

Enhancement of SAW Multi-Sensor Systems Using a Combination of Time and Frequency Diversity Techniques

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Abstract— Passive wireless sensors such as surface acoustic wave (SAW) devices are advantageous for applications such as heavy equipment monitoring and process control where harsh environments, moving parts, or limited battery lifetime preclude the use of wired or battery powered wireless sensors. In this work, Barker coded SAW delay lines with desirable autocorrelation properties were developed using time and frequency diversity to enhance the number of devices that may be accessed simultaneously. SAW device responses were modeled in MatLab and response correlations were simulated. Design parameters were selected to allow 100 sensors to be simultaneously operable in a single wireless system, and simulated and experimental results are presented. Results indicate that the combination of time diversity and frequency diversity techniques can significantly increase the number of individually identifiable passive sensors achievable over currently available systems.

I. INTRODUCTION

Passive, wireless sensors are beneficial when wired sensor installation is problematic or impossible or when battery lifetimes are inadequate for the desired application. Surface acoustic wave (SAW) devices are passive and can be used wirelessly, as has been widely recognized [1]. Individually coded SAW devices can be configured to sense measurand(s) of interest or to act as passive, wireless interfaces to external sensors known as “sensor-tags”, or to serve both of these functions simultaneously. These devices enable wireless multi-sensor systems, where each device (sensor or sensor-tag) responds to a wireless interrogation signal with the device ID and measured parameter(s).

Prior passive wireless SAW multi-sensor systems each utilized specific reader architectures and one of several types of sensor coding schemes, including code division multiple access (CDMA) [2,3], frequency division multiple access (FDMA) [4], time division multiple access (TDMA) [5], orthogonal frequency coding (OFC) [6], and discrete frequency coding (DFC) [7]. However, such systems suffer from code collision interference, and SAW wireless sensor systems capable of detecting more than 6 individual sensors

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had not been realized until recently [8]. In 2011, a combination of DFC and time diversity was utilized by the authors in a novel system architecture to produce a 16-sensor wireless SAW humidity measurement system. However, code cross-correlation between the DFC device codes and the interaction of autocorrelation sidelobes with the responses of other sensors at different delays produced interactions that resulted in calibration difficulties and sub-optimal sensor accuracy.

In this work, a set of SAW sensor tags was designed for simultaneous use in the field of view of a correlation-based reader system. The SAW delay line design incorporated a single 13-bit Barker code, which has desirable autocorrelation properties, with both time and frequency diversity techniques to create 100 uniquely identifiable responses. Based on SAW response simulations performed using MatLab software, design parameters were selected and 100 SAW sensor tags were fabricated. Individual device S_{21} transmission responses were measured in a wired configuration, and the correlation responses of all devices were calculated in MatLab. Results indicate that combining time and frequency diversity techniques allows the creation of larger sets of simultaneously operable sensors than previously achievable, and 100 uniquely identifiable devices are developed. In Section II, the SAW device structure is defined and the design parameters required to create 100 multiple access sensors are discussed. In Section III, the simulated and measured SAW responses are presented and compared. Section IV summarizes conclusions drawn.

II. SAW DESIGN CONSIDERATIONS

A. SAW Delay Line Structure

The passive, wireless sensor tags in this work were developed using SAW delay line devices. The delay lines comprise two interdigital transducers (IDTs) separated by a delay path on a piezoelectric substrate, as shown in Fig. 1. The input IDT (Fig. 1c) incorporates a 13-bit Barker code; negative bits are differentiated from positive bits by reversing the polarity of sections within the IDT. The 13-bit Barker code is listed in Table 1. The output IDT (Fig. 1a) is uncoded and apodized to define the device bandwidth.

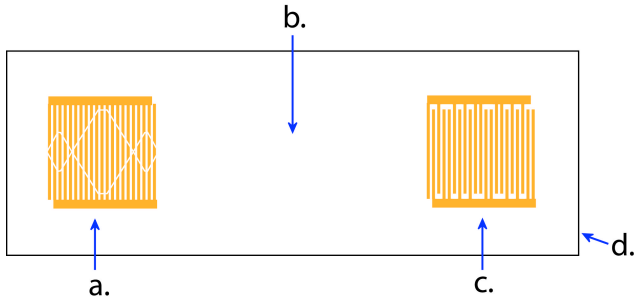


Figure 1. Coded SAW delay line device. a. Apodized IDT, b. SAW delay path, c. Barker coded IDT, d. Piezoelectric substrate.

