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Publication Date
2023-01-19

DOI
10.1109/mems49605.2023.10052463

Peer reviewed

FERRITE-ROD ANTENNA DRIVEN WIRELESS RESOSWITCH RECEIVER

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ABSTRACT

A micromechanical resoswitch receiver coupled to a 23.7-kHz wireless channel via a ferrite-rod antenna successfully demonstrates short-range wireless reception with resoswitch sensitivity better than –62 dBm at an on-off keying (OOK) bit rate of 0.9 kbit/s. The demonstrated performance confirms models that predict the maximum bit rate of such a receiver, revealing an ability to adapt to bit rates as high as 8 kbit/s sans antenna that surprisingly are not limited mechanically, but then reduce upon introduction of finite electrical bandwidth antennas. Indeed, the demonstrated wireless resoswitch receiver displays a bit rate-to-sensitivity trade-off governed by the finite rise time of the signal received by the antenna. Meanwhile, the receiver consumes no power while waiting and listening for valid inputs. Unlike an RFID tag, this resoswitch receiver rejects strong interferers via the much higher Q of its mechanical resonance, allowing it to serve applications that must operate in congested wireless environments.

KEYWORDS

Resoswitch, wireless, receiver, antenna, bit rate, low power, resonator, micromechanical, quality factor.

INTRODUCTION

By harnessing resonance vibration to reduce the power required to close a mechanical switch, micromechanical resonant switches ("resoswitches") [1] [2] provide mechanical means to filter, amplify, and demodulate communication signals, making possible transistor-less mechanical communication receivers capable of 1-kbit/s bit rates and –60-dBm sensitivities while consuming no power when waiting and listening for valid input codes [3]. These attributes enable continuous monitoring without any need for sleep/wake cycling to save power, making resoswitches particularly attractive for always-on monitoring applications. A recent advancement that employs pre-energization to increase the bit rate capacity of resoswitches to 8 kbit/s [4] now provides an opportunity to expand the application range from low bit-rate tagging and label updates to higher-speed voice communications. In fact, theory predicts that pre-energization allows a resoswitch to adapt to any needed bit rate if not constrained by other system limitations, such as noise or finite system bandwidth.

To investigate the effect of finite system bandwidth on practical wireless resoswitch receivers, this work evaluates wireless reception using a resoswitch fed by a ferrite-rod antenna. Ferrite-rod antennas are particularly suited for the resoswitch devices in this work because they can be tuned to the 20-kHz range and support a relatively high output impedance in the >10 kΩ range. While pre-energizing theory suggests that resoswitch device Q poses no limit on the maximum bit rate of a resoswitch receiver [4], this work shows that bandwidth limitations imposed by the Q of the antenna matching network can still limit the bit rate. Ultimately, harnessing the high bit rate supportable by a resoswitch requires proper co-design with the antenna.

RECEIVER STRUCTURE & OPERATION

Fig. 1 summarizes the wireless demonstration set-up employing ferrite-rod antennas and a resoswitch configured as a wireless receiver. The resoswitch consists of a movable gold shuttle suspended 2.5 μm above a silicon substrate by folded-beam springs, flanked on opposite sides by two comb-drive transducer electrode pairs with interdigitated fingers and two sharp impactor protrusions separated 1 μm from spring-softened impact output electrodes. The ferrite-rod receive antenna connects to the left transducer pair, which serves as the input. The right transducer pair is unused but, if desired, can be used to boost the input electromechanical coupling when a differential input signal is available, e.g., as supplied by a balun [1].

