

Orthogonal Frequency Coding for SAW Tagging and Sensors

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Abstract—Surface acoustic wave (SAW)-based sensors can offer wireless, passive operation in numerous environments, and various device embodiments are used for retrieval of the sensed data information. Single sensor systems typically can use a single carrier frequency and a simple device embodiment because tagging is not required. In a multisensor environment, it is necessary to both identify the sensor and retrieve the sensed information. This paper presents the concept of orthogonal frequency coding (OFC) for applications to SAW sensor technology. The OFC offers all advantages inherent to spread spectrum communications, including enhanced processing gain and lower interrogation power spectral density (PSD). It is shown that the time ambiguity in the OFC compressed pulse is significantly reduced as compared with a single frequency tag having the same code length, and additional coding can be added using a pseudo-noise (PN) sequence. The OFC approach is general and should be applicable to many differing SAW sensors for temperature, pressure, liquid, gases, etc. Device embodiments are shown, and a potential transceiver is described. Measured device results are presented and compared with coupling of modes (COM) model predictions to demonstrate performance. Devices then are used in computer simulations of the proposed transceiver design, and the results of an OFC sensor system are discussed.

I. INTRODUCTION

SURFACE acoustic wave (SAW) sensors have been widely studied and offer many advantages, including wireless, passive operation, and the ability to operate in harsh environments, and they are capable of measuring physical, chemical, and biological variables [1]–[3]. Current SAW sensor embodiments include delay line and resonator-based oscillators, differential delay lines, and devices using multiple reflective structures. However, few SAW sensor embodiments are capable of operation in multisensor environments because the sensor must transmit identification and sensor information simultaneously [4], [5]. This paper demonstrates a spread spectrum approach using orthogonal frequency coding (OFC) for SAW sensor applica-

tions [6], [7]. The use of orthogonal frequency concepts are well documented for a wealth of communication and signal processing applications; a good example being M-ary frequency shift keying (FSK) systems [8]–[11]. Generally, there is a required relationship between the local, or basis set, frequencies and their bandwidths that meets the orthogonality condition. As an example, if a time signal is broken into a number of finite length serial chips, and the local adjacent chip frequencies are contiguous, orthogonal and the signal has a linear group delay, then a stepped chirp response is obtained [12]. The OFC technique to be presented allows both frequency and PN coding, and use of a chirp interrogation signal for increased power. Some of the advantages of SAW sensors using chirp interrogation signals and the use of spread spectrum techniques were presented previously [13], [14]. This paper presents the basic theory and OFC coding technique that will be applied to a SAW sensor embodiment for temperature sensing. The approach provides a novel coding technique, advantages associated with spread spectrum, and the ability to simultaneously tag and sense temperature in a multisensor environment. The basic approach to OFC is presented and compared to simple pseudo noise (PN) coding, and the signal identification parameters are discussed. The approach to tagging of a sensor is presented, and a simple embodiment is shown. A SAW sensor device design on YZ lithium niobate (LiNbO_3) is presented, and experimental measurements are provided. Experimental device results are used in a simulated receiver system and compared with predicted results.

II. ORTHOGONAL FREQUENCY DEFINITIONS AND REVIEW

Consider a time-limited, nonzero time function defined as:

$$h(t) = \sum_{n=0}^N a_n \cdot \varphi_n(t) \cdot \text{rect}\left(\frac{t}{\tau}\right),$$

where:

$$\varphi_n(t) = \cos\left(\frac{n\pi t}{\tau}\right) \quad (1)$$

$$\text{rect}(x) = \begin{cases} 1 & |x| \leq \frac{1}{2} \\ 0, & \text{otherwise} \end{cases}.$$

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The function $\varphi_n(t)$, represents a complete orthogonal basis set with real coefficients a_n . The members of the basis set are orthogonal over the given time interval if:

$$\int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} \varphi_n(t) \cdot \varphi_m(t) dt = \begin{cases} K_n, & n = m \\ 0, & n \neq m \end{cases} \quad (2)$$

Given the basis set and constraints, two functional descriptions are obtained that have the forms:

$$h_1(t) = \sum_{n=0}^N a_n \cdot \cos\left(\frac{2n \cdot \pi t}{\tau}\right) \cdot \text{rect}\left(\frac{t}{\tau}\right), \quad (3a)$$

$$h_2(t) = \sum_{m=0}^M b_m \cdot \cos\left(\frac{(2m+1) \cdot \pi t}{\tau}\right) \cdot \text{rect}\left(\frac{t}{\tau}\right). \quad (3b)$$

Each cosine term in the summations in (3) represents a time-gated sinusoid whose local center frequencies are given by:

$$f_n = \frac{n}{\tau} \text{ and } f_m = \frac{(2m+1)}{2\tau}. \quad (4)$$

In the frequency domain, the basis terms are the well-known sampling functions with center frequencies given in (4). From (4), $f_n \cdot \tau$ must be an integer, which requires an integer number of wavelengths at frequency f_n , and similarly there must be an integer number of half wavelengths at f_m . These are required conditions for the orthogonality of the basis functions. Given that each basis term is a frequency domain sampling function, then the null bandwidth is known to be $2 \cdot \tau^{-1}$. The overall frequency function is defined given the choice of the even or odd time function in (3a) or (3b), respectively, the basis frequencies of interest, the weight of the basis function, and either the bandwidth or the time length.

Fig. 1 shows an example of the sampling function basis frequency response terms described in time in (3a) given three terms and (3b) given four terms, normalized to center frequency and having all weights unity. Notice that the center frequency spacing is half the null bandwidth and that the center frequencies between the two plots are offset by $1/4$ the null bandwidth. The time definitions in (3) yield a superposition of the defined functions over the time interval and sets the group delay of each individual function to the same value.