TABLE 1: 13-BIT BARKER CODE SEQUENCE

Barker Code	1	1	1	1	1	-1	-1	1	1	-1	1	1
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Time diversity is built into the SAW delay lines using multiple defined delay lengths at which the Barker code can be reused with minimal interference with other devices. The time it takes a sensor to respond is dependent on the delay path length combined with the impulse response length of the two transducers. Frequency diversity is introduced using the apodized transducer, which defines a discrete frequency bandwidth for the SAW response. The center frequency of each Barker coded transducer is modified to match that of the apodized transducer for each sensor. For the frequency and bandwidth combinations selected, signals in different frequency bands do not interfere with one another.

B. Design Parameters and Correlation Functions

To identify a single wireless sensor response from a signal containing the responses of multiple sensors, the entire received signal is correlated with the known SAW response of the desired sensor. The 13-bit Barker code was chosen for its desirable autocorrelation properties. The linear, bit-wise autocorrelation of the Barker code has a peak to sidelobe ratio of 13:1, as can be seen in Fig. 2.

Creating the necessary number of simultaneously operable devices implementing only frequency or time diversity is difficult due to limitations in the available system bandwidth or device size, respectively. Conversely, by using both diversity techniques, a practical number of delay lengths and frequency bands can be combined to produce a larger set of devices. However, incorporating both frequency and time diversity into a single system results in conflicting objectives. Increasing the number of sensors using frequency diversity requires narrowing device bandwidths to fit more bands into the available system frequency range. Time diversity relies on narrow autocorrelation peaks and low sidelobe to peak ratios to limit interference from signals at adjacent time delays. However, limiting the sensor response bandwidth degrades the ideal autocorrelation response in time. The null-to-null bandwidth (BW) of the coded IDT response is defined by the number of wavelengths (λ) per bit used to create the code:

$$BW = \frac{2 \cdot v_p}{n \cdot \lambda} \quad (1)$$

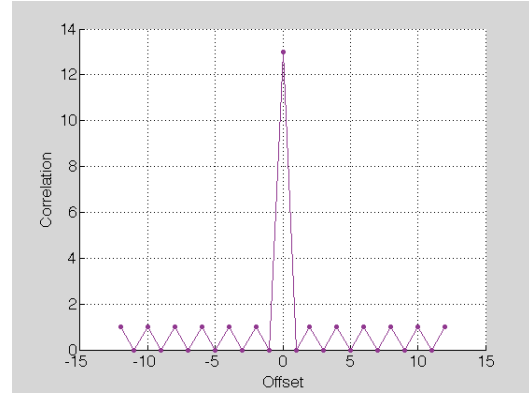


Figure 2. 13-bit Barker code linear, bit-wise autocorrelation.

where v_p is the SAW phase velocity and n is the number of acoustic wavelengths per bit. Larger n values produce narrower frequency bandwidths, but the choice of n is limited by the substrate. For LiNbO₃, used in this work, to avoid overcoupling an IDT can have a maximum length of about 150λ . The 13-bit Barker coded transducer can thus be created using up to $11 \lambda/\text{bit}$. Apodized IDT bandwidths designed to be smaller than the code BW bandlimit the code response and distort the coded SAW autocorrelation function in time.

For example, creating the 13-bit Barker code using $9 \lambda/\text{bit}$ on YZ-LiNbO₃ produces a coded IDT response with a null-to-null BW of 55.5MHz given a center frequency of 250MHz. The linear autocorrelations of the coded SAW responses with several bandwidths defined by the apodized transducer are shown in Fig. 3a, b, and c. As the device bandwidth is decreased below the bandwidth of the coded transducer, the autocorrelation response deviates from the bit-wise autocorrelation function. The sidelobe to peak amplitude ratio increases and the central peak widens.

