RADIOISOTOPE-POWERED SURFACE ACOUSTIC WAVE TRANSPONDER

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Abstract: We demonstrate a ^{63}Ni radioisotope-powered pulse transponder that has a SAW (surface acoustic wave) device as the frequency transmission frequency selector. Because the frequency is determined by a SAW device, narrowband detection with an identical SAW device enables the possibility for a long distance RF-link. The SAW transponders can be buried deep into structural constructs such as steel and concrete, where changing batteries or harvesting vibration or EM energy is not a reliable option. RF-released power to radioisotope-released power amplification is 10^8, even when regulatory safe amounts of ^{63}Ni are used. Here we have achieved an 800μW pulse (315 MHz, 10μs pause) across a 50Ω load every 3 minutes, using a 1.5 milli-Ci ^{63}Ni source.

Key words: self-powered sensor, radioisotope-powered transponder

1. INTRODUCTION

A necessity of an autonomous sensor is a miniature power source with a long lifetime. For sensor networks working in harsh, inaccessible environments (Figure 1), battery replacement can be impossible or expensive. While traditional power sources, such as chemical batteries, can only work up to several years without replacement, radioactive isotope power sources can work for 100 years with their performance mostly unaffected by the environment. For example, ^{63}Ni power sources have a high energy density (~10^5kJ/m^3) and long half-life (100.2 years). Nickel-63 emits β-particles with an average kinetic energy E_{avg}=17.3keV, and a penetration depth of less than 10μm in most solids. As a result, devices powered by ^{63}Ni thin-films can be deployed safely with millimeter or microscale shields.

The power requirements for a typical low-power wireless sensor node are 1-10 nW for retaining memory state, 0.1-1 mW for periodic sensing and processing, and 1-100 mW power for periodic wireless communication [1]. The power to retain memory states can be provided by betavoltaics as reported in [2] even with the low activity radioactive thin films presented here. Furthermore, MEMS radioisotope-powered piezoelectric power generators [3] can generate output power needed for periodic sensing and processing. In this paper, we focus on the radioactive RF power generation with SAW frequency modulation that can be used as a CMOS compatible wireless beacon and for communications.

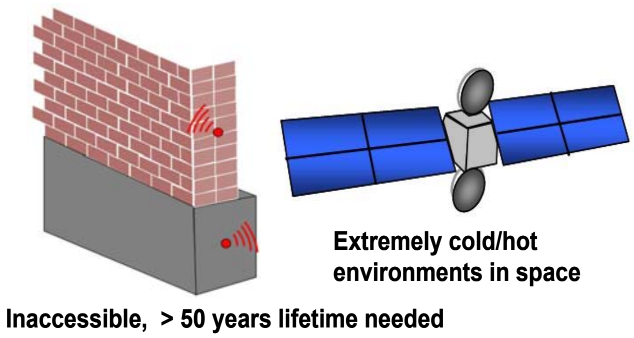

Figure 1. Schematic illustrating the applications of the SAW transponder

Nickel-63 radioisotope actuated reciprocating piezoelectric [4] metal and silicon cantilevers [5] [6] have been previously reported by our group to generate RF pulses upon radioisotope discharge. However, the frequencies of the RF pulses in those previous efforts were determined by the equivalent LC circuit of the system [5]. This makes it a challenge to generate RF signals at different frequency bands for different applications without redesigning the discharging system dimensions. In this paper, the emitted energy is stored inside a high-Q (~8000) surface acoustic wave resonator, whose well-defined and designable resonance frequency determines the emitted signals frequency. Since SAW devices are pervasive in communication and sensor systems, this new result might lead to widespread acceptance of integrated radioisotope power source in the transponder and RF-ID applications.

2. PRINCIPLE OF OPERATION

As illustrated in Figure 2, a gold cantilever is placed 500μm above a ^{63}Ni radioactive thin film with 1.5 mCi activity. Positive charges are accumulated on an electrically isolated ^{63}Ni thin film due to the continuous emission of β-particles (electrons), which are collected on the gold cantilever. The accumulated charge increases with time, increasing the electrostatic

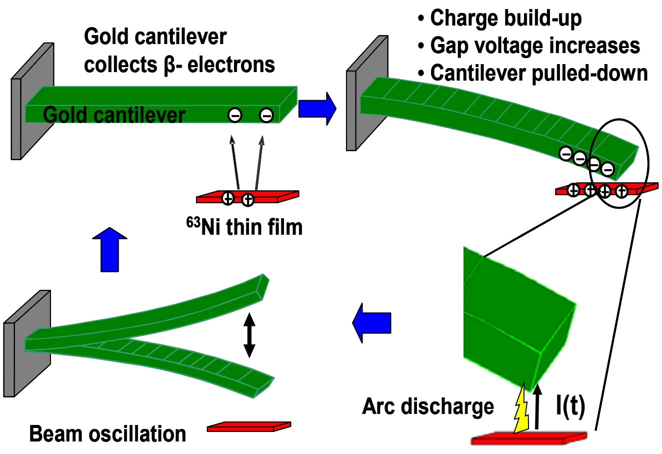

Figure 2. Schematic illustrating the radioisotope actuated reciprocation of gold cantilevers.

