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A comparative study of surface acoustic wave correlators

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ABSTRACT

In this paper, a comparative study for effects of different temperatures or frequency shifts on the response of surface acoustic wave (SAW) correlator is given. In this study, a computer algorithm has been developed to estimate and model the main characteristic parameters of SAW correlator. The detailed parameters of SAW correlator such as different substrates and different codes has been also computed and presented. The results obtained in this work, provide an adequate basis for understanding the parameters effects, and to aid in the optimization processes of SAW correlator based upon these effects. The aim of modeling SAW correlators is to replicate the actual behavior of the device. Manufacturing a correlator to specifically realize a different configuration is both expensive and time consuming. With the continuous improvement in computing capacity, switching to the discussed modeling in this paper would be more appropriate. This modeling approach allows the consideration of different code implementation and device structures. This is demonstrated through simulation results for some Barker sequence encoded SAW correlator.

Keywords: Surface acoustic wave, correlators, inter-digital transducer.

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INTRODUCTION

Fixed surface acoustic wave correlators

One of the most important applications of surface acoustic wave (SAW) devices in communications is the SAW correlator. A SAW correlator is a two transducer piezoelectric device (an input IDT [inter-digital transducer] and a coded output IDT deposited on top of a piezoelectric substrate) used to perform analog signal processing (Figures 1 and 2). The signal processing consists of a comparison for code matches between an input wave and a pre-programmed transducer. The incoming radio wave is a sine wave with 180° phase transitions modulated in a coded pattern, that is, a bi-phase shift keyed (BPSK) signal. The transducer at the front end of the SAW correlator converts this BPSK electromagnetic wave to a surface acoustic wave. The transducer at the output end of the SAW correlator performs bi-phase coded signal processing on the resulting acoustic wave. The match between the input wave and the coded transducer gives an output pulse. The input transducer converts radio waves into acoustic waves only at a selected center frequency and with a selected bandwidth. This is the first aspect of correlator selectivity.

The phase coded output transducer then converts only 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 directly for communication. 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 (Brocato et al., 2005; Brocato et al., 2004). The correlators used in this work make use solely of BPSK signals. It is possible to use correlators with other forms of encoding. However, phase coding offers the best SNR, and BPSK is the simplest form of phase coding.

A coded SAW based communication system, as shown in the Figure 3, consists of an expander IDT in the transmitter and a compressor IDT in the receiver. A narrow

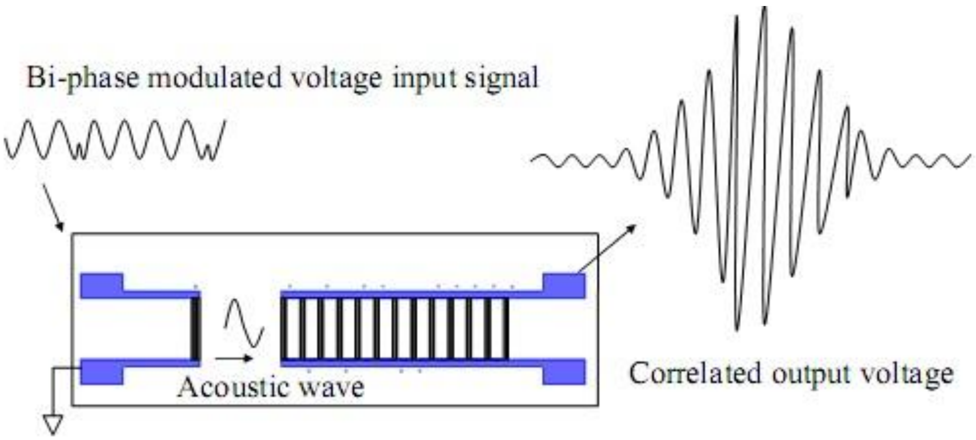

Figure 1. SAW correlator (Tikaa, 2009).

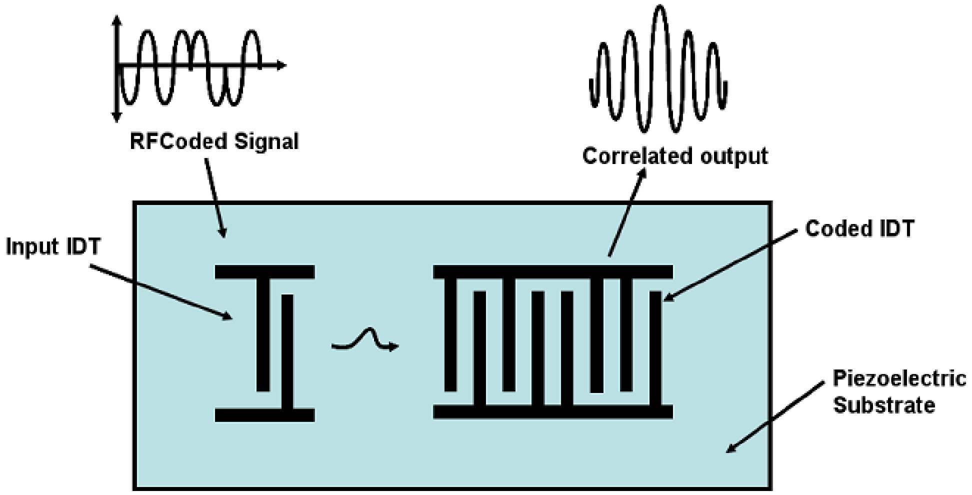

Figure 2. Surface acoustic wave correlator (Tikka et al., 2007).

