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LDRD 26573 Ultra-Low Power Spread Spectrum Receiver, FY02 Final Report

Robert W. Brocato

Prepared by Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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LDRD 02-26573 Ultra-Low Power Spread Spectrum Receiver, FY02 Final Report

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Abstract

This report describes the development of an ultra-low power spread spectrum receiver based on a programmable surface acoustic wave (SAW) correlator. This work was funded under LDRD 02-26573, Ultra-Low Power Spread Spectrum Receiver. The approach taken in this project uses direct demodulation of a radio frequency (RF) signal from carrier frequency to data frequency. This approach was taken to reduce power consumption and size. The design is based on the technique of correlating the received RF signal with the pre-programmed spreading code. The system requirements, applications, design methodology, and testing results are all documented in the following pages.

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NOMENCLATURE

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
IC	-	Integrated circuit
IDT	-	Interdigital Transducer
IF	-	Intermediate Frequency
LDRD	-	Lab Directed Research and Development
LNA	-	Low Noise Amplifier
Mbps	-	Mega bits per second
PCB	-	Printed circuit board
PN	-	Pseudo Random
POP	-	Peak-off-peak ratio
PSAW	-	Programmable surface acoustic wave correlator
RF	-	Radio Frequency
SAW	-	Surface Acoustic Wave
SNR	-	Signal to Noise Ratio
SPICE	-	Simulation Program with Integrated Circuit Emphasis
SS	-	Spread Spectrum

1 INTRODUCTION

This project addresses a number of needs in security related fields. It could potentially be extended to commercial applications. A very small, very low power commercial radio receiver does not exist and, surprisingly, is not likely to become available anytime soon. Commercial wireless product developers are currently focused on techniques that are fundamentally limited in their ability to reduce size and power. IEEE standard 802.11x variant radios are becoming commonplace, but are still more than an order of magnitude greater in both size and power consumption than the devices under investigation in this work.

The primary emphasis in this work is to fundamentally alter the approach taken to construct a very small radio receiver. Conventional radio systems go through a number of subsystems to convert data into the transmitted radio signal and vice-versa. Through sheer force of engineering effort, and with the expenditure of billions of dollars, these systems have been refined to the high level of sophistication present today. Their size and power consumption have decreased dramatically in the last 20 years, but without any fundamental changes in approach.

The approach taken in this work is to combine the functions of many, sophisticated microwave and digital signal processing sub-systems into a single component. This single component, operating in transmission mode, accepts baseband data and passively transforms it into a complex, broadband bi-phase coded microwave waveform. This single component can also be operated in a reverse manner to demodulate the same complex, broadband bi-phase coded microwave waveform into baseband data. It operates without requiring any DC power, although support circuitry may require some DC power. This component is the surface acoustic wave (SAW) correlator. It holds the potential to deliver at least 10x smaller and lower powered wireless receivers.

The idea of using SAW correlators as the basis for radio communications is not new. Basic spread spectrum systems using SAW correlators were reported as early as 1980 at Hewlett-Packard Laboratories [1]. These early systems were hampered by an inability to fabricate devices that operate directly at the transmission frequency. The developers used the correlator as an intermediate frequency (IF) device. As a result, they still needed the same large, power consuming mixers and oscillators that were required by conventional methods. In addition, they were hampered by two other fundamental problems. First, they lacked the lithographic accuracy, manufacturing controls, and process stability needed to reliably produce large quantities of SAW correlators. Second, each correlator code needed for each radio had to be separately produced as a distinct and unique component. The early techniques showed limited promise for reducing power consumption and size, and they did not lend themselves to mass production techniques needed for commercial acceptance.

The intention of this report is to demonstrate that modern lithographic and micro-system fabrication techniques have enabled us to overcome all of the limitations of the early systems. The approach taken in this LDRD-funded effort systematically eliminated all of the limitations mentioned above. First, the use of electron beam lithography demonstrated the ability to fabricate SAW filters that operate directly in the desired microwave band centered at 2.45 GHz. Second, multiple fabrication runs demonstrated the capability to reliably fabricate repeatable results with sufficient frequency stability. Third, fabrication was demonstrated on temperature stable (ST-X cut quartz) and low loss (Y-Z lithium niobate) materials. Fourth, adequate software modeling of SAW correlators was found to be unavailable commercially, and was developed in house. Fifth, fabrication, testing, and packaging of fixed code SAW correlators were demonstrated. Sixth, adequate impedance matching techniques were developed to enable SAW correlators to be used in a fieldable system. Seventh, an electrically programmable SAW correlator was developed, tested, and demonstrated to overcome the manufacturing limitation of requiring a separate SAW correlator to be fabricated for each receiver.

The seventh and final development of the LDRD is the most significant point of the program. As was mentioned, in all early systems, a different correlator had to be fabricated for each transmitter/ receiver pair. If a receiver needed to listen to several transmitters, then it needed to have a separate correlator for each device that it needed to listen to. With the programmable correlator, a single SAW device is built for all transmitters and receivers in a system. The radio then electronically adjusts its correlator for the transmitter that it is to listen to, or the receiver that it is to talk to.

Although the work described in this report is seminal, it will require significant follow-on engineering efforts to produce high volumes of fieldable systems. The intent is to demonstrate the technology and its manufacturability. To produce long range systems, the SAW correlator will need to be refined to lower reflection induced background levels.

2 BACKGROUND INFORMATION

This ultra-low power spread spectrum radio receiver is centered around a SAW correlator. In its simplest form, a SAW device appears as two comb-like metal structures deposited on a piezoelectric crystal surface. 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 takes advantage of this wavelength compression to perform signal processing on radio waves. The second comb-like structure in the SAW serves both as 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 be over 1 billion in 1999 [2]. 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. The MicroChemLab uses SAW filters for chemical discrimination. 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.

