Ultra Wide Band SAW Correlators using Dual Orthogonal Frequency Coded Transducers

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***Abstract*—This paper presents the development of ultra-wideband (UWB) surface acoustic wave (SAW) correlators using dual dispersive orthogonal frequency coded transducers. Orthogonal frequency coding (OFC) is a spread spectrum coding technique with a variety of applications. The OFC SAW correlator spectrally spreads the UWB data beyond that of CDMA due to an increased signal bandwidth. The OFC SAW correlator concept was previously demonstrated using a coded dispersive transducer in conjunction with an unweighted transducer [1]. The performance of the UWB SAW correlator device is distinctly enhanced by using a dual OFC transducer architecture.**

The dual OFC correlator consists of two seven chip dispersive transducers. Each of the two dispersive transducers implements a dissimilar code; the resulting time domain signal is spread to twice the length of the device compared with a single dispersive transducer. The frequency response resembles a signal using orthogonal frequency division multiplexing (OFDM). The properties of the double dispersive device provides decreased chip distortion, a significant lower insertion loss due to improved transducer chip acoustic matching as well as an increased level of code diversity beyond what is offered by OFC alone.

Experimental results of a SAW filter designed with dual OFC transducers are presented. Each SAW correlation filter was designed using seven dissimilar contiguous chip frequencies within the two OFC transducers. SAW correlators with fractional bandwidth of approximately 29% were fabricated on lithium niobate ($LiNbO_3$) having a center frequency of 250 MHz. A coupling of modes (COM) model is used to predict the SAW filter response and is compared to the experimentally measured data. Good correlation between the predicted COM responses and the measured device data is obtained. Discussion of the design, analysis and measurements are presented. Results are shown for operation in a matched filter correlator for use in an UWB communication system and compared to predictions, showing good results.

I. Introduction

Ultra-wideband (UWB) communications is an emerging technology with numerous communications advantages such as the ability to share the FCC allocated frequency spectrum, large channel capacity and data rate, simple transceiver architecture and high performance in noisy environments. The use of ultra-short pulses has become the widely accepted method for achieving the very wide bandwidths and low power spectral density needed for UWB communications. The "impulse radio" method of UWB communications is effective and simple; however the implementation of more complex signals are not feasible with even the fastest silicon technologies. Surface acoustic wave (SAW) devices, however, allow for simple generation and detection of complex UWB communication. The numerous advantages of SAW devices for UWB communications have been demonstrated using a pseudo-noise (PN) coded SAW transducer to implement a CDMA coded signal on a single frequency RF carrier [2]. The use of a SAW correlator eliminates the need for costly high speed silicon CMOS devices as well as many of the costly components needed in the IF section.

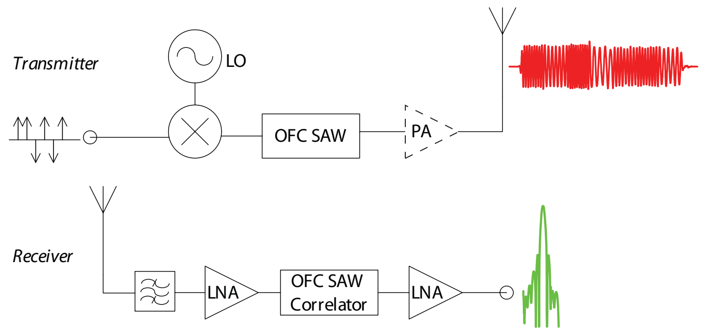

Fig. 1. Conceptual block diagram of UWB OFC transmitter and receiver.

The use of orthogonal frequency coding (OFC) in UWB SAW correlators provides several advantages over CDMA including an increased range due to enhanced processing gain and greater multiple access operation due to greater code diversity [3]. The OFC SAW correlator can be achieved using a single inline dispersive transducer in conjunction with an unweighted transducer. The device is capable of being used as both code generator and matched filter in an UWB transceiver system [4], as shown in Fig. 1. The passive operation of the OFC SAW correlator simplifies the operation of UWB transceiver in comparison to a conventional UWB system and reduces many of the typical UWB deployment challenges [5].