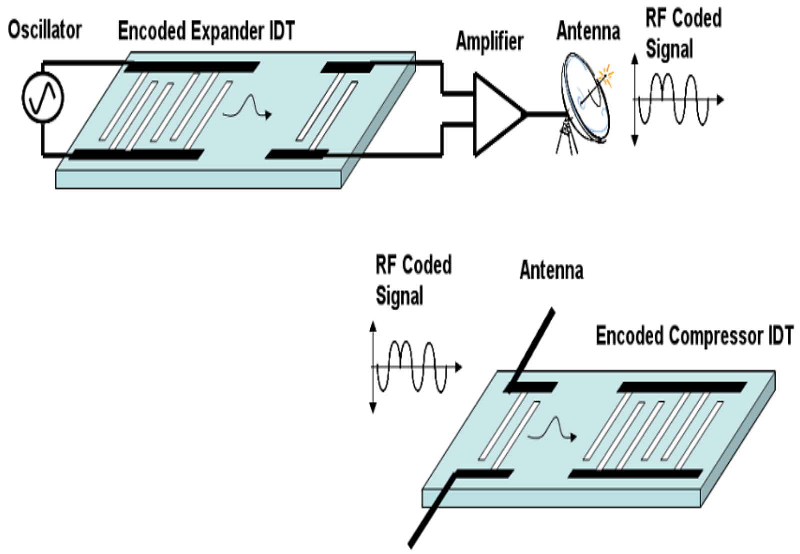

Figure 3. SAW correlator transmitter receiver configuration.

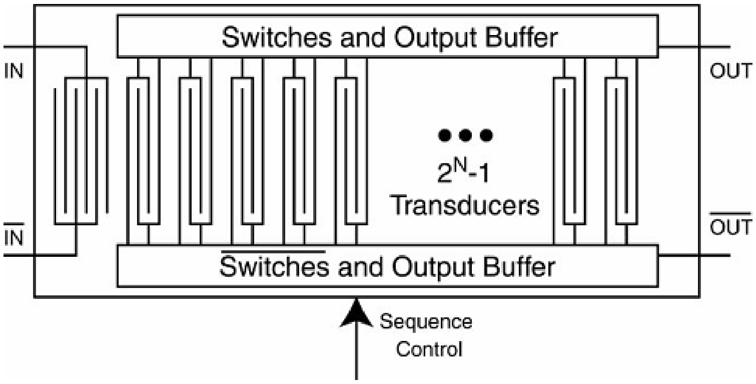

Figure 4. PSAW block diagram.

pulse or a sinusoidal waveform is fed to the expander IDT to generate a coded acoustic signal depending on the geometry of the expander IDT. These acoustic waves propagate through the substrate to the transmitting IDT, which transforms these coded acoustic waves to electrical coded RF signal.

The output from the transmitting IDT is fed to an amplifier, to strengthen the signal, and then to a transmitting antenna. The receiver consists of a correlator, operating as discussed above, with its input IDT connected to a receiving antenna to intercept the transmitted coded RF signal. The expander in the transmitter is an exact replica of the compressor/coded IDT of the correlator. The coding of the expander and compressor determines the autocorrelation function performed by the correlator (Tikka et al., 2007).

Programmable surface acoustic wave correlators

An electrically programmable surface acoustic wave (SAW) correlator was recently completed from design through small scale production in support of low power space-based communications for NASA. A programmable surface acoustic wave (PSAW) correlator is a microsystem consisting of a piezoelectric SAW device; pair of RF switch matrices, and control electronics. The PSAW forms the heart of a small, low power radio, and must itself be small and consume little power. A programmable SAW correlator (PSAW) uses an electrical switch array to reconfigure the polarity of correlator fingers. The bi-phase coding of any BPSK correlator arises from simple phase reversals in the connections of consecutive groups of fingers called “chips”. An electrically programmable correlator enables changes in the connections of these chips.The physical correlator structure consists of an acoustic SAW device with floating finger assemblies joined through an electrical switch array Figure 4. The construction of a PSAW requires the use of dissimilar materials for both the acoustic device and the electrical switch array. The acoustic device is fabricated on a piezoelectric substrate such as lithium niobate or quartz, and the electrical switch array is fabricated on a semi conducting material such as silicon or gallium arsenide. The electrical connections between these two devices must be made in a way to minimize parasitic capacitance. The packaging of this resulting assembly can be performed in a number of ways to minimize these parasitics. The two options that were explored are flip-chip bonding and chip-and-wire thick-film hybrid microcircuit assembly. SAW filters and correlator devices may be fabricated by step-and-flash imprint lithography (S-FIL) or patterned with electron-beam lithography (EBL). S-FIL is a completely viable nanofabrication technology to produce SAW filters and correlators (Cardinale et al., 2004).

SIGNAL CORRELATION

A correlator is also known as a pulse compression filter correlates the input signal with stored replica. In the frequency domain, compression involves manipulating the phases of the different frequency components of the pulse. Binary phase coding is a way of pulse compression where the phase of the radio frequency signal is repeatedly flipped according to the binary code within the duration of the pulse. The code selectivity of the devices is attained by correlating the received signal with a replica of the stored code. By doing, it is possible to consider the transmitting signal with narrow pulse widths without compromising the receiver bandwidth requirements. Thus, the transmission power levels can be kept under permissible limits. In the case of a SAW correlator, the stored replica is encoded in the IDT, as shown in the Figure 5.

