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Passive Wireless Sensor Tags

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Passive Wireless Sensing Tags
NASA Inflatable Structures

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Abstract:

This report gives a description of several types of wireless, unpowered remote sensors. Surface acoustic wave (SAW) devices were coupled with conventional sensors to create entirely new types of sensors. These sensors report physically measurable data in the same manner as the conventional sensors, but they do it remotely and without any local power source. The sensors are measured remotely using a radar-like interrogation device, and the sensors and their related communication electronics draw all of the power needed for communicating from the radar pulse. The report covers only a description of prototype sensors and not of the manufacturing requirements of these devices.

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Contents

Nomenclature

AM - Amplitude modulated
ASIC - Application Specific Integrated Circuit
BPSK - Binary Phase Shift Keying
CDMA - Code Division Multiple Access
CMOS - Complementary metal oxide semiconductor
CSRL - Compound Semiconductor Research Laboratory
DC - Direct current
FH - Frequency Hopping
FPGA - Field Programmable Gate Array
FY - Fiscal Year
GaAs - Gallium Arsenide
GHz - Giga Hertz (billion cycles/sec)
HP - Hewlett Packard
IC - Integrated circuit
IDT - Interdigital Transducer
IF - Intermediate Frequency
IL - Insertion loss
ISM - Instrumentation, Scientific, and Medical frequency band
LC - Inductor-capacitor circuit
LDRD - Lab Directed Research and Development
LNA - Low Noise Amplifier
MATLAB - Simulation software available from MathWorks
Mbps - Mega bits per second
MHz - Mega Hertz (million cycles/sec)
Mm - Milli-meters
NTC - Negative temperature coefficient
OOK - On-Off keyed modulation
PCB - Printed Circuit Board
PTC - Positive temperature coefficient
RF - Radio Frequency
RFID - Radio Frequency Identification
SAW - Surface Acoustic Wave
SNR - Signal to Noise Ratio
SPICE - Simulation Program with Integrated Circuit Emphasis
TEMPCO - Temperature coefficient
UWB - Ultra-Wide Band

Introduction

There has been a great deal of interest in the last few years in the subject of RFID tags. RFID tags can be broadly classified into two categories, passive and powered devices. For this work, the definition of a powered tag is any wireless responding device that uses its own DC electrical power, such as from batteries, power supplies, solar cells, etc. Further, the definition of a passive tag is a wireless responding device that relies solely on the RF energy transmitted from an interrogation device. This work covers several types of passive wireless tags.

Many different manufacturers are developing passive identification tags. As a general rule, these passive tags are short-range devices, typically not readable beyond about 1m [1]. The commercial application driving most RF passive tags is to replace optically readable bar codes with an RF device that can be read while covered and from a slightly greater range than a bar code. These tags must be very low cost devices, if they are to supplant bar codes. The primary application driving development of these commercial tags is identification. The passive tags described in this report are fundamentally different in that they are used to measure physical properties of their surroundings rather than to provide identification. Furthermore, the tags described in this report are readable from much greater distances than 1m.

The specific focus of this work is passive remote sensing of physical properties. Passive remote sensing is the ability to wirelessly measure some physical property being detected by a sensor without using DC power at the tag. It requires transmission and careful sensing of an RF signal by means of an interrogation device. The interrogation device can be thought of as a radar, though it differs in some respects from aviation radars. The basic principle is that an interrogation device will send an RF signal and will receive a modified response from a sensor tag. The response from the tag will be modified in a manner proportional to the physical property being measured by the tag, such as temperature, acceleration, or light level.

It is essential to differentiate one particular tag of interest from any other tags that might be within range of the interrogator. For this work, the tags are designed to respond to different narrow frequency bands, and the interrogator can select the tag of interest by changing the interrogation frequency. The narrow frequency selectivity is accomplished at the tag by means of a surface acoustic wave (SAW) filter. SAW filters provide narrow frequency separation and conversion of variable impedance information into RF signal modulation. Sensors that vary impedance with respect to some physical parameter can be measured remotely by measuring the proportional modulation in the RF return signal from the SAW filter.

Overview: Passive Remote Sensing

Passive remote sensing using SAW filters has common elements regardless of the physical property begin measured. Each sensing arrangement will consist of 1) a small radio transmitter sending out a short burst of radio frequency (RF) waves, 2) a SAW-based tag both receiving and modifying a portion of that signal, and 3) a receiver to pick up the transmitted and modified pulse (figure 1). If the receiver and transmitter are in separate locations, the arrangement is bi-static. If the receiver and transmitter are co-located, the arrangement is mono-static.

A SAW filter is a bandpass, frequency selective device that operates by converting electrical energy into acoustic energy in order to perform signal processing operations on the signal. The SAW filters used for this work are all two port devices. This means that they possess two electrical-to-acoustic transducers, designated arbitrarily as an input and an output port. The SAW-based sensor tag consists primarily of a SAW filter with an antenna connected to its input port and an impedance varying sensor tied to its output port. The sensor tag varies its acoustically delayed radar cross section in proportion to the variable impedance load connected to the SAW's output port. Variations in sensor impedance are caused by variations in the physical property to be measured. This, in turn, induces variations in the SAW filter's acoustic impedance. The variations in the filter's acoustic impedance lead to variations in reflectance for a received RF wave. These variations are acoustically delayed and re-transmitted from the antenna at the input port of the SAW filter. That is, the RF pulse is first received by the tag's antenna. It is converted into an acoustic wave by the input transducer of the SAW filter. The acoustic wave travels across the SAW device and is reflected off of the output transducer of the SAW. The reflectance of the acoustic wave is in proportion to the impedance of the sensor tied to that port. The reflected acoustic wave then travels back across the SAW, where it is re-transmitted by the antenna connected to the input port of the SAW. The variations in the sensor impedance can then be detected as delayed amplitude variations in a received RF signal. In this manner, the sensor impedance can be measured back at the receiver. As will be discussed in detail, the SAW sensor must respond with great efficiency to a weak RF signal in order to be detected by the receiver. Each electronic transaction weakens the RF signal. However, a proper application of a narrowband SAW filter enables clear reception and measurement of the sensor impedance.

