Resistively Actuated Micromechanical Dome Resonators

Robert B. Reichenbach[*a], Maxim K. Zalalutdinov[b], Keith L. Aubin[c], David A. Czaplewski[c], Bojan Ilic[d], Brian H. Houston[e], Harold G. Craighead[c], Jeevak M. Parpia[b]
[a]Dept. of Electrical Engineering, [b]Dept. of Physics, [c]Dept. of Applied and Engineering Physics, [d]Cornell Nano-Scale Science & Technology Facility, Cornell University, Ithaca, NY 14853, USA; [e]Naval Research Lab, 4555 Overlook Ave. S.W, Washington DC 20375, USA;

ABSTRACT

We demonstrate dome-shaped, radio frequency, micromechanical resonators with integrated thermo-elastic actuators. Such resonators can be used as the frequency-determining element of a local oscillator or as a combination of a mixer and IF filter in a superheterodyne transceiver.

The dome resonators (shallow shell segments clamped on the periphery) are fabricated utilizing pre-stressed thin polysilicon film over sacrificial silicon dioxide. The shell geometry enhances the rigidity of the structure, providing a resonant frequency several times higher than a flat membrane of the same dimensions. The finite curvature of the shell also couples out-of-plane deflection with in-plane stress, providing an actuation mechanism. Out-of-plane motion is induced by employing non-homogeneous, thermomechanical stress, generated in plane by local heating. A metal resistor, lithographically defined on the surface of the dome, provides thermal stress by dissipating 4 μW of Joule heat. The diminished heat capacity of the MEMS device enables a heating/cooling rate comparable to the frequency of mechanical resonance and allows operation of the resonator by applying AC current through the microheater. Resistive actuation can be readily incorporated into integrated circuit processing and provides significant advantages over traditional electrostatic actuation, such as low driving voltages, matched 50-ohm impedance, and reduced cross talk between drive and detection.

We show that when a superposition of two AC signals is applied to the resistive heater, the driving force can be detected at combinatory frequencies, due to the fact that the driving thermomechanical stress is determined by the square of the heating current. Thus the thermoelastic actuator provides frequency mixing while the resonator itself performs as a high quality (Q~10,000) intermediate frequency filter for the combinatory frequencies. A frequency generator is built by closing a positive feedback loop between the optical detection of the mechanical motion of the dome and the resistive drive. We demonstrate self-sustained oscillation of the dome resonator with frequency stability of 1.5 ppm and discuss the phase noise of the oscillator.

Keywords: microelectromechanical, shell resonator, thermomechanical, superheterodyne, mixer, intermediate frequency filter, self-sustained oscillations

1. INTRODUCTION

As wireless communication moves into novel micro-sized applications, the scale and power consumption of the electronics in the transceiver become of critical importance. Present transceiver designs cannot avoid bulky, off-chip filters and frequency standards with corresponding impedance matching circuitry for radio frequency (RF) signal processing. However, in small scale applications such as distributed sensor networks and wireless medical devices, power dissipation in the transceiver would ideally be below a milliwatt while the RF circuitry would not consume more than a millimeter of chip real-estate.

Considerable interest[1, 2] has been focused on microelectromechanical structures (MEMS) as an energy and space efficient way to replace and consolidate current RF signal processing components in the front end of wireless transceivers. However, transduction between electrical signals and mechanical motion remains a significant problem in current MEMS designs, resulting in severe performance limitations.

[*] rbr9@cornell.edu; phone 1 607 255-3417; fax 1 607 255-7658

Electrostatic actuation[3,4] is currently the most popular method for producing mechanical motion by applying an electrical signal. However, this transduction method requires a relatively high DC bias voltage or large AC signal to produce measurable displacement in the micromechanical structures. Minimizing the capacitive gap size in the resonator can somewhat overcome this situation but results in a complicated fabrication process and unpredictable performance. In addition to a high actuation voltage, the unavoidable parasitic electrostatic coupling between drive and capacitive detection circuits should result in significant crosstalk between the input and output of the device. Finally, capacitive input impedance of the electrostatically driven MEMS device requires additional impedance matching networks or buffer amplifiers to minimize the signal reflection. The narrow frequency band nature of the matching circuits limits the operating frequency range of the device.

