while filter insertion loss decreases (i.e., improves) as the *Q*'s of the resonators constituting a given filter circuit increase. Note that Table 1 contains all capacitively transduced devices, which in general offer the best frequency-*Q* products among micromechanical resonator types, since they generally are constructed in single high quality materials, and thus suffer less from the material combination losses that can encumber other transducer types (e.g., piezoelectric). They do, however, suffer somewhat from larger-than-conventional impedances, since the electromechanical coupling factors of their capacitive transducers can be small if the dc-bias voltages applied across their electrode-to-resonator gaps must be constrained. (Note that the lower ends of the R_x ranges in Table 1 were achieved by a combination of sub-100nm gap spacing and large dc-bias, which compromise linearity [13], so are impractical for certain applications.)

The last few devices of Table 1 actually achieve *Q*'s >10,000 at GHz frequencies—something no other on-chip resonator technology can match at room temperature. Since the percent bandwidth achievable by a given low-loss bandpass filter depends inversely on the *Q*'s of its constituent resonators, *Q*'s >10,000 might make possible for the first time filter bandwidths small enough to effect RF channel-selection at the front ends of wireless receivers. If possible, this could greatly enhance the robustness and reduce the power consumption of future multiple-input multiple-output (MIMO) radio transceivers [1].

Besides frequency range and *Q*, thermal stability, aging/drift stability, and impedance, are also of utmost importance. Table 2 presents some of the micromechanical resonator devices designed specifically to address these characteristics. In particular, the fixed-fixed beam device of row 1 in Table 2 utilizes a temperature-tailored top electrode-to-resonator gap spacing to attain a total frequency deviation over 27-70^{o}C of only 18 ppm, which actually betters that of AT quartz. This, combined with recent demonstrations of good aging and drift [6], makes micromechanical resonators excellent candidates for reference oscillator applications in communication circuits. In addition, the devices of rows 2 and 3 illustrate strategies for lowering the impedances of stand-alone resonators, the first based on enlargement of the electrode-to-resonator capacitive overlap area to increase electromechanical coupling [14]; the second using piezoelectric transducers [7][15]; and the latter being the more successful in achieving the 50-377Ω impedances desired for matching to off-chip wireless components.

Clearly, there are stand-alone micromechanical resonator devices that equal or better the performance of devices presently used in wireless handsets. Although the benefits attained when replacing existing components by on-chip higher *Q* MEMS ones can be substantial, even greater advantages lie in waiting for a technology and design environment conducive to large-scale-integrated (LSI) networks of vibrating links.

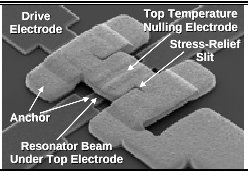
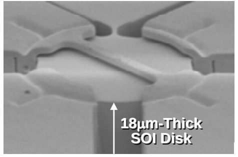
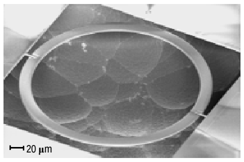
3. MICROMECHANICAL CIRCUITS

Like single transistors, stand-alone vibrating micromechanical elements have limited functionality. To expand their functional range, micromechanical elements (like transistors) need to be combined into more complex circuits that achieve functions better tailored to a specific purpose (e.g., frequency filtering, generation, or translation). Given that the property that allows transistors to be combined into large circuits is essentially their large gain, it follows that mechanical elements can be combined into equally large circuits by harnessing their large *Q*. As a simple example, transistor elements can be cascaded in long chains, because their gains compensate for the noise and other losses that would otherwise degrade the signal as it moves down the chain. On the other hand, mechanical elements can be cascaded into long chains because of their extremely low loss—a benefit of their high *Q*. In essence, if an element has an abundance of some parameter (i.e., gain, *Q*, …), then this can generally be used to build circuits of that element.