The length of the transmitted sequence and efficiency of the compression algorithm determine the output filter signal to noise ratio, which is commonly referred to as processing gain.

In order to study the signal processing functionality of the SAW correlator, the following terms are defined:

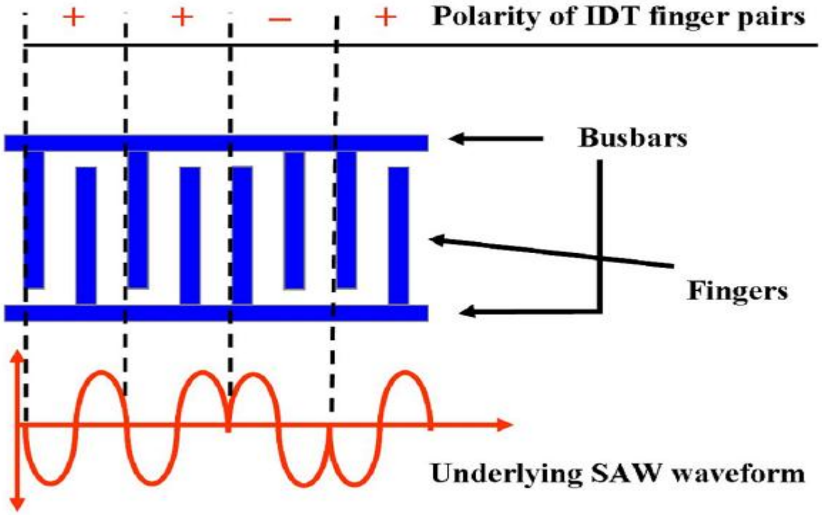

Figure 5. Basic structure of the coded IDT showing relative polarity of finger pairs and the underlying SAW waveform (Eport, 2004).

t = time; fc = centre frequency of the filter; NB = number of binary bits encoded in the IDT; TB= NB / fc = bit time of the filter= 1 / TB = bit rate of the filter; ao = BPSK input code; bo = time reversed input code encoded in the IDT; u(t) = a unit step function.

The BPSK coded input signal represented by a phase varying sine wave is given by:

$$V_{ip}(t) = \sin(2\pi f_c t) \sum_{x=1}^{NB} a_o [u[t - (x-1)T_B] - u(t - xT_B)]. \tag{1}$$

The input IDT transduces the BPSK signal into an acoustic wave. The impulse response of the input IDT is:

$$C_{ipIDT}(t) = \sin(2\pi f_c t)(u(t) - u(t - T_B)). \tag{2}$$

The input BPSK signal is modulated by the bit sequence bo, a reverse of the input signal code ao, encoded in the output IDT. The output IDT serves as a pulse compression filter to the input BPSK signal. The impulse response of the compressor/output IDT is given by:

$$C_{opIDT}(t) = \sin(2\pi f_c t) \sum_{x=1}^{NB} b_o [u[t - (x-1)T_B] - u(t - xT_B)]. \tag{3}$$

The electrical input signal, Vip(t) must pass through the input IDT to be converted into an acoustic waveform. The convolution operation represents the excitation of the SAW correlator by the input signal Vip(t), hence the generated acoustic wave can be written as:

$$AC_{op}(t) = \int_0^t V_{ip}(\tau) C_{ipIDT}(t - \tau) d\tau. \tag{4}$$

The convolution of the acoustic wave with the impulse response of the compressor IDT gives the electrical response (RC) of the correlator.

$$R_C(t) = \int_0^t C_{opIDT}(\tau) AC_{op}(t - \tau) d\tau. \tag{5}$$

When the transmitted code, ao, is received by the SAW correlator a correlated peak with high signal to noise ratio is produced.

SAW CORRELATOR MODELING

SAW correlator is modeled using finite element analysis rather than delta function and equivalent circuit models. Modelling of SAW correlator is not as straightforward as modelling other commonly used SAW devices due to non-periodic nature of the device and the large problem domain. Hence, it cannot be carried out with the same software tools that are commercially available for modelling SAW filters and resonators. To aid the correlator design process a few modelling techniques were developed such as delta-function modelling. Hence, correlator is not available to be purchased commercially (Tikka et al., 2007). The computer algorithm constructed 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 treats the correlator as an ideal mathematical element rather than a physical element. Since it is not a physics-based model, it simulates quickly, but does not include sufficient information detail for correlator design.