An alternative method for RF MEMS actuation based on high speed thermomechanical effects was proposed recently by Zalalutdinov et al.[5] It was demonstrated that local thermal stress, created within a shell type microfabricated structure by a CW laser can distort the shape of the shell, inducing significant out-of-plane deflections. A large amplitude standing wave was created by modulating the laser beam intensity at the fundamental frequency of the dome resonator.

In this manuscript we present an integrated approach to actuation of RF MEMS resonators. A metallic resistor, microfabricated on the top of the dome resonator is employed to create the local thermomechanical stress and thus produce displacement in the mechanical structure. Resistive actuation alleviates many of the problems with previous actuation methodologies by reducing crosstalk between drive and detection, matching 50 Ω load impedance, and operating with less than 1 volt of AC and DC signal. A 30 μm shell type resonator is fabricated and tested to exploit the advantages of the actuation method. The prototype resonator is implemented as a reference oscillator with modes at 10.7 MHz, 14.5 MHz and 17.8 MHz, as well as a combination of a high frequency range mixer and intermediate frequency (IF) filter in a one-step conversion heterodyne FM receiver. Future versions of the resonators have the potential to reach VHF range, allowing implementation as front end RF filters.

2. STRUCTURE AND OPERATION OF HAMMER

Figure 1 is a scanning electron microscope image of the Heat Actuated Mixer and Mechanical Resonator (HAMMER). The fabrication process begins with a CF_4 plasma dry etch of a self aligned apex hole in the device layer. The opened hole provides a way to dissolve the underlying 1.5 μm of silicon dioxide with hydrofluoric acid, creating a suspended

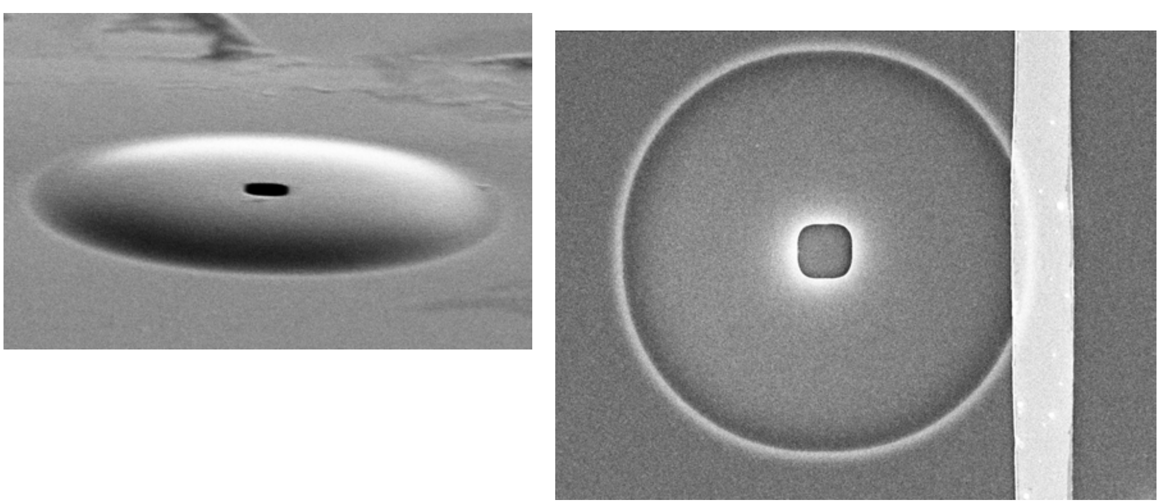

Figure 1. (a) 30 μm diameter polysilicon dome micromechanical resonator. (b) 30 μm diameter dome with a gold resistive actuator on the periphery.

membrane above the substrate. The resulting membrane has non-zero curvature due to the large compressive stress incorporated into the device layer through high temperature post process annealing at 1200 ºC. When the sacrificial silicon dioxide is released through the etch hole, the in-plane stress produces out of plane buckling, forming a shallow shell. The resonator used in the present study is a 200 nm thick polysilicon shallow spherical shell segment, 30 µm in diameter, projecting approximately 1 µm out of plane at the apex.