force which eventually pulls the cantilever into the radioisotope thin-film. When the gap between the cantilever and radioactive source is small enough, arc discharge occurs through the gap. As the electrostatic force is eliminated, the beam oscillates and the process repeats itself. When the gap between the cantilever and the radioactive source is 500μm, the pull-down cycle requires 3 minutes. As the cantilever approaches the source, tunneling and direct conduction-based current results in a pulse that is very short in time (<1ns). The energy integrated over the reciprocation period is released in a very short time allowing us to greatly amplify the power from the radioactive source.

The arc from the discharge generates a transient magnetic and electrical field that can excite the RF-modes of the cavity in which the arc occurs. The RF modes can propagate and serve as beacons as demonstrated in [5]. The frequency of the output RF signal is determined by the equivalent capacitance and inductance of the system, which are hard to model and design to output a specific frequency as needed for various turned RF-link applications. To have precise frequency control, a SAW resonator is connected to the cantilever. In the SAW device, the frequency is determined by the gap between the fingers at the input port (Figure 3). When the resonator is excited at the input interdigitated transducers (IDTs), the acoustic wave travels along the surface of the piezoelectric substrate and is detected at the output IDTs. The SAW device also enables a two port operation as the emitted charges are stored on one port, and the mechanical energy is reradiated at another port. The impedance at the input port can be very high, while the output port can be connected to any desirable impedance. Furthermore, SAW sensors can be implemented by depositing films with sensing properties between the input and output IDTs can modulate the signal transmitted at the output port. In our radioisotope

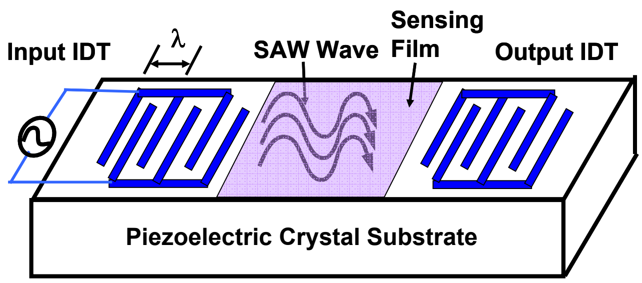

Figure 3. Schematic illustrating operation principle of the SAW resonator

powered transponder, radioisotope energy in the emitted electrons from the Nickel-63 thin films is used to electrostatically charge a cantilever and the SAW resonator is connected such that the high impedance port of the SAW device is in parallel with the cantilever. When the stored electric energy across the cantilever is suddenly released, the SAW resonator is excited as the mechanical and electromechanical energy at the input port is released.

The self-powered SAW transponder can be modeled as an RLC circuit with a SAW resonator connected in parallel (Figure 4), with the components listed in Table 1. The circuit in the right box represents the discharge system, while the equivalent circuit of the SAW resonator is in the left box. In the charging cycle, the electrical energy is stored both in the discharge-system capacitor and the SAW resonator's input ground-coupling capacitor, while mechanical energy is stored in the cantilever and the piezoelectric substrate of the SAW resonator. When an arc discharge occurs across the air gap, a sub-nanosecond high power current pulse is released which excites oscillations in the RLC circuit of the discharge system, at hundreds of megahertz for hundreds of nanoseconds, while at the same time the energy stored in the SAW capacitor and substrate excites the SAW resonator at its resonator frequency. Both signals are measured at the output of the SAW device with the SAW signal having a delay equal to the time needed for the signal to travel from the input to the output

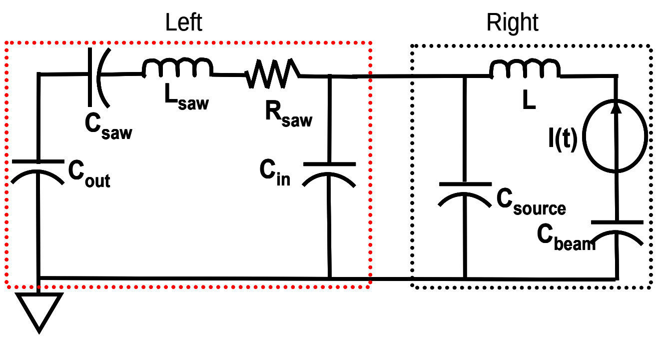

Figure 4. The equivalent circuit model of the SAW transponder

Table 1: Representation and values of R, L, C components in Figure 4 circuit mode

Compo-nent	Representation	Value
C_{beam}	Beam holder capacitance	8.3pF
C_{source}	Source holder capacitance	8.3pF
I(t)	Air gap current	-
L	Discharge system inductance	72nH
C_{in}	Input SAW IDT capacitance	2.2pF
C_{out}	output SAW IDT capacitance	2.2pF
L_{saw}	SAW equivalent inductance	758µH
C_{saw}	SAW equivalent capacitance	0.337fF
R_{saw}	SAW equivalent resistance	84ohm

IDTs. The RF signal from the discharge system reaches the SAW output, through capacitive coupling without the ultrasonic delay.