The development of the UWB OFC correlator device has been demonstrated with a single coded dispersive transducer in conjunction with an unweighted transducer [1]. Using a dual OFC transducer architecture, the performance of the device is significantly enhanced. The properties of the dual OFC correlator device inherently provides an increased code diversity and a significantly lower insertion loss due to improved transducer chip acoustic matching. The results shown in this paper demonstrate the improvements of a dual-OFC SAW correlator for use in UWB communication systems.

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II. Orthogonal Frequency Coding Background

OFC is a spread spectrum coding technique that has been successfully implemented in SAW tags and sensors using reflective structures [3], [6]. The technique uses multiple orthogonal chips, each τ_{chip} long. In the frequency domain, the local chip frequencies are separated by $1/\tau_{chip}$. The final criteria requires that $f_{chip} \cdot \tau_{chip}$ must equal an integer number of half carrier cycles.

A well known example signal is a linear stepped chirp, which contains a series of local chips with contiguous orthogonal frequencies and linear group delay. For OFC, a level of coding is achieved by shuffling the chips in time such that the adjacent chip carrier frequencies are no longer contiguous in time. The OFC signal is mapped into the SAW device using transducers or gratings with center frequencies and electrode counts chosen to match the OFC coded signal. The OFC technique permits multiple signals to occupy the same bandwidth with the data contained in the signal phase. A more complete description of the OFC technique is given by Malocha, et al [7].

III. Device Design Parameters and Measurement

The development process utilized a linear stepped chirp as a benchmark to identify design problems and the necessary solutions. Using up-chirp and down-chirp signals aided in identifying bulk mode problems and transducer design modifications. Since every chip is a constant length (τ_{chip}), as the chip frequency increases the number of electrodes in the chip also increases proportionately. Since the conductance is proportional to the chip frequency (f_{chip}), the beam width (W_a) and the number of chip wavelengths, it is necessary to apodize the chips in order to obtain a uniform conductance for each chip. The complete detailed development of the UWB OFC SAW is discussed in [1].

The filters were designed with a center frequency of 250 MHz and a fractional bandwidth of 29%. The designed fractional bandwidth exceeds the FCC UWB definition of 25%. The center frequency was chosen for proof of concept and ease of implementation using conventional contact lithography techniques. The devices can easily be scaled to higher RF center frequencies using advanced fabrication techniques such as e-beam lithography.

Each dispersive OFC transducer contained seven chips with seven different chip frequencies which yields a time bandwidth product of 49. Each chip is 96 ns (τ_{chip}) in length. Devices were fabricated on YZ $LiNbO_3$ with aluminum electrodes. Each transducer has $3f_0$ electrode sampling in order to eliminate bulk mode conversion effects. The device responses shown were measured using an RF probe station connected to a network analyzer for data acquisition.

IV. Single OFC Transducer Device Background and Results

UWB correlator devices were initially developed with an inline dispersive OFC transducer and a wideband apodized transducer, as shown schematically in Fig. 2. An apodized

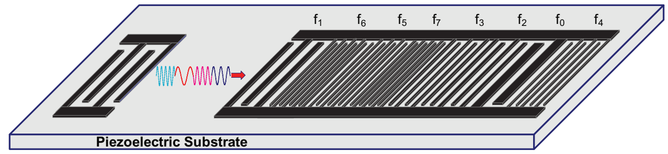


Fig. 2. Schematic representation of single OFC transducer device. The device uses a dispersive OFC transducer in conjunction with an unweighted wideband transducer.

