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Passive Microwave Tags

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Passive Microwave Tags
LDRD 52709, FY04 Final Report

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Abstract:
This report describes both a general methodology and specific examples of completely passive microwave tags. Surface acoustic wave (SAW) devices were used to make tags for both identification and sensing applications at different frequencies. SAW correlators were optimized for wireless identification, and SAW filters were developed to enable wireless remote sensing of physical properties. Identification tag applications and wireless remote measurement applications are discussed. Significant effort went into optimizing the SAW devices used for this work, and the lessons learned from that effort are reviewed.

Contributors to this work include: Edwin Heller, Joel Wendt, Jonathan Blaich, Glenn Omdahl, Gregg Wouters, Christopher Gibson, Emmett Gurule, David W. Palmer, Gayle Schwartz, and Kenneth Peterson.

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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
DS-CDMA	-	Direct Sequence Code Division Multiple Access
DSSS	-	Direct Sequence Spread Spectrum
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
OOK	-	On-Off keyed modulation
PC	-	Personal Computer
PCB	-	Printed Circuit Board
PN	-	Pseudo Noise
POP	-	Peak-Off-Peak ratio
PSL	-	Peak-to-SideLobe ratio (same as POP)
PSPICE	-	PC version of SPICE available commercially
RF	-	Radio Frequency
RFID	-	Radio Frequency Identification
SAW	-	Surface Acoustic Wave
SNR	-	Signal to Noise Ratio
SPICE	-	Simulation Program with Integrated Circuit Emphasis
SS	-	Spread Spectrum
UWB	-	Ultra-Wide Band

Introduction

A great deal of news attention of late has been given to the concept of RFID tags. RFID tags can be broadly classified into two categories, passive and powered devices. We will accept the definition of a powered device as any tag that uses its own DC electrical power, such as from batteries, power supplies, solar cells, etc. We will further define a passive device as a tag that relies solely on the RF energy transmitted from an interrogation device. Most of the effort discussed here has been concentrated on passive devices. Many different manufacturers are developing passive tags. As a general rule, these passive tags are short-range devices, typically not readable beyond about 1m [1]. The general idea behind most commercial applications of 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. These tags must be very low cost devices, if they are to supplant bar codes. A separate but smaller class of passive tag applications can tolerate a higher cost but requires much longer-range readability. These applications often require not only identification, but also other attributes, such as position location or some kind of sensor output like a tamper, pressure, or temperature sensor. These higher performance tag applications and the technology to address them are the primary subject of this report.

The specific focus of this work can be called passive remote tag sensing. Passive remote tag sensing is the ability to wirelessly either identify a tag or to measure some physical property from a tag without using additional DC power at the tag. It requires the careful sensing and re-transmission of the original RF signal sent from an interrogation device. The interrogation device can be thought of as a radar, though it differs greatly from aviation radars. The basic principle is that an interrogation device will send an RF signal and will receive a response from any tags in the vicinity.

Since it is generally essential to differentiate one particular tag of interest from any other tags that might be in the vicinity, the tag must either respond to any general interrogation with a unique code or the interrogation must be specific to the tag of interest. For general interrogation, each tag must be encoded, typically with phase or delay coding, to provide a unique signature to the general interrogation pulse. In addition, each interrogation device must be able to distinguish between all coded tags of interest within range. For specific interrogation, 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. Both the frequency and code space definition and control in the tag are accomplished by means of surface acoustic wave (SAW) devices. SAW filters provide narrow band frequency separation and so are well suited to specific interrogation. As will be shown in more detail, SAW correlators provide a coded response to a general interrogation or a general response to a specific interrogation. As a consequence of these properties, SAW filters are useful for remote sensing, and SAW correlators are useful for tag identification.

Overview: Passive Remote Sensing

Consider first a SAW filter-based passive remote sensing application. 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). A SAW-based sensor tag is a frequency selective device that responds to the sensor impedance load connected to its output port. Amplitude variations in the received signal correlate to the sensor impedance. The sensor impedance can then 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 heard 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

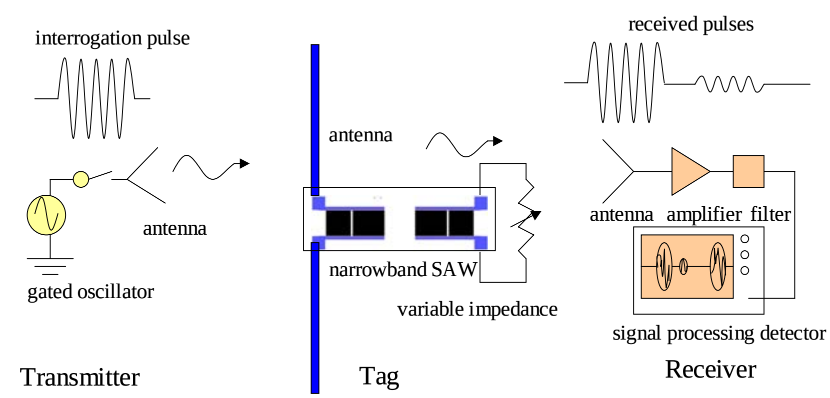


Figure 1: SAW sensor transmitter-tag-receiver configuration

that is reflected from the antenna. The scatter aperture for an antenna will vary depending on the impedance connected to the antenna. If the scatter aperture for an antenna that is impedance matched to free space 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 delayed from the original RF excitation signal, it can be read after all radar reflections induced within the vicinity of the transmitter have moved on or been absorbed.

Overview: Passive Remote Identification

For SAW-based identification systems, a SAW correlator is used for the central part of the tag (figure 2). A SAW correlator is a frequency and code selective device that can respond in two different modes. In a specific interrogation mode, the correlator responds with a non-coded correlation peak only in response to the correct frequency signal with the correct code transmitted from the interrogator. This is the operating mode shown in figure 2. The transmitter sends a coded interrogation pulse that is received and processed into a frequency-modulated pulse by the tag. The desired correlator responds only to the correct frequency signal with the correct code. This is referred to as specific interrogation, since the interrogator controls the code and must select which correlator it wishes to respond. The correlator responds to the specific interrogation by outputting a modulated pulse, at the same frequency as the input signal.

Two antennas are shown on the SAW tag, but there are configurations that only use one antenna with two ports. The SAW correlator is an acoustic device, just like the SAW filter, and it delays its output pulse until after all undesirable radar signals have died away. All SAW correlators within range of a given transmitter and with a center frequency set to that of the transmitter will respond to that interrogation. However, only the correlator with the matching code to the one transmitted, will respond with a correlation peak. All other correlators will respond with pseudo-random noise. These two responses are easily differentiated, and so only the specifically selected correlator can be deemed to have properly responded.

A SAW correlator can also operate in general interrogation mode (figure 3). In this case, the interrogator sends a narrow burst of RF oscillations at the correct frequency to any correlators that may be in the vicinity. All correlators then respond with their coded outputs simultaneously. The receiver sees the interrogation pulse followed by the smaller, coded signal after an acoustic delay. The difficulty with operating in this mode is that the interrogator must then sort out several responses simultaneously. This approach was successfully used for single tag applications and will be discussed in more detail in a later section.