Increasing the voltage and energy output from the SAW resonator can improve the distance over which a RF-link can be established. During the charging process, the equivalent circuit in Figure 4 can be simplified to the one in Figure 5 since the SAW resonator is not excited. To increase the amplitude of the output SAW signal, the voltage at node A (V_A) at discharge needs to be maximized. The discharge voltage is only determined by the gap between the beam and the radioisotope source. The total energy stored in the SAW resonator can also be increased without changing V_A by increasing the value of C_{in} (by increasing the number of fingers at the input IDTs.) Therefore, the output single of the transponder can be increased by having the maximum possible gap at the discharge system with the maximum possible number of finger at input IDT of the SAW devices. This will increase the C_{in}/C_{source} as high as possible, while keeping $C_{in}+C_{source}$ constant to keep the reciprocation interval constant.

3. EXPERIMENT SETUP AND RESULTS

As shown in Figure 6, in a prototype transponder, a gold cantilever (5cm×0.8cm×300µm) and ^{63}Ni source discharging system is housed inside a small glass vacuum chamber that is evacuated and sealed. It is connected to a vacuum pump, and the chamber is pumped down to 10^{-2} mTorr. Both the gold cantilever and the ^{63}Ni source are held in place with 6 mm thick Teflon plates. A 315MHz SAW resonator (RPM RP1239) is connected to the gold cantilever at its input, with the output connected to a high bandwidth oscilloscope (LeCroy WaveMast 8500) with 50-ohm input impedance. The gap between the cantilever and the radioisotope source is fixed at 500µm, which gives a charge time of 3 minutes.

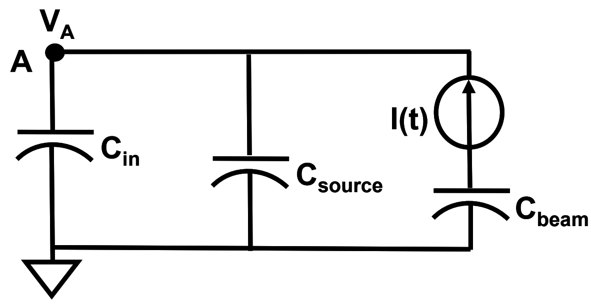

Figure 5. Simplified equivalent circuit model of the SAW transponder during charging process

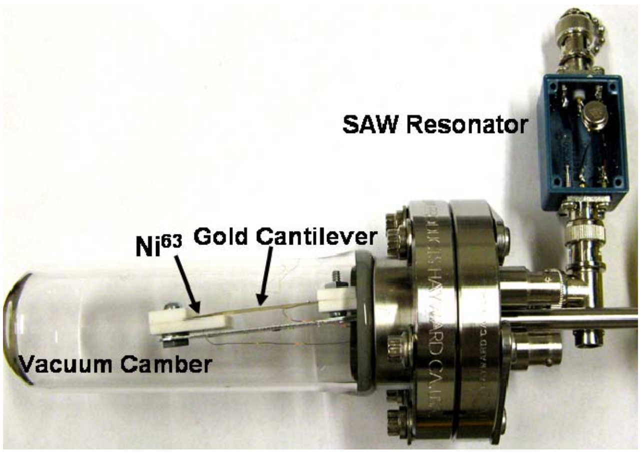

Figure 6. Photograph of the prototype radioisotope-powered SAW transponder

The RF signal from the transponder recorded on the scope is shown in Figure 7. The signal contains two parts, the RF signal generated from the LC circuit of the discharge system, which lasts about 100ns with a maximum peak-peak voltage of 5V, and the RF signal from SAW resonator, which lasts ~10 µs with