III. ORTHOGONAL FREQUENCY CODING CONCEPT

Section II defined the functional descriptions that will be used to define the desired time function. The desired signal will have both frequency and time diversity that will provide a systematic way of implementing a code in a SAW device embodiment. Given a time function $g_{bit}(t)$, having a time length, τ_B , that is defined as the bit length. The bit will be divided into an integer number of chips such that:

$$\tau_B = J \cdot \tau_c \text{ where } J = \# \text{ of chips.} \quad (5)$$

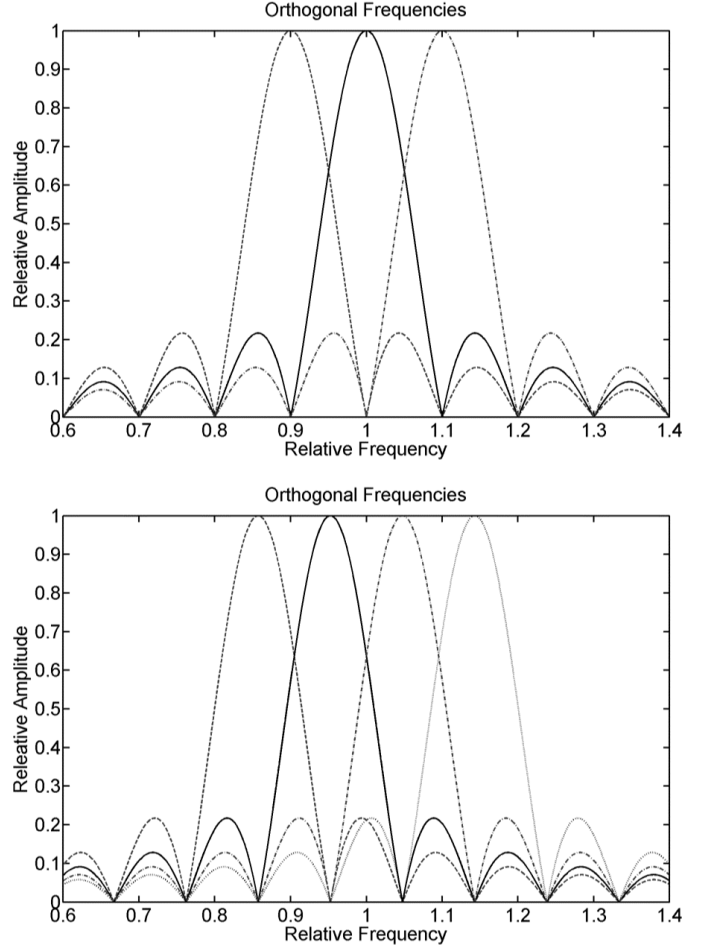


Fig. 1. Example of three and four sampling function frequency response terms, described in time, from (3a) and (3b), respectively, normalized to center frequency and all having weights equal to 1.

The chip interval, τ_c , is set as the time interval in (2) for the basis set. Allowing a time delay, τ_D , such that $t = (t - \tau_D)$ in (1)–(4), and given a definition of each chip as $h_{cj}(t)$, then a bit is defined as the sum of J chips as:

$$g_{bit}(t) = \sum_{j=1}^J w_j \cdot h_{cj}(t - j \cdot \tau_c). \quad (6)$$

Each chip is contiguous without time overlap, and w_j is the bit weight and the functional form for the chip definition, $h_{cj}(t - j \cdot \tau_c)$, is given in (3a) or (3b). In general, multiple local carrier frequencies are possible in each chip, depending on their weighting coefficient. Assuming a chip uses the basis set in (3b), similar results are obtained using (3a). Then, in general:

$$h_{cj}(t - j \cdot \tau_c) = \sum_{m=1}^M b_{jm} \cdot \cos\left(\frac{(2m+1) \cdot \pi \cdot (t - j \cdot \tau_c)}{\tau_c}\right) \cdot \text{rect}\left(\frac{t - j \cdot \tau_c}{\tau_c}\right).$$

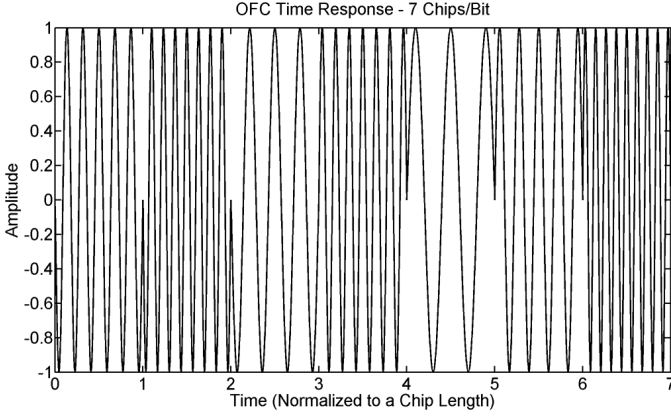


Fig. 2. Example of seven chip time function using the basis set defined in (3a). Time is normalized to a chip length. The lowest and highest chip frequencies have 2.5 and 9.5 cycles, respectively.