For SAW-based sensors, the tag modifies the signal that impinges on its antenna by two mechanisms. The first mechanism arises from conventional radar theory and is called backscatter modulation. Any reflector in the path of a radar beam can be thought of as an antenna. If an antenna within the path of that radar beam is tuned to the frequency of the radar (which also happens to be a narrowband radar), then that antenna will have a large scatter aperture (or radar cross section) for that radar. The scatter aperture is a measure of the power that is reflected from the antenna. The scatter aperture for an antenna will vary depending on the resonance characteristics of that antenna. The resonance of the antenna varies with the impedance connected to the antenna. If the scatter aperture for an antenna connected to a 50Ω is given by A_{opt}, then the scatter aperture will vary from 0 to $4A_{opt}$ as the antenna's load impedance is changed from an open to a short. If the load impedance is varied by an impedance-changing sensor, then the sensor output can be detected at the radar receiver. Using backscatter modulation variations alone to wirelessly sense impedance variations is difficult, as other changes within the scene can cause significant reflectance variations.

The SAW filter provides a second, much more dependable means of measuring the sensor variations. The SAW filter is an acoustic device that delays the reflected signal from its output port. This delayed signal contains the sensor measurement information. Since it is acoustically

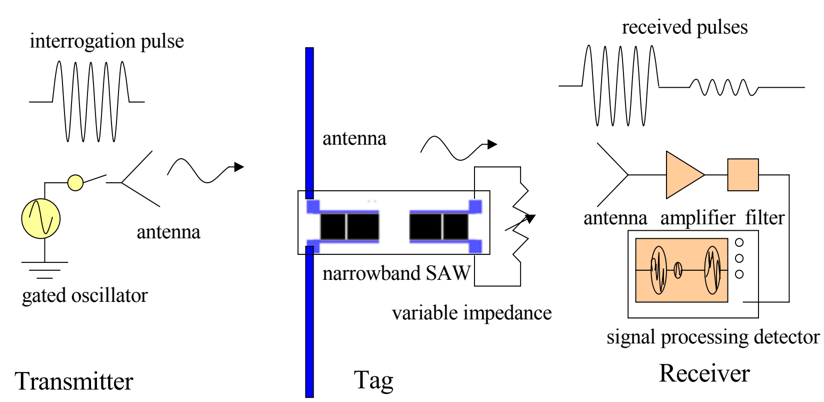


Figure 1: SAW sensor transmitter-tag-receiver configuration

delayed from the original RF excitation signal, it can be read after all radar reflections induced within the vicinity of the transmitter have dissipated.

SAW Device Overview

The key to the passive tag sensor is the SAW filter. A SAW filter appears as two comb-like metal structures deposited on a piezoelectric crystal surface (figure 2). The first comb-like structure, designated as the input port and called an interdigitated transducer (IDT), serves as a transducer to convert long wavelength radio waves to very short wavelength acoustic waves. The second comb-like structure, designated as the output port and also called an IDT, serves both as a signal-processing device and as a transducer to convert the acoustic waves back into an electromagnetic signal. The primary advantage of the SAW is its ability to perform signal processing in a physically compressed space. For instance, 3 GHz radio waves propagating in free space have wavelengths of 10cm, while 3 GHz acoustic waves propagating in lithium niobate, a suitable piezoelectric material, have wavelengths of 0.000116 cm. The SAW device takes advantage of this wavelength compression to perform signal processing on radio waves in a very small space.

SAW devices have been around in a variety of forms for over 35 years. SAW filters are commonly used in many consumer electronic devices. A typical cellular phone contains several SAW filters. The worldwide production of SAW devices was estimated to consist of over 1 billion devices in 1999 [2]. SAW filters also have a long history of production and use at Sandia National Laboratories. Sandia uses SAW filters for a wide variety of both communications and sensor related products. Sandia's MicroChemLab uses SAW filters to make a sensor-on-a-chip used to detect a range of different chemicals.

SAW Device Fabrication

Since SAW devices are central to the passive tag approach for either identification or sensing, a great deal of our available effort went into fabricating optimized SAWs. The fabrication of the SAW correlators on lithium niobate and quartz use both optical and e-beam lithographic technologies. A variety of different SAW filters of different frequencies are made on each fabrication mask set. The SAW filters structures are generally fabricated using industry-standard processing methods. The SAW devices are produced using a two-step lithographic process wherein the IDTs are patterned in a first step, followed by a metal bond pad layer that is patterned in a second step. Different types of metals are used on the two different layers. The IDT layer metal is 500Å of aluminum. This metal layer is kept thin to prevent acoustic reflections from