It does not include the effects of energy removal and wave modification. These can be considered to be second order effects, but in the design of a correlator, they are of significant concern. This model will indicate general advantages and disadvantages of different codes, but it will not faithfully reproduce actual SAW correlator output waveforms. This is because the delta function simulation does not take into consideration the energy lost to the load and the waves re-transmitted when a wave impinges on a given finger-pair of the correlator. The delta function model essentially assumes that each finger-pair of the correlator represents infinite electrical impedance, and this assumption becomes increasingly inaccurate the higher one goes in frequency. Since high frequency electronics are typically designed to be matched to 50Ω, the correlators are also designed to be matched to this impedance. This 50 Ω load removes energy as the wave passes under each finger-pair of the SAW, thus lowering the wave amplitude as the wave energy is intercepted by the output section of the correlator 6.The MATLAB-based simulation software runs quickly on a personal computer, and enables the rapid, but high-level investigation of different correlator designs. In the delta function modelling of the correlator, each electrode of the IDT is treated as a delta function source. The resultant response of the device is obtained by summing the delta sources with respect to the applied voltage. As the correlator is considered an ideal mathematical element it does not provides an accurate frequency domain characteristics. The model only provides a general understanding of the advantages of different code sequences through the normalized output amplitude plots (Bracato, 2004; Campbell, 1998). The transfer function of a SAW correlator comprising of input and output IDTs with transfer functions $|H_i(f)|$ and $|H_o(f)|$, respectively, is given by:

$$|H(f)| = |H_i(f)| \cdot |H_o(f)|$$

where

$$|H_i(f)| = \sum_{-a}^{a} (-1)^a W_a e^{-j\beta x_a} \qquad (6)$$

and

$$|H_io(f)| = \sum_{-b}^{b} (-1)^b W_b e^{-j\beta x_b} \qquad (7)$$

Here, a and b are the number of electrodes, Wa and Wb are the weighting factors related to the finger pair overlap, for the input and output IDT's respectively. Also, xa and xb are the distances from the center of the IDTs. The phase contribution of each electrode and therefore the binary code in the IDT is determined by the term $e^{-j\beta x}$. Where, β is the propagation constant. A simple code included in our computer algorithm using GUI to describe the response of SAW correlator with influence of some different parameters. The program designed to study the ideal response of SAW correlator, with zero temperature difference or frequency. This algoritm enables users from selecting the substrate between different materials ($YZLiNbo_3$, YXQuartz, $LiTao_3YZ$, GaAs Z and Quartz ST). Other parameters included in the program such as center frequency, cycles per chip, code length and its sequence. The same program modified to measure the effects of frequency shifts or temperature changes, code length and substrate change on the response of SAW correlator. These parameters effects are collected in a comparative study figures.

EQUIVALENT CIRCUIT MODEL

In the equivalent circuit modelling approach of SAW correlators, each finger pair of the IDT is considered as a three port model with two acoustic ports and one electric port. The two acoustic ports and the acoustic effects caused by these ports are simulated using transmission delay line elements. The excitation and detection of the acoustic waves is performed by the electrical port. The EM signal propagation in the transmission line is employed to replicate the behaviour of the acoustic wave propagation. The impendence variation of the transmission line facilities the modelling of acoustic wave propagation both on the free surface and metalized area of the piezoelectric substrate. Here, the electric voltages and the excitation currents are considered as acoustic forces and acoustic velocities respectively. The equivalent circuit of the whole SAW correlator is formed by cascading the equivalent circuits of the individual finger pairs. An equivalent circuit model of a SAW correlator, driven by a voltage source VS with source impendence ZS and load impendence ZL, is depicted in the Figure 6.

The acoustic force and acoustic velocity is represented by the electrical voltage and the excitation current, respectively.

Here, CTi and CTo, Bi(f), Bo(f), Gi(f) and Go(f) represent the total capacitance, acoustic susceptance, and radiation conductance of the input and output IDT, respectively. The model provides the transient response and the peak to side lobe ratio of the correlator. The admittance of each IDT can be expressed as

$$Y_X(f) = G_X(f) + j(2\pi f C_{TX} + B_X(f)). \qquad (12)$$

Where, x corresponds to either i or o for input and output IDT, respectively.

The equivalent circuit model is a cross field model where the electric field λινεσ are considered to be normal to the piezoelectric substrate. It can be quite complex to incorporate the effects of diffraction, backscattering, charge distribution and electrical / mechanical perturbations

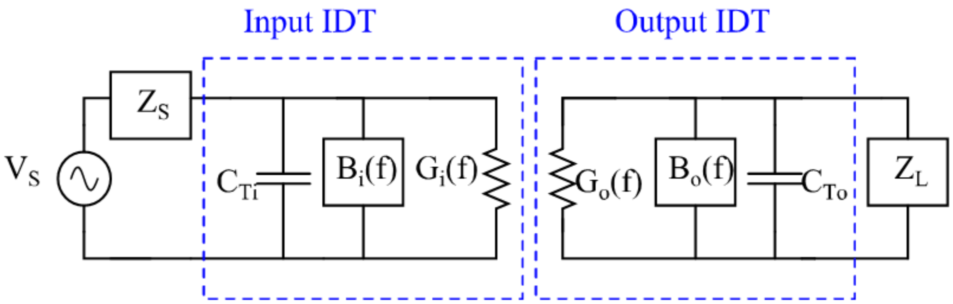

Figure 6. Eequivalent circuit model of a SAW correlator.

