Finite Element Analysis of a 3-Dimensional Acoustic Wave Correlator Response for Variable Acoustic Modes

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ABSTRACT

Complex signal processing functions can be performed by acoustic wave correlators, with simple structures, through the variation of electrode patterns. Numerical simulations of Surface Acoustic Wave (SAW) correlators, previously limited to analytical techniques like delta function and equivalent circuit models, require simplification of second order effects such as backscattering, charge distribution, diffraction, and mechanical loading. With the continual improvement in computing capacity, the adaptation of finite element modelling (FEM) is more efficient for full scale simulation of electromechanical phenomena without model oversimplification. This is achieved by resolving the complete set of partial differential equations. In this paper a novel way of modelling a 3-dimensional acoustic wave correlator using finite element analysis is presented. This modelling approach allows the consideration of different code implementation and device structures. This is demonstrated through the simulation results for a Barker sequence encoded acoustic wave correlator. The device response for various surface, bulk, and leaky modes, determined by the excitation frequency, are presented. Moreover, the ways in which the gain of the correlator can be optimised though variation of design parameters is also outlined.

Keywords: Surface Acoustic Wave (SAW) Correlator, Finite Element Analysis (FEA), Bulk Acoustic Wave (BAW), Leaky Surface Acoustic Wave (LSAW), Barker Sequence.

1. INTRODUCTION

Surface Acoustic Wave (SAW) based devices are increasingly being used in digital communications for code discrimination. These devices, apart from being inherently rugged and reliable, can provide bi-phase coding and processing gain by the variation of finger geometry.[1] A SAW correlator responds with a correlated peak to an interrogating signal that possesses the correct frequency and correct code. This aspect of the correlator can be used to power sensors and actuators in a secure manner. The concept of using a SAW correlator for improving the security and actuation of the wireless controlled microvalve was discussed previously.[2] These applications can dramatically benefit from the development and implementation of correlators with very low insertion loss. Until now, a considerable amount of effort for acoustic wave correlator characterisation was focused heavily on experimentation, fabrication and processing. The dependence on fabricated test structures can be reduced considerably if the design optimization, new material evaluation and mode propagation characterisation of the device is carried out accurately using simulation tools. Finite element analysis appears to be an attractive technique, which comes closest to comprehensive modelling of a complete acoustic correlator with minimal assumptions.

Finite element methods have been developed in the past for modelling periodic structures and simple devices with few IDT electrodes.[3,4] As the geometrical dimensions of practical transducers often demand a full 3-D description, the use of finite element techniques for predicting the response of a complete device is still in its infancy. This is mainly due to the huge constraints placed on the computational resources. However, with the recent advances made on that front we demonstrate the modelling of a 3-dimensional, 5×2-bit Barker sequence

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Modeling, Signal Processing, and Control for Smart Structures 2008, edited by Douglas K. Lindner
Proc. of SPIE Vol. 6926, 692603, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.790608

encoded acoustic wave correlator. The correlator's response quantified in terms of harmonic admittance and electrical voltage can be solved from the derived system of equations. Also, the dynamic responses of the device (such as displacement, and electric potential) when interrogated by different coded signals are studied and presented as a function of frequency. It should be emphasized that while the objective of this paper is to achieve finite element modelling of an acoustic wave correlator, it approaches the objective from a design optimization viewpoint. That is, the aim is to determine how the acoustic modes are influenced by the variable excitation frequencies and substrate thicknesses, and subsequently use those results to optimise the device response.

In this paper, modelling of a 3-dimensional, 5×2-bit Barker sequence encoded acoustic wave correlator is presented using FEM. In Section 2, we discuss briefly the SAW correlator operation, the various modelling techniques. Then in Section 3, we present the SAW correlator design, where the dimensions of the structure, materials used and boundary conditions are discussed. After the description of the model, we present and discuss the simulation results in Section 4, using harmonic analysis. The admittance, output voltage response graphs and contour plots of displacement in the frequency domain are presented to illustrate the effect of all the acoustic modes on the correlator performance for two different piezoelectric substrate thicknesses. Moreover, the correlator's response when there is a code mismatch is also discussed.