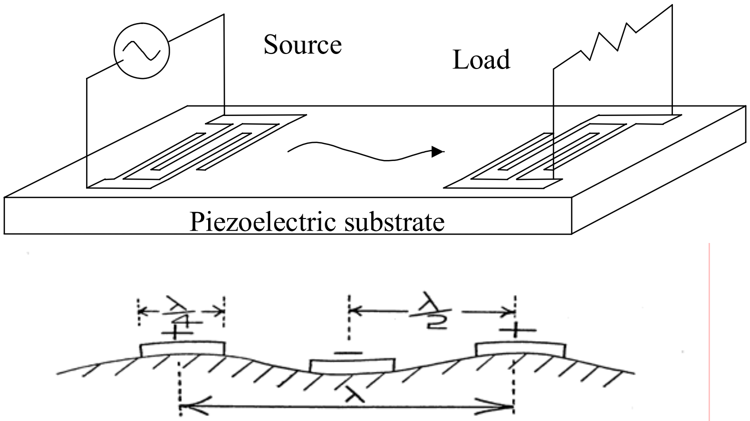


Figure 2: Surface Acoustic Wave Device

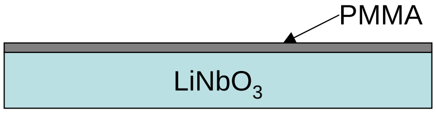
occurring in the IDTs. The second metal layer consists of 5000Å of gold and is added to provide mechanical bond strength and good conductivity of RF signals from bond pads to the IDTs. Contact optical photolithography patterning methods are used wherever possible. Electron beam lithography methods must be used for finger patterning for device frequencies above approximately 800 MHz; therefore, it was not required for this work. In those cases when it is required, an electron beam lithography step is used to fabricate the IDTs, followed by an optical lithography step to define the bond pad layer. An alignment structure is always included in the layout to correctly align the layers during processing.

The starting substrate material is a 100 mm diameter, circular, lithium niobate wafer. There are different crystal orientations available; most of the SAW devices fabricated for this work use Y-Z cut lithium niobate with an acoustic velocity of 3488 m/s. The wafers used are flat to electronic-grade, rather than optical-grade, tolerance. The wafers have very few particles and are very clean directly from the manufacturer, but an organic solvent rinse is used to remove residues that may accumulate during shipping. Many standard pre-cleaning methods can etch lithium niobate, so the organic solvent must be chosen carefully. The IDT layer is patterned on the substrate using a standard liftoff process. That is, the aluminum for the IDT layer is deposited on top of exposed photoresist, which is then selectively removed to leave an aluminum pattern. Following the IDT layer, the wafers undergo both solvent and oxygen plasma cleaning processes to remove organic residues. The metal bond pad layer is then patterned on the wafer. The lithography of the metal bond pad layer is also usually a routine liftoff process. However, most photoresist developers etch the aluminum in the IDT layer. So, the fine aluminum fingers must be protected. Also, as the developer removes exposed photoresist, it begins to etch the bus-bars. A simple multi-step process has been used to alleviate this difficulty. First, a blanket layer of silicon nitride is deposited over the entire wafer, and metal2 (gold- on-chromium) layer for the bond pads is patterned over the top of the silicon nitride. The open areas of the gold are then processed using dry plasma etch through the silicon nitride to expose the aluminum IDT metal. The plasma silicon nitride etch process does not etch the aluminum bus-bars as the liquid photoresist does, and the bus-bars remain exposed. The 5000Å thick gold layer is then deposited with an underlying 150Å thick chromium adhesion layer. This leaves the bond pad metal fully patterned. Finally, following liftoff of the gold layer, a blanket-etch of the silicon nitride exposes the entire wafer. At that point, the process is complete and the SAW devices are ready for testing.

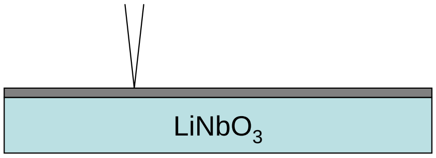
Temperature Effects and Material Choice

Temperature effects are important in passive sensor tags, regardless of the application. Drift of the SAW device center frequency is the primary temperature-induced effect. Since the SAW sensors use the SAW as a narrowband filter, significant drift can cause a complete communication breakdown. This occurs because the interrogator’s transmitter/ receiver pair operate on a fixed frequency determined by a crystal oscillator, while the tag frequency will drift as the tag changes temperature. This effect can be utilized to use the sensor tag as a temperature sensor. For applications where this is undesirable, a means of controlling the tag temperature sensitivity may be necessary, depending on the application.

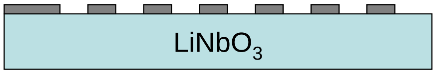
Starting material: 100mm diameter Lithium Niobate (LiNb0$_3$) wafer substrate. Solvent cleaned in Acetone, Methanol, Isopropanol. Rinse in deionized water and blow dry in air.



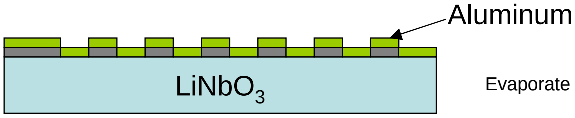
Spin coat with Polymethymethacrylate (PMMA) electron beam photoresist.



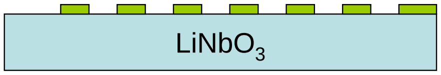
Electron beam patterning of the interdigital transducer (IDT) pattern in the PMMA film. The pattern is transferred from graphical layout software.



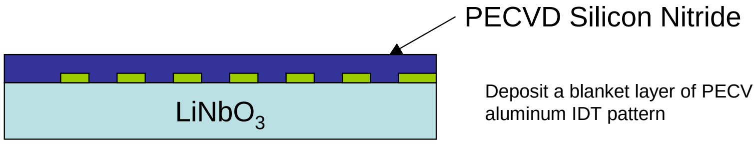
Develop the electron beam pattern. The PMMA is removed where it was exposed to the electron beam.



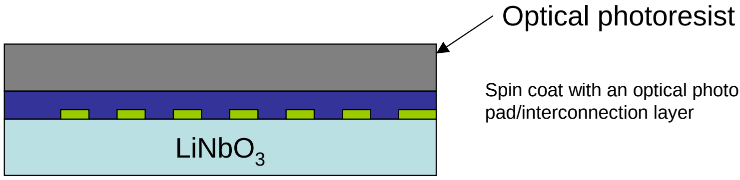
Evaporate Aluminum metal, 500Å thick.