The out-of-plane component in the dome-like segment significantly increases the resonant frequency several fold over a two dimensional structure. The natural frequency of a flat annulus clamped on the periphery and free in the center is described by[6]

$$f_{mn}\Big|_{\substack{2D\\ annular\\ plate}} = \frac{\pi h}{2R^2}\sqrt{\frac{E}{3\rho(1-\nu^2)}}(\beta_{mn})^2 \tag{1}$$

where h is the polysilicon thickness, R is the radial projection of the plate, E is Young's modulus, ρ is the material density, υ is Poisson's Ratio, and β is a geometrical constant. Shallow shell theory[7] is used to derive equation 2 which accounts for the extra rigidity of the out of plain projection

$$f_{mn}\Big|_{\substack{shallow\\ spherical\\ shell}} = \left(f_{mn}^2\Big|_{\substack{flat\\ plate}} + \frac{E}{\rho(2\pi\chi)^2} \right)^{1/2} \tag{2}$$

where χ is the radius of curvature of the dome. The increased stiffness allows large radial dimension structures to achieve significantly higher frequencies. In particular, the aforementioned 30 µm diameter dome displayed a 17.8 MHz γ_{11} resonance with a quality factor of ~10,000 (fig. 2). Numerical modeling suggests that deeper shells with smaller lateral dimensions have the potential to reach into the GHz range. Operation in air has been demonstrated; however, viscous damping forces over the large surface area reduce the Q to ~70.

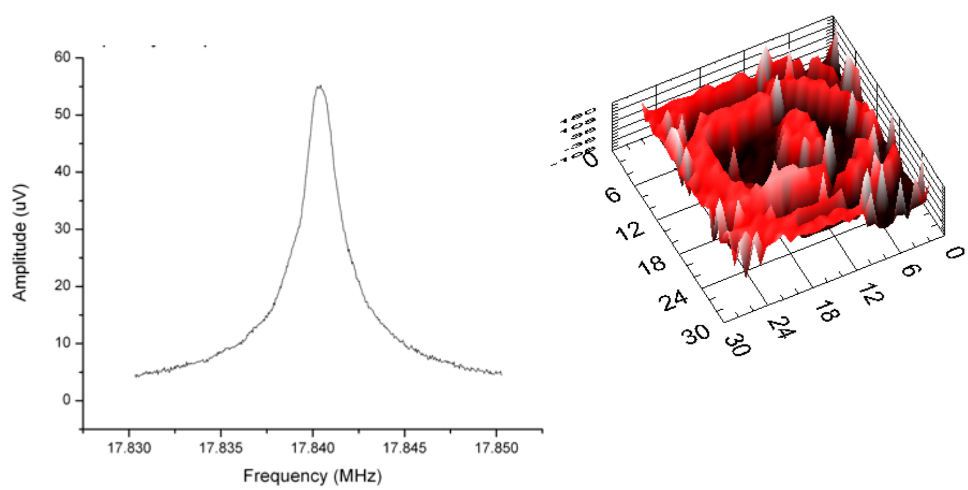

Figure 2. Q=10000, 17.8 MHz γ_{11} resonance peak with corresponding phase map of 30 µm, resistive drive dome. Phase inversions, due to the interferometric detection method and the curved nature of the dome, can be seen in the radial direction of the map.

Transduction between electrical signals and mechanical motion is accomplished by creating a non-homogeneous thermal mechanical stress in the dome structure by means of a resistor dissipating Joule heat into the oscillator. The high rigidity of the dome structure allows us to use a second layer of lithography to create a metallic resistor on the top of the prefabricated shell resonator. Optical lithography is performed on the polysilicon, followed by image reversal in a YES oven. An electron gun evaporator is used to deposit a 5 nm titanium adhesion layer and a subsequent 20 nm film of gold on the polysilicon surface. Liftoff is performed with an acetone soak and IPA rinse. Since the presence of even a thin metallic layer increases dissipation of elastic energy in the moving structure, we can tailor the quality factor of the resonator by placing the heater at locations with different displacement amplitudes. At the same time, matching of the input impedance to that of the corresponding circuitry can be achieved by changing the geometry of the resistor. For the structure described in this manuscript, we define a 50 Ω, 70x3 μm resistor on the periphery of the dome (fig. 1b), allowing the resonator to be undamped by the 2nd layer metallization.

When a 20 mV signal is applied to the resistor, approximately 4 μW of Joule heat is dissipated into the resonator. Adsorbed heat in the resonator produces thermal stress in the polysilicon device layer, and, due to coupling between the membrane and flexural components within the shell structure, this thermal stress produces significant out-of-plane deflections within the resonator. The fact that bending of the resonator is facilitated through the curved structure (rather than through differing expansion coefficients in multiple layers) makes HAMMER not subject to damping induced by lossy layers in bimorph resonators.