2. CORRELATOR OPERATION

A brief description of the correlator operation is provided here for the sake of clarity. A more detailed description of the same was presented in Tikka et al.[2] A SAW correlator, as shown in Fig. 1, is a passive pulse compression filter that operates through the correlation of phase shifts in the transmitted RF signal. It consists of an input IDT and a coded output IDT deposited on top of a piezoelectric substrate. The input IDT transduces the coded input RF signal into an acoustic wave. The electrodes of the output IDT are phase coded during construction in such a way that the correlator converts the correctly phase coded acoustic wave to a RF modulated electrical pulse. The device will respond with a correlation peak only when the code of the interrogating RF pulse matches with the embedded code in the output IDT, thus enhancing the processing gain of the correlator by combining the code reception scheme with the high Q operation of a bandpass filter.[5] For all other transmitted signals with different codes, even the one's excited at the same frequency, the correlator would respond with a pseudo-random noise. The coding scheme used in this work is Binary Phase Shift Keying (BPSK), where the incoming radio wave has 180° degree phase transitions in its waveform. Here, BPSK is the simplest form of phase coding that offers optimum signal to noise ratio. By converting the long input BPSK signal with a matched pattern into a short RF modulated pulse, the correlator can provide considerable process gain.

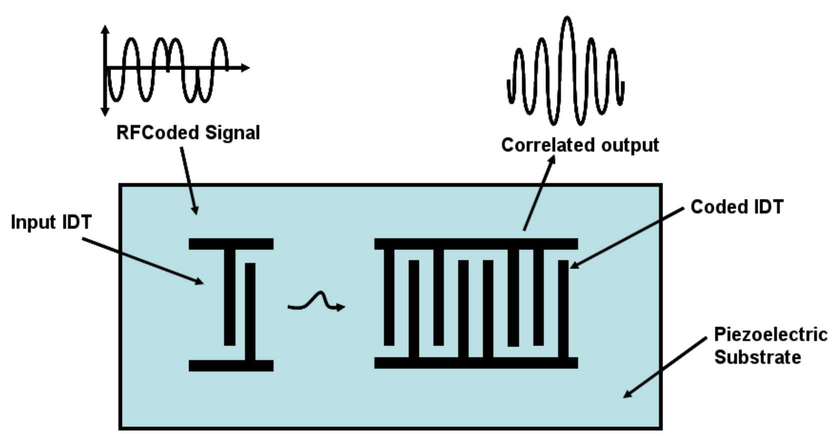


Figure 1. Surface acoustic wave correlator with a input IDT and a coded output IDT.

A coded SAW based communication system, as shown in the Fig. 2, consists of an expander IDT in the transmitter and a compressor IDT in the receiver. A narrow 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

