C. T.-C. Nguyen, R. Liu, and J. N. Nilchi, "An ultra-low power mechanical trigger detector (invited)," *Proceedings*, 2017 Gov. Microcircuit Applications & Critical Technology Conf., Reno, Nevada, March 20-23, 2017, pp. 104-107.

An Ultra-Low Power Mechanical Trigger Detector

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Abstract: A sub-10nW wireless trigger detector is under investigation that employs an all-mechanical signal processing front-end circuit to accept and filter an incoming signal (e.g., from an antenna); convert the signal to a mechanical signal (i.e., a velocity); pre-amplify (if needed) the input displacement amplitude via an energy balancing mechanical circuit; then power amplify and demodulate the signal via nonlinear resonant impact-based switching at an output electrode—in essence, a mechanical filter-amplifier-demodulator circuit. This paper reports a VLF to LF versions of this mechanical circuit demonstrated with sensitivity down to −68dBm capable of receiving FSK words in OOK receive fashion. In trigger detector mode, the circuit detects simple tone triggers with no false positives or negatives over the four hour testing period. Ultimately, this approach might require no transistors, which not only removes the need for quiescent, i.e., DC, power consumption, but also removes noise sources typically associated with active semiconductor devices.

Keywords: micromechanical resonator, resoswitch; radio; low power; receiver; trigger; FSK; sensor network.

Introduction

The widespread expectation that autonomous sensor networks will fuel massively accessible information technology, such as the Internet of Things (IoT) [1] comes with the daunting realization that huge numbers of sensor nodes will be required, perhaps approaching one trillion. Needless to say, besides cost, energy will likely pose a major constraint in such a vision. Quiescent energy consumption will be especially important for an application (e.g., for the DoD) that must "listen" for a rare trigger event, such as the passing of a specific automobile, an animal crossing a trail at a certain location, or a wireless electromagnetic signal received by an antenna. In such applications, solutions that enable orders of magnitude lower "listening" power consumption, e.g., under 10nW, are of great interest. The DARPA N-ZERO program in fact seeks this capability.

Mechanical FSK Receiver Front-End

The mechanical approach to power savings taken here harnesses, first, the extremely high Q of mechanical resonance to select a specific frequency and boost the responsivity of a mechanical detector towards sensitivity better