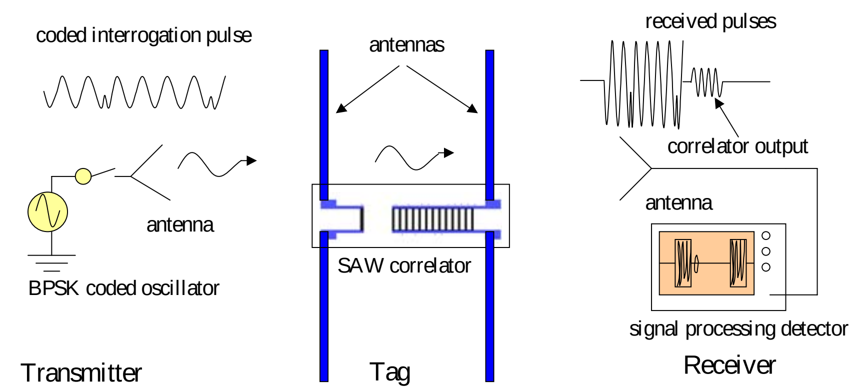


Figure 2: SAW ID-tag specific transmitter-tag-receiver configuration

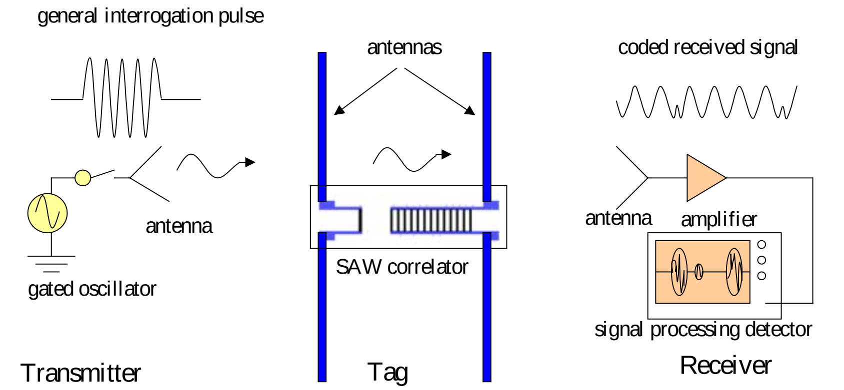


Figure 3: SAW ID-tag general transmitter-tag-receiver configuration

The measure of frequency selectivity that enables a SAW device to respond to a weak RF signal is referred to as Q-factor, or just Q. A SAW filter is simply a passive narrowband filter. It can be designed with varying Q values, but SAW sensing applications typically require a very narrow Q device in order to maximize sensing range. This also means that a small section of frequency spectrum can be used for a moderate number of SAW sensors, since each sensor only occupies a very small section of that frequency band. A SAW correlator combines the narrowband, high Q operation of a bandpass filter with a coded reception scheme that further enhances Q by the use of coding gain. It effectively enables the reception of a very narrow bandwidth of signals while still using a broad bandwidth to transmit the signal. The SAW correlator is a completely passive device. It uses the electromagnetic energy in the input RF wave to convert to an acoustic wave that is subsequently used in a matched filter. The matched filter is a passive correlator in accordance with the convention definition [2]. The SAW correlator's Q is directly proportional to the code length of the matched filter. Therefore, it is important to maximize the code length of the correlator. The ideal zero-power receiver would consist of a very long SAW correlator connected directly to an antenna on one end and a highly efficient, demodulating detector on the other end. Loading effects within the SAW correlator itself limit how far one can take this approach, as described in the following section.

SAW Device Overview

The key to the passive ID-tag is the SAW correlator. The key to the passive tag sensor is the SAW filter. The simpler of the two devices, a SAW filter, appears as two comb-like metal structures deposited on a piezoelectric crystal surface (figure 4). The first comb-like structure serves as a transducer to convert long wavelength radio waves to very short wavelength acoustic waves. For instance, a 3 GHz radio wave propagating in free space has a wavelength of 10cm, while a 3 GHz acoustic wave propagating in lithium niobate, a suitable piezoelectric material, has a wavelength 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. The second comb-like structure in the SAW serves both as a signal-processing device and as a transducer to convert the acoustic waves back into an electromagnetic signal.

Although SAW devices may not be widely understood, they have been around 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 [3]. SAW filters also have a long history of production and use at Sandia National Laboratories. SAW filters are used in communication electronics and sensor applications. Sandia uses SAW filters for a wide variety of sensor related products. Sandia's MicroChemLab uses SAW filters to make a sensor-on-a-chip used to detect a range of different chemicals. In contrast to SAW filters, SAW correlators are not widely used in industry, although research into these devices has been conducted for over 30 years.

A SAW correlator is a two transducer piezoelectric device that also provides a matched filter function (figure 5). The filter, in the case used here, matches to a BPSK phase modulated signal, rather than the usual sine wave used in a SAW filter. That is, the incoming radio wave has 180 degree phase transitions in its sinusoidal waveform, modulated in a coded pattern. A transducer, or IDT, in the front end of the SAW correlator converts the electromagnetic wave to a surface acoustic wave. SAW correlators use this electromagnetic to acoustic wavelength

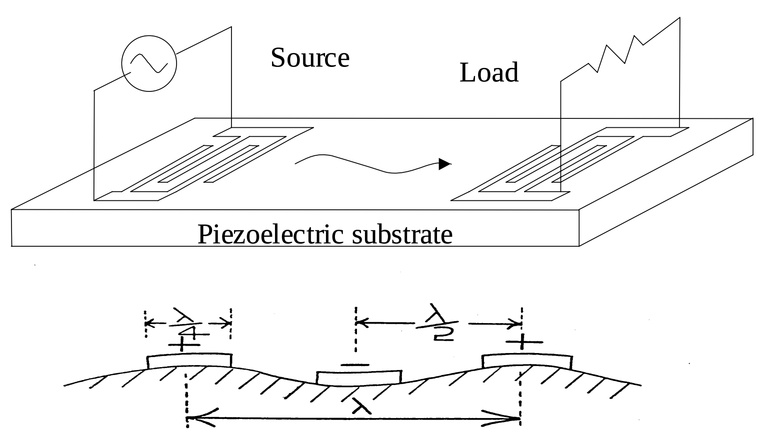


Figure 4: Surface Acoustic Wave Device

compression to perform bi-phase coded signal processing on a radio wave that has been converted into an acoustic wave. The correlator first has a transducer to convert radio waves into acoustic waves at a selected center frequency and with a selected, but typically wide, bandwidth. The acoustic waves travel across the surface of the piezoelectric crystal to a phase coded receiver transducer. The receiver transducer converts the correctly phase coded acoustic wave into an RF modulated electrical pulse. Envelope detection of the modulated pulse yields a base-band electrical pulse. This pulse can be used for low data rate communications or to turn on a higher-power consumption, higher data-rate receiver. The correct correlation coded signal is essentially a long multi-bit "key". The correlator output signals the correct "key" by outputting a voltage spike (figure 6). If an incorrect code is given, the correlator output appears as pseudo-random noise.

The correlators used in this work make use solely of BPSK signals. The correlator can provide considerable process gain by converting the input BPSK signal with a matched pattern into an RF modulated pulse with an envelope at the baseband frequency. This modulated pulse is re-transmitted from the SAW tag antenna. The baseband envelope pulse is then recovered at the receiver using either a microwave detector diode or a down-converting mixer configuration. The number of chips in the correlator determines the code length of the device. This analog conversion approach rejects multi-path and other spurious signals to the same degree as comparable DSSS systems. That is, the signal used to excite the correlator is inherently more robust and impervious to jamming and interference than conventional narrowband radio signals.

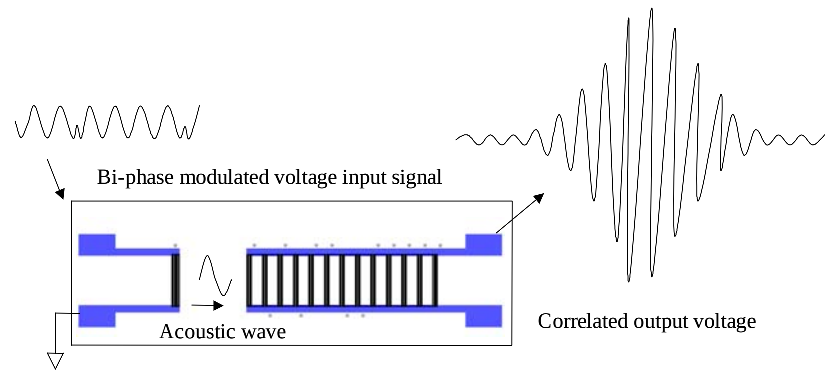


Figure 5: Surface acoustic wave correlator

A limitation to using this approach is the limited code length that can be achieved with conventional SAW correlators. Since the Q-factor of the SAW correlator is proportional to the number of chips, it is desirable to make the correlator as long as possible. The SAW correlator output transducer converts acoustic energy to electrical energy, being electrically terminated in the antenna impedance, which is around 50Ω. Each chip section of the output transducer converts a portion of the acoustic wave that passes under it into electrical power for re-transmission out the antenna. By the time the acoustic wave has passed under about 30 chip-sections of the output transducer, its amplitude has decayed so significantly, that there is little signal left with which to do further correlations. Figure 7 shows the output response of a 2.43GHz, 31 chip long SAW correlator after it has been excited with a burst of RF at the center frequency of the device and with a number of cycles equal to the number of cycles in one chip. This excitation waveform essentially forces the code of the correlator out at the center frequency of excitation. The noteworthy aspect of this figure is the rapid decay in amplitude of the output waveform from the first chips to the last. This rapid decay is a direct result of operating the high speed SAW driving a low electrical impedance, and was much less significant in low frequency, high impedance devices used historically [4]. This decay in correlator response has the same effect when operating as a receiver and severely limits the useful code length of the correlator for high-speed devices. That is, acoustic signal attenuation of long BPSK signal streams limits the useful code length in correlators used as receivers or transmitter.