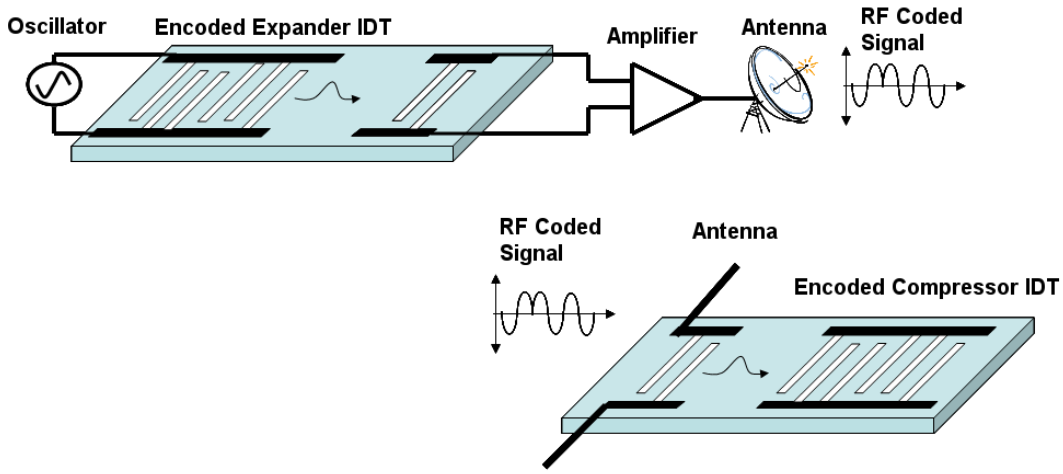


Figure 2. SAW correlator transmitter receiver configuration. The transmitter generates a RF coded signal that triggers the receiver when there is code match.

acoustic waves propagate through the substrate to the transmitting IDT, which transforms these coded acoustic waves to electrical coded RF signals. 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. The preferred coding scheme is Barker sequence, for reasons explained in Tikka et al.[2]

3. CORRELATOR DESIGN USING FEM

Modelling of SAW correlators is not as straightforward as modelling other commonly used SAW devices due to non-periodic nature of the device and the large problem domain. Modelling can not be carried out with the same basic software tools that are commercially available for modelling SAW filters and resonators. To aid the correlator design process a few modelling techniques were developed previously.[5–7] In these models, electrical components are employed to replicate the behaviour of the acoustic devices. Though these models provide a general understanding of the advantages and disadvantages of different code sequences and the peak to side lobe ratio of the correlator, the energy storage effect in electrodes, which are important for modelling leaky SAW modes, and the harmonic response of the device are neglected. Moreover, the effect of various acoustic modes on the output response of the correlator is hard to determine.

The modelling of SAW devices is mathematically equivalent to the resolution of the partial differential equations of piezoelectricity for a given excitation. Finite Element Modelling (FEM) is one of the most accurate methods of modelling a SAW device as the complete set of partial differential equations is solved.[8] This versatile technique automatically takes into account the effects of piezoelectric perturbation, mechanical perturbation, energy storage caused by non-radiating bulk waves, and electric flux leakage from the substrate surface.[9] Moreover, the strong dependence of correlator performance on the electrode pattern, the second order effects, material type of the substrate and the operating frequency provides a realistic prediction of the complex structures response subject to a RF coded signal excitation.

A 3-dimensional SAW correlator modelling was carried out using ANSYS, a commercially available finite element package. The simulations were aimed to characterise the full scale electromechanical phenomenon of the device, subjected to frequency varying excitation. A frequency sweep was performed using harmonic analysis to determine the response of the correlator for different acoustic modes of interest. The charge distribution of the correlator is calculated by solving the inhomogeneous piezoelectric partial differential equations with incorporated boundary conditions. The electrical admittance curve to characterize the electrical behavior of a SAW device was obtained from the charge collected at the IDT. Apart from the admittance curve and the electric response calculation, analysis of various acoustic modes was carried out with the help of the displacement, electric field, and stress contours. Furthermore, these contour plots provide information about the mode depth penetration and interaction of surface acoustic waves (SAW) or leaky surface acoustic waves (LSAW) with radiating bulk waves.

3.1. Model description

Three dimensional (3-D) modelling was employed, as the geometric nature of device and the anisotropic properties of the piezoelectric substrate demanded a full description. A meshed, 5×2-bit Barker sequence encoded, SAW correlator comprising a piezoelectric substrate and two non-uniform input and output IDT's is shown in the Fig. 3. Both the input and the output transducers have 20 electrodes each. As discussed in Section 2, the input IDT of the structure is modelled as an expander to cause it to generate a coded acoustic wave when a normal pulse or a sinusoidal signal is fed to it. The expander IDT geometry determines the code of the generated acoustic wave. A 5(+++-+)×2(++) bit Barker sequence is encoded in the output/compressor IDT. This is carried out by coupling the electrodes of the IDT identical to the way they are connected to the positive and negative busbars. The input/expander IDT is an exact replica of the output/compressor IDT when a code matching is desired. The response of the device for mismatching codes can be observed by varying the input IDT finger geometry, in this case by varying the coupling between the electrodes.