The process of heat diffusion within the resonator can be modeled by a one dimensional heat equation,

$$u_n(r,t) = B_n \sin\left(\frac{n\pi r}{R}\right) e^{-\lambda_n t} \tag{3}$$

with time constant,

$$\lambda_n = \frac{K}{C\rho}\left(\frac{n\pi}{R}\right)^2 \tag{4}$$

where K is the thermal conductivity, C is the heat capacity, R is the radius of a 2D plate, and n=2.4 is the root of a Bessel function $J_0(\mu_\iota^{(0)})=0$. Due to the micron size radius of the device, the cooling rate, 1/λ , is on the order of microseconds, allowing high frequency modulation of the dissipated power through application of an AC signal to the resistor. When the frequency of the applied signal matches the natural frequency of the mechanical vibrations, f_0, provided that $1/\lambda < 1/f_o$, detectable high amplitude vibration occurs.

The driving force, which is proportional to the power dissipated in the resistor, is, after removing 2f components:

$$F_{drive} \propto V_{DC} V_{AC} \cos(\omega_o t) \tag{5}$$

In the 30 μm domes, sufficient mechanical displacement is obtained with a 20 mV AC signal and no DC biasing, reducing power consumption of the transducer. Post production resonator tuning is possible by controlling the DC voltage level through the resistor. The 30 μm dome showed a (2 Hz/μW) dependence on the applied DC bias.

The vertical displacement of the vibrating shell is detected optically by measuring reflectivity of a 632.8 nm HeNe laser beam focused on the device in a 10^{-6} Torr vacuum chamber. The modulation of the reflected light, introduced by a moving Fabry-Perot interferometer[8] (created by the substrate and the suspended structure) was detected by a New Focus 1601 high-speed photodetector and analyzed in an Agilent 4396B spectrum/network analyzer.

3. MICROMECHANICAL SIGNAL GENERATOR, MIXER AND FILTER

A frequency generator was built by including HAMMER in a positive feedback loop. In the test setup, the signal from the photodetector is amplified 60 dB, filtered to select a particular resonant mode, and applied back to the driving resistor. Oscillation conditions are met by adjusting the filter center frequency and amplifier gain in the feedback loop. A frequency counter, connected to the output of the generator, was used to monitor the stability of the oscillations and calculate the standard deviation δf. Short-term stability, $\delta f/f \sim 1.5$ ppm (fig. 3a) was demonstrated at 14.5 MHz for the 30 μm resonator. Phase noise (fig. 3b) of the same mode was measured to be -80 dBc/Hz at a 1 kHz offset. Our measurements indicate that the value of the phase noise was determined by the high noise floor of the detection and sustaining circuitry. Further improvement in the stability of the oscillator should result from substitution of the laser detection with a capacitive sensor. Such a modification will reduce the frequency noise by eliminating position dependant laser DC heating and intrinsic laser instability.

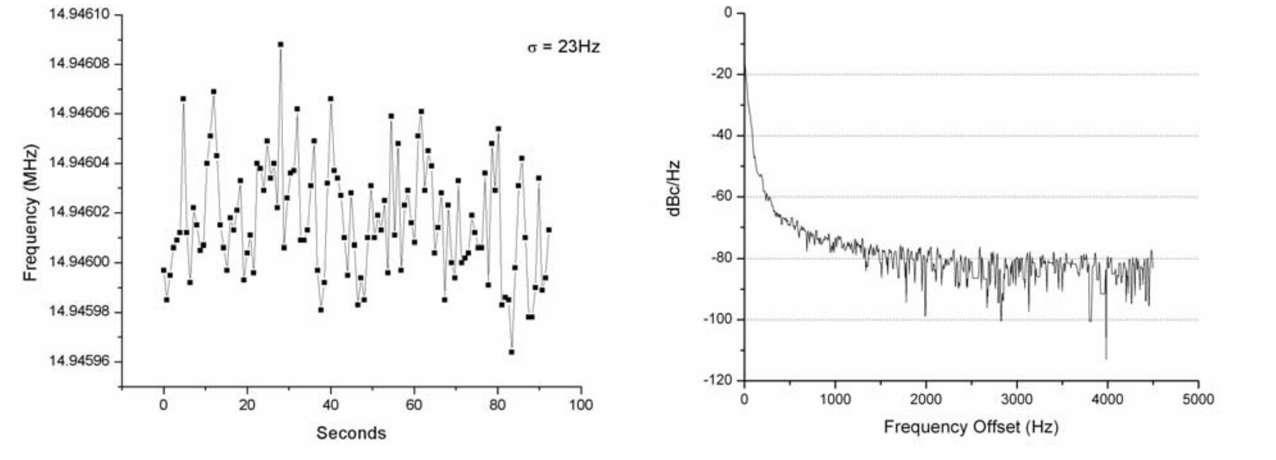

Figure 3. Short term stability (a) and phase noise (b) in a 30 µm dome oscillator.