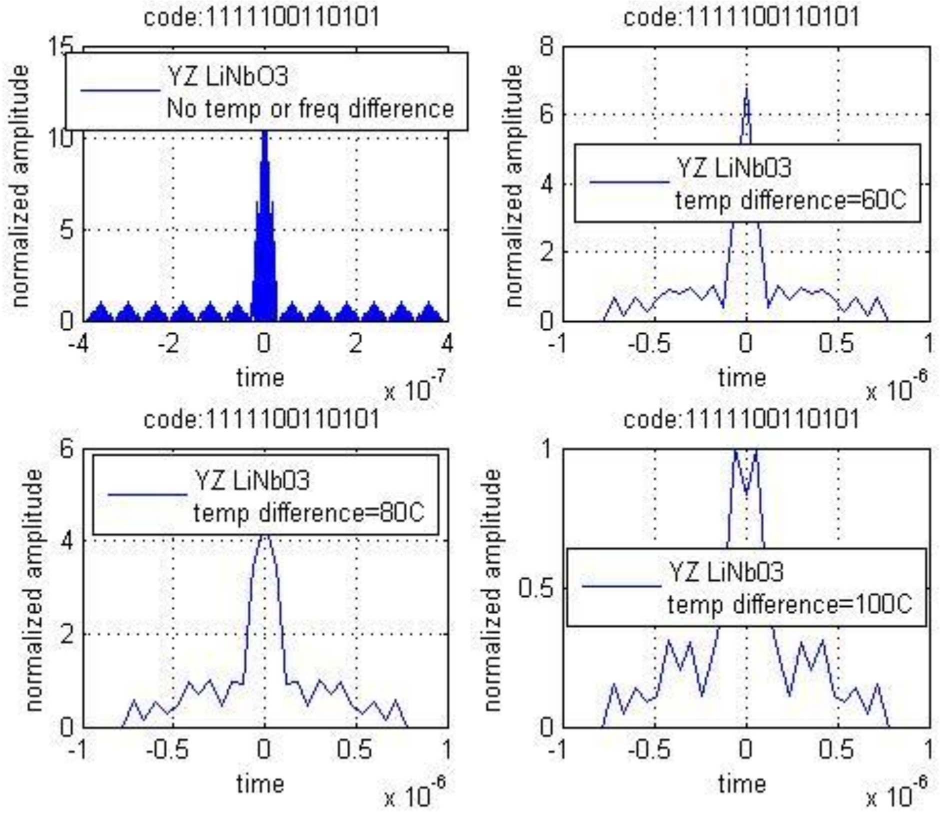

Figure 7. effect of different temperature values (0, 60, 80 and 100) on SAW correlator with anYZ $LiNbO_3$ substrate and 1111100110101 Code sequence.

in the model. The electrode discontinuities and thereby the variations in the electrical loading caused by the impairing phase modulated acoustic waves is crucial for pulse compression operation of the SAW correlator and hence cannot be compromised with simplified assumptions. Apart from the frequently used Rayleigh waves, leaky waves or surface transverse waves are much more difficult to describe with this analytical technique. Though, these simulations are computationally intensive, due to the non-parallel nature of the model components, they do not determine the effect of higher order modes on the performance of the correlator. Moreover, it is hard to optimise the output response of the device for variable structural dimensions and complex geometries.

RESULTS AND DISCUSSION

Temperature difference effect

Temperature effects are important in communications-based applications. Drift of the SAW device center frequency is the primary temperature-induced effect 13.

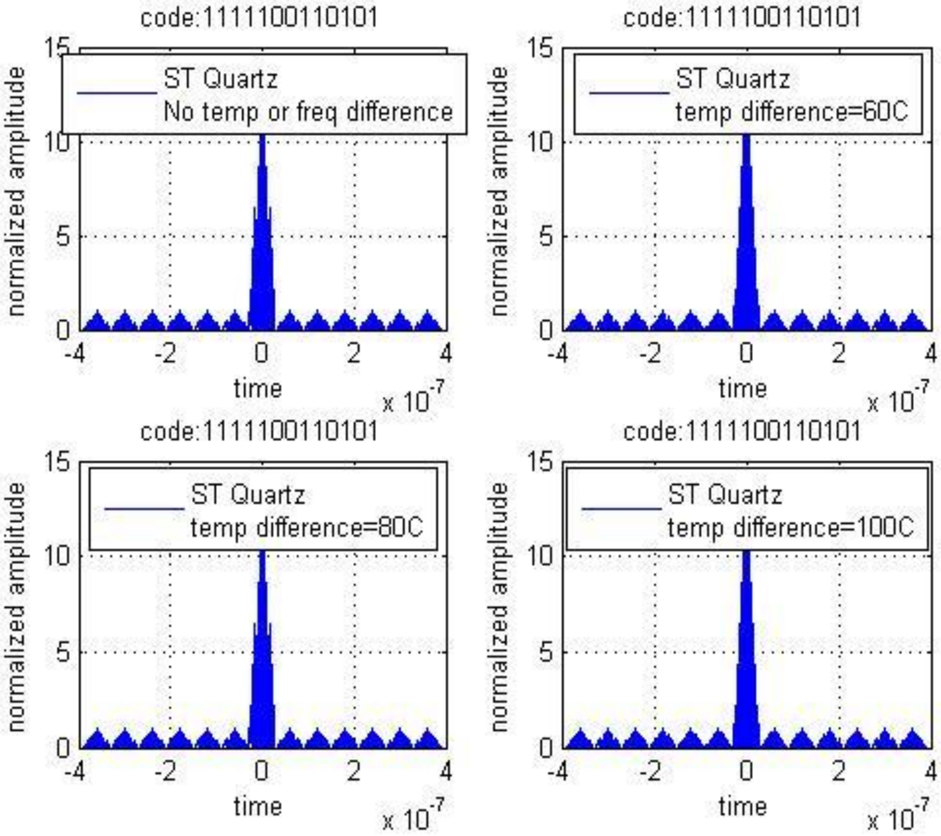

Figure 8: Effect of different temperature values (0, 60, 80 and 100) on SAW correlator with an ST Quartz substrate and 1111100110101 Code sequence.