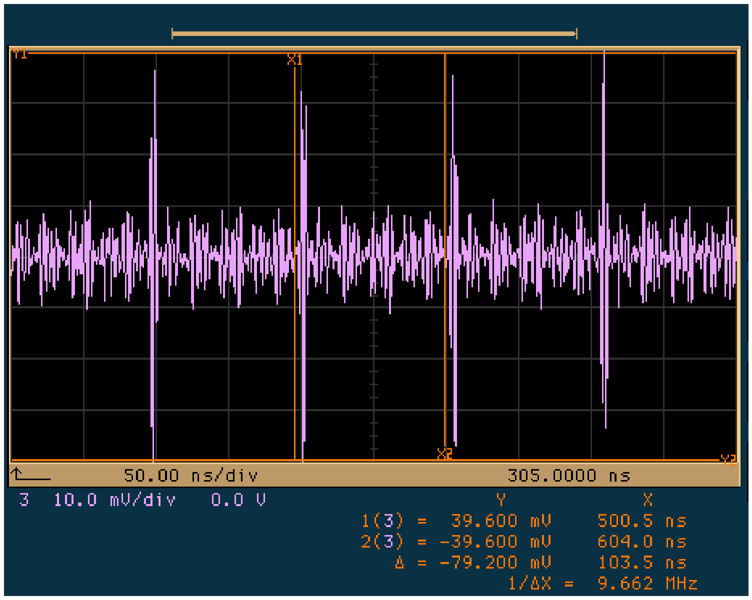


Figure 6: SAW correlator output at 2.43GHz.

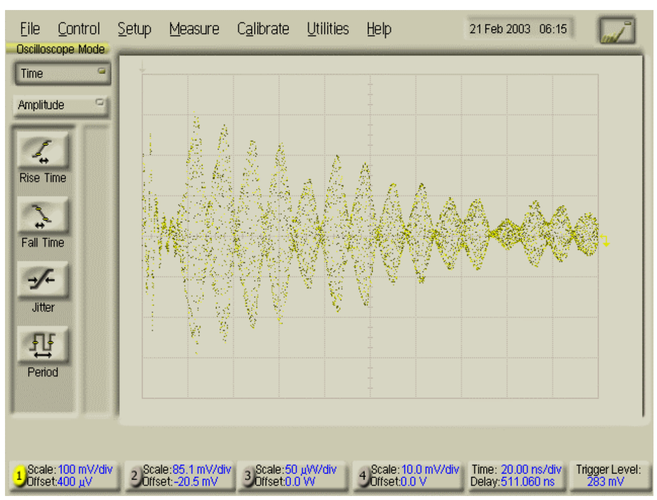


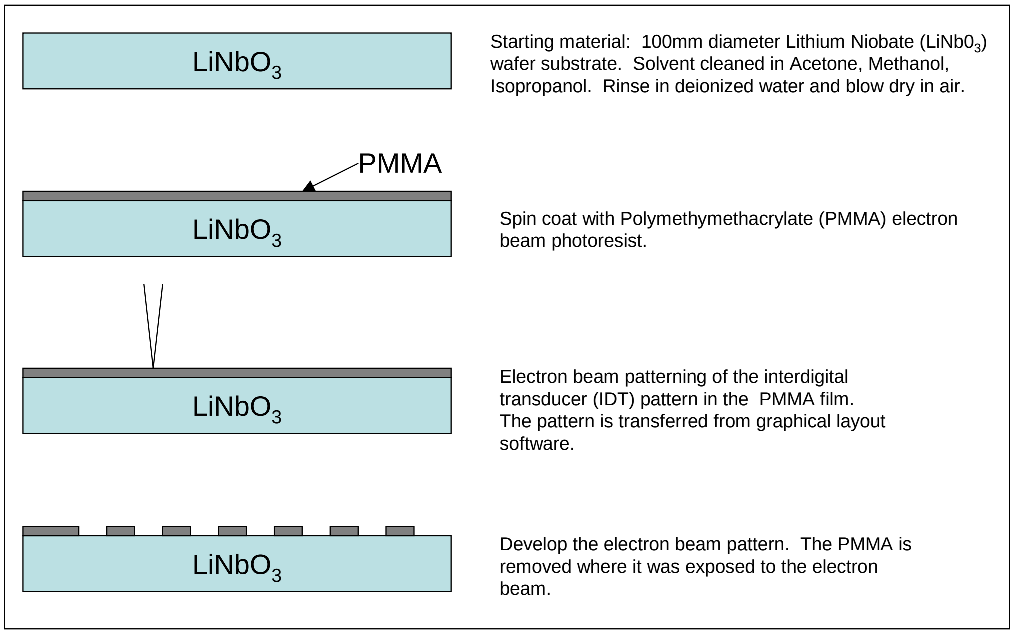
Figure 7: SAW correlator reverse mode excitation

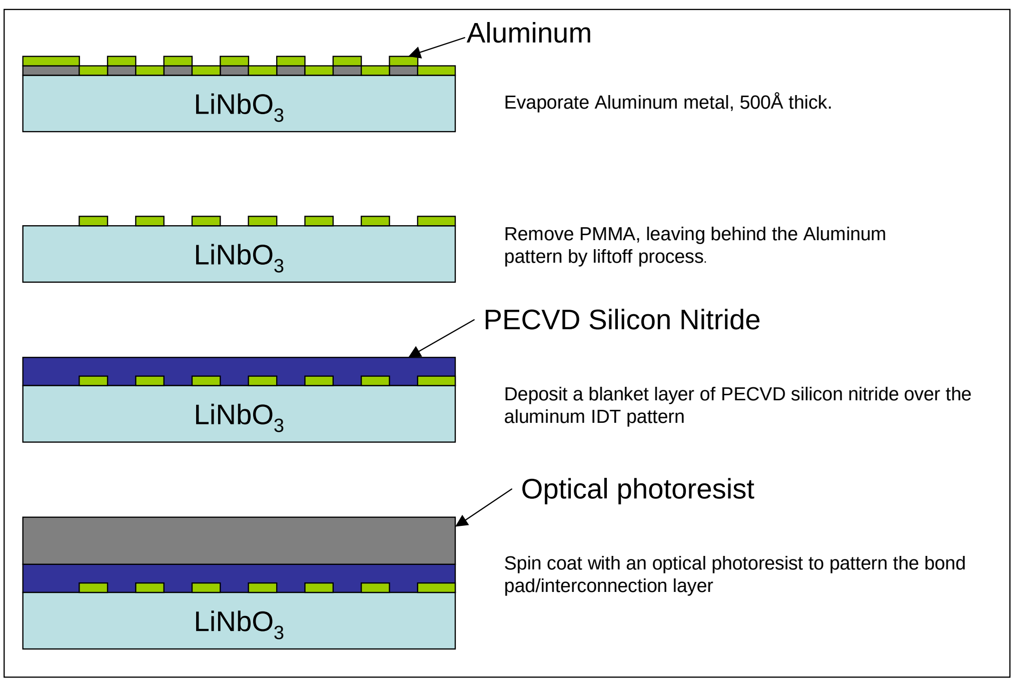
This limitation in correlator code length, N, limits the process gain available from the device, since the best possible process gain available from a correlator is equal to N. In a correlator, the process gain corresponds to the peak-to-sidelobe (PSL) ratio, which is N for a synchronously filled Barker code device. The longest Barker code only has N=13. For longer codes, such as maximal length sequence codes, the PSL is more typically $(4N)^{1/2}$ or lower [5]. Ideally, one would like to make the process gain a very large number, but the acoustic attenuation through the device limits correlator length for a single acoustic device to about 31 chips, especially in high frequency, low impedance devices. *This result is a key finding in this project.*

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 combination of SAW filters, for process diagnosis, and fixed SAW correlators are made on each fabrication mask set. The SAW filters and correlator structures are generally fabricated using industry-standard processing methods. The SAW devices are produced using a two-step lithography 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 the IDTs. The second metal layer consists of 5000Å of gold 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. In those cases, 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 only flat to electronic-grade, not 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) 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.