To generate the required signal, let $b_{jm} = 0$ for all m , except $m = MM_j$ where $1 \leq MM_j \leq M$. Then:

$$h_{cj}(t - j \cdot \tau_c) = b_j \cdot \cos\left(\frac{(2 \cdot MM_j + 1) \cdot \pi \cdot (t - j \cdot \tau_c)}{\tau_c}\right) \cdot \text{rect}\left(\frac{t - j \cdot \tau_c}{\tau_c}\right). \quad (7)$$

The form in (7) shows that each chip has a single local carrier frequency, $f_{cj} = (2MM_j + 1)/(2 \cdot \tau_c)$, and b_j is the chip weight. In order to build the desired time function, the following design rules are used: $b_j = \pm 1$ for all j and the bit null bandwidth is $BW_{bit} = J \cdot 2 \cdot \tau_c^{-1}$, which means that f_{cj} form a contiguous set similar to Fig. 1. The rules, however, do not require that the local frequency of adjacent chips that are contiguous in frequency must be contiguous in time. In fact, the time function of a bit provides a level of frequency coding by allowing a shuffling of the chip frequencies in time.

Fig. 2 shows an example seven chip sequence where $f_{cm} \neq f_{cn}$ for all $m \neq n$, and there are an integer number of half wavelengths in each chip. The seven local chip frequencies are contiguous in frequency but are not ordered sequentially in time, and the chip weights are all unity. If the local chip frequencies were ordered high to low or low to high, the time sequence would be a stepped down-chirp and up-chirp, respectively.

The given chip sequence represents the orthogonal frequency code for the bit. If there are J chips with J different frequencies in a bit, then there are $J!$ possible permutations of the frequencies within the bit. A signal can be composed of multiple bits, with each bit having the same OFC or differing OFC. For the case of a signal, J chips long and having a single carrier frequency, the signal is a simple gated radio frequency (RF) burst τ_B long.

In addition to the OFC coding, each chip can be weighted as ± 1 , giving a PN code in addition to the OFC, namely PN-OFC. This does not provide any additional processing gain because there is no increase in the time bandwidth product, but it does provide additional code diversity for tagging.

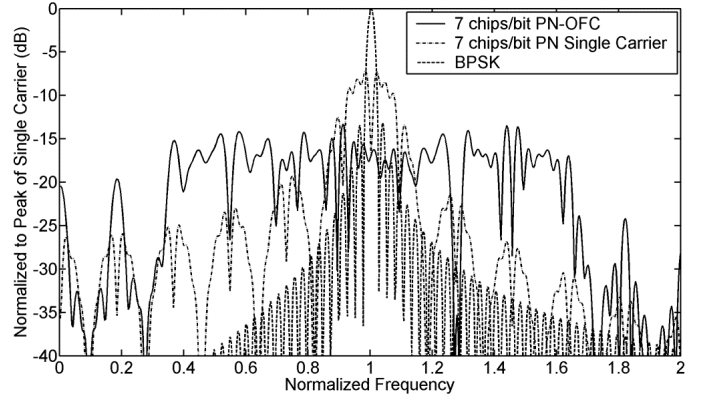


Fig. 3. Frequency of seven chip OFC, seven chip PN, and single frequency carrier. Each has identical time lengths. Magnitude is 10 dB/div and frequency is normalized to 0.

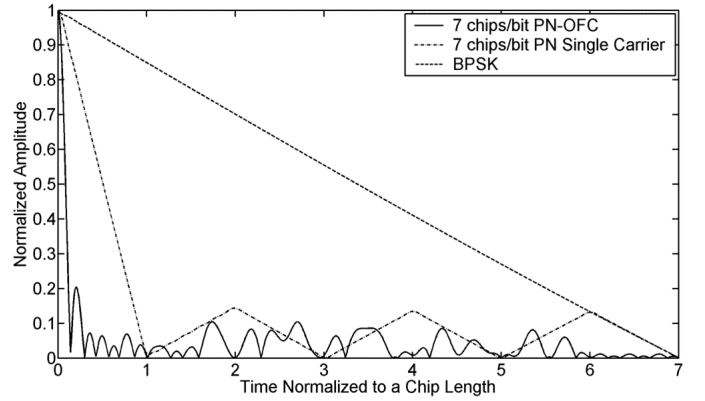


Fig. 4. Time autocorrelation of seven chip PN-OFC, seven chip PN, and single frequency signals having identical time lengths. The PN is a Barker code sequence. Amplitudes of signals are normalized to the same value. Time is normalized to a chip length. Peak compressed pulse amplitudes are identical.

Fig. 3 shows the bit frequency responses of a seven chip OFC, seven chip PN, and single carrier signal with time functions normalized to unity and having identical impulse response lengths. The single carrier is narrowband and has greater amplitude at center frequency than the PN (−9 dB) and OFC (−17 dB) signals. The bandwidths of the PN and OFC signals are 7 and 49 times greater than the single frequency carrier bandwidth, respectively, as expected due to the spread spectrum nature of the signals. The power spectral density is lowest for the OFC signal.

Fig. 4 shows the autocorrelation functions of the signals used in Fig. 3. The peak autocorrelation is exactly the same given the identical time amplitude and signal lengths, but the compressed pulse widths for the coded signals are narrower than that of the single carrier, as expected. This provides the measure of processing gain (PG), which is the ratio of compressed pulse width to bit length. The PG for the PN and OFC signals are 7 and 49, respectively, and PN-OFC provides a lower PSD than single carrier PN and uncoded single carrier signals of equal amplitude. As a result, PN-OFC yields the greatest correlated output in relation to peak spectral power.

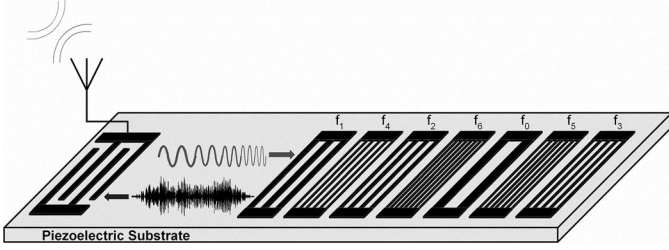


Fig. 5. Schematic of SAW OFC identification tag. Each reflector is a chip long and has a reflector period corresponding to the desired chip frequency.