In order to effect a micromechanical circuit design environment as broadly applicable as today's electronic circuits, constituent mechanical circuit elements with the following attributes are desired:

1. *CAD-amenable design*. For example, frequencies should be determined by lateral dimensions, which can be specified via CAD, not just vertical dimensions, which cannot. This makes possible an ability to attain many different frequencies in a single layer on a single-chip. (Note that herein lies the biggest deficiency of FBAR's, for which frequency is determined primarily by the thickness of the piezoelectric film, which is not specifiable by CAD.)
2. *Q's >10,000 from 1–5000 MHz*. Only *Q*'s this high can enable an RF channel-select filter bank capable of removing all interferers (including in-band ones) before they reach any transistor electronics. Such a capability could greatly enhance robustness and lower power consumption in wireless transceiver circuits. High *Q* also allows long cascades of interconnected mechanical links, as already described above.
3. *Thermal and aging stability to better than 2 ppm*, or at

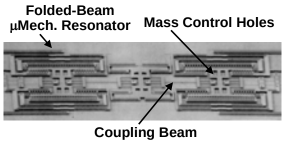
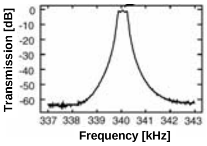
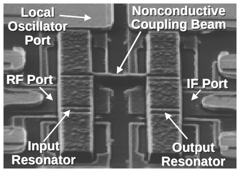
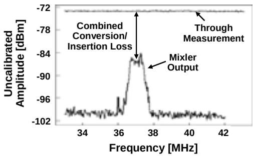
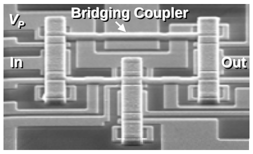
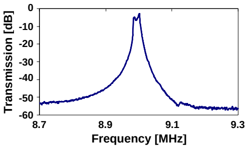
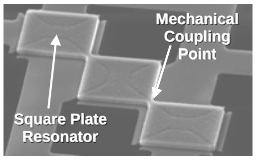
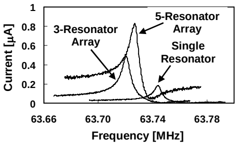
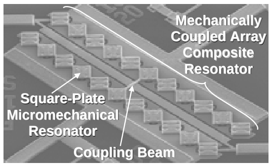
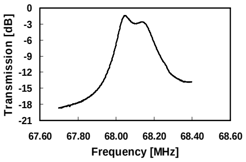
Table 2. Thermal Stability and Impedance of Microresonators

	Photo	Performance
Electrical Stiff. Comp. Res. [5]		Demo'ed: *Q* ~4,000 @ 10MHz (vac) Temperature-tailored gap to effect an electrical stiffness variation that cancels Young's modulus variation 18 ppm freq. variation over 27-107^{o}C
SOI Silicon WG-Disk [14]		WGDisk: *Q* ~26,000 @ 149MHz (air) SiBAR: *Q* ~40,000 @ 137 MHz (vac) *Q* ~3,700 @ 983 MHz SOI thickness to effect large capacitive overlap for low Series Resistance, R_x ~5.5kΩ @ 137 MHz
Lateral Piezoelec. Ring [7]		Demo'ed: *Q* ~2,900 @ 473 MHz (air) Contour-mode ring-shaped AlN piezoelectric resonator Driven laterally via the d_{31} coeff., so freqs. determined by lateral dims. Series Resistance, R_x ~80Ω

least amenable to compensation or control to this level.

4. *On/off switchability*. Here, the overriding preference is for vibrating micromechanical devices that can switch themselves, i.e., that do not require extra series switches, and that thus avoid the extra insertion loss.
5. *Massive-scale interconnectivity*. In some cases, several levels of both mechanical and electrical interconnect are desired.
6. *Nonlinear characteristics* that enable such functions as mixing, amplification, limiting, and other useful signal processing abilities.
7. *Amenability to low-capacitance single-chip integration with transistors*. This not only eliminates the impedance issue described previously, since the tiny magnitudes of on-chip parasitic capacitors allow impedances in the kΩ range, but also affords designers a much wider palette of mechanical and electrical circuit elements.