The number and size of the frequency bands is limited by system requirements. For the reader considered here, the transmitted pulse used to excite the sensors has a useable bandwidth of approximately 150MHz, so all SAW frequency responses must also fit into that range. A 13-bit Barker coded IDT created with $11 \lambda/\text{bit}$ has a null-to-null bandwidth of 45MHz at a center frequency of 250MHz. If the apodized IDT were designed to match that BW, only two frequency-diverse bands could fit into the specified frequency range without overlapping. To increase the number of frequency diverse regions, the SAW response bandwidth must be chosen as a compromise between narrow frequency bands and preservation of the coded IDT response.

Device responses at different time delays are identified by their autocorrelation peak locations in the time domain. To implement time diversity, the autocorrelation peaks of signals with similar delays must not overlap. Delay steps in time must be at least $\frac{1}{2}$ the width of the autocorrelation peak to avoid the overlap of adjacent signal correlations. Additional spacing may be required to take variation in device performance over the desired environmental operating range into account. It has been shown that increasing the λ/bit used to create the coded SAW transducer decreases the code

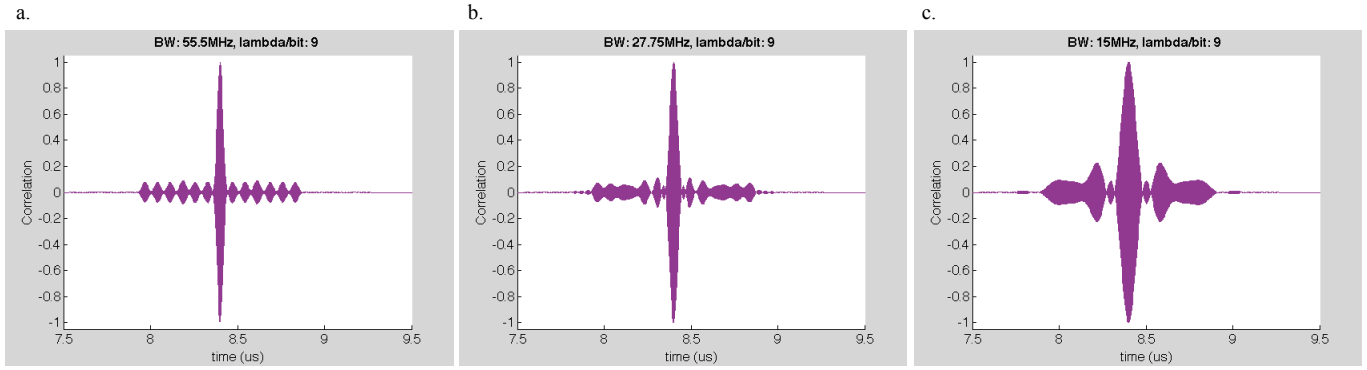


Figure 3. Simulated 13-bit Barker coded, 9 λ /bit SAW response autocorrelations. a. 55.5MHz device. b. 27.75MHz device. c. 15MHz device.

bandwidth and thus allows for the use of smaller frequency bands. Although this is a benefit for frequency diversity, increasing the code λ /bit also increases the width of the main autocorrelation peak in time. In Fig. 4, SAW response autocorrelations are plotted for coded transducers implementing the 13-bit Barker code with 5 λ /bit and 10 λ /bit given an apodized transducer bandwidth chosen to match the coded transducer null-to-null bandwidth. The autocorrelation response of the SAW device coded using 10 λ /bit has an autocorrelation peak twice as wide as the SAW device coded with 5 λ /bit.