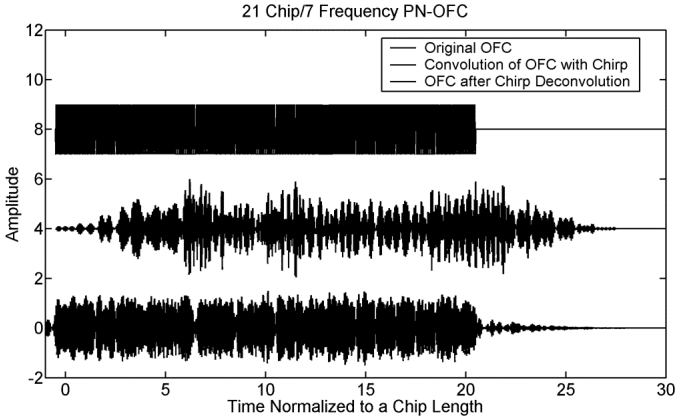


Fig. 6. Top trace is PN-OFC signal; middle trace is the convolution of PN-OFC; lower trace is the OFC after the chirp-matched filter process. Scale is relative amplitude versus time normalized to a chip length.

IV. OFC SAW DEVICE APPLICATIONS

The PN-OFC can be implemented in SAW devices for communication, tagging, and sensors. The following discussion will demonstrate the OFC application to a SAW tag system. An example tag is designed having a center frequency of 250 MHz composed of a PN coded 21 chip, 7 frequency OFC signal with $\tau_c = 0.1 \mu\text{s}$, using 21 reflectors each having a center frequency dependent on the electrode period. For this example, the reflectors are assumed to have equal reflectivity and have a rectangular time function response; a device schematic is shown in Fig. 5.

The input transducer is assumed wideband, and its effect is assumed negligible for the example. The OFC tag impulse response has uniform amplitude versus time and is 21 chips long as shown in Fig. 6 (top trace). The OFC SAW transceiver schematic diagram is shown in Fig. 7, in which the SAW tag is interrogated with a linear stepped up-chirp possessing the same time length and bandwidth of one bit. For a given PSD, (W/Hz), the chirp provides increased interrogation power as compared to a simple RF tone burst. The retransmitted signal from the tag is 28 chips long due to the convolution of the interrogation chirp and tag impulse response; producing a noise-like signal, as seen in Fig. 6 (middle trace). The tag response is a spread spectrum signal that is wideband and has inherent

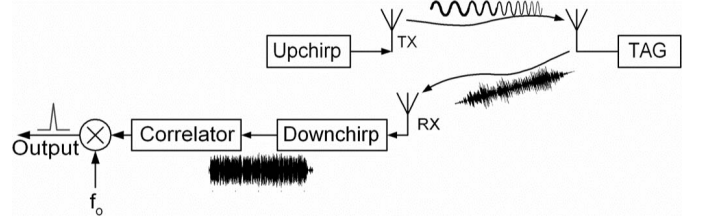


Fig. 7. The OFC SAW system block diagram showing stepped linear upchirp interrogation and returned noise-like signal. Compressed pulse results after application of downchirp and matched filtering.

security. Because the chips have orthogonal frequencies, there is no intersymbol interference, even with overlapping chips, unlike a conventional single frequency carrier PN sequence. At the receiver, the tag signal is filtered through the matched filter, a linear stepped down-chirp, which unscrambles the code sequence, as seen in Fig. 6 (lower trace), where the signal is again approximately 21 chips long but having some amplitude modulation due to the matched filter process.

The signal is then match filtered with the coded PN-OFC producing the correlated compressed pulse, as shown in Fig. 8 (lower trace), which is $0.14 \tau_c$ long, yielding the processing gain of 49. Fig. 8 (upper trace) shows the ideal convolution of the OFC signal and the system simulation. The compressed pulses are nearly identical, demonstrating that the chirp interrogation signal and matched filter process accurately reconstructs the desired tag signal and that the processing gain is achieved.

Fig. 9 shows a typical autocorrelation and cross correlation of two differing 21 chip, 7 frequency PN-OFC codes. The cross correlation sidelobes are comparable to the sidelobes of the autocorrelation signal, demonstrating good discrimination between codes.

V. OFC SAW ID TAG IMPLEMENTATION

The OFC waveforms can be used in SAW devices using transducers and/or periodic reflector gratings as discussed in the previous example. For this discussion, each chip of the OFC waveform is implemented using a shorted periodic reflector grating. The grating periodicities are chosen so that the grating center frequencies correspond to the chip carrier frequencies. In order to keep the chip length constant, each grating must contain different numbers of electrodes as the periodicity changes. This is a direct result of the orthogonality condition. The equation used to find the grating electrode counts is given by:

$$N_j = \tau_c \cdot f_j, \quad (8)$$

which shows that the grating electrode count is directly proportional to the local chip frequency. Also to be considered, the normalized metal thickness increases with frequency. Therefore, in a device fabricated with a single metal thickness for all reflectors, the magnitude of SAW reflection for each chip will not be equal. As an example, typical COM predicted grating responses are shown

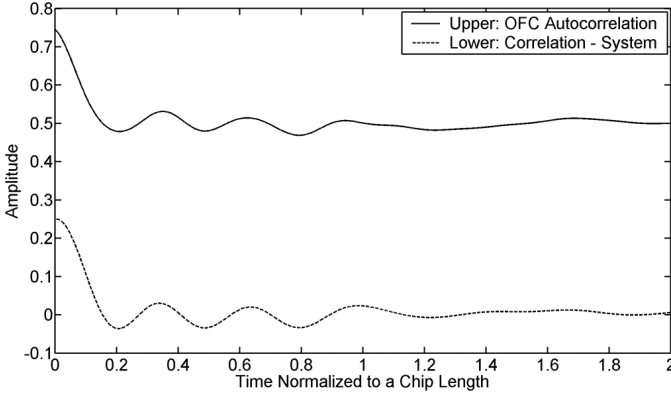


Fig. 8. The SAW system simulation autocorrelation of PN-OFC (lower trace) and the autocorrelation of the ideal PN-OFC (upper trace). Compressed pulse width and sidelobes are nearly identical. Plot is linear amplitude, and time is normalized to a chip length.