2.1.1 SAW Correlators

A SAW correlator is a two transducer piezoelectric device used to provide a matched filter output. The filter in the case used here matches to a bi-phase-coded phase modulated signal, rather than the usual sine wave. That is, the incoming radio wave has 180 degree phase transitions in its sinusoidal waveform, modulated in a coded pattern. An interdigital transducer (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 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 bandwidth. The correlator then has a phase coded receiver transducer to convert 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. If an incorrect code is given, the correlator output appears similar to broadband, low-level noise. Figure 1 shows a block diagram of a SAW correlator with its waveform.

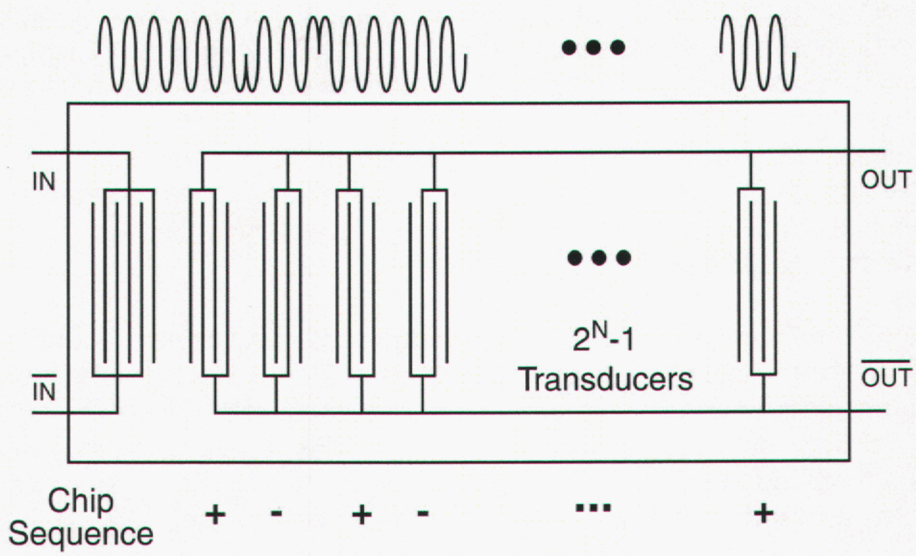

Figure 1. Fixed Code SAW Correlator

Figure 2 shows the expected electrical signals present in a SAW correlator.

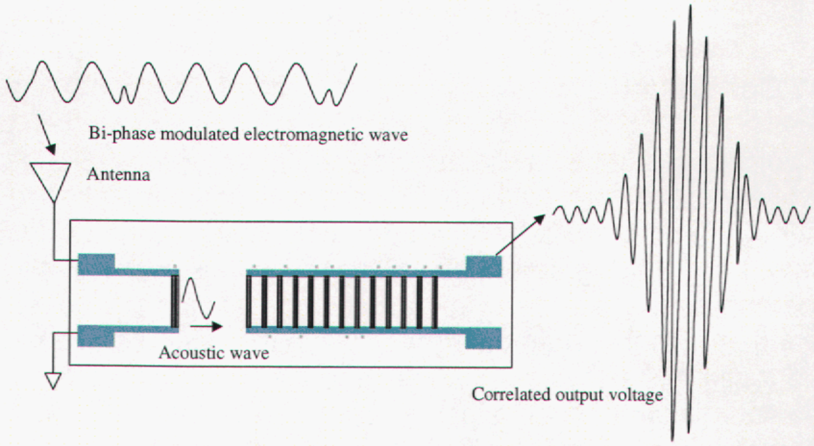

Figure 2: SAW correlator electrical and acoustic signals

2.1.2 Principles of Spread Spectrum Communications

The SAW correlator forms the heart of the low power spread spectrum communications system, but one might ask, "Why bother with using spread spectrum techniques?" Spread spectrum communications approaches provide a number of advantages over conventional narrow-band communication approaches. First, a broad band signal is inherently less susceptible to a radio wave propagation problem called multi-path interference. Multi-path interference arises when a radio wave simultaneously takes different length paths to the same receiver antenna. The waves that have traveled over different paths will have different phases and can interfere destructively with each other. Spread spectrum communications can avoid this problem by using a very broad bandwidth to transmit the message. A broad bandwidth signal can only interfere with itself over short path length differences. In effect, the path length difference of potential interference goes as the inverse of the signal transmission bandwidth. This multi-path immunity provides a significant range and power advantage over conventional narrow-band communications.

Additionally, spread spectrum techniques provide several security-related advantages. The type of spread spectrum technique of use in this system is called Direct Sequence Code Division Multiple Access (DS-CDMA). The other type of spread spectrum technique commonly used is called Frequency Hopping (FH). FH is a technique that involves changing the narrow-band transmission frequency at a rate greater than the rate of the data that is being transmitted. It has some of the advantages of DS-CDMA, but does not lend itself to low power techniques and is not used here.

DS-CDMA has the security advantages of being resistant to jamming, having a low probability of intercept, and being able to support many users in its broad bandwidth. The concept of spread spectrum communications was originally developed primarily for its security related features. The basic approach with DS-CDMA is to modulate a data stream at a higher frequency referred to as the chip rate. The modulation is done using a pseudo-random (PN) code which gives the resulting signal noise-like spectral qualities. It broadens the bandwidth of the signal, makes it difficult to detect and “unravel”, and lowers the required power to transmit the signal. The required power to transmit the signal is lowered due to the inherent process gain resulting from the technique.

Process gain is conceptual product of the work originally done by C.E. Shannon, and expressed in an equation for channel capacity [3]:

$$C \quad W \log \quad 1 \quad \frac{S}{N}$$

In this equation C is the capacity in bits per second, W is the bandwidth in Hertz, N is the noise power, and S is the signal power. This equation defines the trade-off relationship between transmitted signal power and signal bandwidth for a desired channel capacity. This equation describes the basis for spread spectrum communications. That is, for a desired data rate, if more bandwidth is used to transmit the signal, less power will be needed to transmit it.