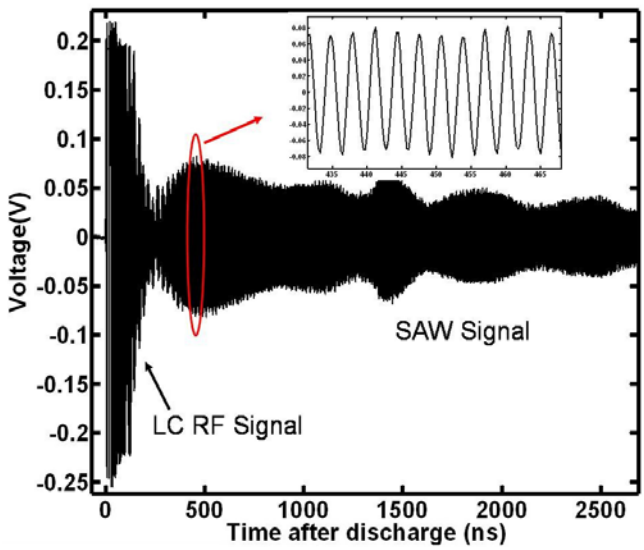

Figure. 7 Measured RF signal waveform with 315MHz SAW resonator connected

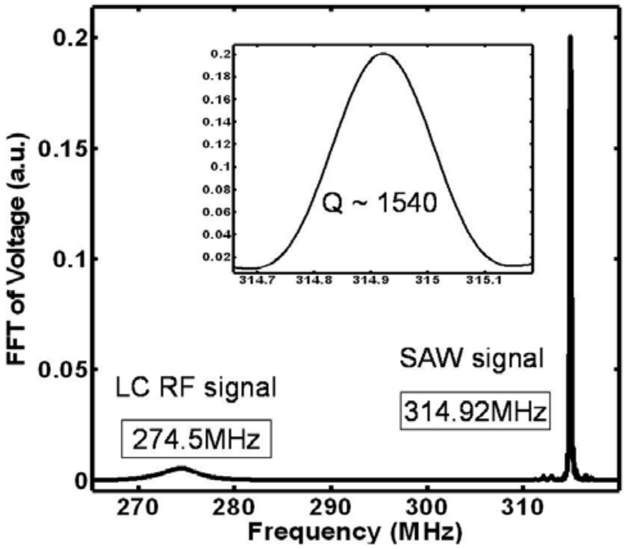

Figure. 8 Frequency of the RF signal with 315MHz Saw resonator connected

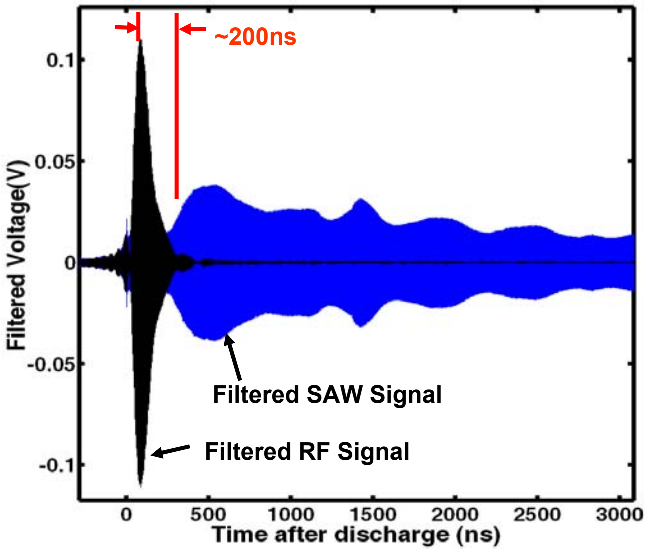

Figure.9 Bandpass-filtered signals illustrating the SAW resonator signal delay

$0.2V_{pp}$. The total energy in the SAW pulse is calculated to be 2nJ, while the total energy in the RF pulse is 5 nJ (calculated by integrating the power over RF signal duration.)

The FFT of the transdcued signal shown in Figure 7 is plotted in Figure 8. The signal component from the 315MHz SAW device is shown with a quality factor (Q) of 1540, while the discharge LC system has a frequency of 274 MHz with a Q of 60. The SAW resonator signal has a 200ns delay, measured by comparing the signals bandpass-filtered at 315MHz and 274 MHz respectively (Figure 9.) The system is also tested with a 434 MHz SAW resonator. The 434 MHz SAW signal with a quality factor of 1560 and a 277 MHz (Q = 70) discharge RF frequency are detected.

4. CONCLUSIONS AND FUTURE WORKS

In this paper, we demonstrate a ^{63}Ni radioisotope powered SAW transponder which can transmit an RF signal (800 μW, pulse duration 10 μs) every 3 minutes frequency-locked to a 315MHz SAW resonator, using a 1.5 milliCi ^{63}Ni source. The magnitude and energy of the RF signal from the SAW resonator can be increase significantly by increase the gap of the discharge system with the input IDTs capacitance of the SAW device. In the near future, efforts in developing a smaller and more reliable discharge system with micro-fabrication and microscale vacuum packaging will be undertaken to reduce the volume. Furthermore, SAW resonators with sensing film will be fabricated to be integrated with a microscale discharge system to implement radioisotope-powered SAW sensor that could be mass-produced for different applications.

5. ACKNOWLEDGMENT

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