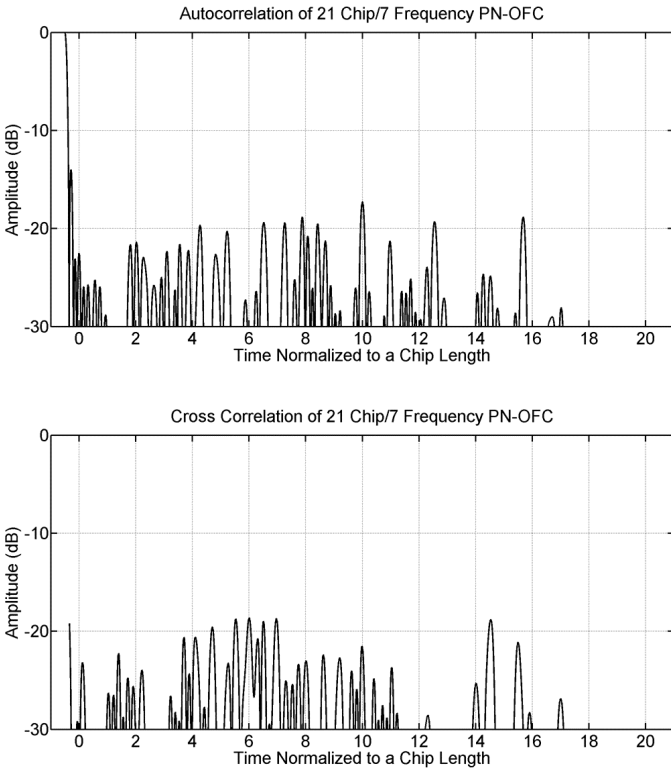


Fig. 9. The normalized auto correlation (upper trace) and cross correlation (lower trace) of two differing 21 chip, 7 frequency PN-OFC codes. The cross and auto correlation sidelobes are comparable. Magnitude is decibels (10 dB/div) and time is normalized to a chip length.

in Fig. 10. This chip amplitude modulation effect produces varying chip weights, but it has little effect on the correlation response.

VI. OFC SAW SENSOR IMPLEMENTATION

The OFC concept is readily applied to SAW-sensing applications, and the resulting system offers the advantage of simultaneous sensing and tagging.

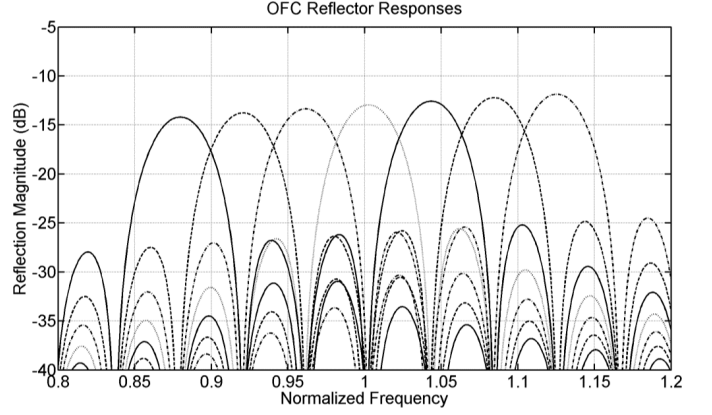


Fig. 10. Shorted reflector grating responses for a seven chip OFC SAW tag predicted from COM modeling; reflection magnitudes increase with frequency. Magnitude is decibels (5 dB/div), and frequency is normalized to f_0 .

For this work, the sensor embodiment uses identical reflector banks on either side of a wideband transducer, as shown in Fig. 11; however, a different free-space delay is used on either side of the device designated by τ_1 and τ_2 . When this device is used with the transceiver described, two compressed pulses will result. The differential time delay between pulses gives the sensed information, in this case temperature.

The device was simulated using a COM model and verified by experiment using devices fabricated on YZ LiNbO₃. The designed center frequency was 250 MHz, and seven chips were implemented using seven frequencies that occupied a 25% fractional bandwidth. Each chip was approximately 100 ns long, resulting in a bit length of roughly 700 ns. The free-space delays τ_1 and τ_2 , were approximately 0.7 μ s and 1.5 μ s. The resulting device's length was approximately 1 cm. The transceiver then was simulated using the predicted and experimental responses of the sensor.

Fig. 11 shows the predicted (upper trace) and measured (lower trace) time domain responses of an OFC SAW temperature sensor embodiment. The experimental response is obtained by measuring S_{11} of the transducer using an Agilent 8753ES and RF probe station. A fast Fourier transform is applied to the measured swept frequency response to obtain the time domain response of Fig. 11. As seen, the COM prediction compares extremely well with the measured response. The predicted reflectivity variation versus local carrier frequency is observed and confirmed from the time-domain measurements.