2.1.3 Ultra-Low Power Spread Spectrum Receiver.

The SAW correlator-based spread spectrum receiver is a low power analog equivalent to digital demodulation and synchronization. As already described, the SAW correlator serves to encode (or decode) the data as well as to up-convert (or down-convert) the frequency of the signal. A spread spectrum data communication link can at a minimum consist of a data generator connected to a transmitting SAW correlator connected (via a suitable communications medium) to another SAW correlator controlling a data producer. This simple system has all of the main advantages of a sophisticated, digital signal processor-based DS-CDMA system while consuming much less power and occupying much less volume. The work under this LDRD centered on the novel components and techniques needed for such a system. A commercial low noise amplifier can be connected to the front end of the system to enhance its range. Additionally, commercial digital data generators can be used both to test the device and as transmitters to communicate with lower power SAW-based receivers. The work in this LDRD focused on the heart of an ultra-low power spread spectrum receiver.

3 PROJECT FUNDING

LDRD 26573, Ultra-Low Power Spread Spectrum Receivers for Micro-Tags to Improve Security during Critical Operations, was jointly funded between MESA Technologies and Nonproliferation and Materials Control (NPMC). This project is the second year of a two-year total duration. First year accomplishments are documented in the LDRD 01-0784 Final Report.

4 REQUIREMENTS

From a series of meetings conducted in the first year of the LDRD, a requirements document was generated (see LDRD 01-0784 Final Report, Appendix A). The document includes the environments, electrical, mechanical, and compatibility requirements. Since this LDRD is a research project many of the requirements were regarded as targets.

5 SAW MODELING

Software for modeling SAW correlators is not available from industry. A few basic software packages exist for modeling SAW filters and resonators, but these programs possess very limited capabilities and do not have the ability to model correlators. To aid the correlator design process an effort to develop MATLAB models was undertaken and completed by means of a contract with the University of New Mexico.

The proposed receiver communication protocol has been completely modeled in MATLAB. Figure 1 is the theoretical output of a SAW correlator with a 10% input bandwidth and a code length of 127. The spread spectrum code is a maximal length sequence (i.e. M-sequence code). This simulation software is based on the delta-function model. The delta-function model treats each SAW transducer element as a delta function in a finite series of delay elements. It is really a representation of an ideal transversal filter. This model does not include material characteristics or second order effects of the SAW device.

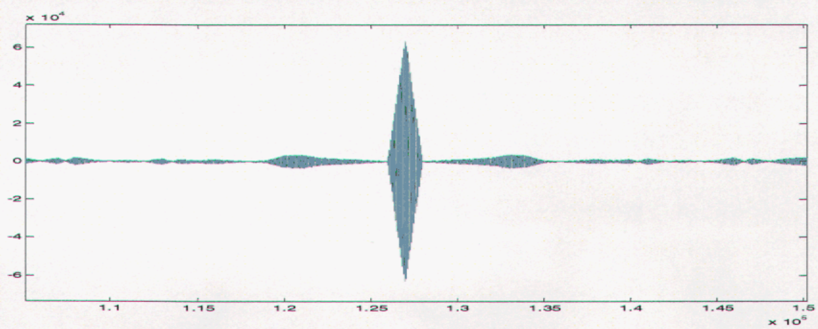

Figure 3: Delta function simulator output

The MATLAB-based simulation software runs quickly on a personal computer, and enables the rapid, but high level investigation of different correlator designs. A second modeling effort was undertaken at Sandia to develop a model for SAW correlators that includes material properties, electrical parasitics, and device second order effects. This modeling effort was completed in SPICE. The SPICE-based software uses SPICE (either PSPICE or ChileSPICE) as a solver engine on an electrical model of the SAW device. The SAW model used is a crossed-field model derived from the Mason equivalent circuit [4]. It models each device as a three port admittance network and makes use of transmission line delay elements in SPICE to simulate the acoustic effects of the material.

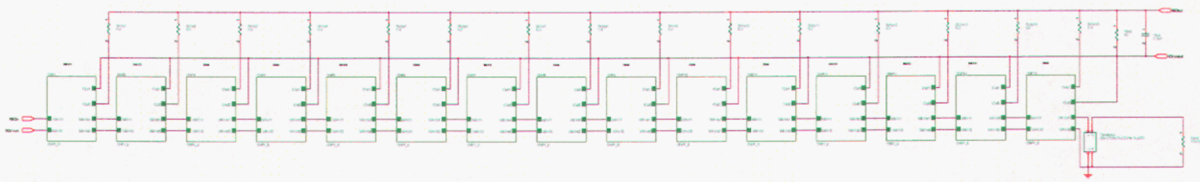

Figure 4: Hierarchical model of a 15-chip SAW correlator receiver

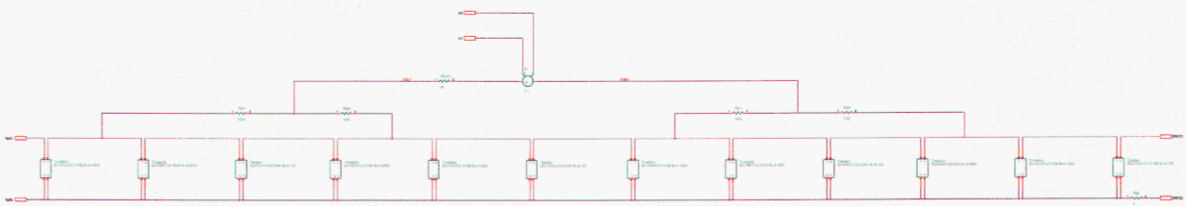

Figure 5: SPICE model of a single SAW split-finger pair

The SPICE simulation is capable of including various electrical parasitic components that occur in the fabrication of a programmable correlator. In addition, the model includes acoustic end reflection and bulk wave effects. It has proven useful for evaluating the relative advantages of SAW physical layout variations.