At a selected center frequency 100 MHz, code length 13, with code sequence (1111100110101), and selected substrate YZ LiNbO3, with different temperature differences. The ideal response (zero temperature response) of SAW correlator, are obtained compared with the response at different temperatures 60°, 80° and 100° (Figures 7 and 8).

Substrate selection

Switching between different four substrates at a common value of temperature and the same previous parameters (center frequency, code length and number of cycles per chip), does not affect on the ideal response, but has a clear effect on the normalized amplitude and correlated time at non-zero temperature (Figure 9).

Changing the code length

Increasing the code length may increase the normalized amplitude of correlated signal, the results taken twice, one with effect of temperature change, the other with including frequency shift into consideration (Figures 10 and 11).

Frequency shift

Drift of the correlator output center frequency is the primary temperature induced effect. Frequency drift can be mitigated by selection of the substrate material type. ST-X quartz has a zero temperature coefficient at room temperature. Unfortunately, ST-X quartz also has a low electromechanical coupling coefficient (0.16%). This creates two significant problems; the correlator transmission coefficient is low, and the resulting input IDT impedance proves difficult to match (Brocato et al., 2003). The frequency shift effect has shown using the estimated algorithm (Figure 12).

CONCLUSION

In this paper, an influence of some different parameters on the response of SAW correlator have been discussed. Temperature changes, frequency shift, different substrates and code length are the main parameters studied. We have developed a simple computer algorithm

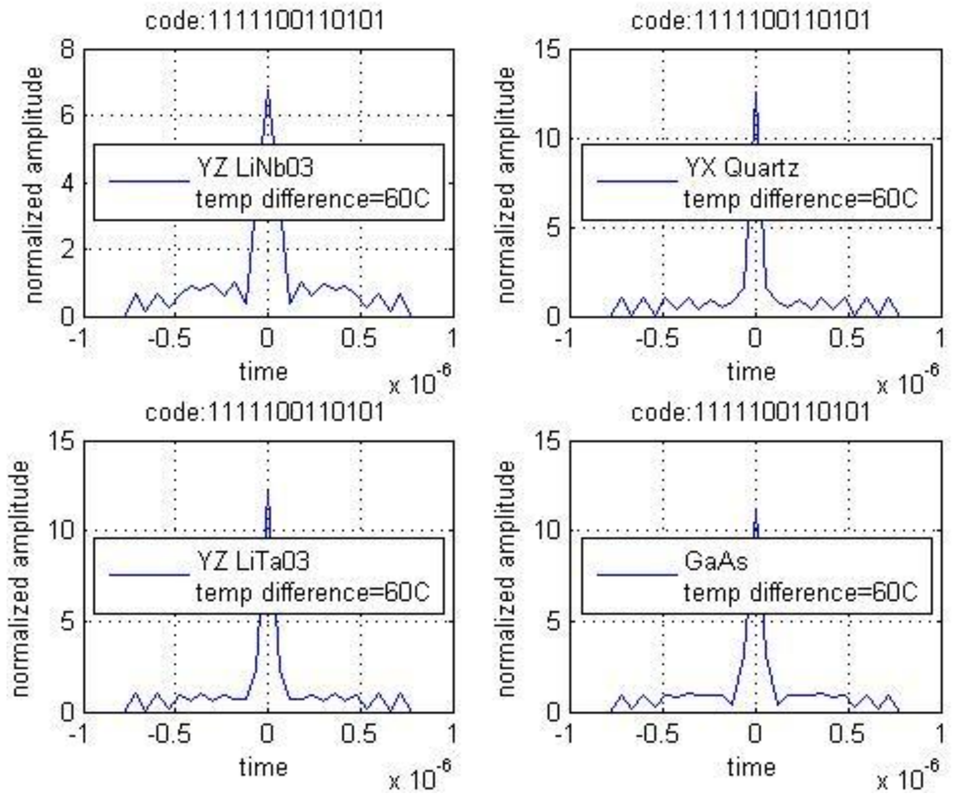

Figure 9. Effect of using different substrates on the response of SAW correlator.