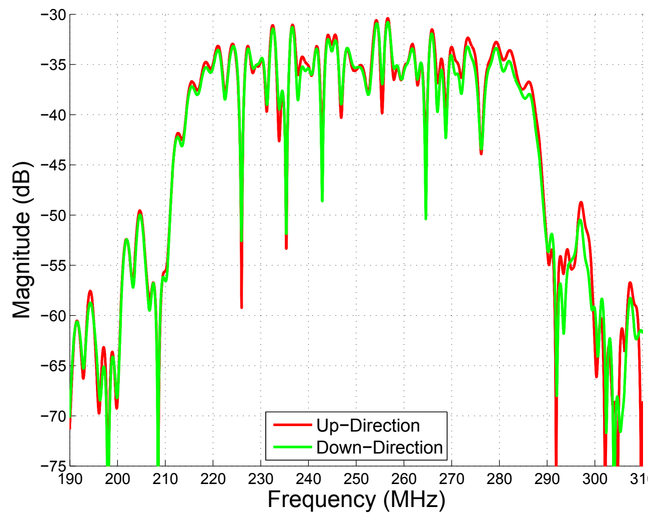
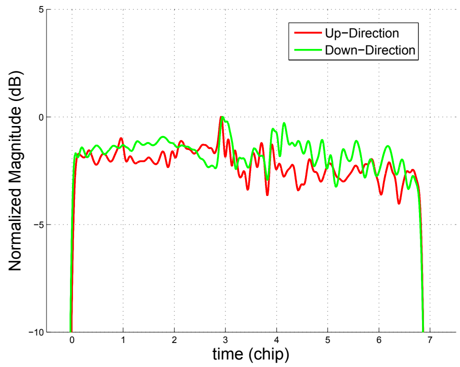


Fig. 3. Experimental frequency response (S_{21}) of a seven chip UWB OFC device with center frequency of 250 MHz and fractional bandwidth of 29%. The up and down directions of the OFC code sequence are compared.

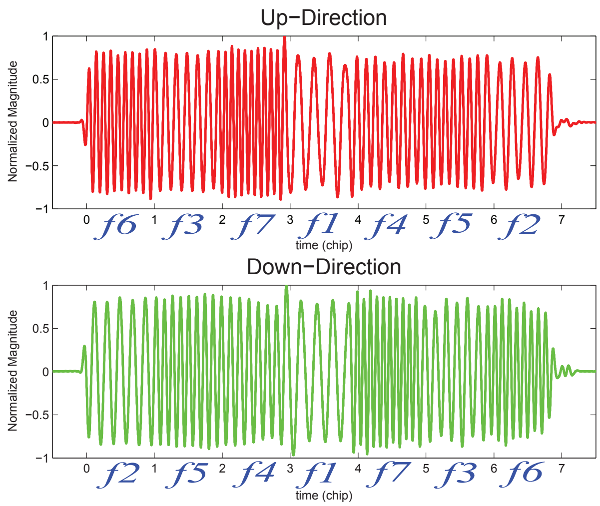
transducer was placed on either side and at equal distance from the OFC transducer to be used as a coding device and the matched filter in the transmit and receive portions of the system, respectively.

The experimental frequency response data for a single OFC SAW correlator device, obtained via wafer-level RF probe, for the up and down directions are shown in Fig. 3. The term up-direction refers to the defined OFC code sequence and down-direction refers to a reversed code sequence measured from the wideband apodized transducer located on the opposite side of the dispersive transducer. The results presented here are for a device with OFC code sequence of $\{f_6, f_3, f_7, f_1, f_4, f_5, f_2\}$ in the single dispersive OFC transducer. The sequence was chosen arbitrarily with out considering code optimization. An additional level of coding is theoretically achievable through pseudo-noise phase coding or repeated frequencies, further increasing the code diversity.

Comparing the up and down directions of the OFC sequence, we see that the frequency response magnitudes compare extremely well at all frequencies and are nearly reciprocal as desired. The time response of the OFC device is shown in Fig. 4. The normalized magnitude response, shown in Fig. 4(a) in dB, shows a relatively flat response as desired. The linear time response, shown in Fig. 4(b), allows the determination the code sequence by simple observation of the relative carrier



(a) Time Magnitude (dB)



(b) Linear Time

Fig. 4. Experimental time response of UWB OFC device design. The time axis is normalized to chip length. The OFC sequence of $\{f_6, f_3, f_7, f_1, f_4, f_5, f_2\}$ is labeled under each chip in the linear time plot and can be seen by observing the relative number of cycles in each chip.

cycles of the experimentally measured signal. The transition of the chip frequencies occurs at the zero crossing for the OFC device due to the properties of the orthogonal frequencies.