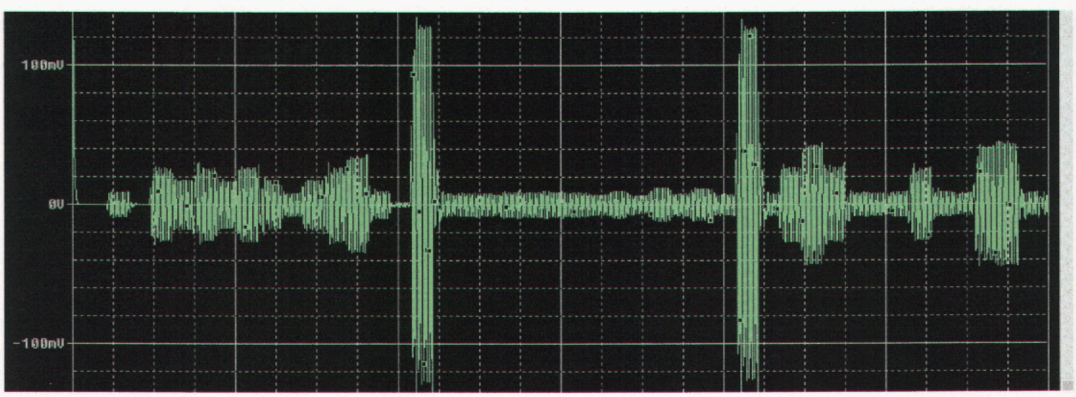

Figure 6: SPICE simulation output of programmable SAW correlator including electrical parasitics and end reflection effects.

SPICE simulations have been used to reproduce degradations due to second order reflections. This is a common problem in the fabrication of SAW correlators and needs to be further investigated and corrected in future work.

6 Development of Fixed SAW Correlators

The first phase of the second year of the LDRD centered on fabrication of fixed code SAW correlators. As mentioned in the introduction, there were several key issues to be resolved to determine if advances in microfabrication had been sufficient to overcome the limitations that early SAW correlator-based spread spectrum communication systems had encountered. The first issue was whether it was even possible to fabricate SAW correlators at the high frequencies of the 2.45 GHz instrumentation, scientific, and medical (ISM) band. Electron beam lithography techniques developed during the first year with SAW filters proved adequate to produce a SAW correlator on quartz at 2.45 GHz. ST-X quartz has a linear temperature coefficient of zero at 300 ^{o}K. Unfortunately, quartz has a very low coupling coefficient. A SAW correlator designed as a filter with no phase transitions in the receiver can be used to measure signal transmission. The response curve for such a device fabricated on quartz is shown in figure 7. The peak response has a loss of about –53 dB. This is too large of a loss to be overcome in a low power system. It was useful for settling the question of fabrication repeatability. To test this, multiple fabrication runs were produced on quartz. They demonstrated repeatable results with excellent frequency stability.

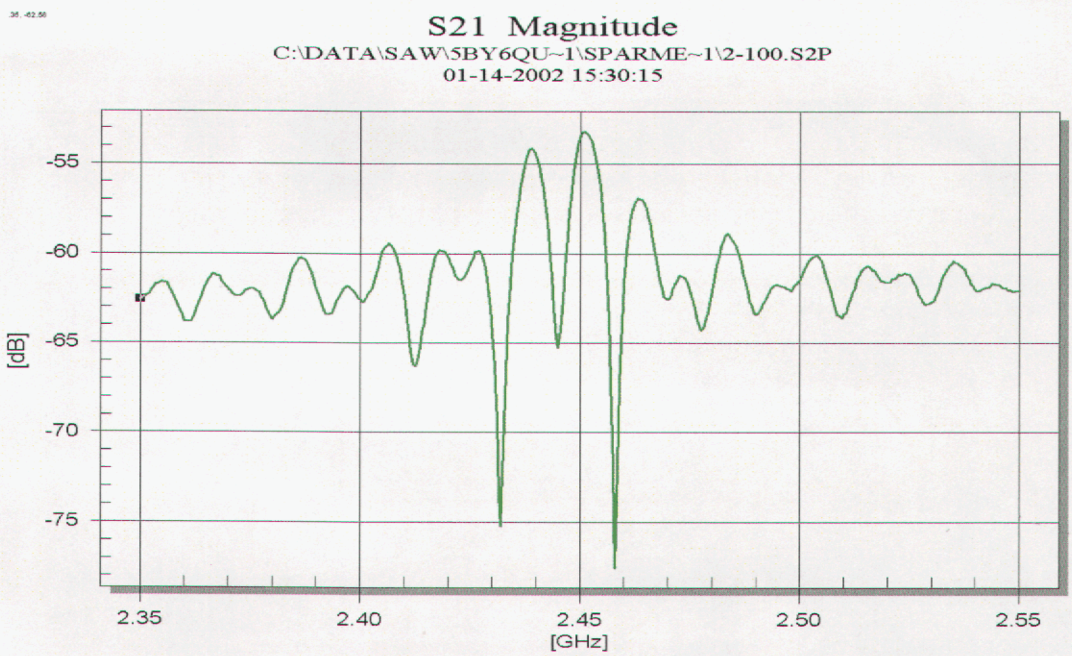

Figure 7: SAW correlator transmission curve for uncoded quartz device

The next step involved fabricating a series of fixed code SAW correlators on a high coupling coefficient piezoelectric material. Y-Z oriented lithium niobate substrate material was obtained, and the same series of SAW correlators and filters that was fabricated on quartz was also fabricated on lithium niobate. The lithium niobate substrates have a slightly higher transmission velocity (see table 1), so the resulting SAW correlators have a center frequency of 2.7 GHz. The higher coupling coefficient of lithium niobate gives much lower loss SAW devices. Early devices showed losses of about –35 dB for an unmatched 2 finger pair input to 100 finger pair output device (see figure 8).