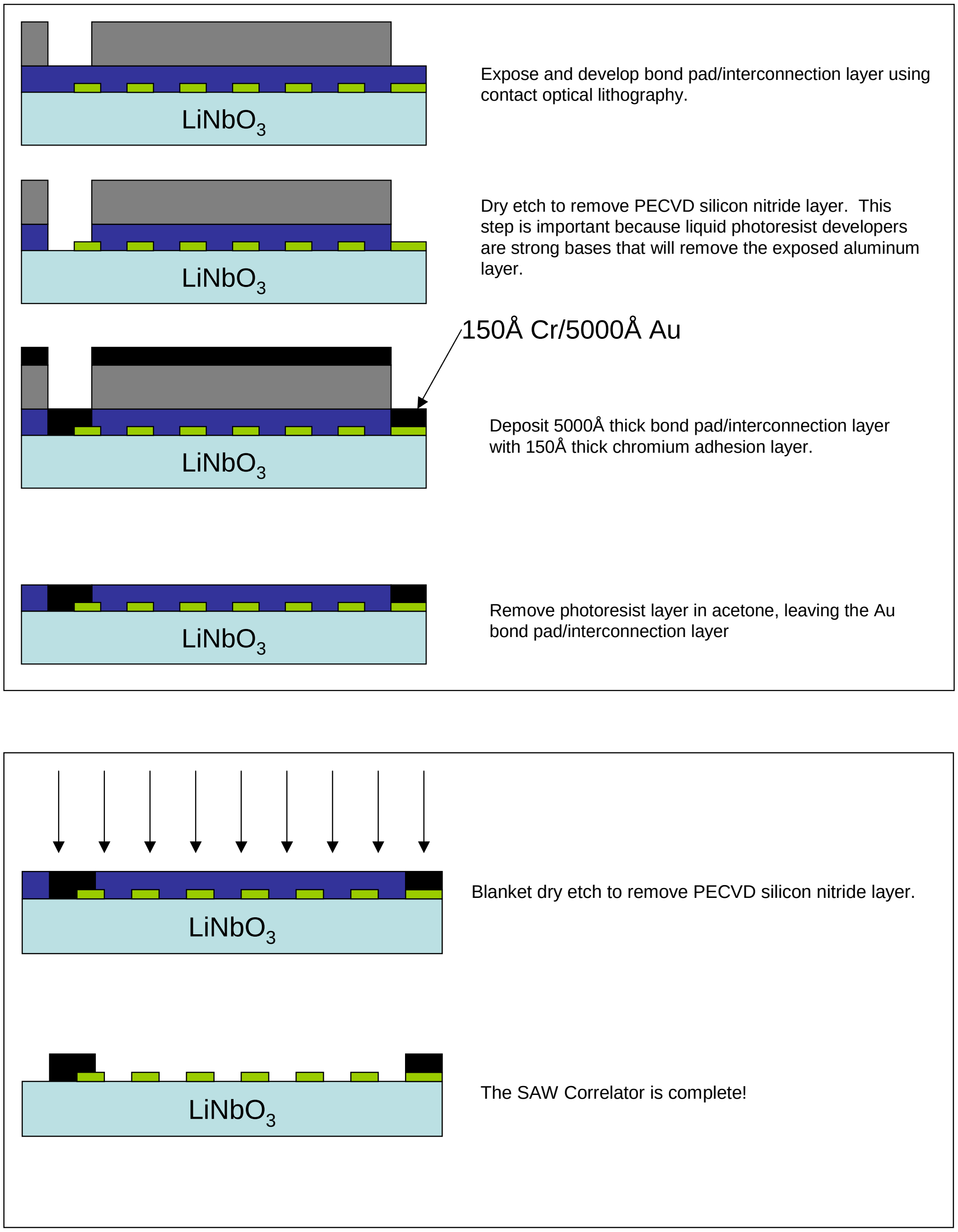
Remove PMMA, leaving behind the Aluminum pattern by liftoff process.



Deposit a blanket layer of PECVD silicon nitride over the aluminum IDT pattern



Spin coat with an optical photoresist to pattern the bond pad/interconnection layer



Expose and develop bond pad/interconnection layer using contact optical lithography.

Dry etch to remove PECVD silicon nitride layer. This step is important because liquid photoresist developers are strong bases that will remove the exposed aluminum layer.

Deposit 5000Å thick bond pad/interconnection layer with 150Å thick chromium adhesion layer.

Remove photoresist layer in acetone, leaving the Au bond pad/interconnection layer

Blanket dry etch to remove PECVD silicon nitride layer.

The SAW Correlator is complete!

Figure 3: SAW device fabrication flow

Frequency drift can be mitigated by selection of the substrate material type. ST-X quartz is a piezoelectric material suitable for surface wave propagation that has a zero temperature coefficient at room temperature. We have fabricated a variety of devices on ST-X quartz and verified stable performance over a temperature range of 7 to 100°C. Unfortunately, ST-X quartz also has a low electromechanical coupling coefficient (0.16%). The electromechanical coupling coefficient determines the insertion loss of the SAW tag, and therefore it also limits the useful range of the device. A low coupling coefficient in a SAW filter creates two significant problems. First, the resulting input IDT impedance can prove difficult in impedance matching. Second, the low insertion loss can render the useful operating range of the completed tag inadequate for the application.

For this work lithium niobate, $LiNbO_3$, was used for the SAW filters, primarily to provide a high coupling coefficient and a low insertion loss. Originally, it was intended to use the SAW filter itself as the temperature sensor, but it was found to be preferable to use a thermistor connected as a temperature sensor to the SAW's output port. Both negative temperature coefficient (NTC) and positive temperature coefficient (PTC) thermistors were found to give adequate thermal response when used as sensors in SAW-based wireless applications. Future applications that require a high degree of stability over a wide temperature range may require the use of other, lower temperature coefficient materials. There are reports in the literature of high coupling coefficient, zero-temperature coefficient thin films, such as AlN over sapphire [3]. These materials will completely alleviate the temperature drift problem. However, the development of this technology was considered to be beyond the scope of this project. Future applications that require wide-temperature range SAW devices should make provisions to develop this technology.