Frequency translation of multiple input signals can be naturally performed by HAMMER due to inherent nonlinearity of the thermoelastic drive mechanism. Equation 6 illustrates the operation of HAMMER when a heterodyne local oscillator signal (ω_{LO}) and an input RF signal (ω_{RF}) are linearly superimposed and applied to the micro-fabricated resistor. The driving force, proportional to the power dissipated in the heater is:

$$P = \frac{\left(V_1 \sin(\omega_{LO} t) + V_2 \sin(\omega_{RF} t)\right)^2}{R} \tag{6}$$

The terms can be expanded to yield

$$P = \frac{1}{R}\left(...... + V_1 V_2 \cos(\omega_{LO} - \omega_{RF})t - V_1 V_2 \cos(\omega_{LO} + \omega_{RF})t + ...\right) \tag{7}$$

where terms at the combinatory frequencies, $\omega_{LO} \pm \omega_{RF}$, (also called intermediate frequencies or IF) represent the translated RF signal. If the frequency of the local oscillator signal is chosen such that the IF frequency corresponds to the resonant frequency of the dome, high amplitude motion will be produced in the resonator, and the down-converted RF signal will be detected as the output signal of the dome. Unwanted components in the driving signal are filtered out by the high-*Q* mechanical passband, thus, signal processing, equivalent to multiplication in a nonlinear analog mixer and subsequent IF filtering, is performed by the 30µm dome oscillator.

In contrast to electrostatically actuated micromechanical mixer+filters[1] HAMMER does not rely on DC biasing to produce detectable displacement in the resonator. If DC biasing of the input signals is included in equation 6, the driving power at the intermediate frequency, $\omega_{LO} \pm \omega_{RF}$, remains $V_1 V_2 \cos(\omega_{LO} \pm \omega_{RF})t$, unchanged by the DC level present in the input signal. Electrostatically actuated resonators would require a large amplitude AC signal from the LO to provide acceptable signal-to-noise ratios. HAMMER, however, achieves detectable displacement with 20 mV of signal, lending itself to low level signal mixing applications.

The ohmic input resistance offered by the HAMMER actuation method also provides an important performance advantage over capacitively driven resonators. Electrostatic drive, due to its reactive nature, requires impedance matching components to surround the actuation mechanism, consuming significant real estate while placing severe frequency restraints on the input signal. In the HAMMER system, the micron-sized heat dissipater can present a purely resistive 50 Ohm load to its sustaining circuitry. No passive components are needed to obtain maximum signal transfer, reducing the size, power consumption and component count in the system. Moreover, a wide range of RF frequencies can be downconverted with equal efficiency, an important advantage in a superheterodyne receiver setup.

Figure 4a shows the lorentzian response of the dome resonator (γ_{01} mode) when driven by intermediate frequency signal f_{IF} = 14.3 MHz in the micromechanical mixer+filter implementation. The input frequency of the radio signal, ω_{RF}, and the corresponding local oscillator frequency, ω_{LO}, have been varied over a wide range while maintaining a constant IF frequency, ω_{LO} - ω_{RF}. Linear response of the mechanical oscillator and minimal signal attenuation are preserved across a 1.5 GHz ω_{RF} input frequency range. The variations in amplitude of the response are caused by parasitic capacitance and inductance in the experimental setup. Figure 4b shows the S_{11} parameter for our test chamber over the same frequency range. S_{11} for both the resistor/dome actuator and an equivalent test resistor are plotted to show the baseline reflection coefficient; thus we fully expect mixing to be more linear in an actual integrated setup where such parasitics are not present.