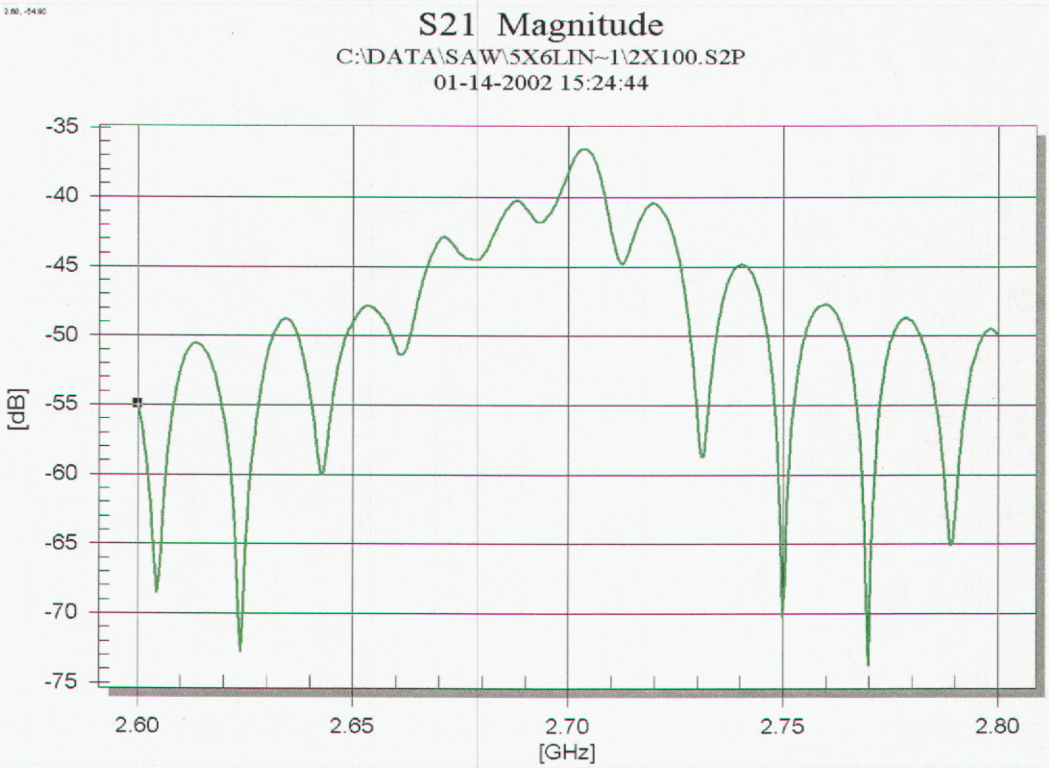

Figure 8: SAW correlator transmission for uncoded lithium niobate device

The SAW correlators are tested on a probe station by inserting the phase modulated waveform into the input port of the correlator and observing the output waveform. All of the test instrumentation is impedance controlled microwave test equipment. A typical output waveform of a 15-chip correlator is shown in figure 9. A measure of correlator quality that is commonly applied is called the peak-off-peak (POP) ratio and is a measure of the output correlation voltage peak to the side-lobe voltage peak [5]. The theoretical maximum POP ratio for the 15-chip correlator is 15:1. The observed POP ratio for the devices that we have built is typically 4:1 before the devices are packaged. The reason for the degradation from theoretical maximum performance to the observed levels is believed to be due to spurious reflections on the wafer. The observed degradations have been reproduced by inserting end reflections into a SPICE simulation of the correlator.