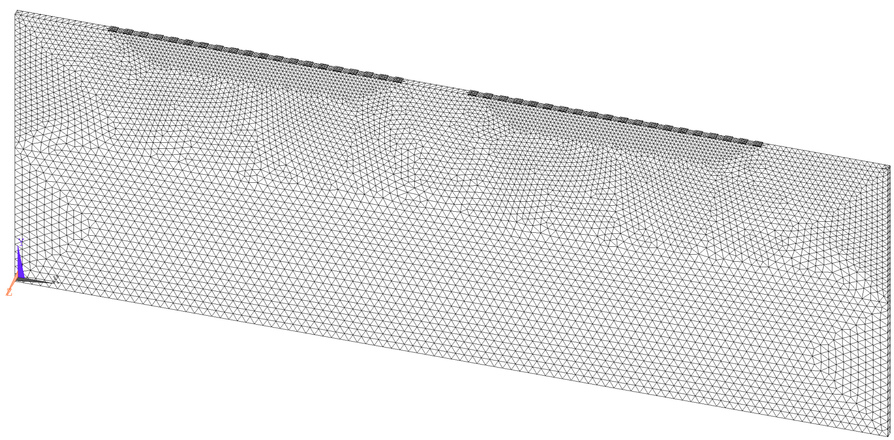


Figure 3. Meshed acoustic wave correlator model. The mesh is discretized to higher densities near the surface than near the bottom as the surface acoustic wave displacements are largest near the substrate surface.

Here, 128° YX $LiNbO_3$ is chosen as the piezoelectric substrate due to its high electromechanical coupling constant. The structure has a piezoelectric substrate of 28λ ($\lambda = 40$ μm) length, 10λ thickness. The aperture or the width of the structure is limited to 10 μm as a higher value would require large number of elements limiting the practical applicability of the method. Aluminium is used to model the electrodes with a metallization ratio (MR) of 0.4, and an electrode thickness of 3%. The material properties of piezoelectric substrate and electrodes were obtained from Auld[10] and scaled to μMKS units. The separation between the IDT's was chosen to be 2λ. This was found to be an optimal distance to improve the gain and keep the electromagnetic feedthrough, electromagnetic coupling between the two transducers, under control.[11]

Coupled field quadratic elements with 4 degrees of freedom (DOF) are used to model the device. These degrees of freedom are the displacements in the longitudinal (x), normal (y), and shear horizontal (z) directions and the fourth being the voltage. The displacement profiles along the different directions is independent of each other as the substrate is anisotropic. The reactive charge component of the element was utilised to obtain the admittance curve. The model consists of approximately 100 thousand nodes forming over 45 thousand elements.

A denser mesh was generated at the surface and through out the middle of the structure to realise an accurate representation of surface waves. However, the relatively coarser mesh near the bottom surface would still ensure an accurate characterisation of bulk waves as their wavelengths are about twice those of surface waves.[12]