Signal Detection and Range

As discussed in the Sensor Tag Overview, the detection of a signal from a sensor tag is similar to any radar signal reception. The range of a passive SAW-based sensor is governed by the radar equation. The interrogation device transmits a pulsed burst of narrowband RF energy and the receiver detects, processes, and interprets any return signals. Most of the return signals come from undesirable backscatter modulation from nearby surroundings. Any antenna tuned to the center frequency of the radar pulse will exhibit a large radar cross section and so may dominate the radar return signals. However, all conventional radar return signals quickly die away to below the noise level. Radar signals travel at about 1ft/nsec, so within about 600nsec, all signals within 100m have returned. Similarly, within 6 μsec, all radar reflections within about 1000m have returned. The expected maximum return time defines a time window during which the frequency band is cluttered and unusable. The acoustically delayed return signal from the SAW device can be set to be outside of this time window, when signal noise is at a minimum.

The SAW receives energy from the radar beam and temporarily stores it in the form of an acoustic wave. The acoustic wave travels across the SAW, reflects off of the back IDT, and then is re-transmitted by the antenna. The reflected signal finally re-emitted by the antenna is smaller than the initially received signal by 10-20dB, but it is re-transmitted after all other radar reflections have disappeared. As a consequence, the signal from the SAW stands out strongly. In addition, the magnitude and phase of the acoustic reflection are strong functions of the load impedance connected across the SAW back transducer. This means that a sensor variable load impedance will modulate the SAW's acoustic reflection coefficient. The modulations of the reflection coefficient then, in turn, modulate a re-transmitted signal out of the antenna that can be intercepted by the radar receiver.

The SAW's acoustic reflectivity, $P_{acoustic}$, is given as a function of load impedance Z_{load} by [4]

$$P_{acoustic}(Z_{load}) = P_{acoustic}(@Z_{load} = 0) + \frac{2K^2}{(\frac{1}{Z_{transducer}} + \frac{1}{Z_{load}})}$$

where Z_{load} is the electrical impedance connected to the back transducer, $Z_{transducer}$ is the electrical impedance of the transducer alone, and K is the SAW electro-acoustic coupling coefficient. If

P_{opt} is the reflectance for a matched transducer, the reflectivity can vary from 0 to $6P_{opt}$ as the back impedance changes. The result is that sensor impedance changes can be wirelessly measured at the receiver. This effect can be enhanced by use of a reference SAW attached to the same antenna but also attached to a reference load impedance in the same tag. The difference between the modulated load impedance and the reference load impedance will show up as a measurable difference in received signal amplitudes. Since the relative time delay between the reference and the modulated signals is a known constant, a precise measurement can be made.

By using acoustically delayed reflections at low frequencies one can measure sensors at a significant range. Some actual measured values are included below for reference. The range, r, at which the tag modulations can be measured, is given by the radar equation as

$$r := \frac{\lambda}{4\cdot\pi}\cdot\sqrt[4]{\frac{P_o\cdot G_t\cdot G_r\cdot {G_s}^2}{{S_{21}}^2\cdot SNR\cdot kTBF}}$$

with λ being wavelength (= 4.3m at 69MHz), G_t being transmitter antenna gain (= 1.64 for a dipole), G_r being the receiver antenna gain (= 1.64 for a dipole), G_s being the tag antenna gain (= 1.64 for a dipole), S_{21} being the SAW filter insertion loss (= 13dB as measured), kT (= 4.14 e-21 J), B being the receiver bandwidth (= 600kHz as measured), F being the receiver noise figure (= 3dB), SNR being the minimum detection signal-to-noise ratio (= 48dB), and P_o being the transmitted power. Note that the minimum detection SNR (48dB) is much higher for a sensing application than the SNR required for an identification application (6dB). The SNR chosen here is that required to obtain an 8-bit resolution of the received and detected sensor output. This choice is reasonable for many applications but is still somewhat arbitrary. Some applications may require greater SNR, many will require less. It is important to make an accurate and reasonable estimate of the required sensor resolution, as this will limit the range of detection. For the actual measured values already given the detection ranges are as follows:

Transmitted power P_o	Detection range
1 mW	10.8 meters
100 mW	34 meters
10 W	108 meters

SAW-Sensor Tag Results

The results shown above were confirmed in a test arrangement as shown in figure 1. For a bi-static radar configuration, there are three main elements to the test setup, the transmitter, the tag, and the receiver. The receiver (figure 4) consists of an antenna tuned to the frequency band of interest that is connected to a SAW filter that is then connected through an amplifier to an oscilloscope. A more sophisticated receiver could include a gating device to block all return signals except for the acoustically delayed signal. This receiver did not include a gating device.

The transmitter (figure 5) consists of an RF burst generator pulsed repetitively by a low frequency oscillator. The transmitter center frequency is exactly at the center frequency of the SAW filter in the tag. The RF burst generator is connected directly to an antenna without an additional amplifier.

The tag (figure 6) consists of an antenna coupled directly to a narrowband SAW filter. The SAW filter (figure 7) actually consists of two SAW filters operating in parallel. Both SAW filters have their input ports tied directly to the antenna, and their output ports tied to resistive loads. The first SAW filter serves as a reference arm of the sensor. It is attached to a fixed 50Ω resistance. The second SAW filter is tied to the impedance-changing sensor. The sensor can be an accelerometer, a light sensor, a thermistor, etc.

The transmitter operates by sending a burst of RF centered at 69 MHz. For this particular test, the burst is 100 cycles wide. The RF burst generator gives an on-off signal amplitude difference greater than 100dB; this is a lower "off" signal than can be obtained solely with a gated oscillator. It is important to have a very small "off" signal leakage from the transmitter, as any "off" signal will mask the desired return signal from the tag. The transmitted signal generates many reflections from objects around the room, but these prompt return signals quickly die away.

