Toward the Creation of the World's Smallest Radio

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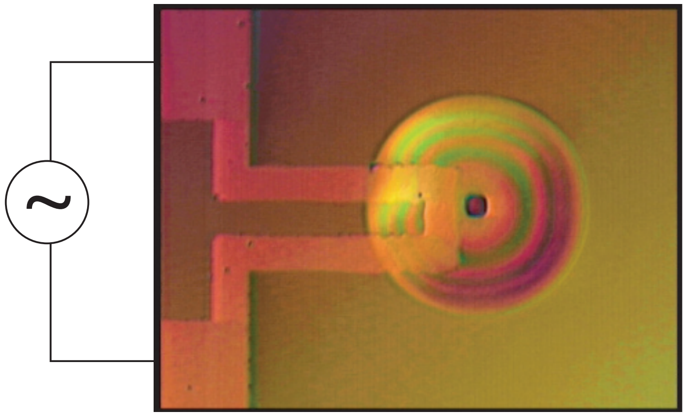
Introduction: Micro- and nanoelectromechanical systems (MEMS and NEMS) promise revolutionary scientific and technological solutions to long-standing Navy problems that include a range of distributed sensor and signal processor applications. Breakthroughs in microminiaturization of remote sensors and radio transceivers as well as dramatic reductions in their power consumption are enabled by the development of a new class of high frequency micron- and nanometer-size components where signals are no longer associated with electric current or voltage but by time-varying mechanical parameters, such as displacement, curvature, and stress. High speed performance of such devices is governed by scaling laws that shorten the time of the mechanical response and bring resonance frequencies for micron-size mechanical structures into the MHz and GHz range.[1] By converting a radio-frequency (RF) electrical signal into the physical motion of micromechanical structures and exploiting their mechanical resonant properties, one can replace traditional RF components (e.g., quartz crystal, surface acoustic wave (SAW) filters, inductors) with their MEMS/NEMS counterparts. One of the goals of our research is to demonstrate a "radio-on-chip," an RF transceiver with dimensions less than 100 micrometers, where novel RF signal processing is implemented in these small mechanical structures and fully integrated with transistor circuitry.

Thermoelastic Activation: A critical element of this technology is thermoelastic activation of microresonators where we take advantage of ultrashort thermal response times at these small scales.[2] Figure 4(a) shows an optical image of a "dome resonator" fabricated in polysilicon with a resistive microheater. When an AC electric current is applied to the microheater, the resulting modulated local thermal expansion produces large amplitude mechanical standing waves (Fig. 4(b)), when the frequency of the input current coincides with a mechanical resonance of the dome. A variety of methods—optical, capacitive, piezoresistive—can be used to detect this motion, converting it back to an electric signal for further processing.

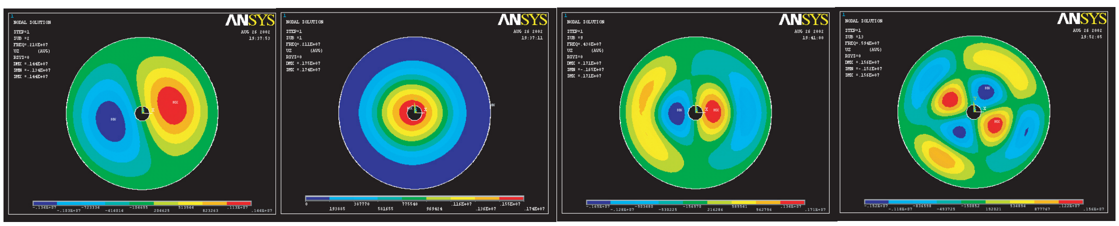
MEMS-based Transmitter and Receiver: By amplifying the output signal of the mechanical resonator and applying it again to the thermal drive, we close a positive feedback loop and set conditions for limit cycle oscillations. The high spectral purity of these vibrations allows us to use the device as a local oscillator (LO) for an RF transmitter and thus substitute an off-chip quartz resonator. In our prototype of a MEMS-based FM transmitter, the self-sustained oscillations of the dome resonator provide the carrier frequency (up to 400 MHz), while the FM modulation is implemented by a fine tuning of the dome's resonant frequency in response to a base-band signal applied to an additional microheater (Fig. 5(a)). Recently, by utilizing an additional oscillator and phase-locking phenomena, we have demonstrated phase modulation as well.

For an RF receiver, the thermal incarnation of the signal enables a broadband mixer implementation. When a linear superposition of several signals at different frequencies is applied to the microheater, the resulting temperature oscillations can occur at sum and difference frequencies because the heating is proportional to V^2/R. These temperature oscillations can drive the mechanical resonator when a beat frequency coincides with the mechanical resonance of the dome. In that way, the microheater acts as a frequency converter, while the dome resonator acts as a narrow pass-band filter for the down converted signal. In the widely used superheterodyne RF receiver architecture, our thermomechanical mixer-filter replaces both the intermediate filter (IF, most commonly implemented as off-chip SAW) and a mixer (usually a Gilbert cell with significant power consumption). This combination of mixer and filter—a cornerstone of a superheterodyne receiver—largely determines the performance of the device. A simple two-tone intermodulation test of our MEMS mixer-filter produces a 3rd order input intercept point of +30 dBm for interferers spaced at a 50 kHz offset from the carrier frequency. This performance far exceeds 3G W-CDMA specifications (+10 dBm at 10 MHz offset).