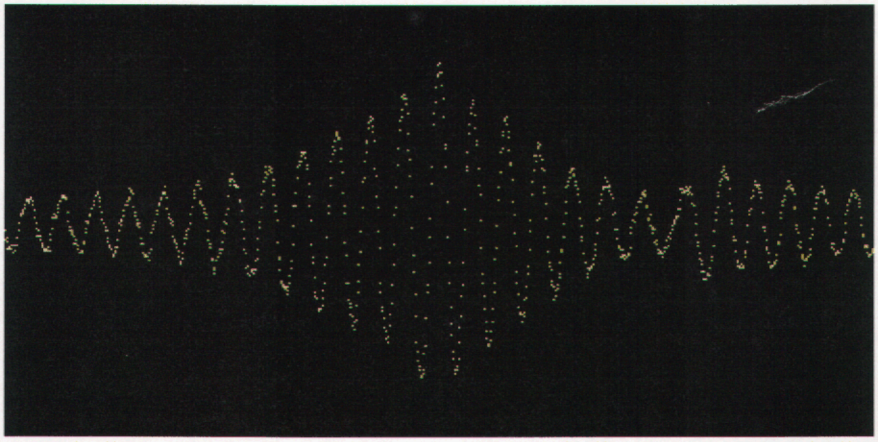

Figure 9: Zoom view of actual correlator peak voltage

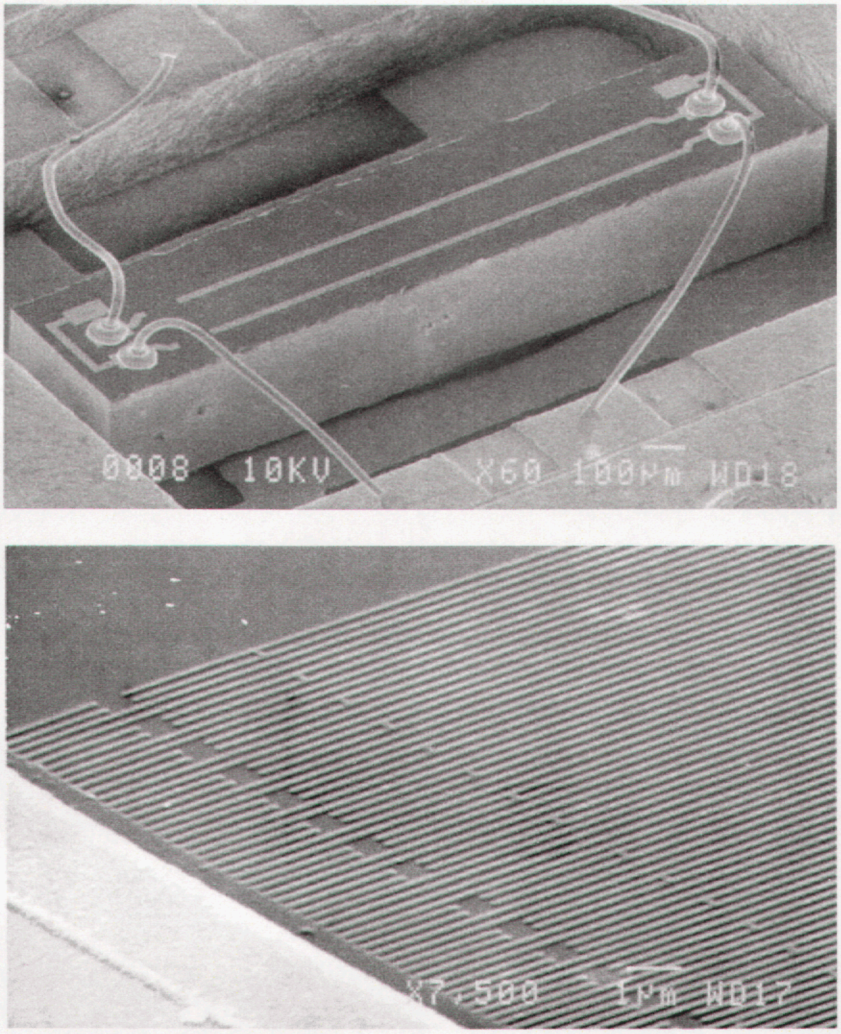

Figure 10: Scanning electron microscope images of SAW correlators

Use of materials other than lithium niobate or quartz has been considered. Lithium niobate is commercially available in high-grade crystals. There are materials, such as thin film aluminum nitride on alumina which have good coupling coefficients, zero temperature coefficient at room temperature, and high velocities. These materials are not available commercially, and their use will require a materials development effort. The use of a zinc oxide thin film on either silicon or diamond coated silicon could be highly desirable from a performance standpoint, but this will also require a materials development effort.

Piezoelectric material	Orientation	wave velocity	coupling coefficient	temperature coefficient
lithium niobate	ROTY-Z	4000 m/s	5.70%	-57 ppm/C
lithium niobate	Y-Z	3488 m/s	4.50%	94 ppm/C
lithium niobate	128 deg. -X	3992 m/s	5.30%	75 ppm/C
quartz	Y-X	3259 m/s	0.23%	-22 ppm/C
quartz	ST-X	3158 m/s	0.16%	0 ppm/C
gallium arsenide	[100]-[110]	<2841 m/s	<0.06 %	35 ppm/C
bismuth germanate	[110]-[001]	1681 m/s	1.40%	120 ppm/C
bismuth germanate	[100]-[011]	1681 m/s	1.50%	130 ppm/C
bismuth germanate	[111]-[110]	1708 m/s	1.70%	128 ppm/C
lithium tantalate	77.1deg. ROTY-Z	3254 m/s	0.72%	35 ppm/C
lithium tantalate	Y-Z	3230 m/s	0.74%	37 ppm/C
Zn0-diamond-Si	NA	10,500 m/s	1.50%	NA
PZT-1	ceramic	2400 m/s	22%	9 ppm/C
AlN(1um)-alumina	ceramic	5910 m/s	1.00%	0 ppm/C

Table 1: SAW piezoelectric materials and their properties

7 Impedance Matching Circuitry

A crucial issue to be resolved in the development of a complete spread spectrum system using SAW correlators is impedance matching. Due to the physical nature of the SAW transducer elements, the electrical impedance seen looking into the SAW correlator is not a good match for any practical antenna. It is therefore necessary to transform the small capacitive load of the input transducer into a 50 Ohm resistive impedance, or as close to it as possible. This is a requirement both for any practical use of the device in a standard microwave circuit and even for testing of the device on commonly available microwave test circuitry.

Several different matching networks were developed for the correlators. A bulk component matching network was developed for quartz and is shown in figure 11. The output waveform of an impedance matched quartz device is shown in figure 12. The bulk element matching network is difficult to make as a very broad band match, so the resulting waveform shows greater accentuation of the correlation peak. This may prove to be a desirable side effect, and may need to be examined further in the future. Microstrip based impedance matching networks were also developed for both quartz and lithium niobate devices. The microstrip approach proved to be simpler for matching to packaged devices due to the nature of the packaging parasitics. Also, the microstrip matching network appears to be of a wide enough bandwidth to accommodate any SAW correlator.

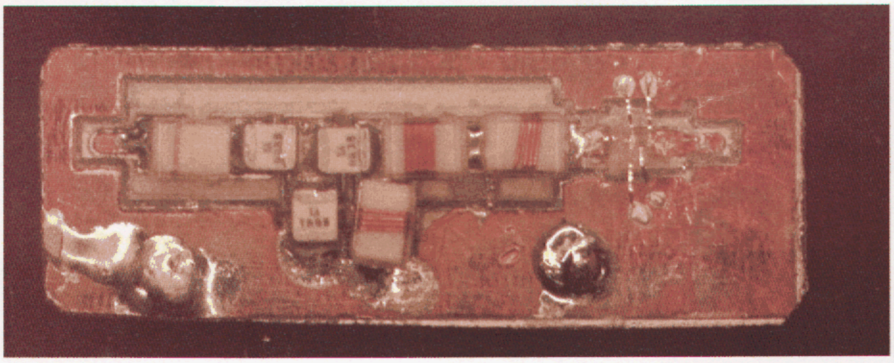

Figure 11: Quartz SAW mounted with a bulk element matching network.