Proper resoswitch operation requires application of a dc bias V_{DD} to its conductive shuttle, in this case 5V, that serves to amplify the force induced by a voltage input signal applied to its input electrode, e.g., by the antenna in Fig. 1. Note that merely applying V_{DD} to the resoswitch shuttle

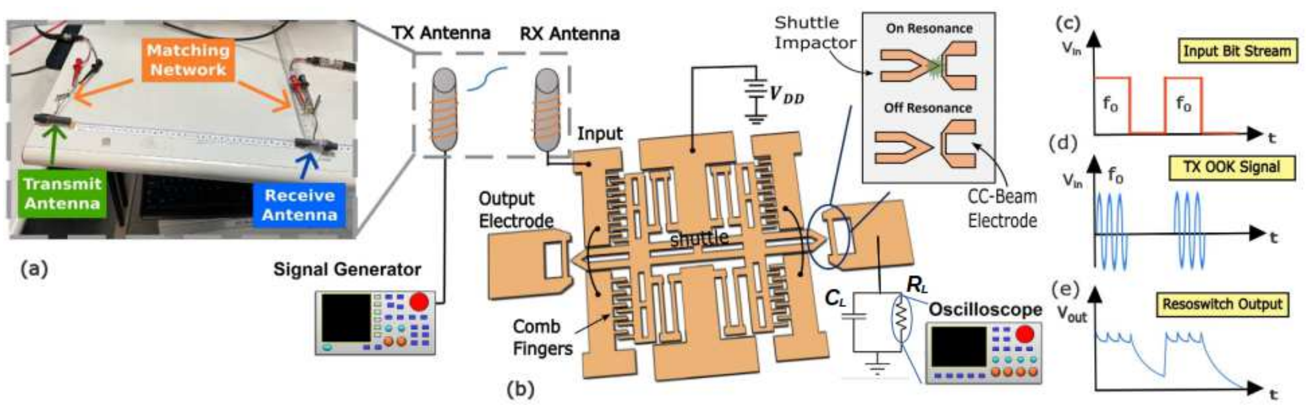

Fig. 1: Wireless communication demonstration set-up employing (a) ferrite-rod antennas and (b) an all-mechanical resoswitch to receive and demodulate the (d) OOK-modulated data bit stream of (c) into the matching resoswitch output bit stream of (e).

draws no dc current and consumes no power, since when at rest, the resoswitch shuttle is effectively one plate of a charged capacitor. In this state, the resoswitch is effectively listening for valid inputs while consuming no power. It consumes power only upon reception of a valid input that it must demodulate and amplify.

In this wireless demonstration, data in the form of a bit stream as shown in Fig. 1(c) is modulated onto a carrier frequency before sending it through the communication channel. Here, on-off keying (OOK) serves as a convenient modulation scheme, where at the transmitter, each '1' maps to a sinusoid at the resonance frequency of the resoswitch, and each '0' maps to 0V. Thus, when sending a '0' bit, no signal is transmitted nor received, the shuttle remains stationary, and any charge on the load capacitor C_L drains to ground via a large bleed resistor R_L, which in the demonstration setup is the 1 MΩ oscilloscope input impedance. Since the output across the load capacitor measures 0V, this indicates successful transmission of the '0' bit. On the other hand, when sending a '1' bit, the transmit antenna outputs a sinusoid at the resoswitch resonance frequency. Once received by the receive antenna, the signal drives the resoswitch shuttle to vibrate at resonance and periodically impact its output electrode. The metal-to-metal contact of each impact transfers charge from V_{DD} to C_L, charging the output to V_{DD}, which constitutes successful transmission and reception of a '1' bit.

Note that only input signals with frequencies in the passband of the resoswitch can excite it to impact, since only these signals benefit from amplification by the high Q of the mechanical device. Stray off-resonance signals, e.g., from other wireless devices, will not generate enough amplitude for impact. In this way, the resoswitch rejects out-of-band interferers as a good wireless receiver should.

ANTENNA-RESOSWITCH CO-DESIGN

Feeding a resoswitch receiver efficiently using a ferrite-rod antenna poses several challenges. One challenge is impedance matching, where the very high impedance of a comb-driven resonator practically precludes matching; another is the small, tuned bandwidth of the ferrite-rod antenna and its matching network.