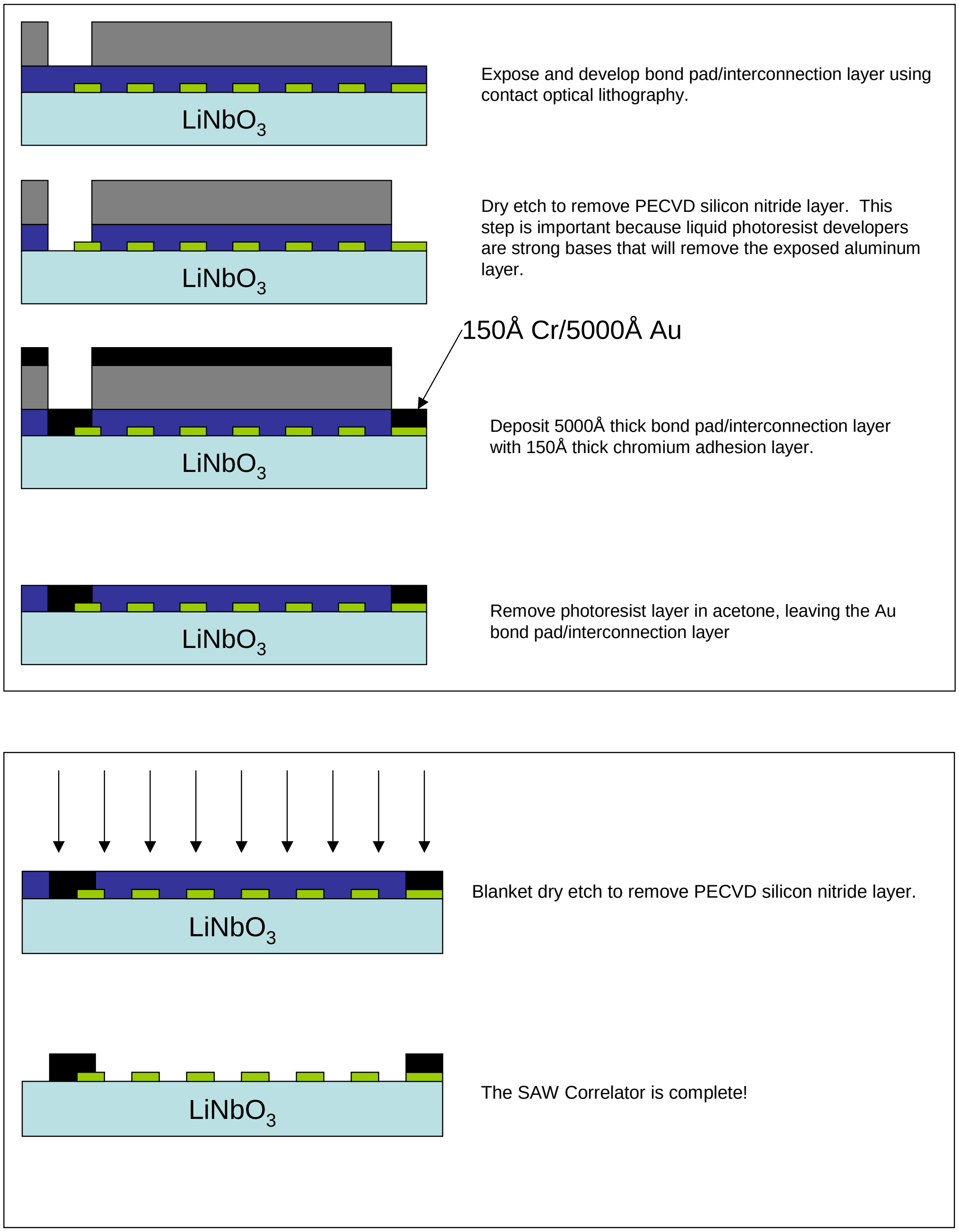


Figure 8: SAW device fabrication flow

Temperature Effects and Material Choice

Temperature effects are important in passive tag applications, either for sensing or identification. Drift of the SAW device center frequency is the primary temperature-induced effect. Since the SAW sensors use narrowband filters, significant drift can cause a complete communication breakdown. SAW correlator center frequency drift can have similarly severe consequences, in spite of the wider input bandwidth that these devices possess. The effective bandwidth of a SAW correlator is determined in part by its chip bandwidth and is comparable to that of many SAW filters.

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 fabricated a variety of devices on ST-X quartz and verified stable performance over a temperature range of 7 to 100°C (figure 9). 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 determines the useful range of the device. A low coupling coefficient in a correlator 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.

The one-way insertion loss for an unmatched SAW frequency-type filter, useful for sensor-type tags, is about –25dB. A SAW filter was built at 2.45 GHz on quartz with 100 finger-pairs that are 90 λ long in both the input and the output IDTs. These devices had insertion losses that ranged from –25dB on down. This is a relatively poor value for filter applications, but the structure of a correlator will lead to even poorer insertion loss values. The small input IDT of a correlator couples energy into a surface wave less efficiently than the input of a typical SAW filter. An S-parameter measurement of a bi-phase modulated SAW correlator is not meaningful due to the phase reversals in the output IDT. However, an S-parameter measurement on a similarly sized SAW filter without any phase reversals in its output section will give a comparable estimate of the insertion loss of a correlator. Using this approach, an unmatched SAW filter built at 2.43 GHz on quartz with 2 finger-pairs (90 λ wide) in its input and 100 finger-pairs (90 λ wide) in its output has an insertion loss of –53 dB at the peak. This is the same physical structure that a 50-phase transition correlator at the same frequency has, and so this represents a measure of a correlator's insertion loss. It is a low enough value to render these quartz correlators unusable in most system applications.

These measurements on quartz establish the necessity of using a high coupling coefficient material such as lithium niobate in SAW correlator fabrication. Unfortunately, this limits the useful temperature range that such an ID tag can be used over. The useful temperature range of a lithium niobate, SAW correlator-based ID tag is determined by the length of the code, input bandwidth, and other correlator parameters. A useful rule of thumb is that a typical 20-chip correlator will respond adequately to an input frequency range of about 0.2% of its input center frequency. This corresponds to a temperature shift of only 20 °C in YZ-cut lithium niobate. Since the SAW ID tag is a passive device, there is no self-heating, as in conventional powered electronics. Still, the useful temperature range is very limited, if the interrogation must be performed at a fixed frequency. It is important to note that an interrogation can be frequency shifted to adjust to changes in ambient temperature. Such an approach is a straightforward solution for many applications.

There are reports in the literature of high coupling coefficient, zero-temperature coefficient thin films, such as AlN over sapphire [6]. These materials will completely alleviate the temperature drift problem. However, the technology to implement these films is not compatible with existing CSRL processing equipment, and so this technology was considered to be beyond the scope of this project. Future applications that require wide-temperature range SAW devices should develop this technology.

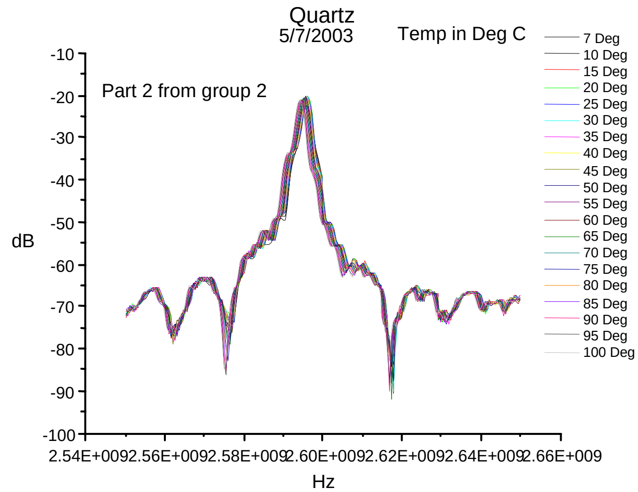


Figure 9: Quartz SAW S21 vs. frequency over temperature

SAW Correlator Performance

Identification tags based on SAW devices require SAW correlators with code lengths as long as possible. A wide variety of different correlator designs and frequencies were experimented with in an effort to maximize code length. The optimum design proved to be a fixed code SAW correlator with a code length of 31 chips. Two different variations on this approach were used. For the first, the correlators were designed for 2.43 GHz ISM-band operation; these use 30 cycles/chip to attain a bandwidth of about 80 MHz at the center frequency. The second utilize ultra-wideband UWB correlators with 4 cycles/chip in the same 2.43 GHz ISM band. An output signal from one of these UWB correlators is shown in figure 6. These correlators have output bandwidths of about 600 MHz, but otherwise have very similar performance to the 80 MHz wide devices. The peak-to-sidelobe (PSL) ratio for the UWB device shown in figure 6 is about 6:1. The output of an 80 MHz wide device is shown in figure 10. The PSL ratio for this typical device is also about 6:1.

PSL ratios are greatly increased by the use of a properly designed square-law detector in a correlator signal detection circuit. The passive tags themselves cannot use such a detector, as the signal attenuation through the device is too great. However, radar detection circuits need such a device to serve as a demodulator and can easily make up for the accompanying signal attenuation by using amplifiers. The detector aids in signal differentiation by boosting the PSL. The PSL becomes about 25:1 at the detector output (figure 11). This is much more than adequate for the purposes of differentiation of a correct code from an orthogonal code, and that is the only purpose of the PSL ratio in a radar using these devices.