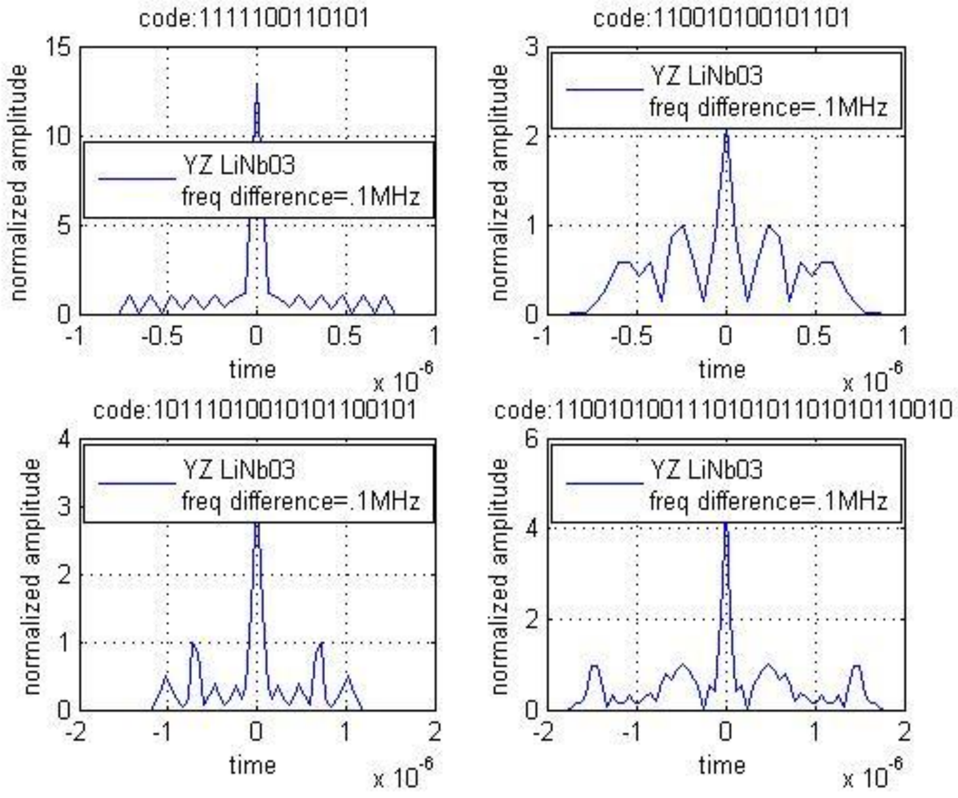

Figure 10. Effects of changing code length upon the response of SAW correlator, including the frequency shift effect, and regardless the effect of temperature changes.

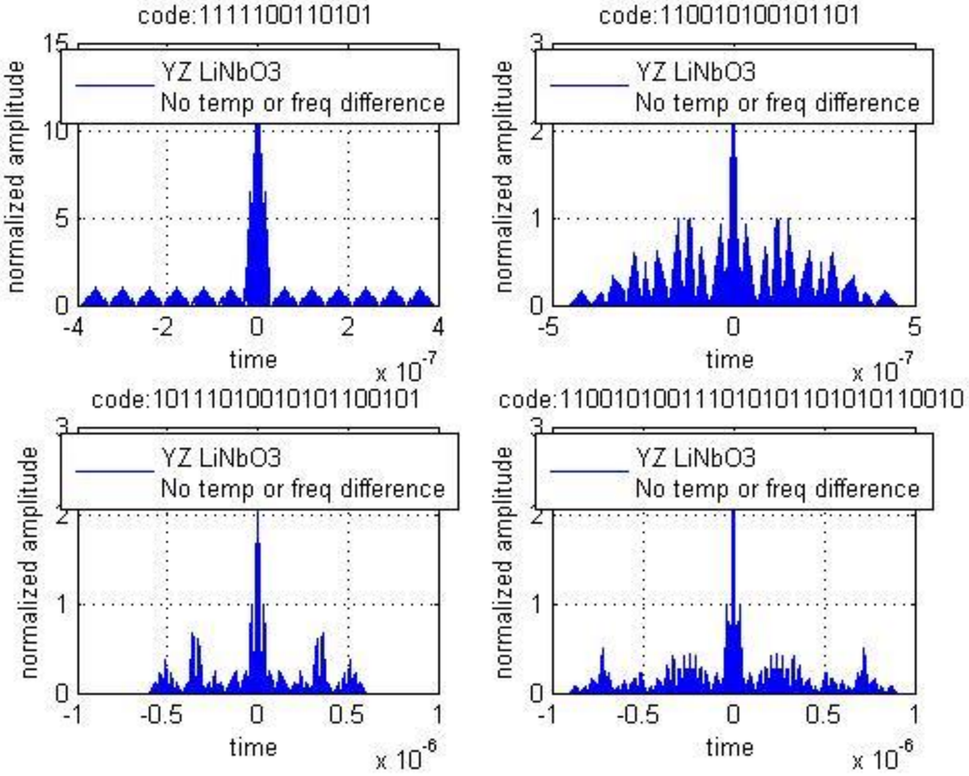

Figure 11. Effect of changing code length upon the response of SAW correlator, including the temperature changes effect, and regardless the effects of frequency shift.