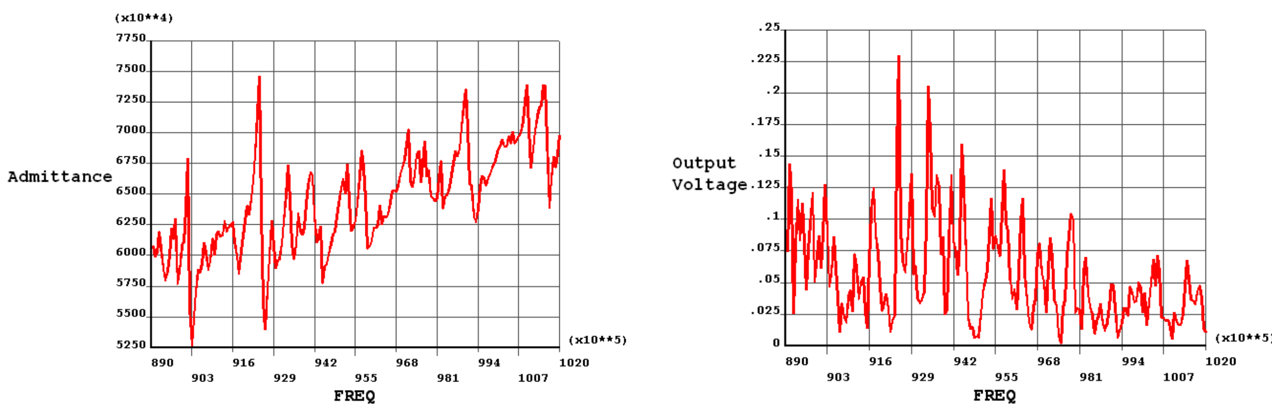
The correct application of boundary conditions is important to ensure a realistic modelling of the device. In this model, the bottom surface of the correlator is fixed and grounded to reduce the electromagnetic feedthrough.[12] A stress free boundary condition is applied at the top surface of the correlator. The length of the piezoelectric substrate is extended by 3 wavelengths at the IDT ends to counter the electromechanical coupling contribution of the reflected waves from the side boundaries.

4. RESULTS

The mode propagation properties and the electrical response of the FEM modelled, 3-dimensional, 5×2-bit Barker sequence encoded acoustic wave correlator is described in this section. Modal analysis was performed on the design to identify the freely propagating modes, particularly the SAW modes, through the examination of eigenvectors and eigenfrequencies. This was used as a starting point for the harmonic analysis.

4.1. Harmonic Analysis

A valuable insight into the excitation properties of the model can be gained from harmonic analysis. In this work, the frequency response of correlator is obtained by driving the input IDT electrodes with an alternating voltage of ±1V. Our main objective is to model a correlator with low insertion losses, that can power miniature wireless actuators in a secure manner, through the optimisation of design parameters. Therefore, it is important not to restrict the results to the modes corresponding to surface acoustic waves. Hence, the harmonic analysis was carried out for a wide frequency range.



(a) (b)

Figure 4. Frequency response of the correlator for a substrate thickness of 10λ (a) Admittance curve. (b) Magnitude of the voltage across the output IDT.

The complex admittance of the device was computed based on the accumulated charge at the electrodes when excited by a harmonic frequency. As can be seen from the Fig. 4.(a), the magnitude of the complex admittance attains a high value at the resonant frequencies and thus provides a easy identification of the excited modes. The two dominant admittance peaks to the left of the admittance curve, at frequencies of 90.1 MHz and 92.4 MHz, are those corresponding to the surface acoustic wave modes.

Depending on the excitation frequency, various acoustic wave modes like the surface acoustic waves, bulk acoustic waves (BAWs), and leaky surface acoustic waves (LSAWs) are excited. They are analysed by observing the contour plots, e.g. displacement, potential, and stress of the structure. Fig. 5 shows the displacement contour, summation of the x, y and z displacement components, of the structure for the SAW mode at 92.4 MHz. It can be observed that the displacement is confined to the top surface of the structure with a maximum value of 0.47 nm close to the electrodes. On the basis of the wave propagation into the bulk of the substrate, the modes in the mid region of the admittance curve were identified as bulk acoustic wave modes. The resonant peak at 101.2 MHz was identified as leaky surface acoustic wave (LSAW) mode as both the surface and bulk wave propagations are observed along with a significant particle displacement in shear direction perpendicular to the sagittal plane.[13]