Ferrite-Rod Antenna

Each ferrite-rod antenna in Fig. 1 comprises a magnetic rod wrapped in winds of wire, which allows it to be electrically small. In such a small loop antenna, the current around the perimeter of the loop is in phase, since the total conductor length is a small fraction of the signal wavelength, λ. The ferrite core increases the effective area of the antenna by concentrating magnetic field lines. Increasing the loop area and the number of turns raises the voltage between the two antenna terminals for a fixed field strength at the cost of increasing the physical size of the antenna.

Electrically, a ferrite-rod antenna simply behaves like an inductor with reactance $X_L = 2\pi f L$, where f is frequency and L is the inductance of the coil. While there is also radiation resistance R_R and additional loss resistance R_L in series with the inductor, they are small in magnitude compared to the reactance [5]. Ferrite-rod antennas are inefficient due to their small size (compared to λ) and low

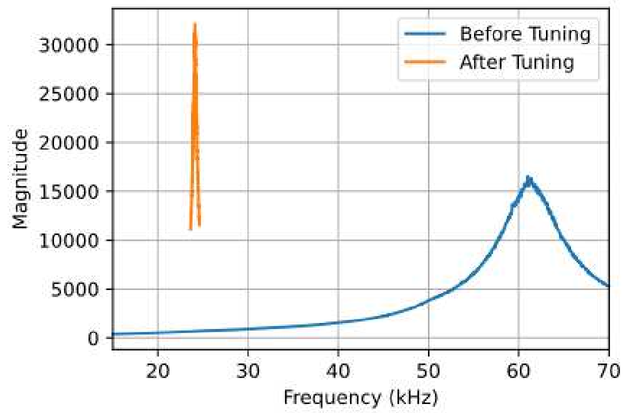

Fig. 2: Z parameter magnitude, derived from measured S parameters, of the ferrite-rod antenna before and after tuning.

radiation resistance. As a result, practical ferrite-rod antennas are typically tuned with a parallel capacitor across the loop terminals. This forms a parallel-resonant LC circuit that boosts the output voltage Q_{ant} times greater. While Q_{ant} boosts the voltage, it also limits the bandwidth to $f_{BW} = f_o/Q_{ant}$, where f_o is the center frequency.

The antennas demonstrated in this work are commercial ferrite-rod antennas pre-tuned for cross-continent domestic time broadcast reception near 60-kHz. Both S_{11} and LCR meter measurements indicate coil inductances in the 10-15 mH range. Tuning this antenna to the 23.7-kHz measured resonance frequency of the resoswitch requires an external 6.8 nF tuning capacitor connected in parallel. Fig. 2 plots the real part of the measured S_{11} converted to Z parameters. Before tuning, the antenna is resonant near 60 kHz, but only has about 22 Ω of real resistance at 23.7 kHz. After tuning, the resonant frequency shifts down, boosting the real part of the antenna's impedance up to 31 kΩ, which helps the match to a resoswitch. Note also how the bandwidth of the antenna reduces from 5.6 kHz at 60 kHz to only 3 kHz at 23.7 kHz—a rather consequential event that (as will be seen) will reduce the maximum receiver bit rate.

Impedance Matching

The motional resistance R_x of the resoswitch is that of a comb-driven resonator [6], so is a strong function of the finger gap spacing, as well as the dc bias voltage across the drive and shuttle fingers. Device 1 in Table 1 summarizes the design of the resoswitch used herein and computes an expected R_x of 1654 MΩ, which is clearly much too high to match the 31kΩ of the receive antenna.

A more aggressive resoswitch, such as summarized in Device 2 of Table 1 which employs the lithography technology of [6] and the high Q offered by [7] could be made to match the antenna impedance. For present purposes, however, using the sensitivity formula from [1], the 1654 MΩ to 31 kΩ resoswitch-to-antenna impedance mismatch of the demonstrated device imposes 47 dB of loss between the antenna and resoswitch versus a matched condition, meaning that -18 dBm must appear on the antenna to cause impacting for a -65 dBm resoswitch sensitivity. This is still sufficient for short range applications, e.g., in RFID tags.