Fig. 12 shows the correlated compressed pulses from the transceiver simulation using an ideal OFC signal (upper trace) and the predicted (middle trace) and experimental (lower trace) SAW responses, respectively. The differential delay between compressed pulses varies with temperature and is extracted at the receiver. There is excellent agreement between prediction and experiment. Also note the time ambiguity of the compressed pulses compares well between theory and experiment. Each pulse is approximately

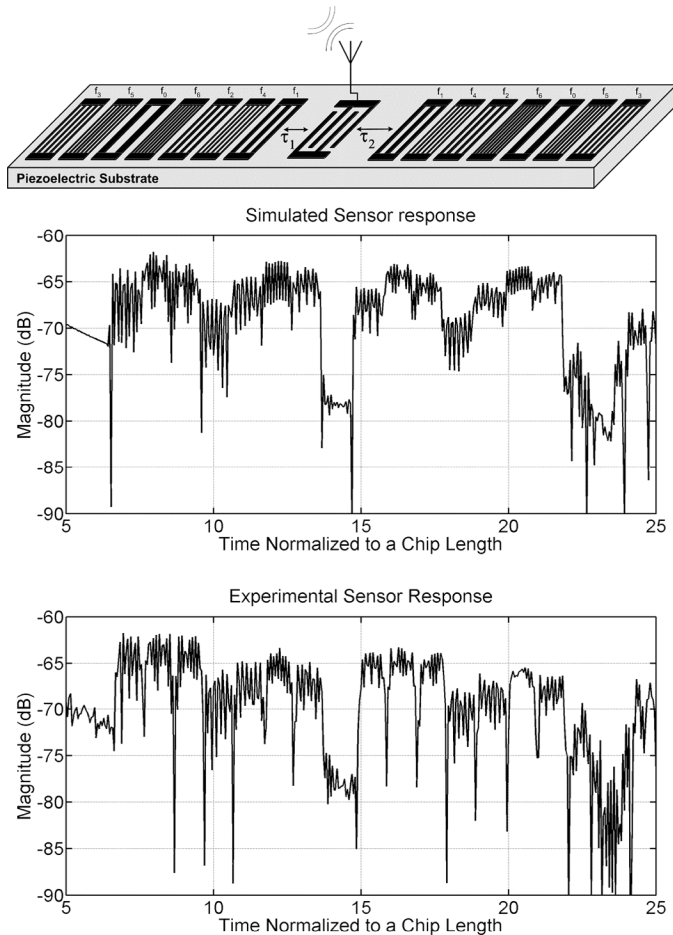


Fig. 11. The OFC SAW sensor schematic drawing and corresponding impulse response from reflector gratings. COM model (upper trace). Experimental data (lower trace). Magnitude is decibels (5 dB/div), and time is normalized to a chip length.

$0.28 \cdot \tau_c$ long, which corresponds to a processing gain of 49, seven times greater than that of a seven chip PN sequence using a single frequency carrier. As a result, the OFC system has increased range and sensitivity when compared to conventional single frequency pulse implementations.

The device described was tested over temperature using a temperature controlled RF probe station to verify temperature-sensing capability. It was observed that the correlated compressed pulse responses degraded as temperature was increased as shown in Fig. 13 (upper trace). As the temperature was increased from 13.8°C to 53.8°C the correlated compressed pulse peak power was decreased by 5 dB, and the sidelobe level was increased by 7 dB. This is a direct result of changes in SAW velocity causing errors in the matched filter frequencies, chip lengths, and chip locations. In order to compensate for these errors, both compressed pulses were produced using a matched filter that was generated using previous adjacent temperature measurements similar to the wavelet transform technique described in [15]. The pulse power remains high and the sidelobe level is maintained at -15 dB as shown in Fig. 13 (lower trace). This would be an advantageous option in a hardware-implemented system.

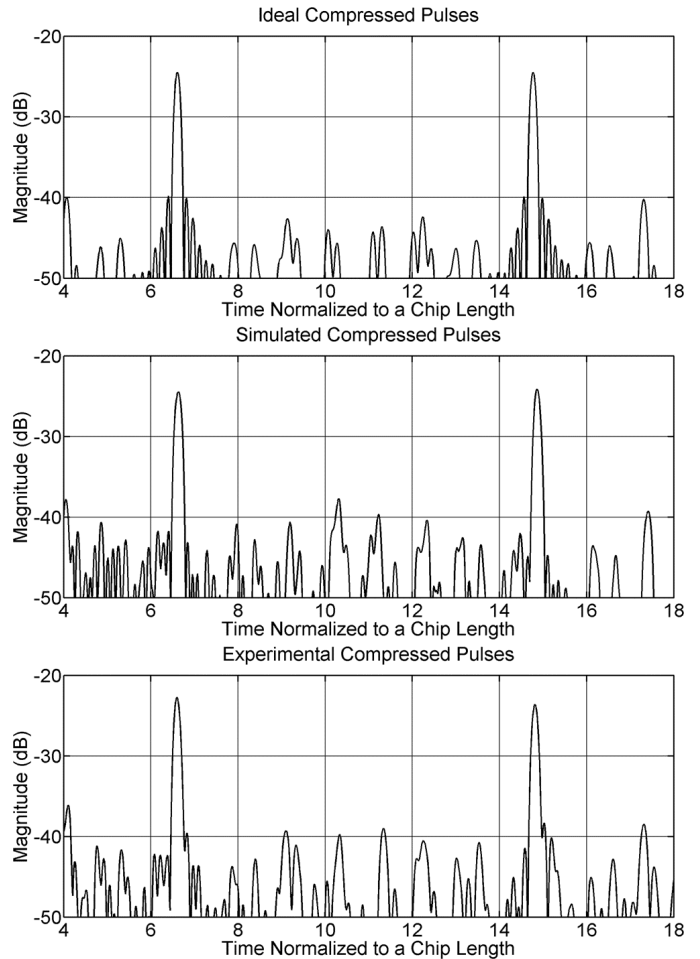


Fig. 12. The OFC SAW sensor compressed pulses. Upper trace is the ideal OFC auto correlation; middle trace is autocorrelation produced using the COM model; lower trace is autocorrelation using experimental data on a YZ LiNbO₃ device.