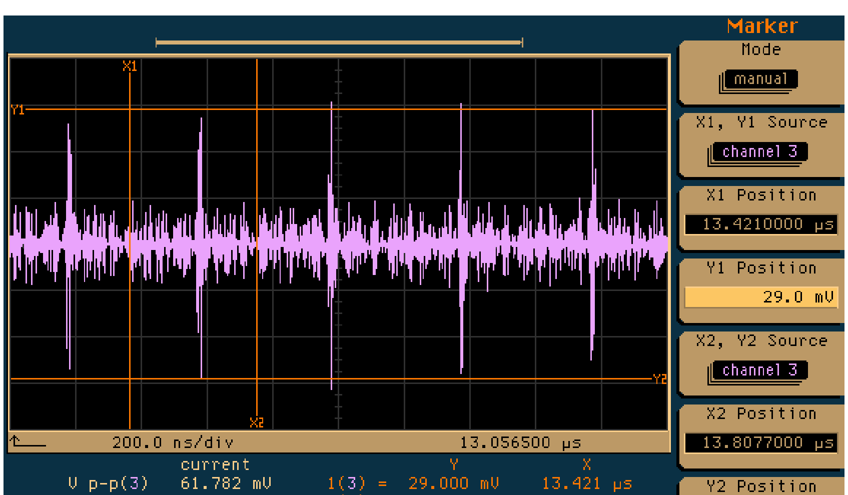


Figure 10: 80MHz ISM-band correlator output

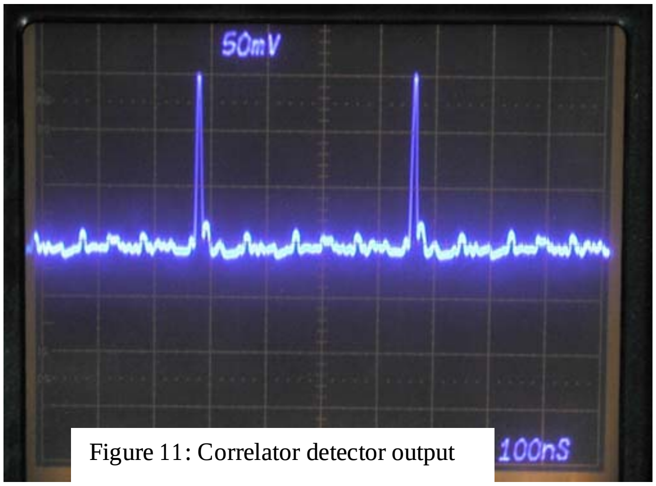


Figure 11: Correlator detector output

Signal Analysis

In the specific interrogation mode, a SAW correlator responds with a correlation peak output only in response to the correct frequency signal with the correct code transmitted from the interrogator. This is the most successful mode in which SAW correlators are used as identification tags. The signal processing involved in this transformation is worth studying. In order to proceed with a more detailed discussion of the resulting signals, it is first necessary to define terms, as follows:

t = time, typically in nsec for GHz simulations
f_{oi} = center frequency of the correlator
N_{Bi} = number of cycles per chip in correlator
N_{ci} = number of chips in correlators 1 and 2
$T_{ci} = N_{Bi} / f_{oi}$ = chip time of correlators
$T_{Bi} = N_{Bi} N_{ci} / f_{oi}$ = bit time of correlators
$f_{ci} = 1 / T_{ci}$ = chip rate of correlators
$f_{Di} = 1 / T_{Bi}$ = data rate of correlators
$f_{Do} = 1 / T_{Bo}$ = data rate of complete assembly
a_{x1} = 1,-1,-1,1,1,... = BPSK input code, corr. 1

a_{x2} = -1,-1,1,1,-1,... = orthogonal code, corr. 2
b_{x1} = 1,1,-1,-1,1,... = time reversed input1 code
b_{x2} = -1,1,1,-1,-1,... = time reversed input2 code
u(t) = 0 if (t < 0), else 1 = unit step function

The signal sent out by the transmitter in the specific interrogation mode is a wideband (sometimes ultra-wideband) BPSK coded signal. The input BPSK signal (figure 12) to obtain a correct response from a SAW correlator can be described as a stream of sine waves with varying phases as seen in

$$v_{i1}(t) := \sin(2\pi \cdot f_{oi} \cdot t) \cdot \sum_{x=1}^{N_{ci}} a_{x1}\left[u\left[t-(x-1)\cdot T_{ci}\right] - u\left(t - x \cdot T_{ci}\right)\right]$$

A second SAW correlator may be within the same field as the first correlator just described. In order to have code diversity from the first correlator, this second correlator must have an orthogonal code from the first correlator. The input BPSK signal to obtain a correlation output pulse from this correlator is

$$v_{i2}(t) := \sin(2\pi \cdot f_{oi} \cdot t) \cdot \sum_{x=1}^{N_{ci}} a_{x2}\left[u\left[t-(x-1)\cdot T_{ci}\right] - u\left(t - x \cdot T_{ci}\right)\right]$$

Here a_{x1} and a_{x2} are the coefficient vectors that are mutually orthogonal. Both of these input signals consist of a sine wave at the center frequency of the input correlator modulated by the chip sequence of the input codes. Here it is assumed that both correlators have the same center frequency, chip rate, and number of chips. If any of these parameters differ, the correlators will behave as if their codes are orthogonal, whether or not they are. Each code shown above will excite a single correlation pulse output from one of the correlators, but not the other. The correlator output transducer serves as a matched filter to the input BPSK signal. The impulse response of the transducer for the first correlator is

$$c_{i1}(t) := \sin(2\cdot\pi \cdot f_{oi} \cdot t) \cdot \sum_{x=1}^{N_{ci}} b_{x1}\left[u\left[t-(x-1)\cdot T_{ci}\right] - u\left(t - x \cdot T_{ci}\right)\right]$$

Note that the transducer's code, b_{x1}, is the reverse of the input signal's code, a_{x1}. Also note that the input frequency, f_{oi}, chip rate, T_{ci}, and number of chips, N_{ci}, must be identical to those of the input signal. Either electrical input signal, $v_{i1}(t)$ or $v_{i2}(t)$, must pass through an input transducer to be converted into acoustic waves. This input transducer typically consists of N_{Bi} finger-pairs of metal spaced at the center frequency of the correlator. The impulse response of this type of input transducer for the first correlator is given by

$$p_{i1}(t) := \sin(2\cdot\pi\cdot f_{oi}\cdot t)\cdot\left(u(t) - u\left(t - T_{ci}\right)\right)$$

and typically $p_{i1}(t) = p_{i2}(t)$. This input transducer describes a windowing function. That is, the operation of electrically exciting this transducer with the input wave $v_{i1}(t)$ or $v_{i2}(t)$ is represented by a time domain convolution operation, so that the output acoustic wave is given by

$$ac_1(t) := \int_0^t v_{i1}(\tau)\cdot p_{i1}(t-\tau)\,d\tau$$

The acoustic wave represented by $ac_1(t)$ (figure 13) shows some distortion due to the band limiting action of the input transducer. The wave, $ac_1(t)$, is then convolved with the output transducer impulse response to produce the final electrical output $y_{i1}(t)$ of the SAW correlator. The electrical output of this convolution operation is given by

$$y_{o1}(t) := \int_0^t c_{i1}(\tau)\cdot ac_1(t-\tau)\,d\tau$$

This resulting output signal is a correlation pulse modulating a sinusoidal center frequency signal only when the transmitted code, a_{x1}, is the time reversed version of the correlator code, c_{x1}. If the transmitted code, a_{x2}, is orthogonal to the correlator code, c_{x1}, then the output will be a stationary pseudo-noise signal. Simulation results for a 31-chip correlator at the 2.4GHz center frequency are shown in figures 12-14. This analysis includes the effect of the correlator input transducer, which causes some distortion to the acoustic wave (figure 13) and, as a result, also to the output waveform (figure 14). The second SAW correlator produces a corresponding $y_{o2}(t)$ output signal by a similar convolution when excited by the $v_{i2}(t)$ input signal. When excited by the $v_{i1}(t)$ input signal, the second, orthogonal correlator will not produce an output pulse but only a pseudo-noise signal.

Either of these output pulses represented by $y_{o1}(t)$ and $y_{o2}(t)$ can be detected at the radar receiver. The receiver can use a time-gating function tuned to the acoustic delay of the SAW correlator to reject all spurious radar reflections. The correlator's acoustically delayed signal will then stand out clearly if the correlator is within the field of the radar. The detected correlator signal will first be amplified, then demodulated by a microwave diode detector. This device typically operates in some combination of linear and square-law operation, depending on the strength of the input signal. The detector output is given as

$$y_{o2}(t) := k_1\cdot\left(y_{o1}(t)\right)^2 + k_2\cdot y_{o1}(t)$$

with k_1 and k_2 being constants that vary with the input signal amplitude. This raw detector output is typically not an observed signal, as the output is further filtered by a combination of parasitic and added capacitance at the output of the detector. This filtered output signal (figure 15) is given by

$$y_{o3}(t) := \int_0^t y_{o2}(\tau)\cdot e^{\frac{-(t-\tau)}{\tau_o}}\,d\tau$$

The time-constant, τ_o, of this output filter is determined by the detector video resistance R_v and the output capacitance C_v. The resulting output pulse shown in figure 15 can clearly show the presence of a properly coded correlator within the radar's reception field. The results shown in figures 12-15 are from simulations based on the above analysis. Actual test data confirm these results, as shown in a subsequent section.