EXPERIMENTAL RESULTS

A 23.7-kHz gold micromechanical resoswitch was fabricated via a one-mask process similar to that of [1],

Table 1: Resoswitch Design and Performance

Parameter	This Work (Device 1)	Scaled (Device 2)
Thickness, h [μm]	1.3	1.3
Finger Gap, d [μm]	1.0	0.1
Impact Gap, d_0 [μm]	1.0	0.1
Number of Fingers, N_f	38	270
Finger Width [μm]	1	0.1
Shuttle Mass [kg]	1.55×10^{-12}	1.50×10^{-12}
Frequency [kHz]	23.712	23.712
Q_{res}	706	7,200
V_P [V]	5	5
R_x [MΩ]	1654	0.032
Sensitivity [dBm]	-65.2	-92

with key device attributes summarized in Table 1 and its SEM shown in Fig. 3.

The resoswitch was placed in a LakeShore FWPX vacuum probe station at 1 mTorr to reduce gas damping and improve Q. Input, output, and shuttle electrodes were probed within the vacuum chamber, then routed outside the chamber to the receive antenna, a Keysight DSO1024 oscilloscope, and a dc power supply, successively. A Tektronix AFG3102 function generator delivered the OOK-modulated bit stream to the ferrite-rod transmit antenna. Fig. 4 plots the power received by the resoswitch as a function of the distance between antennas when sourcing 13.6 dBm (~23 mW) from the function generator, showing an expected inverse square dependence on distance. Despite the antenna's small size, which makes it inefficient for transmit, the setup shown in Fig. 1 with 23 mW output still provides sufficient transmission to meet the –65.2 dBm sensitivity of the resoswitch receiver at up to 18 cm.

Antenna-Imposed Bit Rate Reduction

The ability of a resoswitch to adapt to its input bit rate described in [4] relies on resonance energy stored in the device during non-driven periods, i.e., during '0' inputs, where the high Q of the device allows it to continue vibrating after the input drive is gone. The more energy in the device when the drive returns, i.e., when a '1' bit arrives, the faster it can return to impacting, since it need only traverse the distance from its initial pre-energized vibration amplitude to the impact threshold.

The amount of stored energy in a resoswitch depends on the drive efficiency during the pre-energization period, which practically means it depends on the drive amplitude during a '1' input. OOK signals directly fed to a resoswitch input would appear as the orange curves in Fig. 5 (measured at the function generator output), where the gated-sinusoid envelopes have sharp edge transitions, indicating the presence of energy at higher harmonic frequencies. On the other hand, if the OOK signals go through a band-limited channel before appearing at the resoswitch receiver input, the loss of high frequency content results in the blue curves measured at the 3-kHz bandwidth receive antenna output, showing reduced amplitude and more gradual up and down transitions. These less efficient waveforms not only hurt the receive sensitivity of the resoswitch but also deliver energy more slowly, so reduce its pre-energization.

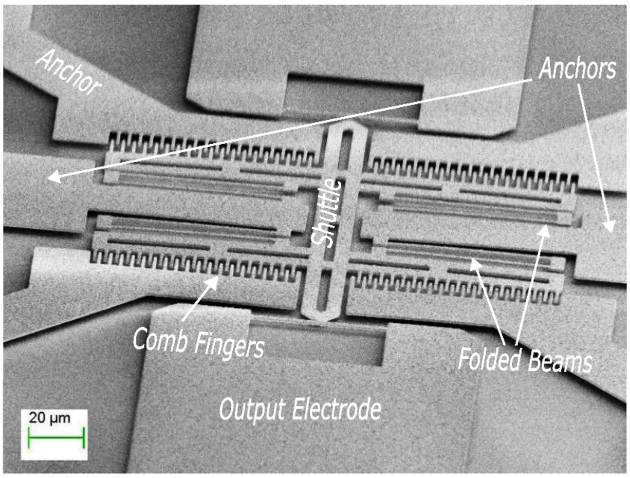

Fig. 3: SEM micrograph of the single-mask electroplated-gold resoswitch fabricated for this work.