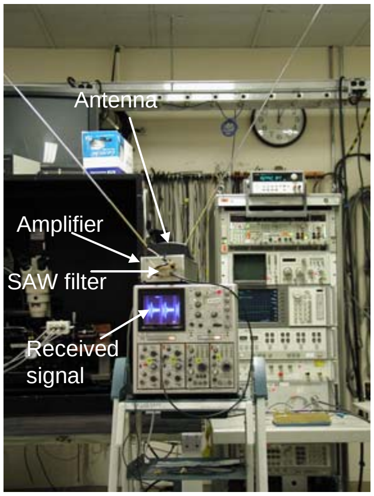


Figure 4: Interrogator Receiver

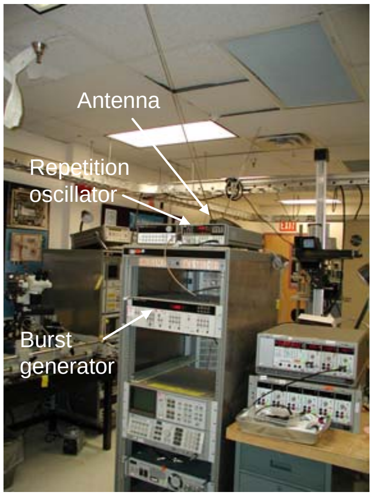


Figure 5: Interrogator Transmitter

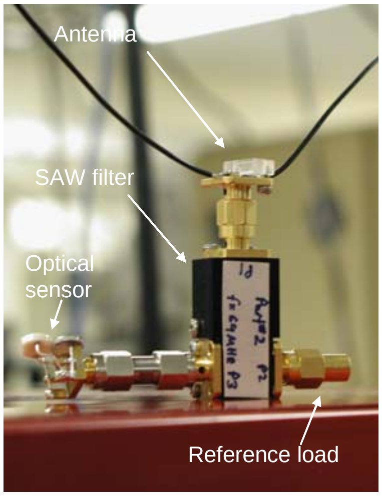


Figure 6: Sensor Tag

The tag antenna intercepts the transmitted RF burst very efficiently, as the antenna and tag are tuned to the transmitter's center frequency. In radar parlance, the tag has a large radar capture cross section for the transmitted signal. Upon intercepting the transmitted signal, a prompt radar return signal is reflected from the antenna. This prompt return signal from the tag antenna will be one of the strongest radar return signals seen at the receiver, if the tag is in close proximity to the transmitter or receiver. The SAW filter in the tag converts a portion of the received RF signal into acoustic energy. The acoustic wave travels across the SAW device and reflects off of the SAW's second IDT. In this case, there are two SAWs and two pairs of output IDTs. The IDT's electrical impedance, in accordance with the equation shown on the previous page, determines the amount of acoustic reflectance. This reflected acoustic signal is converted back into an electrical signal by the input IDT. The converted signal is then retransmitted from the tag antenna after a total delay equal to the round trip time delay of the SAW filter. Here there are two SAWs and two re-transmitted signals, each with different delay times. The retransmitted signal is smaller than the originally received signal by an amount equal to twice the SAW filter's insertion loss. For the tag shown in figure 7, the insertion loss is about 13dB, representing a voltage diminution from input to re-transmission of about a factor of 20 (26dB).

A portion of the re-transmitted tag signal is intercepted by the receiver antenna. The received signal is filtered through a matching SAW, then amplified and, in this case, displayed on an oscilloscope (figure 8). This figure shows the original radar signal followed by the acoustically delayed reference signal followed, in turn, by the measured signal. The acoustically delayed signal is smaller than the original radar return signal by about 26dB. The acoustically delayed reference signal has an amplitude of about 250mV peak-to-peak. The acoustically delayed measurement signal, derived from the sensor, has an amplitude that varies from about 40 mV to about 90 mV peak-to-peak. These signals are at a range of about 3m from the transmitter to the tag and 3m from the tag to the receiver.

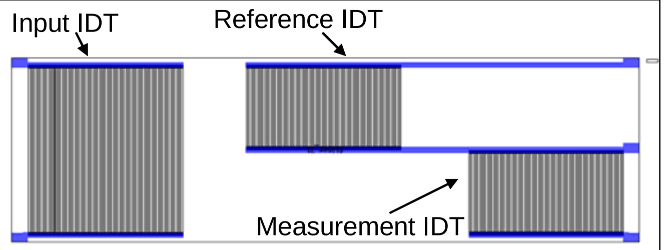


Figure 7: SAW Filter Used for Wireless Remote Sensing

For tests involving greater ranges, the received signal strength will diminish. In these cases, it is desirable to use both a gating device and a time averaging device in the receiver. A gating device will simply block any signal that does not meet the acoustic delay criterion of the SAW. It is straightforward to implement and easy to understand. An averaging device will reduce noise in the receiver by averaging over N cycles. The device will generate an average, $r_N(t)$, of both the signal, r(t), and the received noise, n(t), according to [5]

$$r_N(t) = \frac{1}{N} \cdot \left(N \cdot r(t) + \sum_{k=1}^{N} n_k(t) \right)$$

Since the signal transmission and reception is a linear process, the cross correlation between different noise samples is zero. Here the channel and electronics noise are assumed to be additive white Gaussian noise. The noise power, P_n, is reduced by averaging according to

$$P_n = \frac{1}{N^2} \cdot \sum_{k=1}^{N} E\left\{ (n_k(t))^2 \right\}$$

where E(…) is the rms average of the noise voltage signal in each sample, $n_k(t)$. The averaging process will increase the signal-to-noise ratio by a factor of N. That is, the total signal energy available for detection increases by N. This further improves the detectable range beyond that shown in the table on the previous page.