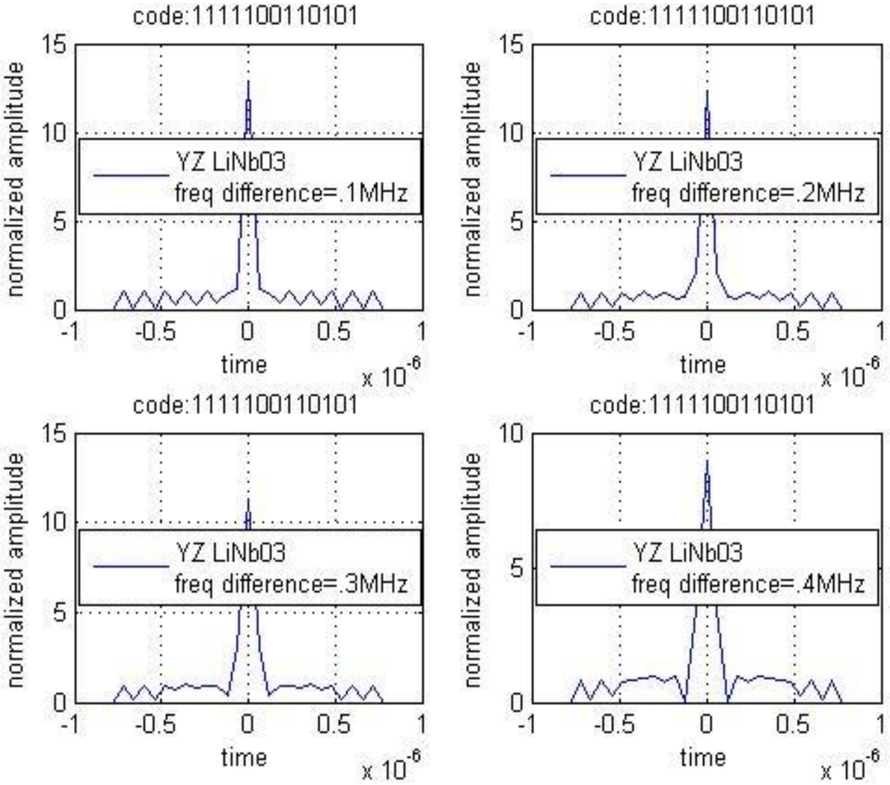

Figure 12. Effects of frequency shift on the response of SAW correlator, using YZ LiNbO3 substrate and 1111100110101 code sequence.

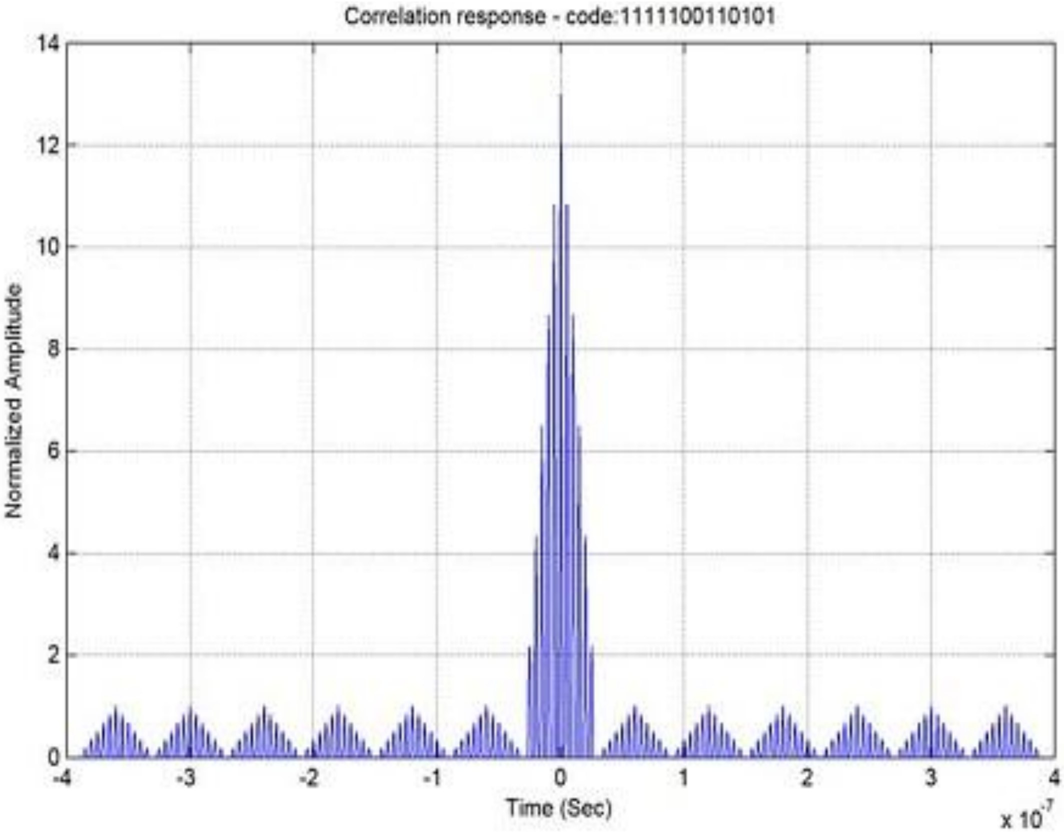

Figure 13. A 13-bit Barker sequence encoded SAW correlator's response using delta function model. The normalized amplitude plot provides a qualitative description of the peak-to-slide lobe ratio, which in this instance is 13.

to give a comparative study for these parameters. This constructed program simulates quickly, but does not include sufficient information detail for correlator design. A 13-bit Barker sequence encoded SAW correlator's response is calculated using the delta function model developed by Bracato (2004) (Figure 13) (Tikka et al., 2007). Also, a similar response can be obtained with our constructed program. Finally, this model may give approximately similar results for those in published paper (Tikka et al., 2007). The suggested algorithm that is used in this paper maybe used to the examination of vibration loading, For instance, can it steady operate at vibrations in 80 or 100 decibel and in wide codes and temperature ranges. This model relies on simplistic approximations although it is incapable of considering some other parameters. Finally, surface acoustic wave (SAW) technology is beginning to seriously attract interest for a broad range of sensor applications, especially in aerospace and health monitoring applications (Bulst et al., 2001; Wilson et al., 2009). Now many studies on orthogonal frequency coded (OFC) SAW devices for communication using SAW sensor correlator have been published (Kozlovski et al., 2008; Gallagher et al., 2006; Brocato et al., 2006).

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