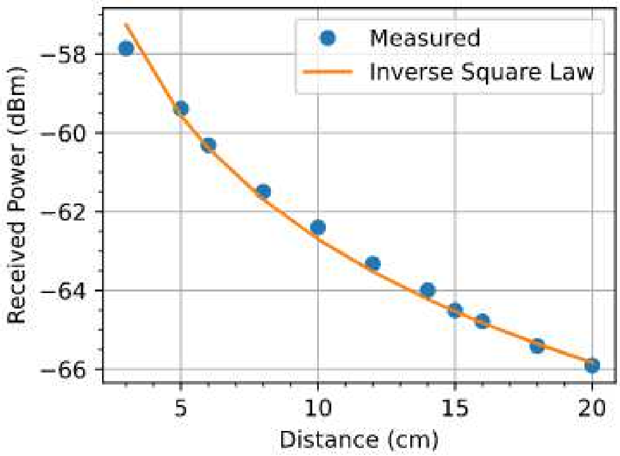

Fig. 4: Measured power delivered to the resoswitch vs. antenna separation distance falls off with an inverse square law.

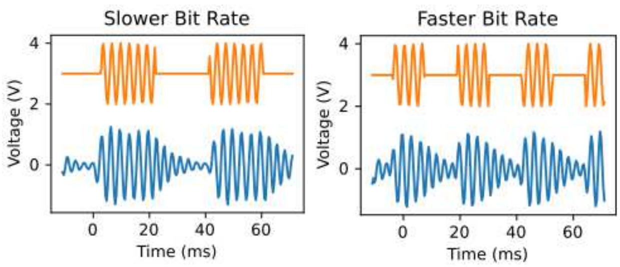

Fig. 5: Transmitted (orange) and antenna received (blue) waveforms (decimated to show sinusoid) for the cases of slow and fast bit rates.

This then compromises its ability to adapt to the incoming bit rate, thereby reducing its maximum bit rate.

To illustrate this phenomenon, Fig. 6 presents measured OOK-modulated waveforms transmitted at 13.6 dBm (green) over 15 cm and received (blue) by the respective antennas, clearly showing waveform distortion caused by finite channel bandwidth. Despite this, the resoswitch still successfully demodulates the waveform, where the output bit stream (orange) matches the input up to 900bit/s. Fig. 7 presents similar plots using a 1 kbit/s rate that ensue when first using a much wider channel bandwidth, then attempting this same bit rate via the antenna-band-limited wireless channel. Without the antennas, the bit rate adapting ability of the resoswitch can keep up with the 1 kbit/s rate and further permits a rate of 8 kbit/s [4], which is 8 times faster

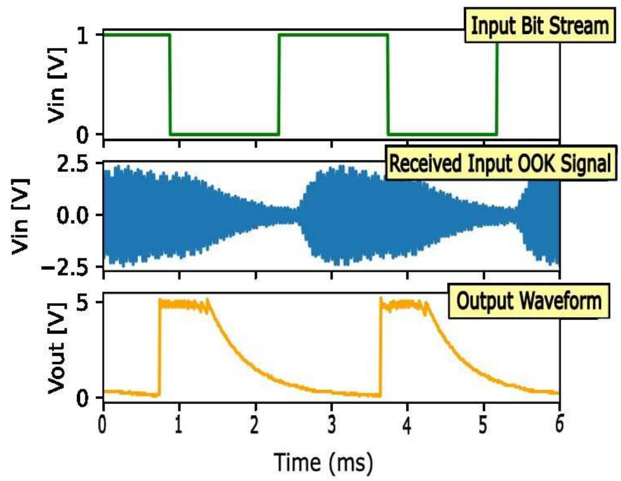

Fig. 6: Measured waveforms showing successful wireless demodulation using the antenna-fed resoswitch receiver.

than this and the highest yet demonstrated. The addition of the antennas and consequent bandlimited channel results in the last plot (green), where the resoswitch clearly can no longer track the incoming 1 kbit/s data stream, confirming the impact of the 3-kHz channel limit.