Figure 5(b) shows a schematic diagram of a MEMS-based radio receiver. Here, a 30-μm-diameter dome-type resonator is shown with a 50-Ohm resistive actuator that provides mixing and filtering at f_{IF} = 14 MHz. We also utilize a side of the resonant peak of the MEMS filter to demodulate FM signal (slope-type FM-AM conversion) in order to produce an audible signal from local FM radio stations. Since the thermal actuator is essentially an ohmic resistor, it can be designed to match exactly the output impedance of



(a)



(b)

FIGURE 4
Dome-type micromechanical resonator (film thickness 200 nm, radius 15 μm, apex elevation 0.9 μm) with (a) resistive thermal actuator and (b) normal modes corresponding to different resonance frequencies.

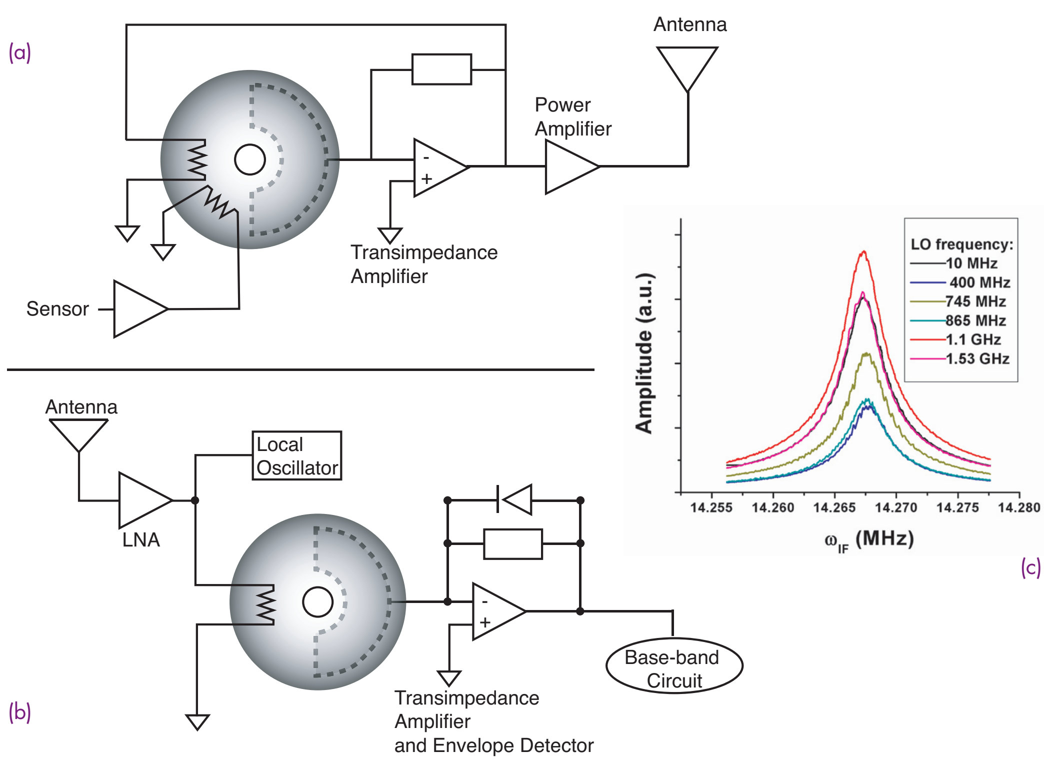


FIGURE 5
Schematic diagrams for (a) RF transmitter and (b) superheterodyne receiver; (c) shows resonant response of the dome to a downconverted RF signal.

the front-end RF amplifier over a very wide frequency range. In our demonstration, we are able to select sources of RF signals in a frequency range from 10 MHz to 1.5 GHz by tuning the LO (Fig. 5(c)).

Conclusions: The significance of this demonstration derives from the fact that no other frequency-selecting RF component (i.e. neither coils nor quartz nor SAW devices) is required for our radio. Currently, we are working on a design of RF MEMS resonators that can be fabricated in a standard CMOS fabrication process. Further, our research efforts are also devoted to the expansion of the idea of MEMS-based signal processing to include coupled arrays of resonators (Fig. 6). A variety of complex RF components, from variable-width, high-order filters to broadband RF spectrum analyzers, can be built based on such arrays. It is our belief that such signal processors, when integrated with MEMS/NEMS-based sensors, will result in a powerful technology for distributed systems.

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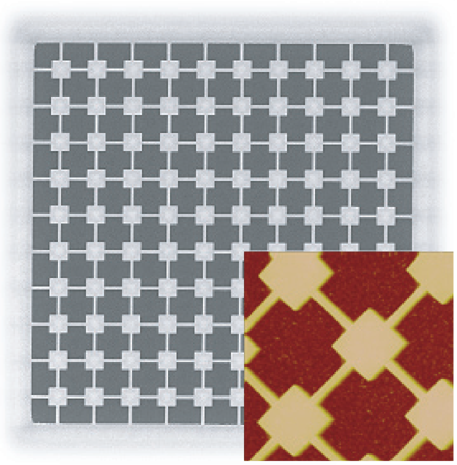

FIGURE 6
An array of coupled nanomechanical diamond resonators for RF signal processing.

References

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[2] M. Zalalutdinov, K. Aubin, R. Reichenbach, A. Zehnder, B. Houston, J. Parpia, and H.G. Craighead, "Shell-type Micromechanical Actuator and Resonator," *Appl. Phys. Lett.* **83**, 3815-3817 (2003).