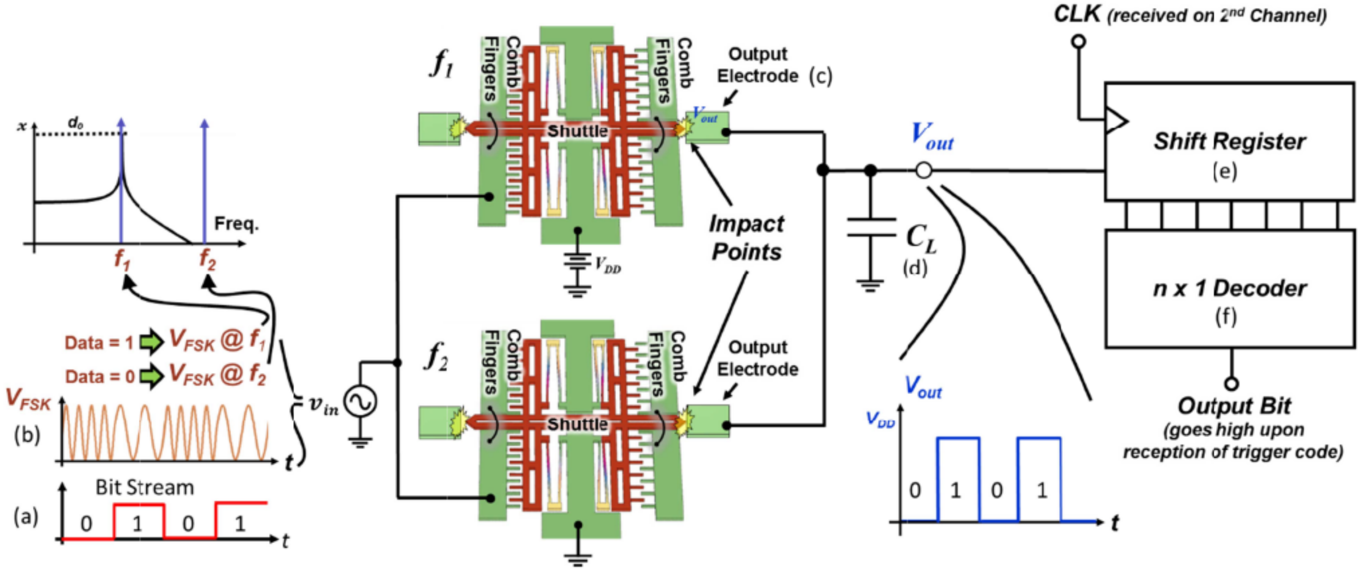


Figure 1. Illustrative summary of the low-frequency all-mechanical zero quiescent power signature detector under investigation. Here, the (a) input bit stream is (b) FSK-modulated into an off-resonance signal to represent a '0' or an on-resonance signal to denote a '1'. Reception of a '1' at the input electrode induces resonance vibration of the top structure, in turn instigating impacting of the shuttle to the output electrode at (c). Impacting then periodically transfers charge from V_{DD} to the output load capacitor (d) C_L, eventually charging it to V_{DD}, which corresponds to a '1'. Any '0' input received afterwards stops resonant impacting of the top resonator and instigates it in the bottom one, which impacts to connect the output node to ground, allowing C_L to discharge to ground, denoting a '0'. In this way, the input bit stream is faithfully reproduced at the output and captured by (e) a shift register connected to (f) logic that delivers an output '1' when the registered bit stream matches the trigger code.

than −60dBm; and second, resonance impacting to transfer charge from a battery to an output load only when a valid input frequency arrives. Without a valid input frequency, the receiver front-end consumes no power, i.e., it “listens” with zero quiescent power consumption.

Figure 1 summarizes a LF (e.g., 60-kHz) version of the mostly-mechanical trigger detector. Here, two resonant switches (resoswitches) [2], one that resonates at an FSK mark frequency, while the other at the space frequency, feed a single output capacitive load C_L. Each resoswitch comprises a movable shuttle (perhaps constructed in gold [2] [3] or metal-coated polysilicon [4] [5]) suspended by stress-relieving folded-beams, flanked by capacitive-comb transducers, and employing sharp protrusions to impact with the indicated output electrodes. Once driven to resonance at a sufficiently large amplitude, the shuttle protrusion impacts the output electrode, closing a metal-to-metal switch contact and delivering charge from the supply V_{DD} to the output load capacitor C_L. Whether or not C_L charges depends upon competition between the upper and bottom resoswitches, which ultimately depends upon whether a mark or set FSK freqsuency dominates the input—a requirement for realization of full FSK demodulation versus the less efficient OOK.

Digital circuits—e.g., realized via low power static CMOS or perhaps MEMS switches—comprising a shift register and decoding logic then follow the mechanical front-end to decide whether or not the right bit sequence trigger has been received. If correct, they deliver an output high, equal to V_{DD}; otherwise, it remains low.

Mechanical OOK Receiver Front-End

If only one resonator is available, then OOK reception is still possible via the simpler circuit of Figure 2, where the input still connects to the comb fingers and impact switching still periodically charges an output capacitor C_L, but now a bleed resistor R_{bleed} discharges C_L, sending the output to 0V during non-impacting periods. This circuit will still demodulate an FSK input, like that shown in Figure 1(b), but will do so in an OOK fashion, without the full benefits of FSK. It will also, of course, detect and demodulate the OOK input signal shown in Figure 2.

Resoswitch Design Specifics

The design and operation of the resoswitch device used for the demonstrations herein are well described in [2] and [3].

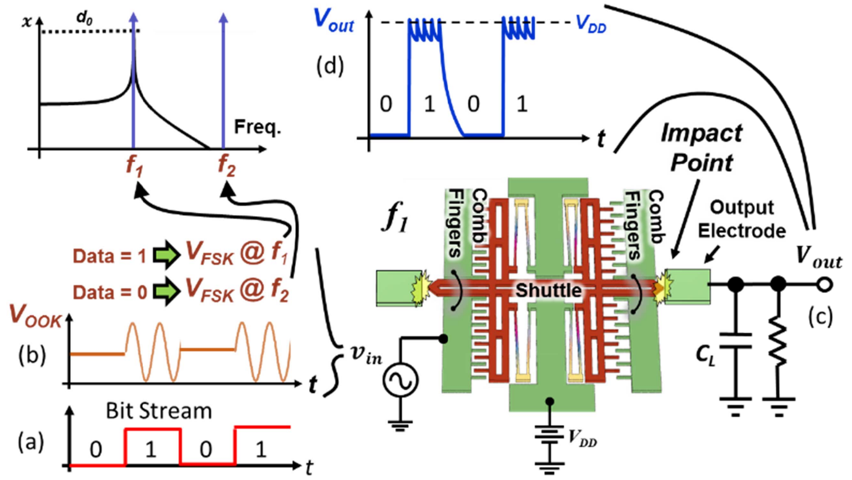


Figure 2. Illustrative summary of the low-frequency all-mechanical zero quiescent power OOK signature detector under investigation. Here, the (a) input bit stream comprises a (b) OOK-modulated on-resonance carrier signal that drives the device into resonance vibration during “on” periods that then charges C_L as in Figure 1 delivering a (d) output high. During “off” periods, the resoswitch does not move, so does not impact the output, allowing bleed resistor R_{bleed} to discharge C_L to 0V (i.e., output low).