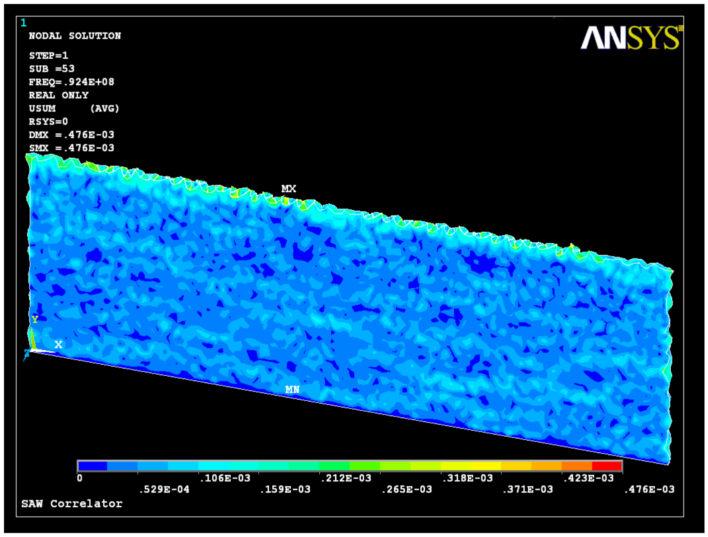


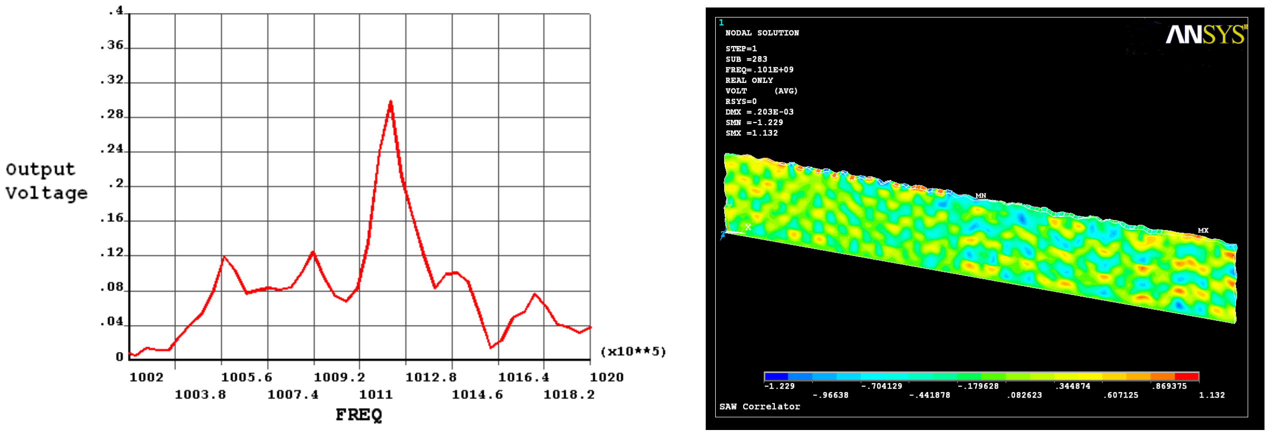
Figure 5. Surface acoustic wave displacement contour for a substrate thickness of 10λ. The acoustic wave displacement is confined to the top surface of the substrate and, as can be seen from the scale, is in nanometers

Fig. 4.(b) shows the output voltage response of the correlator, when the code matches, for different acoustic modes determined by the excitation frequency. The modes definitely impact the response of the correlator and as can be seen from the Fig. 4.(b), the output response is high for the SAW modes compared to the other modes. Hence, it is desirable to operated the correlator at the SAW modal frequencies to achieve high electromechanical coupling. However, operating the device even at the SAW modal frequency results in high losses as can be observed from the peak response of the output voltage. This could be partly due to the low value of the aperture considered for the modelling. With the continuous improvement in computation power, modelling of correlators with high apertures can be considered as future work.

4.2. Correlator design with reduced substrate thickness

For the above discussed correlator structure, the piezoelectric substrate thickness is reduced to 5λ and finite element modelling is carried out. As the SAW modes are confined to the top surface of the structure there is not much difference in the output response. The propagation properties of LSAW's on several cuts of $LiNbO_3$ and $LiTaO_3$ substrates were modelled previously with FEM using periodic structures.[14, 15] The LSAW can be used as the main signal if it has a better electromechanical coupling than the SAW. The LSAW mode is observed at the 101.2 MHz frequency, which is similar for both models. It displays a significant rise in electromechanical coupling, as can be seen from the increase in the peak value of the voltage across the output IDT in Fig. 6.(a). The electric potential contour for the structure at the LSAW resonant frequency is given in Fig. 6.(b). It can be clearly observed that the electric field is not just confined to the top surface, as there are bulk wave components propagating through out the thickness of the substrate asserting the propagation characteristics of a LSAW mode.