Table 3: Summary of Vibrating Micromechanical Circuits

	Photo	Data	Performance
3-Res. Folded-Beam Filter [16]			Freq. = 340 kHz BW = 403 Hz %BW = 0.09% StopB Rej. = 64 dB Ins. Loss < 0.6 dB
Mixer-Filter [18]			Mixes a 240MHz RF down to 37MHz IF, then filters Conv. Loss = 9.5dB %BW = 1.7% Ins. Loss = 3.5dB
3 Res. Bridged CC-Beam [19]			Freq. = 9 MHz BW = 20 kHz %BW = 0.2% StopB Rej. = 51 dB Ins. Loss < 2.8 dB
Mech.-Coupled Res. Array [20]			Automatic matching of resonators achieved via mech. coupling; current multiplied by number of resonators *N*
Array Composite Filter [21]			Freq. = 68.1 MHz BW = 190 kHz %BW = 0.28% StopB Rej. = 25 dB Ins. Loss < 2.7 dB

Among the devices discussed, the capacitively-transduced devices of Table 1 and rows 1-2 in Table 2 possess all of the above attributes. It is no surprise then, that the most complex micromechanical circuits to date have been constructed using capacitively-transduced resonators. Table 3 summarizes several purely micromechanical circuits, from bandpass filters with impressive on-chip insertion losses of only 0.6dB for 0.09% bandwidth, some using non-adjacent bridging to effect loss poles [19]; to mixer-filter ("mixler") devices that both translate and filter frequencies via a single passive structure [18]; to impedance transforming mechanically-coupled arrays that combine the responses of multiple high-impedance resonators to allow matching to a much lower 50Ω [20]; to a filter using mechanically-coupled composite resonators to allow matching to 50Ω while attaining the lowest insertion loss to date for a VHF micromechanical filter [21]. Each of the filters in Table 3 were designed using equivalent electrical circuits defined by electromechanical analogies [10][16], which allowed the use of electrical circuit simulators, like SPICE—an important point that implies mechanical circuits should be amenable to the vast automated circuit design environments already in existence.

The arraying used in the devices of rows 3 and 4 not only provides a lower filter termination impedance by increasing the effective capacitive transducer overlap area, but also raises the 3rd order intermodulation intercept point (IP_3) of the composite device [13] (i.e., raises its linearity) in the process. Furthermore, Fig. 1 illustrates how arraying can achieve a much larger increase in capacitive transducer overlap area than a single device specially designed for larger transducer area—a clear example of how a circuit technique can be superior to the use of a single "advanced" device.

The similarities between the described arraying approach and similar strategies in transistor integrated circuit design are noteworthy. In particular, the use of an array of resonators to match the impedance of a micromechanical circuit to an off-chip macroscopic element (e.g., an antenna) is really no different from the use of a cascade of progressively larger inverters (or actually, in layout, arrays of smaller inverters) to allow a minimum-sized digital gate to drive an off-chip board capacitor. In essence, micro (or nano) scale circuits, whether they be electrical or mechanical, prefer to operate with higher impedances than macro-scale ones, and interfacing one with the other requires a proper impedance transformation. In a building block circuit environment, such an impedance transformation is most conveniently accomplished via large numbers of circuit elements, whether they be electronic transistors or mechanical resonators.

Table 3 also implicitly indicates the progression of micromechanical circuit complexity with time. In particular, the composite array filter in row 4 uses more than 43 resonators and links, which qualifies it as a medium-scale integrated (MSI) micromechanical circuit. And this is just the beginning. After all, the aforementioned RF channel-select filter banks (c.f., Fig. 2) aim to use hundreds or thousands of filters like this, which would inevitably lead

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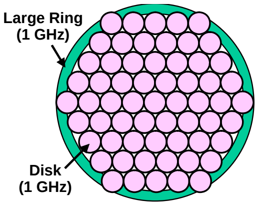

Fig. 1: Illustration showing that, in the same footprint, an array of small 1GHz disks can achieve a larger sidewall surface area (hence, larger electromechanical coupling and smaller filter impedance) than a single 1GHz ring made large to minimize impedance.