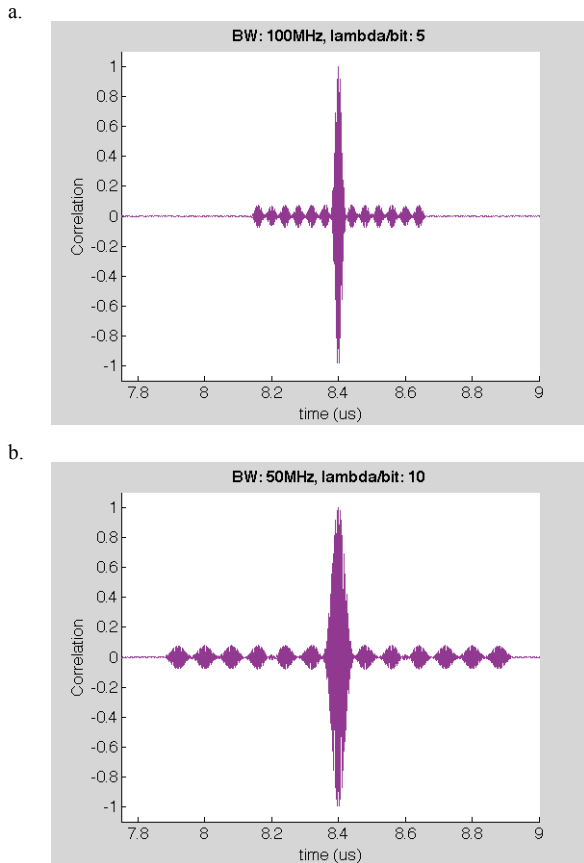


Figure 4. Simulated 13-bit Barker coded SAW response autocorrelations. a. 5 λ /bit code. b. 10 λ /bit code.

III. RESULTS

The SAW delay line bandwidths, code λ /bit, and time-diverse delay lengths implemented were selected based on the analysis presented in Section II. Ltoff patterning techniques were used to fabricate 100 time and frequency diverse Barker coded delay line devices on YZ LiNbO₃. Electrode metallization was e-beam deposited using a 50 Å titanium adhesion layer and 1800 Å of aluminum. The SAW propagation path was left bare. The sensor S₂₁ transmission responses were collected with an Agilent E5070B network analyzer in a wired configuration. Response correlations were calculated using MatLab software.

Ten frequency bands and 10 time delays were chosen to create 100 uniquely identifiable devices. The 13-bit Barker code was created in the IDTs using 9 λ /bit as a compromise between the bandwidth reduction achieved with large λ /bit, which enhanced frequency diversity but degraded the code correlation response, and the narrow autocorrelation peaks produced with small λ /bit. A fractional bandwidth of 6% was chosen to create discrete frequency bands, resulting in response bandwidths ranging from 11MHz to 19MHz for center frequencies ranging from 185 MHz to 322 MHz, respectively. SAW delay lengths used to create time diverse responses were chosen based on the width of the simulated SAW response autocorrelation peaks given the selected BW and λ /bit.

The frequency diversity achieved is illustrated in Fig. 5a, which shows the simulated autocorrelation response of a single sensor (frequency 5, delay 5) correlated with itself (yellow curve) as well as the 9 other sensor responses at delay 5 (frequencies 1-4, 6-10, black curve). Successful frequency diversity can be seen from the small total cross-correlation response. The cross-correlation maximum over the entire time span is only 3% of the autocorrelation maximum.

The simulated time diversity achieved using the chosen parameters is shown in Fig. 5b. The yellow curve represents the autocorrelation of a single sensor (frequency 5, delay 5) while the black curve indicates the correlation of that sensor with the 9 other sensors in frequency band 5 (delays 1-4, 6-10). Note that the cross-correlation indicated by the black curve is nearly zero at the time autocorrelation peak and very small throughout the response. Cross-correlation peaks of amplitude comparable to the autocorrelation peak can be