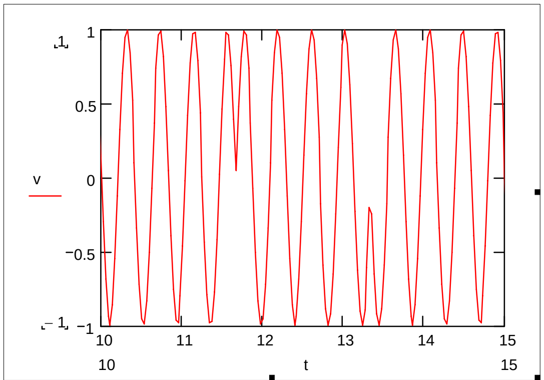


Figure 12: BPSK input signal

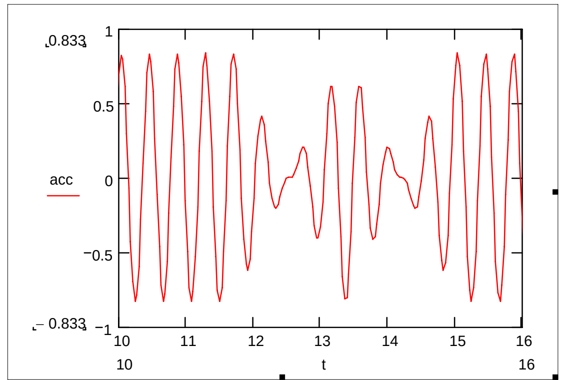


Figure 13: Acoustic signal after input IDT

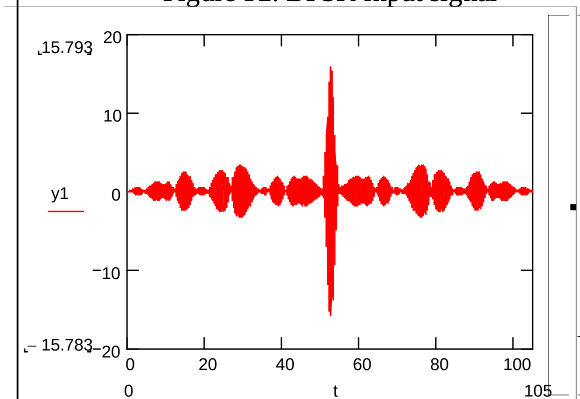


Figure 14: Correlator electrical output

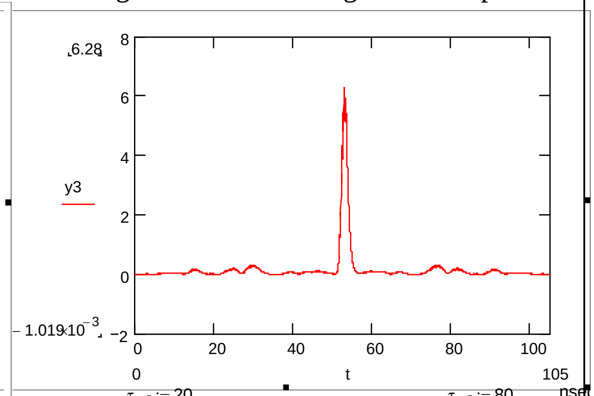


Figure 15: Filtered detector output

Signal Detection and Range

As discussed in the section on SAW-based passive remote sensing (pages 8-10), the signal detection operation is essentially a radar problem. The range of a passive SAW-based sensor is governed by the radar equation. The interrogation device transmits a pulsed burst of narrowband RF and the receiver interprets any return signals. Most of the return signals come from backscatter modulation from the 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. The radar return signals quickly die away to below the noise level, as the transmitted signal is typically not very strong. These 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 transducer, 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 about 13dB, but it is re-transmitted after all other radar reflections have disappeared and so stands out strongly. The effect of the acoustic wave reflection is similar to the effect of the antenna's scatter aperture. 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 [7]

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

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 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 delays between the reference and the modulated signals can be set, 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 read 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 (= 4.26m at 70MHz), 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 (= 6.85dB 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 reasonable detection signal-to-noise ratio (= 6dB), and P_o being the transmitted power. Using this methodology, sensor measurements can be taken at a considerable range. For the actual measured values already given the detection ranges are as follows:

Transmitted power P_o	Detection range
1 mW	120 meters
100 mW	380 meters
10 W	1.2 kilometers

SAW-Sensor Tag Results

These results were confirmed in a test arrangement based on that shown in figure 1. There are three main elements to the test setup, the transmitter, the tag, and the receiver. The receiver (figure 16) consists of an antenna tuned to the frequency band of interest connected to a SAW filter that is then connected through an amplifier to an oscilloscope. The transmitter center frequency is exactly at the center frequency of the SAW filter. A more sophisticated receiver could include a gating device to block all return signals except for the acoustically delayed signal. The transmitter (figure 17) consists of a bit-error-rate tester to generate the RF burst connected to an amplifier connected to an antenna. The tag (figure 19) consists of an antenna coupled directly to a narrowband SAW filter that has its second port tied to a variable inductor. The variable inductor simulates an impedance-changing sensor.

The transmitter operates by sending a burst of RF centered at 70 MHz. For this particular test, the burst is 100 cycles wide. The bit-error-rate tester 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.

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 being struck by the transmitted signal, a prompt radar return signal is reflected from the input to the tag. This return signal 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 the SAW's second IDT. 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. This signal is then retransmitted from the tag antenna after a total delay equal to the round trip time delay of the SAW filter. 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 15, this total insertion loss is just over 13dB, representing a voltage diminution from input to re-transmission of about 5x.

A portion of the re-transmitted tag signal is intercepted by the receiver antenna. The received signal is then amplified and, in this case, displayed on an oscilloscope (figure 18). This figure shows the original radar signal followed by the acoustically delayed signal. The acoustically delayed signal is smaller than the original radar return signal by about 18dB. The acoustically delayed signal is shown with an amplitude of about 40mV. From one trace to the next, SAW back-impedance variations were clearly visible. The amplitude could be changed from 0-60mV, by varying the sensor inductance from 50 to 300nH. This signal was so large, because the range was kept small (8m) for this test. The test confirms the veracity of the projected range vs. power table shown on the previous page.

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 [8]

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

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.