V. Dual OFC Transducer Device

The dual OFC correlator consists of two seven chip dispersive transducers; eliminating the apodized transducer used previously. Each of the two dispersive transducers implement a dissimilar code sequence; the resulting time domain signal is spread to twice the length of the device compared with a single OFC transducer. Each dispersive OFC transducer is designed with the same parameters as the single OFC device, with a 250 MHz center frequency and 29% fractional bandwidth.

The dual OFC transducer correlator device is shown in Fig. 5. The device is configured with RF probe pads on each dispersive transducer for convenient wafer probing. The distinct colors produced by the wavelength of the transducer electrodes depict the differing OFC frequencies of $\{f_7, f_5, f_3, f_4, f_1, f_2, f_6\}$ and $\{f_6, f_3, f_7, f_1, f_4, f_5, f_2\}$; which are labeled for both transducers.

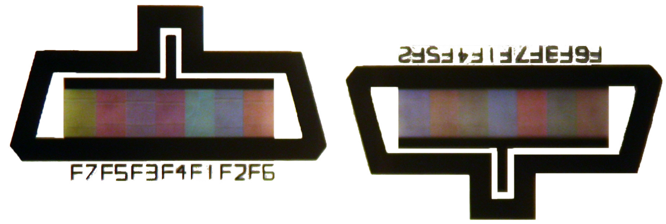


Fig. 5. Microscopic image of the UWB OFC SAW correlator using dual dispersive transducers. The colors produced by wavelength of the transducer electrodes depict the differing chip frequencies of the code.

VI. Dual OFC Transducer Device Results

The dual OFC transducer frequency response is shown in Fig. 6. The figure compares the experimentally measured dual OFC device frequency response with the coupling of modes (COM) model simulation and ideal matched filter responses. Comparison with the COM model prediction shows that the experimentally measured response is accurately predicted over the entire frequency range.

The dual OFC transducer response has a significantly lower insertion loss compared to the single transducer response shown previously in Fig. 3. The reduction in insertion loss is more evident when the experimental responses for two devices are plotted on the same axis, as shown in Fig. 7. The improved transducer chip acoustic matching yields an insertion loss reduction of approximately 10dB. The sidelobe levels shown are similar for both devices, resulting in a higher degree of out of band rejection for the dual OFC transducer correlator device.

The experimental dual OFC transducer device time response obtained using the FFT is shown in Fig. 8 and looks noise-like. The time response resulting from the convolution of two OFC

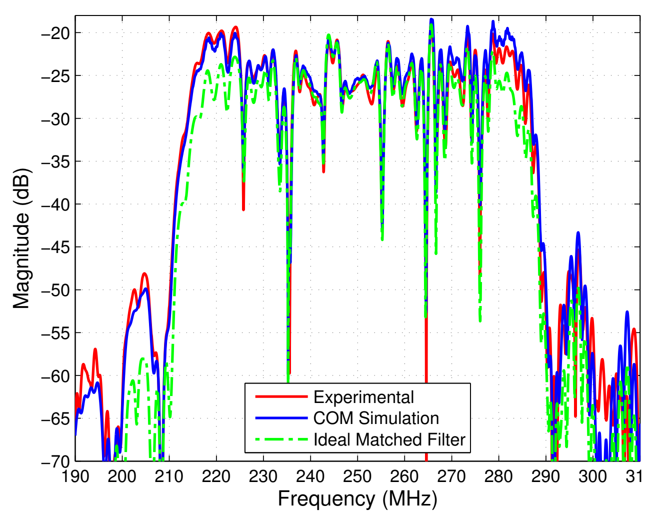


Fig. 6. Comparison of experimental dual OFC correlator device, in red, with coupling of modes (COM) model simulation, in blue, and ideal matched filter response, in green.