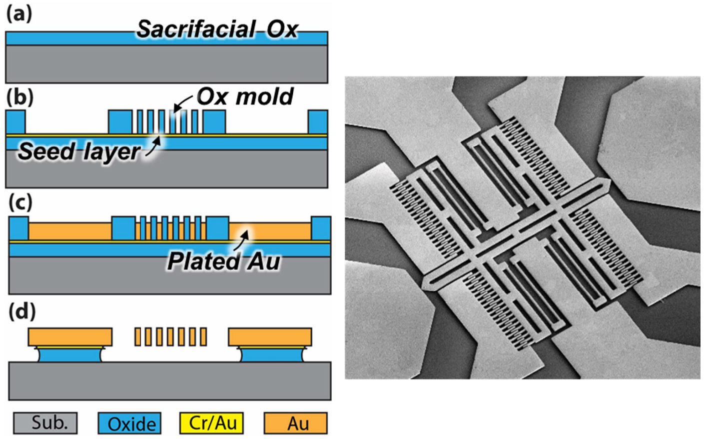


Figure 3. Process flow and SEM of an electroplated Au comb-driven resoswitch. (a) Deposit 2μm of sacrificial oxide. (b) Evaporate 7nm/20nm/20nm of Cr/Au/Cr to serve as a seed layer, then deposit 3μm of PECVD oxide to serve as a mold for electroplating. (c) Etch oxide mold, etch top Cr protection layer, and electroplate the gold structure. (d) Etch away oxide mold, then wet etching seed layer in the field. Release structures in 5:1 BHF.

Aside from sensitivity, of particular interest among performance parameters is the input impedance of this device, which should be able to match that of a typical VLF or LF magnetic coil receive antenna, on the order of several tens of kΩ, e.g., 50kΩ. The impedance of the design of [2] is a strong function of the number of fingers, the gap spacing, the Q, and the DC-bias voltage, V_P (*cf.* Figure 5). For example, with 38 fingers, 0.8μm finger gaps, Q=10,000, a switch gap of 0.5μm, and V_P =30V, a gold resoswitch achieves a sensitivity of −75dBm with an input impedance of 3.7MΩ. Increasing the number of fingers to 50, moving to gold-tipped polysilicon material with Q=100,000, and using 0.5μm finger gaps, yields a sensitivity of −94dBm and a motional impedance of only 7.4kΩ that matches easily to LF antenna impedances.

Resoswitch Fabrication

Figure 3 presents the fabrication process flow and SEM of a fabricated resoswitch such as used here to demonstrate both mechanical reception of an FSK input and reliable tone trigger detection. The fabrication process starts with sequential blanket depositions of sacrificial oxide, Cr/Au seed layer, and a second oxide, all over a starting silicon substrate. Next, the only masking step of this process followed by a dry etch step together pattern the top oxide to form a mold in (b) that delineates the needed resoswitch geometries. Electroplating to yield (c), followed by timed wet etch steps to remove the seed layer and the bottom sacrificial oxide under the structure, while retaining oxide under anchors so they stay put, then yield the final cross-section of (d).

The fact that this process requires only a single mask makes its cost suitable for use in enormous sensor networks.

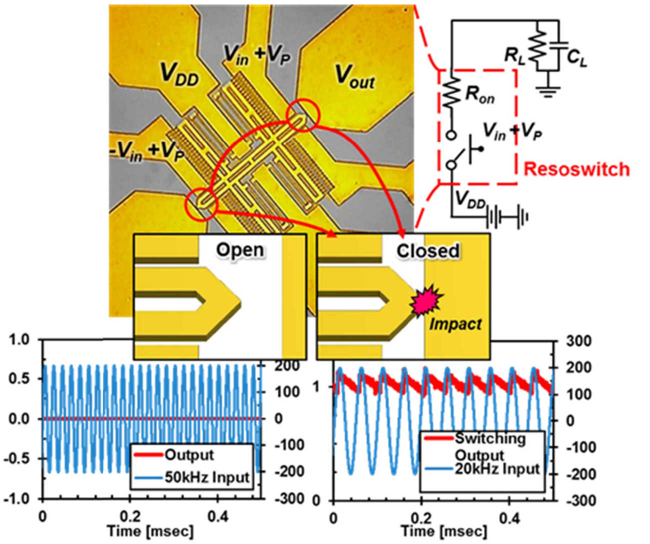


Figure 4. Illustrative summary of resoswtich operation. Left Plot: An off-resonance input does not induce impact switching, so produces no output. Right Plot: An on-resonance input induces impacting, which connects V_{DD} to the output, allowing it to deliver power.