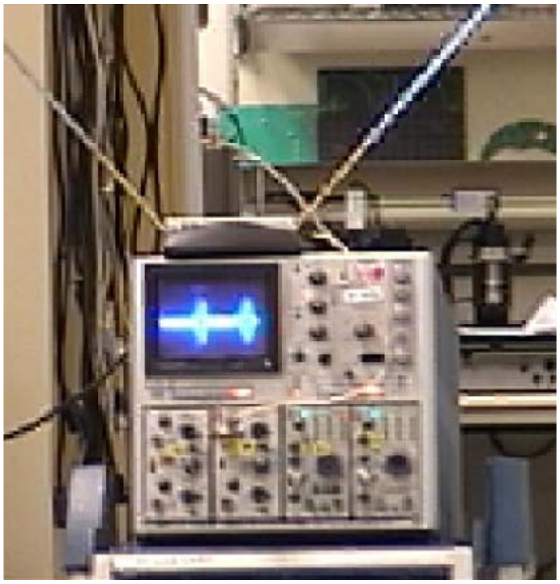


Figure 16: SAW-sensor receiver

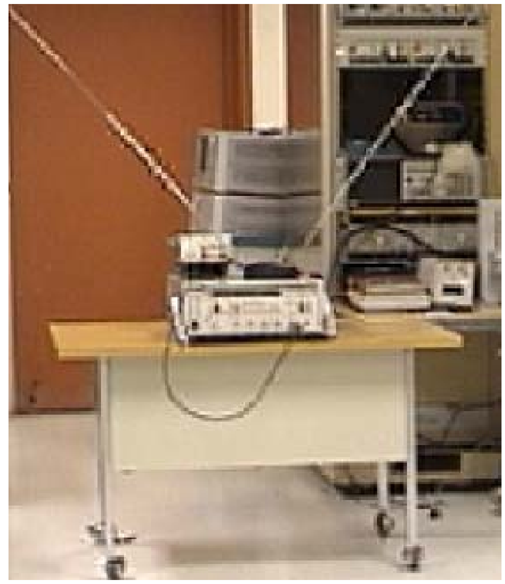


Figure17: RF burst transmitter

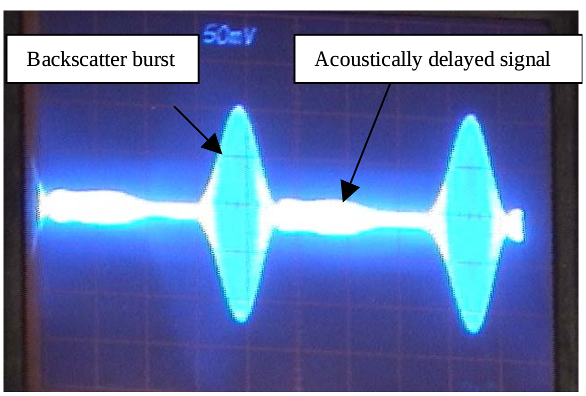


Figure 18: Received signals

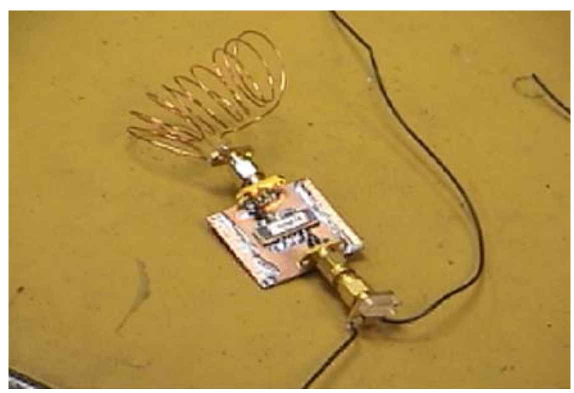


Figure 19: SAW-sensor tag

SAW Identification Tag Results

Operation of a SAW correlator-based identification tag measurement system was confirmed with several different test arrangements based on that shown in figure 2. As with the sensor-tag configuration, there are three main elements to a SAW-based identification tag test setup, a transmitter, a receiver, and the tag itself. The transmitter for the first test appears the same as that shown in figure 17 and was discussed in the previous section. It consists primarily of a bit-error-rate tester connected through an amplifier to an antenna. The antenna may change drastically in appearance for higher frequency operation, i.e. it may be much smaller at GHz frequencies. The bit-error-rate tester is programmed with a BPSK encoded carrier frequency. For a typical 2.43GHz, 31-chip SAW correlator, this is a complex coded serial stream of data

1860 bits long running at 4.86GHz. A compact transmitter based on a matched SAW correlator was built (figure 20), but the bit-error-rate tester is software controllable and easy to use for general testing.

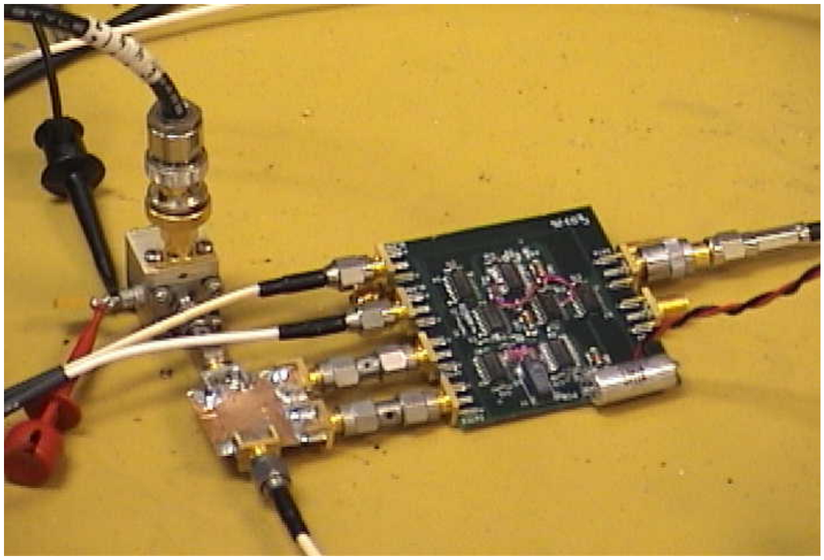


Figure 20: SAW correlator-based compact transmitter

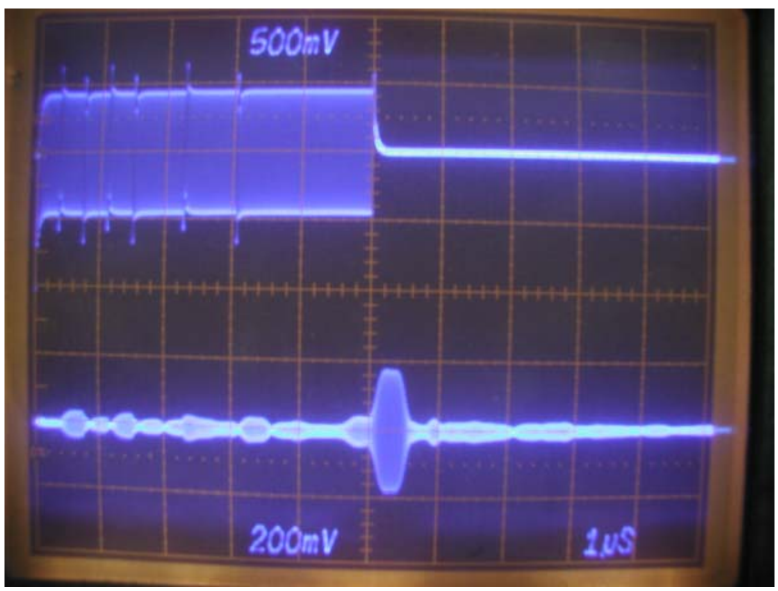


Figure 21: Transmitted BPSK signal and correlator output peak

A wide variety of different SAW correlators were built and tested. Several different configurations and frequencies were found to be optimal for different SAW ID tag applications. Some of the SAW correlators tested in a complete ID tag arrangement are the following:

1) Corr4b: 5 different m-sequence encoded devices, 2.43GHz center frequency, 31-chips, 30 cycles/chip, 80MHz bandwidth, 14dB insertion loss.
2) Corr6: 1 each, forward and reverse encoded devices, m-sequence code, 2.43GHz center frequency, 31-chips, 4 cycles/chip, 600MHz ultra-wide-bandwidth, 14dB insertion loss.
3) Corr9: 1 forward encoded, Barker code, 62 MHz center frequency, 13-chips, 24 cycles/chip, 2.6 MHz bandwidth, 12dB insertion loss.