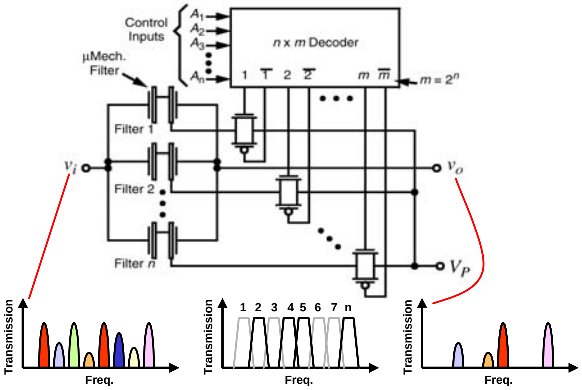

Fig. 2: Schematic diagram for an RF channel-select micromechanical filter bank, with an example showing how various input frequencies can be simultaneously selected via mere application or removal of the dc-biases applied to capacitively-transduced filters. (This is the self-switching advantage of capacitively-transduced resonators). In the bottom plots, filters 2, 4, 5, and *n* are on, while all others are off.

to LSI or VLSI micromechanical circuits. When combined (preferably on the same chip [22]) with transistor integrated circuits, the time domain prowess of transistors can be merged with the frequency domain capabilities of mechanical circuits to achieve even greater functionality. The GSM-compliant oscillators already demonstrated in [23][24] only scratch the surface of what is possible.

4. CONCLUSIONS

With extremely low loss (i.e., high *Q*), flexible interconnectivity, and switchability, vibrating micromechanical resonators have all the characteristics needed to support an LSI (perhaps even VLSI) micromechanical circuit technology. Although such circuits are expected to be most advantageous for frequency processing applications, where high *Q* can generally be traded for power consumption and used to enhance circuit robustness [1], they should also be capable of computation (perhaps, in the frequency domain) and even data storage. With transistors to handle time domain processing, and micromechanics to handle the frequency domain, revolutionary advances in the performance of low-power wireless networks, timekeepers, and other frequency-centric applications, might soon be feasible.

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References.

[1] C. T.-C. Nguyen, "Vibrating RF MEMS for next generation wireless applications," *Proceedings*, 2004 IEEE Custom Integrated Circuits Conf., Orlando, Florida, Oct. 3-6, 2004, pp. 257-264.

[2] J. Wang, *et al.*, "1.51-GHz polydiamond micromechanical disk resonator with impedance-mismatched isolating support," *Proceedings*, 17th Int. IEEE Micro Electro Mechanical Systems Conf., Maastricht, The Netherlands, Jan. 25-29, 2004, pp. 641-644.

[3] J. Wang, *et al.*, "1.156-GHz self-aligned vibrating micromechanical disk resonator," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 51, no. 12, pp. 1607-1628, Dec. 2004.

[4] S.-S. Li, *et al.*, "Micromechanical Hollow-Disk Ring Resonators," *Proceedings*, 17th Int. IEEE Micro Electro Mechanical Systems Conf., Maastricht, The Netherlands, Jan. 25-29, 2004, pp. 821-824.

[5] W. -T. Hsu and C. T. -C. Nguyen, "Stiffness-compensated temperature-insensitive µmechanical resonators," *Tech. Dig.*, IEEE Int. MEMS Conf., Las Vegas, Nevada, Jan. 20-24, 2002, pp. 731-734.

[6] Unpublished data and communication.

[7] G. Piazza, *et al.*, "Low motional resistance ring-shaped contour-mode aluminum nitride piezoelectric micromechanical resonators for UHF applications," *Tech. Dig.*, 18th IEEE Int. Conf. on MEMS, Miami Beach, Florida, Jan. 30-Feb. 3, 2005, pp.20-23.

[8] R. C. Ruby, *et al.*, "Thin film bulk wave acoustic resonators (FBAR) for wireless applications," *Proceedings*, IEEE Int. Ultrasonics Symposium, Atlanta, GA, 2001, pp. 813-821.