Experimental Results

To first confirm resoswitch responsivity, Figure 4 presents measurements that show no response when off resonance power (i.e., an FSK '0') is applied to the indicated input electrode; but vibration and output charging when the input is on resonance (i.e., an FSK '1'). With a dc-bias voltage V_P of 16V, input powers of −60dBm were sufficient to incite impacting at the output node, which then delivered −11dBm to the backend circuit. This equates to more than 49dB of power gain via this mechanical switching mechanism. To be clear, because the resoswitch input impedance range from 50kΩ to 20MΩ, depending on the dc-bias, the stated input powers are computed based on the measured voltage at the resoswitch input and its measured input resistance.

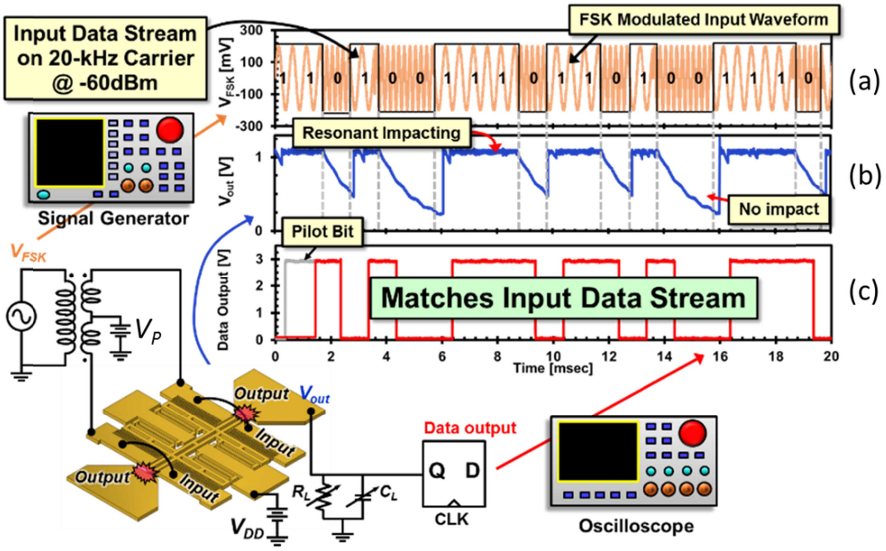


Figure 5. Test circuit to evaluate single-resoswitdch OOK detection of an FSK input bit stream. Here, the input FSK bit stream in (a) is faithfully reproduced in the output of (b) and the square-waved output of (c).

Figure 5 presents waveforms confirming successful OOK reception in (b) of the FSK input signal in (a) using the test circuit shown, which essentially mimics that of Figure 2. Here, the actual waveform across C_L takes on a trapezoidal shape, since this test circuit uses a bleed resistor to sink current (rather than the second resoswitch of Figure 1). An optional flip-flop can provide a square wave output, if desired, as shown in (c). Since the flip-flop belongs to the stage following the receiver, Figure 5 essentially presents successful demonstration of an all-mechanical receiver front-end that uses no transistors, providing strong testament to the efficacy of all-mechanical circuits.

To demonstrate trigger detection, the OOK detecting mechanical circuit of Figure 2 was again utilized, but now transmitting only one bit (i.e., a short tone burst) instead of the stream of bits shown. As shown in Figure 6, the length of the tone can actually be extremely short, e.g., only 100μs, as the resoswitch responds quite fast to the burst and charges C_L immediately.

Figure 7 summarizes the experiment performed to determine the false alarm rate of the resoswitch trigger detector. In particular, it tabulates the resoswitch response to intermittent 1ms −60dBm trigger inputs (*cf.* (a)) superimposed over a continuous white noise input higher than −80dBm (*cf.* (b)). As shown, the trigger detector successfully provides an output high for all trigger inputs and never triggers without a trigger tone, giving it a false alarm rate of zero. And it does all this while consuming an average power of less than $(16)(1\text{ms})(1\text{V})^2/(1\text{M}\Omega)/(4\text{hrs}) = 1.1\text{pW}$ over the entire 4 hour test period.