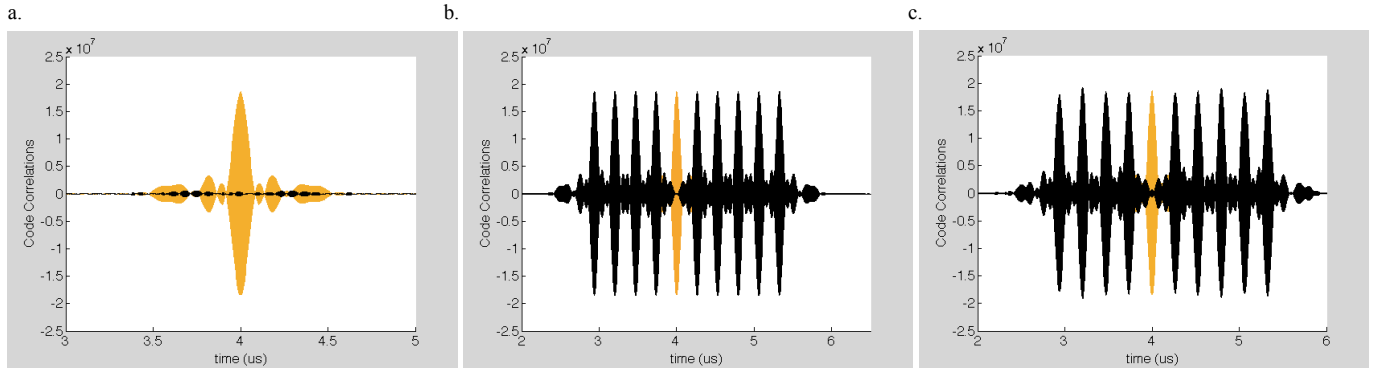


Figure 5. Simulated SAW responses. The yellow curves represents the autocorrelation of a single device (frequency 5, delay 5). The black curves represent the cross-correlation of that device with other devices in the field of view. a. Correlations of a single device with itself and with 9 other devices at different frequencies. b. Correlations of a single device with itself and with 9 other devices at the same frequency and different delays. c. Correlations of a single device with itself and with 99 other devices at different frequencies and/or different time delays.

found at other time locations, and these peaks indicate the presence of sensor responses at the 9 other time delays.

A simulation of the autocorrelation of a single device (frequency 5, delay 5) along with its cross-correlation with the 99 other devices is shown in Fig. 5c. The slight increase in cross-correlation within the autocorrelation peak, which is caused by the addition of the adjacent frequency bands, produces a cross-correlation amplitude of 4% of the autocorrelation amplitude at the time of the autocorrelation peak.

The S_{21} transmission responses for all 100 fabricated SAW delay line devices were collected, and a typical calculated correlation of the measured responses is shown in Fig. 6. The green curve indicates the autocorrelation of a single sensor with itself, and the black curve indicates its cross-correlation with the other 99 sensors. It can be seen in Fig. 6 that the autocorrelation peak is visible above the cross-correlation responses of the 99 other devices. A correlating reader system can thus identify the presence of any of the 100 devices by searching for an autocorrelation peak at the desired time.

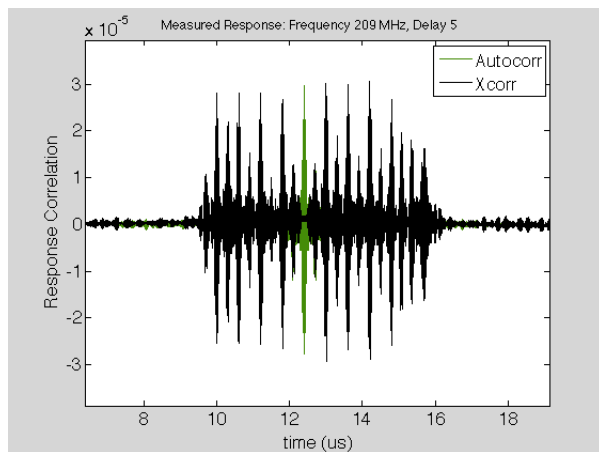


Figure 6. Typical correlation response of measured devices. The green curve indicates the autocorrelation of a single device (frequency 3, delay 5). Black curves indicate that device's correlation with the other 99 devices.

IV. CONCLUSIONS

Frequency and time diversity techniques were combined with Barker coding to create 100 uniquely identifiable SAW delay line sensor tags. SAW device simulations in MatLab were used to compare the drawbacks and advantages of SAW delay line design parameters including bandwidth, code λ/bit , and time-diverse delay lengths. Wired measurements of the fabricated sensors were performed and correlation responses were calculated using MatLab. Simulated and measured results indicate 100 identifiable correlation peaks. The authors believe this work represents the largest set of simultaneously operable sensor tags developed to date. Wireless testing, which was not done due to the many antennas required, will be conducted in the near future based on antenna availability.

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