Using the adaptive matched filter, the SAW temperature sensor results are shown in Fig. 14. This plot compares the YZ LiNbO₃ sensor with thermocouple measurements. The measurements were conducted using an RF probe station and a temperature-controlled chuck. The device was tested between 10°C and 190°C in 5°C increments. Overall, there is good agreement between the sensor and the thermocouple. The device measurements were made with a thermocouple that was placed on the surface of the wafer. The greatest error is probably in the thermocouple temperature versus the actual device temperature due to temperature lag and differing thermal paths. The temperature was extracted using peak detection of the processed time domain signal. The accuracy is determined by the sampling rate, which is a variable in the simulation program. The device sensitivity is a function of the substrate choice, which is approximately $92 \text{ ppm}/^\circ\text{C}$ for YZ-LiNbO₃. A real system would optimize device parameters and signal processing to obtain the desired temperature accuracy. Research on system designs and implementations is currently under investigation.

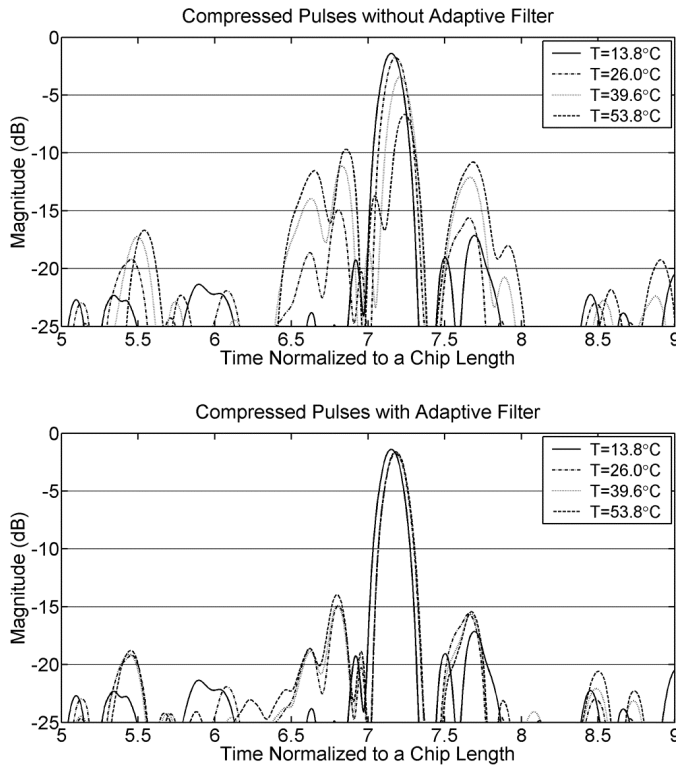


Fig. 13. Degradation of compressed pulse response over temperature using static matched filter (upper tracing), and improved compressed pulse response using adaptive matched filter (lower tracing).

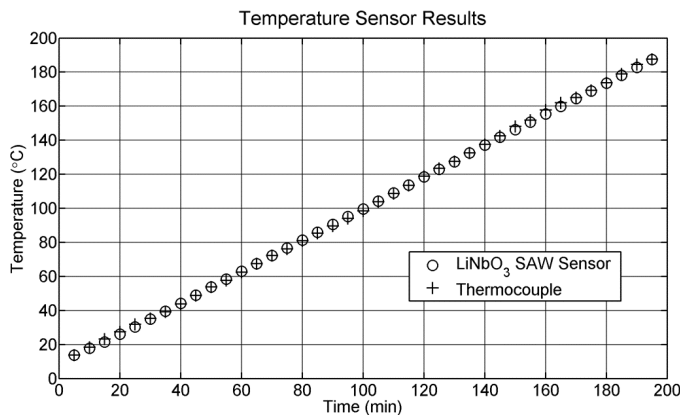


Fig. 14. Seven chip OFC SAW temperature sensor tested between 10°C and 190°C in 5°C increments and compared to thermocouple measurements.

VII. CONCLUSIONS

This paper has presented the concept of OFC and its application to SAW sensors. This OFC SAW approach allows for simultaneous identification and sensing in multisensor environments. The theory of OFC was presented and discussed, defining the fundamental equations and showing the time and frequency relationships. The technique provides a wide bandwidth spread spectrum signal that provides a reduction in compressed pulse time ambiguity when compared with conventional single carrier PN coding. Interrogation using a linear stepped chirp provides in-

creased power and range. Code diversity is increased by the addition of pseudo-noise coding (PN-OFC). Implementation of OFC has been demonstrated using shorted reflector gratings on YZ LiNbO₃, and experimental measurements were compared with COM model predictions showing good agreement between results. An example transceiver was simulated using software, and the resulting compressed pulses were shown. The SAW temperature sensors on YZ LiNbO₃ were tested over temperature and applied to the simulated transceiver. The results compared very well with thermocouple measurements, and a discussion of the results was provided. The current device demonstrated a fractional bandwidth of approximately 25%; such fractional bandwidths would allow these devices to be classified ultrawide bandwidth (UWB), which could be useful for specific system implementations. Work on integration of the OFC devices into a wireless system is currently being pursued.