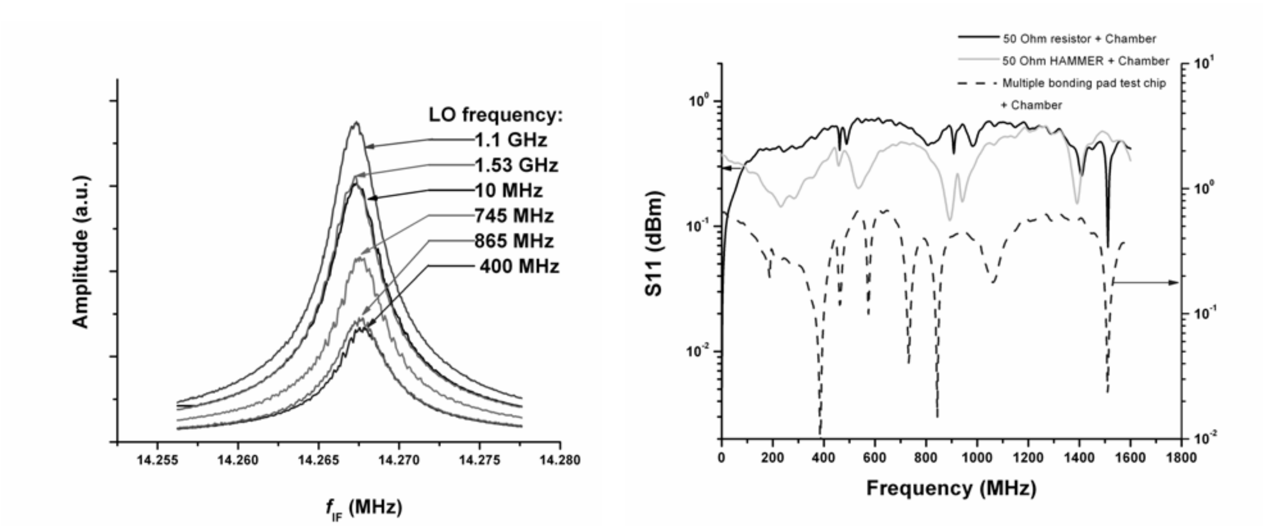

Figure 4. a) Output response of HAMMER at the intermediate frequency f_{LO} - f_{RF} = f_o over a 1.5GHz range of input LO and RF frequencies. Variations in the peak amplitude are the result of an attenuated RF drive signal caused by partial reflection from test chamber and bonding pad paracitics in the multiple resonator and bonding pad test chip (figure 5b). Good agreement is found between the S_{11} input reflection measurement of a single 50 Ω HAMMER and a 50 Ω resistor in place of the HAMMER.

4. FM RADIO RECEIVER

To demonstrate the potential of the resistor/dome transduction method, a superheterodyne FM receiver was built and tested using the MEMS device as a one-step down conversion mixer and IF filter. The setup is described in figure 5. The local FM station spectrum was received by an antenna and amplified. Using a linear power splitter, the FM spectrum was superimposed on a tunable reference local oscillator and applied to the HAMMER. In order to listen to 91.7 MHz we chose the local oscillator to be

$$f_{LO} = 91.7MHz - 2\pi\omega_o = 77.48MHz \quad (8)$$

centering the 100kHz bandwidth of the FM radio station in the vicinity of the resonance of the dome. The mechanical response of the dome resonator (the IF signal) was detected interfermetrically and the photodetector signal was applied to a spectrum analyzer for demodulation. Demodulation of the FM signal can be performed in one of two ways. First, direct frequency demodulation can be used; however, since the passband (Q=3000) of the dome resonator is much narrower than the bandwidth of the radio station, considerable information is lost, and only distorted audio can be discerned, even with fine tuning of the LO. To overcome this problem, the LO is slightly detuned and the slope of the mechanical resonance passband is used to convert FM modulation to AM modulation, which is subsequently demodulated. The mechanical passband could also be widened by placing the actuation resistor in a position where larger dissipation in the metal would occur, deliberately decreasing the device Q.