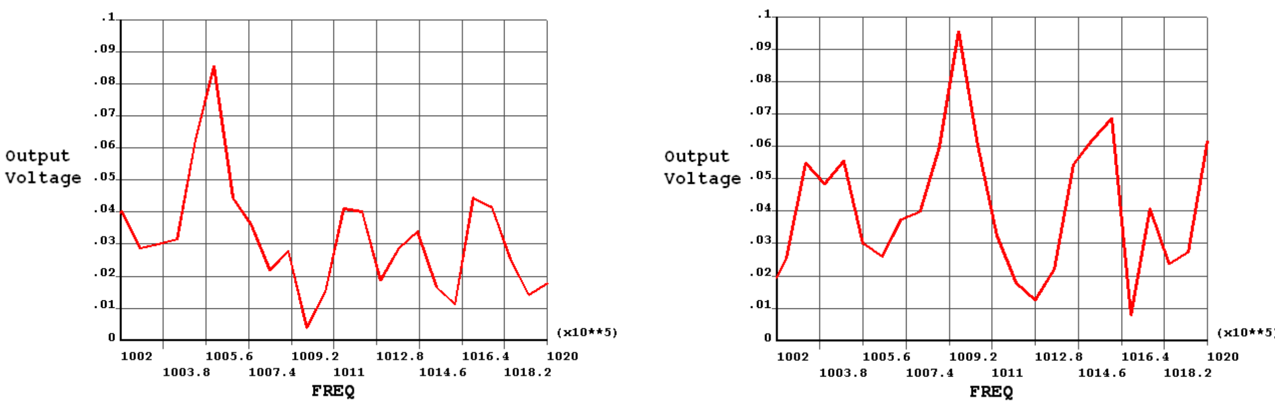
The results, so far, are for a matched code between the input signal, in this model the expander IDT, and the compressor IDT of the correlator. The functionality of the correlator can only be verified by observing its response to a mismatched input code. This is carried out by varying the electrode coupling of the expander



(a) (b)

Figure 6. Frequency response of the correlator for a substrate thickness of 5λ. (a) Magnitude of the voltage across the output IDT at LSAW mode. (b) LSAW potential contour.

IDT. The response of the correlator to two different codes, a delay line input and other non-correlating input, is provided in the Fig. 7, while all other parameters are kept the same.



(a) (b)

Figure 7. Voltage across the output IDT when there is a code mismatch (a) Delay line input (b) Other mismatching input.

By comparing these responses, with the correlating peak response of the Fig. 6.(a), it can be established that in addition to the excitation frequency, the correlator's response is determined by the code in the RF signal. Furthermore, a frequency shift of the peak voltage response was observed for both the non-correlating inputs. Even in the case of a delay line input, when the two codes are very similar, the device response is much less than its response to the matched code, as shown in Fig. 6.(a).

5. CONCLUSION

A rigorous numerical technique for simulating a acoustic wave correlator is presented. As certain modes have displacement components in all three directions 3-D modelling is employed. The results discussed in this work include: (*i*) Comprehensive FEM modelling of a 3-dimensional, 5×2-bit Barker sequence encoded acoustic wave correlator (*ii*) analysis of the device response for variable acoustic modes (*iii*) optimization of the substrate thickness for achieving high-Q correlators and (*iv*) analysis of difference in electrical response when there is a code mismatch. Hence, finite element analysis provides an effective way of gaining a deeper understanding of the correlator's response to various propagating modes and ultimately the full optimisation of correlator design.

ACKNOWLEDGMENTS

The authors would like to thank the Australian Research Council (ARC) and the School of Electrical and Electronics Engineering (University of Adelaide) for the funding and support for the project.

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