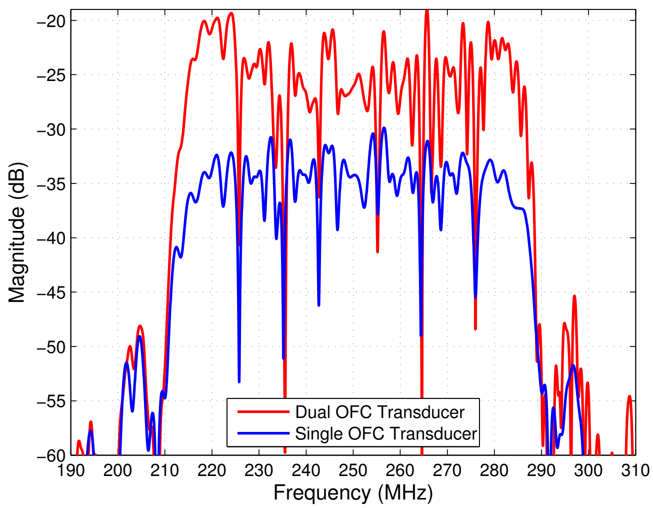


Fig. 7. Comparison between Dual and Single OFC transducer device. Dual OFC transducer provides a noticeable reduction in insertion loss with similar sidelobe levels.

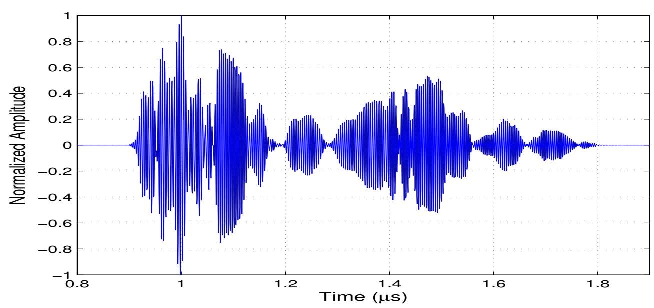


Fig. 8. Experimental linear time response of dual OFC transducer device. The time response, obtained via the fast fourier transform of the measured frequency response, looks noise-like.

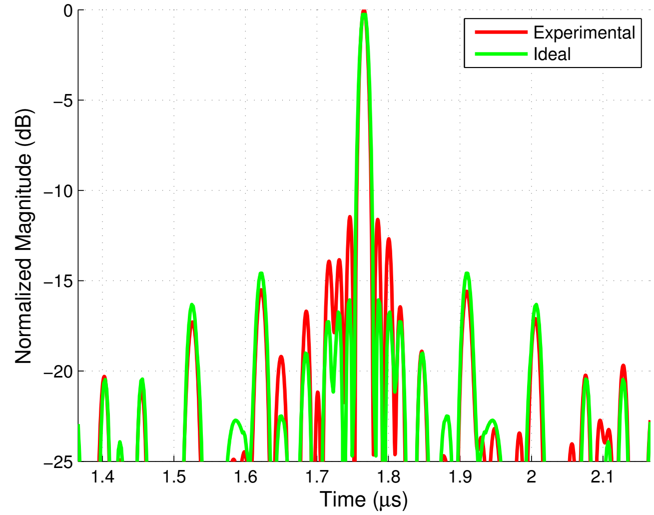


Fig. 9. Correlation of the experimental dual OFC response against the ideal matched filter, in red, compared to the matched filter autocorrelation, in green.

transducers is a much more complex coded signal compared to the single OFC device shown in Fig. 4(b); which was also obtained via FFT.

The correlation of the experimental dual OFC response against the ideal matched filter is shown in Fig. 9 and is compared to the matched filter autocorrelation. The ideal matched filter is mathematically formed from gated sine bursts for each chip and generated by computer program. The matched filter does not account for certain SAW device effects such as varied chip conductances. This contributes to the decreased compressed pulse peak to sidelobe level observed.

VII. Conclusion

The use of dual OFC transducer SAW correlators in UWB systems have been investigated in this paper. The use of OFC transducers offers the advantages of matching chip bandwidths, better coupling to the SAW, increased processing gain, and increased coding. Experimental results were presented for both single and dual OFC transducer devices and compared to simulated COM model showing strong comparison. Compared to the single OFC device, dual transducer OFC correlators yielded increased code diversity, decreased insertion loss of approximately 10dB, and improved out of band rejection. Experimental correlation of the UWB dual OFC transducer with its matched filter was presented and compared to an ideal autocorrelation response. These results demonstrate the feasibility and performance of a dual OFC SAW correlator in an UWB communication system.

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