[9] H. Yu, *et al.*, "Film bulk acoustic resonator at 4.4 GHz with ultra low temperature coefficient of resonant frequency," *Tech. Dig.*, 18th IEEE Int. Conf. on MEMS, Miami Beach, Florida, Jan. 30-Feb. 3, 2005, pp. 28-31.

[10] F. D. Bannon III, *et al.*, "High freq. µmechanical filters," *IEEE J. Solid-State Circuits*, vol. 35, no. 4, pp. 512-526, April 2000.

[11] K. Wang, *et al.*, "VHF free-free beam high-*Q* micromechanical resonators," *IEEE/ASME J. Microelectromech. Syst.*, vol. 9, no. 3, pp. 347-360, Sept. 2000.

[12] M. A. Abdelmoneum, *et al.*, "Stemless wine-glass-mode disk µmechanical resonators," *Proceedings*, IEEE MEMS Conf., Kyoto, Japan, Jan. 19.-23, 2003, pp. 698-701.

[13] R. Navid, *et al.*, "3rd-order intermod. distortion in capacitively-driven CC-beam µmechanical res.," *Tech. Dig.*, IEEE MEMS Conf., Interlaken, Switzerland, Jan. 21-25, 2001, pp. 228-231.

[14] S. Pourkamali, *et al.*, "Vertical capacitive SiBARs," *Tech. Dig.*, 18th IEEE Int. Conf. on MEMS, Miami Beach, Florida, Jan. 30-Feb. 3, 2005, pp. 211-214.

[15] D. T. Chang, *et al.*, "A new MEMS-based quartz resonator technology," *Tech. Dig.*, Solid-State Sensor, Actuator, and Microsystems Workshop, Hilton Head, South Carolina, June 6-10, pp. 41-44.

[16] K. Wang and C. T.-C. Nguyen, "High-order medium frequency micromechanical electronic filters," *IEEE/ ASME J. Microelectromech. Syst.*, vol. 8, no. 4, pp. 534-557, Dec. 1999.

[17] S. A. Bhave, *et al.*, "Fully-differential poly-SiC Lamé-mode resonator and checkerboard filter," *Tech. Dig.*, 18th IEEE Int. Conf. on MEMS, Miami Beach, Florida, Jan. 30-Feb. 3, 2005, pp. 223-226.

[18] A.-C. Wong and C. T.-C. Nguyen, "Micromechanical mixer-filters ("mixlers")," *IEEE/ASME J. Microelectromech. Syst.*, vol. 13, no. 1, pp. 100-112, Feb. 2004.

[19] S.-S. Li, *et al.*, "Bridged micromechanical filters," *Proceedings*, IEEE Int. Ultrasonics, Ferroelectrics, and Freq. Control 50th Anniv. Joint Conf., Montreal, Canada, Aug. 24-27, 2004, pp. 144-150.

[20] M. U. Demirci, *et al.*, "Mech. corner-coupled square µresonator array for reduced series motional resistance," *Dig. of Tech. Papers*, Transducers'03, Boston, MA, June 8-12, 2003, pp. 955-958.

[21] M. U. Demirci and C. T.-C. Nguyen, "A low impedance VHF micromechanical filter using coupled-array composite resonators," *Dig. of Tech. Papers*, the 13th Int. Conf. on Solid-State Sensors & Actuators (Transducers'05), Seoul, Korea, June 5-9, 2005.

[22] A. E. Franke, *et al.*, "Polycrystalline silicon-germanium films for integrated microsystems," *IEEE/ASME J. Microelectromech. Syst.*, vol. 12, no. 2, pp. 160-171, April 2003.

[23] V. Kaajakari, *et al.*, "Square-extensional mode single-crystal silicon micromechanical resonator for low-phase-noise oscillator applications," *IEEE Electron Device Letters*, vol. 25, no. 4, pp. 173-175, April 2004.

[24] Y.-W. Lin, *et al.*, "Series-resonant VHF micromechanical resonator reference oscillators," *IEEE J. Solid-State Circuits*, vol. 39, no. 12, pp. 2477-2491, Dec. 2004.