Sensor Measurement Results

The test-bed shown in figures 4-6 is sufficiently general to enable the testing of a wide variety of different sensors. Any sensor that varies its impedance in some relation to the physical quantity to be measured can be used as a wireless SAW sensor. Of course, it is only reasonable to use passive, or unpowered, sensors, since the communication apparatus is also passive. As a result, the entire SAW sensor configuration is unpowered and can be permanently configured without batteries or a power source. For instance, a SAW sensor configuration can be embedded in the walls of a building, a transportation container, a vehicle, or a bridge or other structure. The sensor tag will then be available for monitoring that object indefinitely.

A total of 5 different classes of sensors were measured using the wireless SAW sensor test bed. These sensors were temperature, acceleration, mechanical switches, photoconductors, and a phototransistor. The simplest, and perhaps most useful, category of sensor is a switch. The raw signals received from a switch in the open and closed positions are shown in figures 7 and 8. The magnitude of the reference signal is not dependent on the position of the switch. The delayed, re-transmitted measurement signal varies strongly with switch position, as can be seen by comparing the two photos. Many extraneous factors can cause both the reference and the measurement signals to vary in tandem, but only the switch position causes the relative difference in the two signals to change.

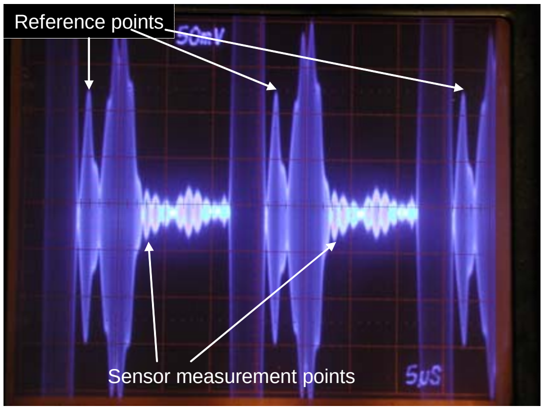


Figure 8: Tag measurement, switch response in closed position

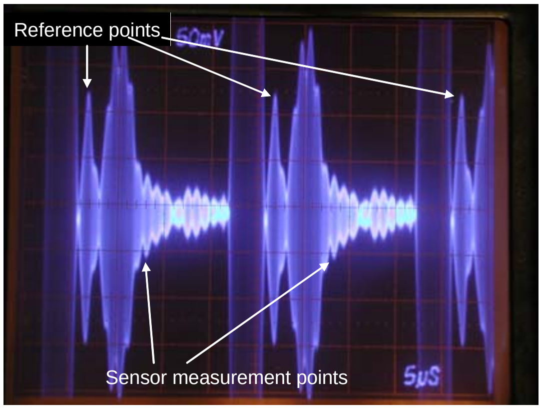


Figure 9: Tag measurement, switch response in open position

The results of measuring the accelerometer remotely are shown in figures 10 and 11. The accelerometer used was an Endevco 2221F piezoelectric device. This is a high impedance device, and a special technique, detailed in the next section, was used to interface the accelerometer to the low impedance SAW IDT. Figure 10 shows the accelerometer with no excitation. The delayed response has a peak magnitude of about 80mV, corresponding to an open circuit condition. Figure 11 shows the accelerometer response as the accelerometer is receiving a shock. The configuration provides signal integration, so that the charge from the shock acceleration is stored and made available for about 1 second. This time constant can be varied from a maximum of about 1 second to as fast as the time constant of the shock or the accelerometer, whichever is slower.