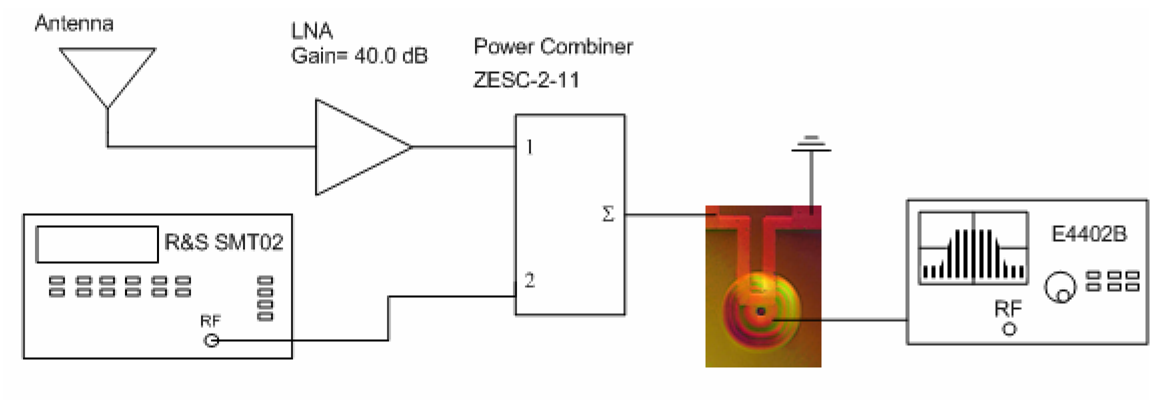

Figure 5. Block diagram of the micromechanical FM radio receiver.

5. CONCLUSIONS

Using a 30 µm diameter shell-type micromechanical oscillator and an integrated resistive actuation method, a high frequency reference oscillator with 1.5 ppm short term stability and phase noise of -80 dBc/Hz at a 1 kHz offset is demonstrated. The resistor/dome actuator is also shown to perform as a low power mixer and Q=10,000 IF filter with a 1.5 GHz input frequency range and 50 Ohm transduction impedance. Functionality of the HAMMER mixer+filter is demonstrated in a FM heterodyne receiver setup.

Such a device can be readily integrated in CMOS or BJT circuitry, eliminating the need for matching and discreet components while consuming minimal power and chip area. Improvements in oscillation stability will be possible by replacing the optical detection setup with a thermally stable method.

ACKNOWLEDGMENTS

This work was supported by the Cornell Center for Material Research (CCMR), a Materials Research Science and Engineering Center of the NSF (DMR-0079992). Work was performed in part at the Cornell Nano-Scale Science & Technology Facility (a member of the National Nanofabrication Users Network) which is supported by the National Science Foundation under Grant ECS-9731293, its users, Cornell University and Industrial Affiliates. The authors would also like to acknowledge the Office of Naval Research and DARPA for their support.

REFERENCES

[1] A.-C. Wong, H. Ding, and C.T.-C. Nguyen, “Micromechanical mixer + filters,” *Tech. Dig.,* IEEE Int. Electron Devices Meeting, San Francisco, CA, Dec. 6-9, 1998, pp. 471-474.

[2] B.P. Otis, J.M. Otis, “A 300-µW 1.9-GHz CMOS Oscillator Utilizing Micromachined Resonators,” *Solid-State Circuits, IEEE Journal of*, **38** (7) July 2003, pp. 1271-1274.

[3] J. Wang, Z. Ren, and C.T.-C. Nguyen, “Self-Aligned 1.14-GHz Vibrating Radial-Mode Disk Resonators,” *Solid State Sensors, Actuators and Microsystems, 12th International Conference on*, **Volume 2**, June 8-12, 2003, pp. 947-950.

[4] V. Kaajakari, T. Matilla, A. Oja, J Kiihamäki, H. Kattelus, M. Koskenvouri, P. Rantakari, I. Tittonen, and H. Seppä, "Square-Extensional Mode Single Crystal Silicon Micromechanical RF resonator," *Solid State Sensors, Actuators and Microsystems, 12th International Conference on*, **Volume 2**, June 8-12, 2003, pp. 951-954.

[5] M. Zalalutdinov, K.L. Aubin, R.B. Reichenbach, A.T. Zehnder, B. Houston, J.M. Parpia, and H.G. Craighead, "Shell-type micromechanical actuator and resonator," *Appl. Phys. Lett*. **83**, 3815 (2003)

[6] P.M. Morse and K.U. Ingard, *Theoretical Acoustics*, Princeton University, Princeton, NJ, 1986.

[7] W. Soedel, "A Natural Frequency Analogy between Spherically Curved Panels and Flat Plates," *J. Sound Vib.* **29** (4), 1973, pp. 457.

[8] D.W. Carr, L.Sekaric, and H.G. Craighead, "Measurement of nanomechanical resonant structures in single-crystal silicon," *J. Vac. Sci. Technol.* B **16** (6), Nov/Dec 1998, pp. 3821-3824.