Conclusions

Although its single resoswitch allows only OOK reception, rather than full FSK, the mechanical receiver demonstration of Figure 5 represents a very compelling leap forward in low power receiver capability, not only in its mostly-mechanical implementation, but also its ability to listen while consuming practically zero power. The full FSK implementation is further expected to consume not only zero quiescent power, but also only 5nW when processing a valid input trigger using a 1V supply and 5pF load at a 1-kHz data rate. Efforts are ongoing to demonstrate full FSK rendition.

As a trigger detector, this all-mechanical circuit also performs flawlessly, detecting all intended trigger inputs with zero false alarms over a rather noisy background.

Although the impedance of the demonstrated resoswitch trigger detector is rather high, designs that lower impedance to the tens of kΩ needed to match the magnetic coil antennas often used at VLF and LF are available and demonstrations are likely in the near future.

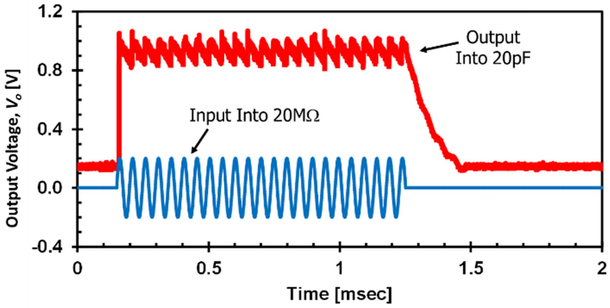
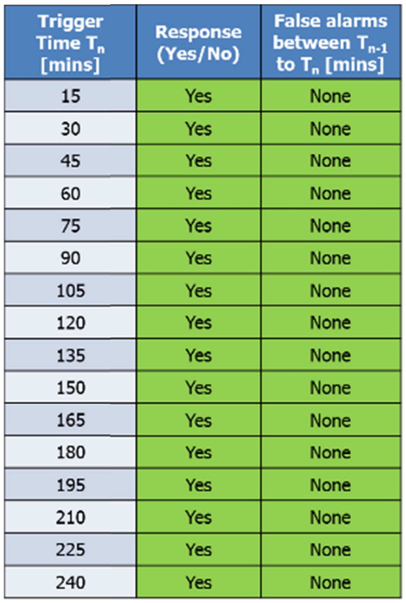


Figure 6. Meaured output V_{out} response to a burst resonance input v_{in} tone. Here, the resonator is biased to a 20MΩ input resistance, making the input waveform shown effectively a −60dBm input. The speed by which the responding resoswitch charges the output capacitance is remarkable and should allow trigger detection with input energy less than 50pJ.



Trigger Time T_n [mins]	Response (Yes/No)	False alarms between T_{n-1} to T_n [mins]
15	Yes	None
30	Yes	None
45	Yes	None
60	Yes	None
75	Yes	None
90	Yes	None
105	Yes	None
120	Yes	None
135	Yes	None
150	Yes	None
165	Yes	None
180	Yes	None
195	Yes	None
210	Yes	None
225	Yes	None
240	Yes	None

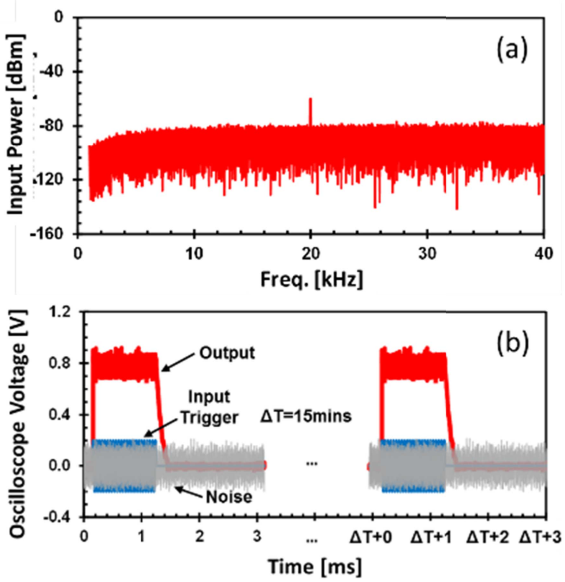


Figure 7. Summary of the experiment to measure the false alarm rate of the resoswitch circuit when configured as a trigger detector, including a table documenting true and false positives as well true and false negatives; (a) a measured frequency spectrum showing the −60dBm trigger energy over -80dBm white noise; and (b) time domain oscilloscope waveforms of the input trigger tone burst, the background noise, and the output.

Acknowledgment:

DARPA N-ZERO funded this work.

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