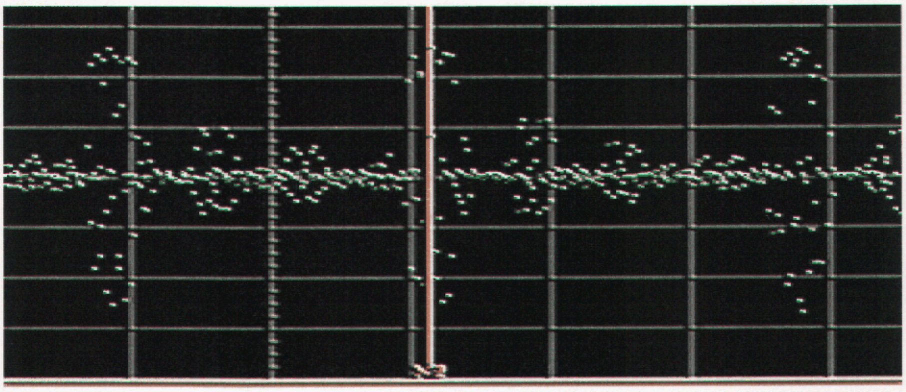

Figure 12: Waveform of quartz SAW correlator with matching network.

8 Packaging Issues

SAW correlators present several challenges to packaging. First, sawing the devices up causes degradation in performance due to greater interference from end reflections. That is, the wave experiences less attenuation due to travelling across the material surface, since there is less distance to travel before and after being reflected from the ends. More work needs to be performed to minimize end reflections in SAW correlators.

A second challenge to packaging the SAW arises from package parasitics. Standard 1 milli-inch diameter gold bonding wire adds a significant amount of inductance (about 5 nH) to the input and output of the SAW transducers. This proves to be an advantage when matching the device to 50 Ohms. Efforts were made to mount unpackaged SAW correlators directly to a Duroid® microstrip matching printed circuit board. The copper cladding on the circuit board needed to be heavily plated with gold to enable bonding wires to stick to the board. Both 4 milli-inch gold ribbon wire and 1 milli-inch diameter gold wire were made to stick to the board, but only when a heavy layer of gold was plated. Standard, thin gold plating layers were not sufficient. It was found to be possible to work with unpackaged correlators in the manner, but it is more desirable to use the devices in a package.

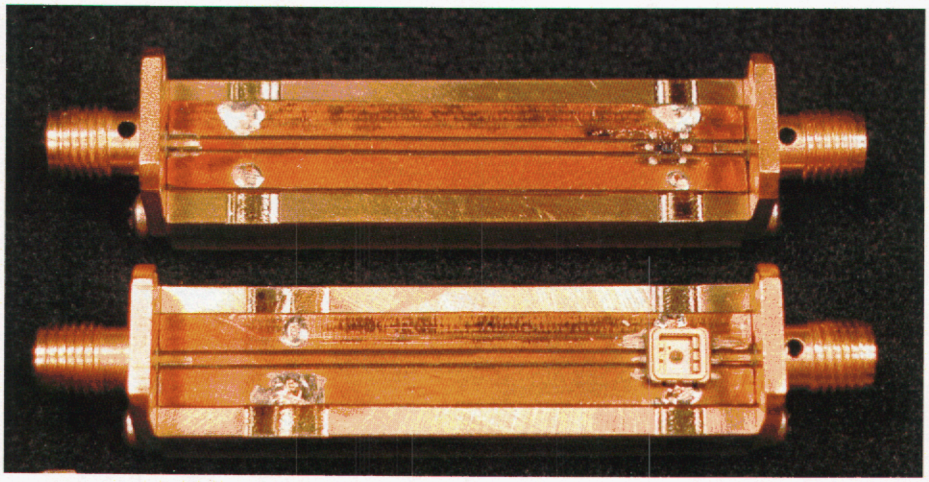

Figure 13: Unpackaged and packaged SAW correlators on PCBs.

9 Programmable SAW Correlator

A central goal of this LDRD was the development of the first electrically programmable SAW correlator (PSAW). As already mentioned, the development of the PSAW removes the last main obstacle to mass production and implementation of SAW correlators in wireless applications.

The PSAW developed for this project is a hybrid device composed of a silicon base integrated circuit (IC) coupled to a lithium niobate SAW. The silicon base chip was fabricated in an American Microsystems, Inc. 0.5 micron CMOS process. The base IC contains the switches to configure the phases of each SAW chip. The SAW device itself was fabricated at the Compound Semiconductor Research Laboratory (CSRL) at Sandia National Laboratories. It was made on a lithium niobate substrate with electron beam lithography used to pattern the aluminum fingers. The base integrated circuit and the top SAW device are joined together by flip chip bump bonds using 50 x 50 micron pads lined up on the two chips. The combined hybrid device is shown in figure 14.

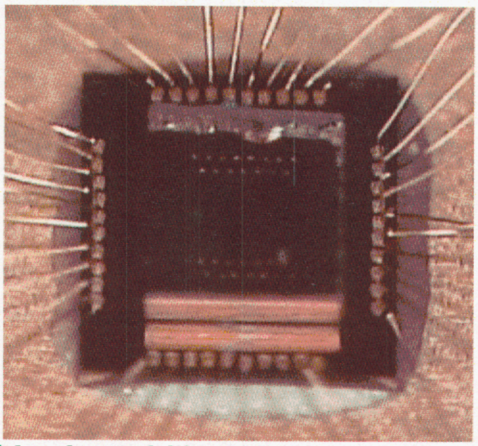

Figure 14: Side view of flip chip bonded programmable SAW

Note: View is at a 45 degree angle and reflections are present in the foreground.

To the radio frequency signal, the PSAW is a two port network. That is, the radio signal from the antenna enters the input port of the PSAW. The processed data exits from the output port of the PSAW after passing through the receiver section of the correlator and the silicon programmable switches. The silicon switches enable each chip of the correlator receiver to be programmed with a 0 or 180 degree phase shift from the input wave front. The PSAW has a center frequency of approximately 300 MHz and a full bandwidth of 150 MHz. A relatively low frequency was chosen to make flip chip assembly more reliable for this feasibility prototype. The center frequency and bandwidth are both a function of the number of wave phases per chip and are only coarsely programmable. The PSAW is shown in figure 15. This diagram can be compared to the fixed correlator diagram shown in figure 1.