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REFERENCES

- [1] A. Pohl, G. Ostermayer, L. Reindl, and F. Seifert, "Monitoring the tire pressure at cars using passive SAW sensors," in *Proc. IEEE Ultrason. Symp.*, 1997, pp. 471–474.
- [2] E. Benes, M. Gröschl, F. Seifert, and A. Pohl, "Comparison between BAW and SAW sensor principles," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 45, pp. 1314–1330, Sep. 1998.
- [3] F. Seifert, W. E. Bulst, and C. Ruppel, "Mechanical sensors based on surface acoustic waves," *Sens. Actuators*, vol. A44, pp. 231–239, 1994.
- [4] C. S. Hartmann, "A global SAW ID tag with large data capacity," in *Proc. IEEE Ultrason. Symp.*, 2002, pp. 65–69.
- [5] G. Ostermayer, A. Pohl, C. Hausleitner, F. Seifert, and L. Reindl, "CMDA for wireless SAW sensor applications," in *Proc. IEEE Int. Spread Spectrum Techniques Appl.*, 1996, pp. 795–799.
- [6] D. C. Malocha, D. Puccio, and D. Gallagher, "Orthogonal frequency coding for SAW device applications," in *Proc. IEEE Ultrason. Symp.*, 2004, pp. 1082–1085.
- [7] D. Puccio, D. C. Malocha, D. Gallagher, and J. Hines, "SAW sensors using orthogonal frequency coding," in *Proc. IEEE Int. Freq. Contr. Symp.*, 2004, pp. 307–310.
- [8] R. B. Blackmann and J. W. Tukey, "The measurement of power spectra from the point of view of communication engineering—Part II," *Bell System Technical J.*, pp. 485–569, Mar. 1958.
- [9] D. C. Malocha and C. D. Bishop, "The classical truncated cosine series functions with applications to SAW filters," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 34, pp. 75–85, Jan. 1987.
- [10] R. W. Chang, "Synthesis of band limited orthogonal signals for multi-channel data transmission," *Bell System Technical J.*, pp. 1775–1796, Dec. 1966.
- [11] L. L. Yang and L. Hanzo, "Overlapping M-ary frequency shift keying spread spectrum multiple access systems using random

signature sequences," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1984–1995, Nov. 1999.

- [12] S. E. Carter and D. C. Malocha, "SAW device implementation of a weighted stepped chirp code signal for direct sequence spread spectrum communication systems," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 47, no. 4, pp. 967–973, July 2000.
- [13] F. Schmidt, O. Sczesny, C. Ruppel, and V. Mágóri, "Wireless interrogator system for SAW-identification-marks and SAW-sensor components," in *Proc. IEEE Int. Freq. Contr. Symp.*, 1996, pp. 208–215.
- [14] A. Pohl, G. Ostermayer, L. Reindl, and F. Seifert, "Spread spectrum techniques for wirelessly interrogable passive SAW sensors," in *Proc. IEEE Int. Symp. Spread Spectrum Techniques Appl.*, 1996, pp. 730–734.
- [15] A. Pohl, G. Ostermayer, C. Hausleitner, F. Seifert, and L. Reindl, "Wavelet transform with a SAW convolver for sensor application," in *Proc. IEEE Ultrason. Symp.*, 1995, pp. 143–146.



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As an undergraduate and master's student his research focused on the characterization of new SAW materials. Specifically, he studied langasite-structure compounds such as langatate and CTGS. He is currently pursuing a Ph.D. degree at UCF where he is researching coded SAW sensors and systems.

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Dr. Malocha was an elected member of the IEEE UFFC AdCom and served for over 10 years in several chairs, including president. He received the Electronic Industries Association's 1998 David P. Larsen Award, the 2000 IEEE Third Millennium Medal, and the 2004 UCF Distinguished Researcher of the Year.

Currently, he is an Associate Editor for IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control and serves on the IEEE symposium technical program committees for ultrasonics and frequency control. He is the Technical Program Chair for the upcoming 2006 and 2007 International Frequency Control Symposium. His

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He is an IEEE Fellow, a member of Tau Beta Pi, Eta Kappa Nu, and a member emeritus of the Electronic Industries Association.



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Jacqueline H. Hines (S'88–M'88) was born in 1962 in Alamogordo, NM. She received a B.S. degree in applied and engineering physics from Cornell University College of Engineering, Ithaca, NY, in 1984, a M.S. degree in electrical engineering in 1988, and a Ph.D. degree in electrical engineering in 1996, both from the University of Central Florida, Orlando, FL. She served on active duty in the U.S. Navy from 1984 through 1988 as an instructor at the U.S. Naval Nuclear Power School in Orlando, FL. She remained on drilling status in the Naval Reserves until 1996, completing Engineering Duty Officer qualifications and leaving the service as a Lieutenant Commander.

In 1988 Dr. Hines joined Sawtek Inc., Apopka, FL, a company specializing in surface acoustic wave device technology, as a research scientist. While at Sawtek, she was responsible for establishing and managing a SAW-based chemical sensor product development program, including all aspects of program coordination, planning, and contracting with the Advanced Research Projects Agency (ARPA) and the Department of Energy (DOE), staffing, program management, and reporting. The sensor system developed was successfully demonstrated at DOE's Savannah River Site in June 1998, and is capable of detecting, identifying, and quantifying volatile organic chemical vapors alone and in mixtures of up to two vapors plus water.

Dr. Hines served as Manager of Research and Development for a number of years, and left Sawtek to found her own consulting company in 2000. She currently consults on chemical sensor technologies. She has been active in a wide range of professional activities, and currently serves as the Secretary/Treasurer for the Administrative Committee (ADCOM) of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society (UFFC-S).

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