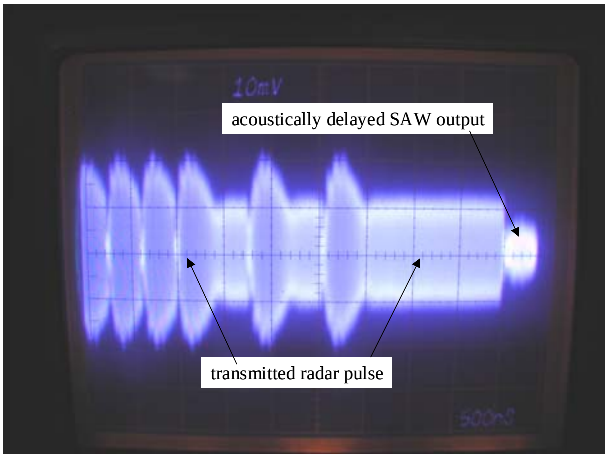


Figure 22: Received signal with correlator present

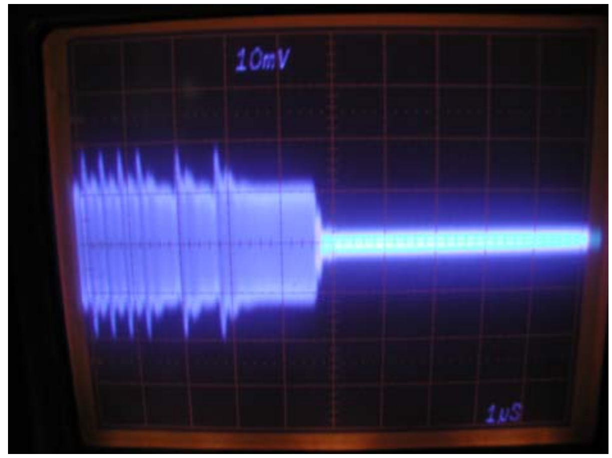


Figure 23: Received signal without correlator

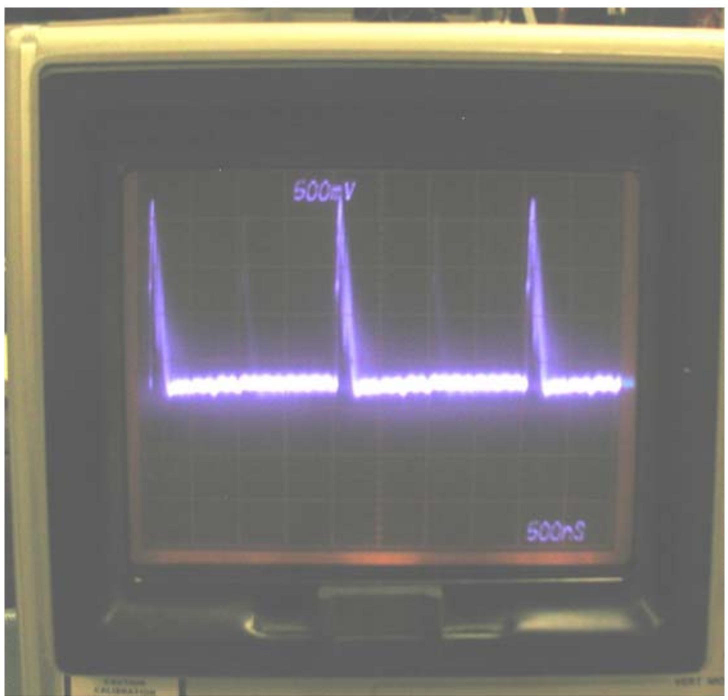


Figure 24: Received correlation signal after demodulation

The SAW correlator-based ID system using specific interrogation was tested using the transmitter and receiver shown in figures 16 and 17 and using a corr9 correlator as a re-transmitting ID tag. The receiver did not require an amplifier, as the received signal was large enough to be viewed directly with the oscilloscope. Recall that specific interrogation involves sending out the BPSK encoded RF signal for the desired tag. All tags within radio range will respond to the RF signal, but only a tag with the correctly coded correlator will respond with a correlation peak. The physical tag arrangement used for this test was similar to that used for the SAW sensor tests, and the tag required no DC power source. Total range and transmitter power levels were kept the same as for the SAW sensor tests. That is, the transmitter to tag to receiver range was about 4m and 4m respectively, for a total combined range of 8m. The transmitted power level was about 0dBm. Figure 21 shows two traces. The top trace is the transmitted coded RF burst at 62 MHz, needed for specific interrogation. The bottom trace shows the corr9 correlator response to the coded RF burst. The correlator output is the characteristic peak with a time delay that enables the signal to be differentiated from the original transmission and its return echoes. Figures 22 and 23 show the signal at the receiver both with and without the correct tag in the radar field, respectively. Unfortunately, the time scales for the two signals in the two photos differ by 2x. When being observed directly, the tag return signal was clearly visible, being about 6dB below the originally transmitted signal. Furthermore, the tag return signal would clearly change in phase and amplitude with changes made to the physical location of the tag but not with changes made to other aspects of the test setup.

The SAW correlator-based ID system using general interrogation was tested using several different receiver, transmitter, and tag arrangements. The general test setup is as shown in figure 3. The microwave tags that respond to general interrogation were based around corr6's and corr4b's. Both of these correlators have center frequencies of 2.43 GHz. For these tests, the compact transmitter shown in figure 20 was used. This transmitter was used without a correlator directly connected to the output of the switch in the foreground. The cable seen leaving the photo in the foreground went through a power amplifier to a high-gain (23dBi) antenna. Average transmitted power is only about 0dBm, since the duty cycle on the pulse is low. Peak transmitted power is about 1w for about 12nsec. The RF burst used to excite the correlator was then transmitted from the antenna to the receiving correlator-based tag. The correlator responds to the RF burst by re-transmitting its code.

The receiver uses a matching SAW correlator for signal processing on the incoming coded signal. The receiver's correlator will produce a correlation pulse only if the matching correlator had transmitted its code. Any other correlator within the range of the receiver will not produce a correlation peak. A video showing this SAW identification-tag test named SAW_ID_Tag.AVI is available at \\Dr-seuss\horton\Saw\videos An example of the post-demodulation correlation peak is shown in figure 24. It is possible to obtain clear correlation-peak signals, in spite of the significant path losses with this setup. The range equation indicates a maximum range of about 25m using the components we had available. That is, peak transmit power was about 1w, receive and transmit antennas had gains of 23dBi, tag antennas had gains of 2dBi, correlator S21 was 14dB, maximum SNR is about 6dB, receiver noise figure is about 3dB, receiver bandwidth is 81MHz (for corr4b), and frequency of operation is 2.43 GHz. These values give a maximum range of 25m using the equation on page 22. The test was conducted using a range of 8m, so the received signal levels gave much better SNR than 6dB. The clear limitation of this approach is that the transmit and receive antennas used are too bulky to be easily carried around. The tag and its antennas are small and can easily be made smaller, and this is the primary item to keep small.

Conclusions

A variety of different long-range passive microwave and RF tags were developed and evaluated. All of these tags are capable of being wirelessly read, and all require no DC power of any kind. These tag types fall into two general categories, tags for sensing specific physical properties, and tags for identification purposes. Both types of tags make use of SAW devices; the sensing tags use SAW filters, and the identification tags use SAW correlators. A significant portion of the total effort went into designing, fabricating, and testing optimally performing SAW devices. This design and manufacturing capability for SAW devices ought to be further refined and used for an expanding range of applications at Sandia Labs. Also, future development work for SAW sensing tags should be geared towards developing specific wireless sensors, such as pressure, temperature, and strain. These tags might also make use of novel measuring SAW correlators.

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6) Tsubouchi, K. and Mikoshiba, N., "Zero-Temperature-Coefficient SAW Devices on AlN Epitaxial Films," *IEEE Trans. Sonics and Ultrasonics*, SU-32, 1985, pp. 634-644.
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Appendix: Design and Layout Files

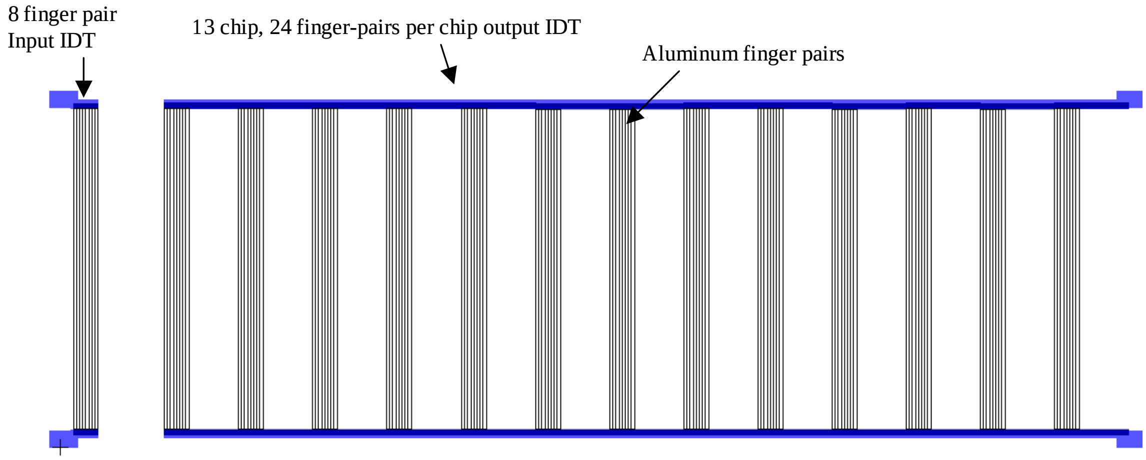

Figure 25: Corr9 SAW correlator with 13 chips at 62 MHz

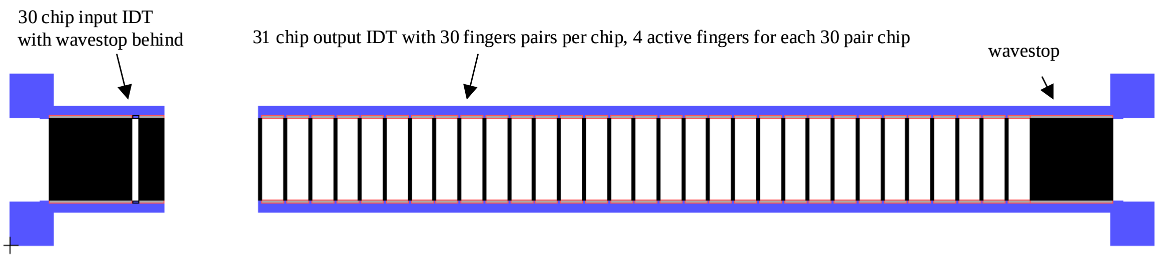

Figure 26: Corr4b, 31_4 code, 2.43GHz center frequency, 31 chips

Distribution

8	MS0874	Robert W. Brocato, 1751
5	MS0874	David W. Palmer, 1751
1	MS0874	Glenn D. Omdahl, 1751
1	MS0874	Gregg A. Wouters, 1751
1	MS0874	Matthew A. Montano, 1751
1	MS0874	Emmett J. Gurule, 1751
1	MS0874	Christopher L. Gibson, 1751
1	MS0603	Joel R. Wendt, 1743
1	MS0603	Jonathan D. Blaich, 1763
1	MS0874	Vincent M. Hietala, 1738
1	MS0865	Regan W. Stinnett, 1903
1	MS1371	Dianna S. Blair, 6926
1	MS1071	Michael G. Knoll, 1730
1	MS1202	Ann N. Campbell, 5940
1	MS1202	John P. Anthes, 5940
1	MS0529	Michael B. Murphy, 2346
1	MS0529	Kenneth W. Plummer, 2346
1	MS0986	Judd A. Rohwer, 2664
1	MS0782	Rebecca Darnell Horton, 4148
1	MS1078	Stephen J. Martin, 1707
1	MS0123	LDRD Office, Donna L. Chavez
1	MS9018	Central Technical Files, 8945-1
2	MS0899	Technical Library, 9616