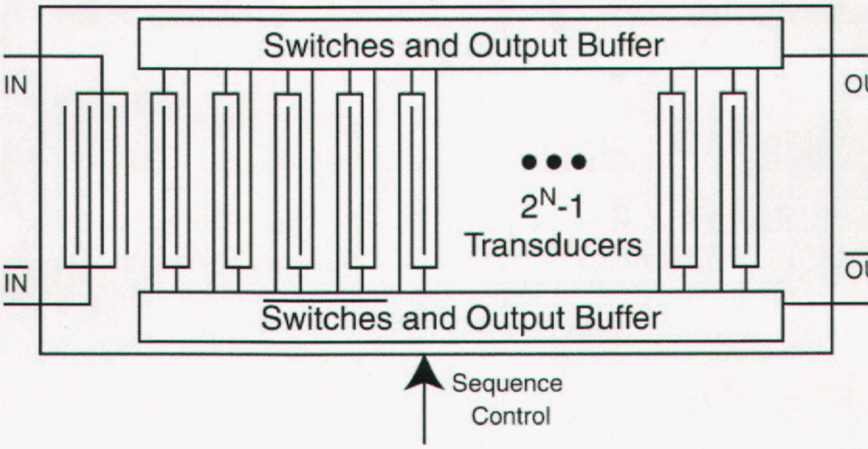

Figure 15: Programmable SAW electrical diagram.

A SAW correlator should give a significant correlation peak only when the RF input contains its matched signal. It should conversely give no significant response when the input signal contains a code other than its expected code. These two responses can be observed in the output waveforms shown in figures 16 and 17.

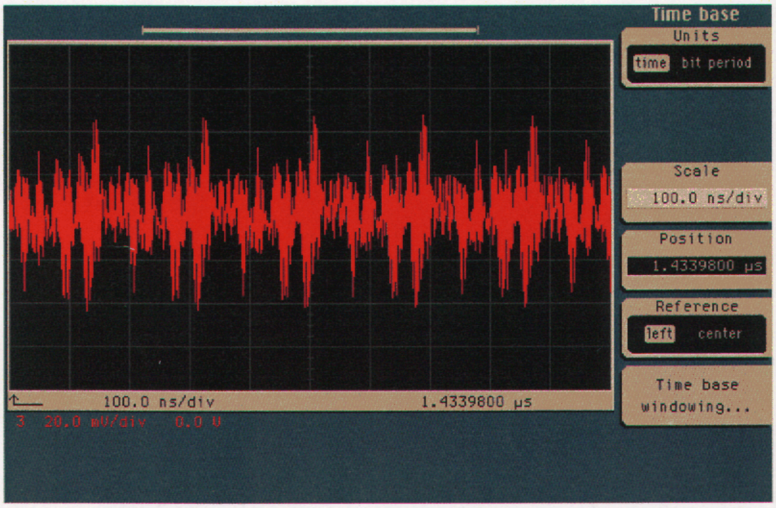

Figure 16: 15 chip M-sequence code into matched, programmed PSAW

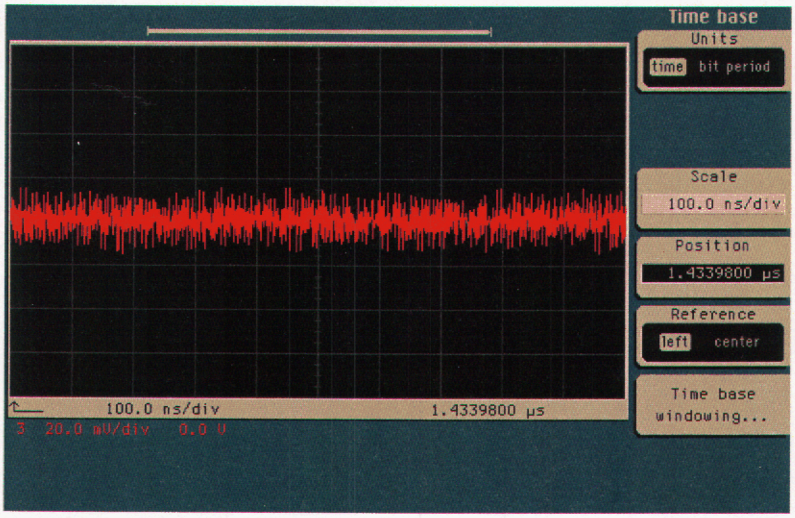

Figure 17: Code sequence into unmatched, programmed PSAW

10 Summary

This two year LDRD successfully demonstrated the fabrication of the key element needed for an ultra-low power spread spectrum receiver. As noted in the introduction, the use of a SAW correlator as a central component in such a system enables the elimination of many large, complicated, high power RF sub-systems. This work succeeded in refining the SAW correlator and overcoming previous limitations in seven key ways, as follow:

1) The use of electron beam lithography demonstrated the ability to fabricate SAW filters that operate directly in the desired microwave band centered at 2.45 GHz.
2) Multiple fabrication runs demonstrated the capability to reliably fabricate repeatable results with sufficient frequency stability.
3) Fabrication was demonstrated on temperature stable (ST-X cut quartz) and low loss (Y-Z lithium niobate) materials.
4) Adequate software modeling of SAW correlators was found to be unavailable commercially, and was developed in house.
5) Fabrication, testing, and packaging of fixed code SAW correlators were demonstrated.
6) Adequate impedance matching techniques were developed to enable SAW correlators to be used in a field-able system.
7) An electrically programmable SAW correlator was developed, tested, and demonstrated to overcome the manufacturing limitation of requiring a separate SAW correlator to be fabricated for each receiver.

This two year LDRD, originally advertised as a three year effort culminating in a complete microsystem, ran out of time before we could successfully build a field-able prototype microsystem. The necessary components to accomplish this are now in place but will have to be supported from other sources.

The success of the work done to date has been great enough to attract significant interest. As noted in various places throughout this report, there are refinements and improvements that should be made to the SAW correlators. At the conclusion of this effort, though, the future prospects for these devices appears to be promising.

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