Fig. 8 finally presents a measured plot of wireless sensitivity (i.e., the minimum detectable power delivered to the resoswitch) vs. the input bit rate, showing a sensitivity of –65 dBm at 100 bit/s that worsens (due to waveform distortion) to –62.2 dBm at the maximum bit rate of 900 bits/s, both sufficient for short range sensor network applications.

CONCLUSIONS

The 900 bit/s data rate over a wireless channel via an all-mechanical receiver, despite high impedance mismatch, is an encouraging demonstration. While the observed antenna-derived bandwidth constraints dampen somewhat the excitement surrounding a resoswitch's bit rate adaptability, it is important to note that the employed ferrite-rod antennas were of the wrong frequency, so required wide tuning that ultimately limited their bandwidth. Antennas that start at the proper frequency could easily provide much more bandwidth, which would then allow the resoswitch receiver to operate at a non-limited 8 kbit/s good enough for voice communications. The use of even smaller ferrite-rode antennas at frequency co-designed with a more aggressively dimensioned resoswitch for better impedance matching (e.g., Device 2 in Table 1) is the next logical step towards longer range voice communications.

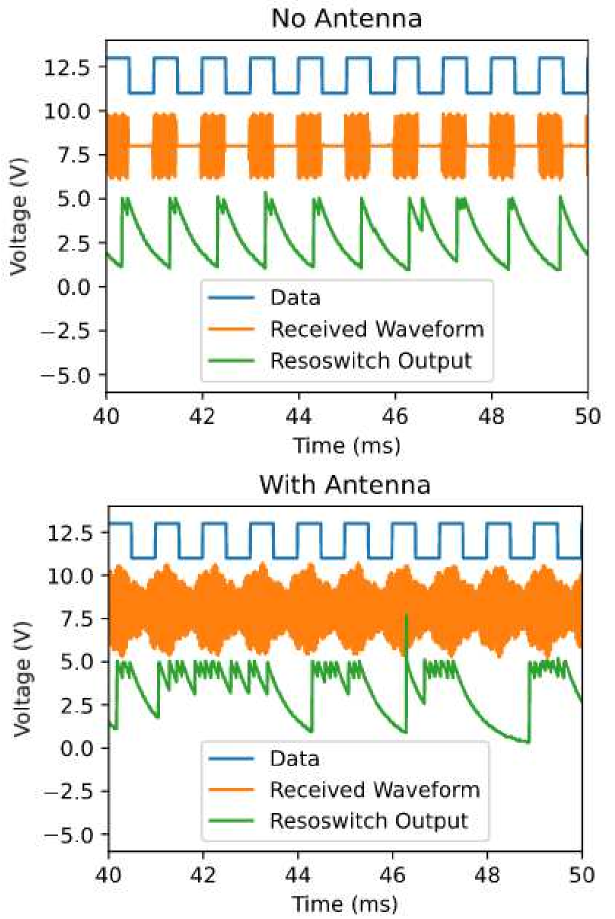

Fig. 7: Measured comparison of received waveforms (orange) and resoswitch outputs (green) at 1 kbit/sec connected directly (top) and wirelessly using an antenna (bottom).

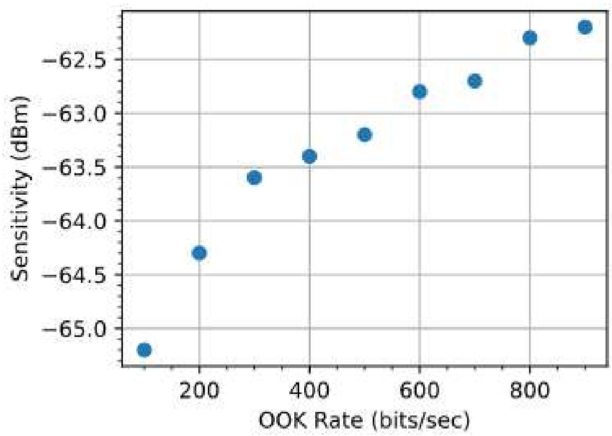

Fig. 8: Measured ferrite-rod antenna-driven resoswitch receiver sensitivity vs. transmit bit rate.

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