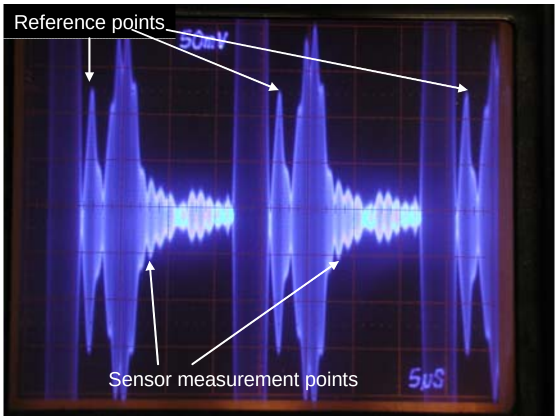


Figure 10: Tag measurement, accelerometer with no excitation

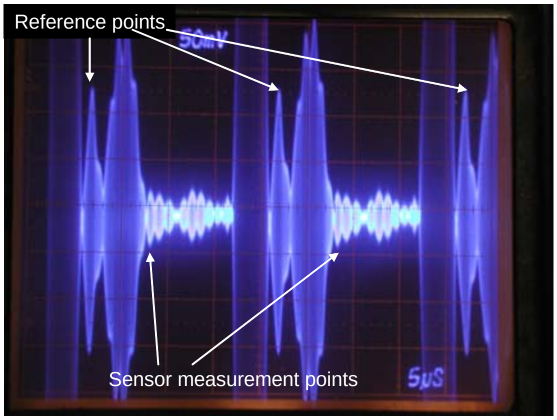


Figure 11: Tag measurement, accelerometer receiving a shock

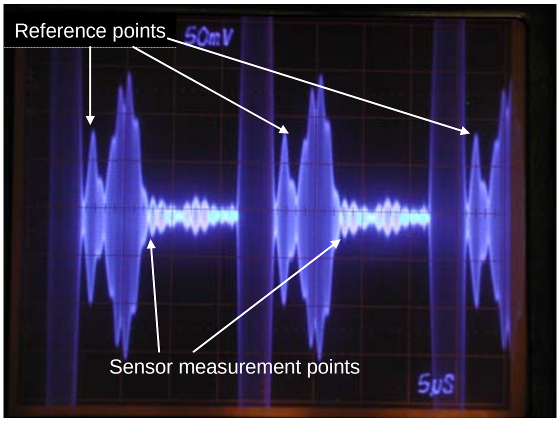


Figure 12: Tag measurement, photo detector in dim light

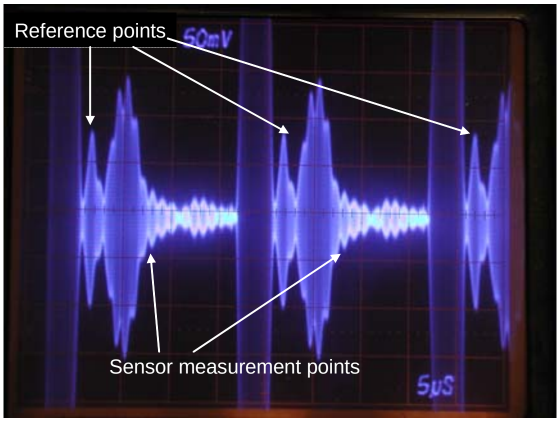


Figure 13: Tag measurement, photo detector in bright light

The results of remotely measuring a photodetector using the same methodology are shown in figures 12 and 13. The photodetector used here was a CdS photoconductor with an impedance that varies between 400Ω under dim light to 35Ω when placed directly under a 60W bulb. The results are similar to those described for the previous sensors. Under dim light, the tag delayed response is about 40mV peak-to-peak. Under bright light, the tag delayed response increases to about 60mV. More signal response can be obtained using a photodetector with lower impedance. Results from tests of other sensors are similar to the three cases just presented. Impedance variations lead to variations in delayed responses in the received signals. These are easily detected using the approach outlined.

Method for Interfacing to a High Impedance Sensor

The impedance variations of the sensor create a measurable acoustic impedance mismatch at the SAW back port if the sensor impedance is close in value to the SAW impedance. For instance, if the SAW's interdigitated transducer (IDT) is designed to have an impedance of 50Ω, sensors with impedances that vary around 50Ω will be measurable. Directly coupling a sensor to the SAW is useful only for sensors with impedances close to the impedance of the SAW IDT. Sensors with impedances that are very different from the impedance of the SAW IDT appear as either a short or an open circuit. However, it is possible to use an interface device to passively measure sensors with very high impedances using low impedance SAW transducers.

The approach to measuring a high impedance sensor is shown in figure 14. The sensor, in this case a piezoelectric accelerometer, is connected to the gate of a field effect transistor (FET). The gate of a metal oxide semiconductor field effect transistor (MOSFET) has very high impedance, typically greater than 1 TΩ. This provides an impedance match to the highest impedance sensors, such as piezoelectric or pyroelectric sensors. The sensor impedance variations will then modulate the low output impedance of the FET channel. This variation is described by the standard FET r_{DS} vs. V_{GS} curve pertaining to the particular device. A standard enhancement or depletion mode MOSFET or junction field effect transistor (JFET) can be used as the impedance transforming device. These will need a battery to shift the sensor equilibrium voltage up or down to about the FET's V_T or threshold voltage. The battery will push a current equal to the gate leakage current of the FET, a very small value and much less than the battery's own internal leakage. A more desirable device is to use a FET with a threshold shifted to 0V. Then, sensor voltage or charge variations will translate directly into variations of a resistor with a value close to that of the SAW IDT. Such as device will be entirely passive, drawing no DC power, but operating solely from radio signals transmitted to it from the SAW interrogation unit.

Using this approach, sensor impedance and time constant can also be tailored by adding or adjusting a shunt resistor, shown in figure 14. To understand this, an example is worth considering. Very high impedance sensors, such as piezoelectric sensors, are a good impedance match for a MOSFET gate. The time constant can be as long as several seconds, as it is the product of the gate and sensor capacitance multiplied by the effective resistance represented by the charge leakage paths. To shorten this time constant, a shunt resistor is placed across the sensor output to ground. Such a resistor can also serve to match impedances between a sensor and a FET input.

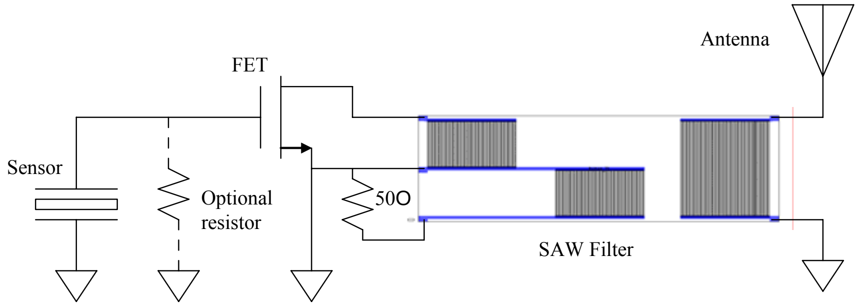


Figure 14: SAW Measurement Tag with a High Impedance Sensor

A high impedance piezoelectric accelerometer was first connected directly to the back port of a SAW, as in figure 1. No response was observed, as expected. Next, the same accelerometer was connected through a depletion mode FET biased with its input voltage about equal to its threshold voltage. The accelerometer output with a 1-2 second time constant was then measurable using the wireless interrogation unit. The accelerometer will be similarly measurable with a zero threshold FET as the impedance transforming element. Also, other high impedance sensors, hitherto not usable as SAW wireless sensors, are easily measured using this approach.

Conclusions

Passive SAW wireless sensors to remotely measure acceleration, temperature, switch position, and light level were developed and tested. The test hardware and approach were described. A special technique for interfacing high impedance sensors to the low impedance SAW filter was developed and evaluated. The transmitter and receiver were both configured from general purpose lab equipment. A dedicated and compact interrogator/ radar will be built to eliminate the existing transmitter and receiver, once allocated funding is received.

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