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Impulse Modelled Response of a 300 MHz ST-Quartz SAW Device For Sensor Specific Applications

Haresh M. Pandya[1*], M. U. Sharma[2], A.T. Nimal[2], K. B. Rajesh[1]

[1]*Department of Physics, Chikkanna Government Arts College, Tiruppur, Tamil Nadu.*
[2]*Solid State Physics Laboratory (DRDO), Timarpur, Delhi..*

Abstract

In recent years a big spurt has been observed in the usage and applications of Surface Acoustic Wave(SAW) devices as sensors not only for the detection of physical and chemical quantities but also as environmental biosensors for detecting volatiles, toxic agents, explosives and narcotics. The design of such sensors assumes importance as the technology enables reproducibility, reliability, portability and cost-effective sensing in real time. This paper presents the frequency response of a 300 MHz ST-Quartz SAW delay line device fabricated with uniform IDTs. Based on the first order Impulse response model and employing a unique custom made MATLAB algorithm, the device is accurately modelled. The results obtained are analyzed to ultimately help in the effective design, development and modelling of such devices as application specific sensors. Comparison of modelled and simulated results with experimental device response shows good agreement.

Keywords *: Impulse Response Model, Interdigital Electrodes (IDT), Surface Acoustic Wave (SAW) devices, SAW Sensors*

1. INTRODUCTION .

Surface Acoustic Waves (SAWs) are elastic waves that prop-agate along the surface of an isotropic elastic medium such that the energy density is confined to a depth of few wavelengths below the surface. Even though discovered by Lord Rayleigh in the year 1885 [1], these waves had to wait for nearly eight decades, when in 1965 the situation changed dramatically with the invention of the thin-film *Inter-Digital Transducers (IDT)* by White and Voltmer at the University of California, Berkeley [2] who suggested that SAWs can be excited and detected efficiently in the laboratory by using an metal thin-film IDT placed on a piezoelectric substrate fig. 1. This discovery enabled a relatively simple yet efficient and reception of SAWs and signalled a new interest in the application of acoustic waves.

Haresh M. Pandya
E-mail : haresh.pandya@rediffmail.com

The IDTs consists of two comb-like structures of metal electrodes made of aluminum/ gold photo-deposited on a precisely oriented suitable piezoelectric substrate such that these IDTs act as transmitters and receivers of acoustic wavesin a SAW device. This device is bidirectional as SAWs are launched both to the left and to the right from the IDTs. The geometry of these IDTs plays an important role in the functioning of the device and usually the devices are designed such that the widths of the electrodes are adjusted to be equal to the widths of the electrode gaps. In its simplest form, a SAW device with IDTs and all external components (Fig.1) can be modelled as one wherein,

- an alternating voltage V_{in} applied to the

IDT facilitates an efficient electrial-to-mechanical transformation via an interaction of the EM fields of the IDT with the piezoelectric crystal (converse piezoelectric effect) such that SAW is launched by the input IDT and propagates to the output IDT through the free or metallized crystal.

- an output voltage $\mathbf{V}_{out}$ is received at the output IDT due to mechanical-to-electrical transformation (direct piezoelectric effect).

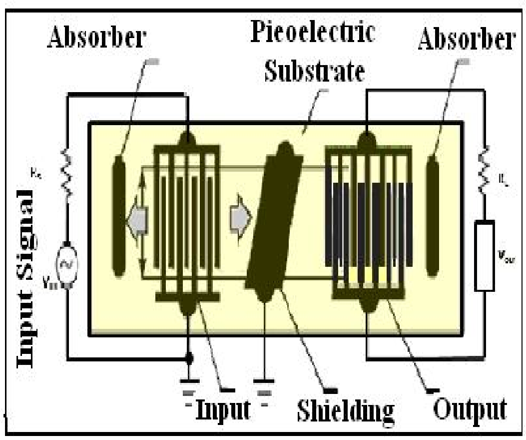

Fig. 1: Complete Schematic of a SAW Device

The SAW that travels on the surface of the piezoelectric substrate causes a strain of periodicity ë and if the excitation frequency of the IDT transducer is f_0 such that $f_0 = v_{SAW}$/ë, where ë is also the surface wavelength and v_{SAW} the SAW velocity on a free piezoelectric surface, there is a strong coupling into the surface wave energy and surface waves are launched on the substrate. The amplitude of such a SAW is found to be confined within about one acoustic wavelength under the free surface of the piezoelectric. Reviewing the properties of these surface waves, the first and the most important property is their extremely slow velocity, about 10^5 times slower than that of EM waves which makes them possess extremely small wavelengths when compared with EM waves of the same frequency. The reduction in size is therefore again of the order of 10^5. Acoustic devices therefore offer dramatic reduction in size and weight. Moreover since these state of the art devices are fabricated on the surface of a crystal, they are generally more rugged, reliable and power efficient and compatible with IC technology so that they can be mass produced at relatively low cost with precise and reproducible characteristics. This can bring about substantial eco-nomic and performance benefits as well as aid in the further miniaturization of products and components with ever increasing functionalities. Currently, SAW devices find themselves in many common commercial applications like consumer electronics and tele communications, where their ability to create, condition and process radiofrequency (RF) signals is employed to manufacture devices like delay lines, bandpass filters, resonators, convolvers, radar pulse compression filters, radiofrequency identification tags (RFID) etc., [3], [4]. All these properties have made SAW devices to be integral components in mobile, wireless and space borne communication systems.

Furthermore, these devices have been found to be of crucial importance in the continuous transduction and sensing of volatile, toxic organic compounds and other physicochemical quantities of interest in industry, environment and medical therapeutics [5-14]. An entire self-sustained SAW sensor system consisting of several miniaturized array of polymer/thin film coated SAW devices can be condensed in to a single small stainless steel ruggedized case which then makes it either hand-held or portable. This allows it to be deployed in a variety of media including air, soil and even water and thus offers the advantage of a viable alternative for in-situ liquid and gaseous media sensing like indoor air quality for work place safety and fire prevention as well as taste sensors or e-noses for perfume and flavor identification. As sensors of the sorption type, these devices have great capabilities to successfully identify, discriminate and provide a finger print response from an aggregate of closely related chemical compounds within a short sampling time. In such devices, the crucial sensing mechanism involves detection of small deviations in acoustic wave propagation characteristics (like velocity, frequency and phase response etc.,) on the sensitive active/coated surface of the device in-between the IDTs caused by mass loading in the active area of the device between the two IDTs. It is in this context that the design, modelling and development of SAW devices for sensor specific applications assumes importance.

2. MODELLING STRATEGY

Generation and transduction of acoustic waves on a piezoelectric substrate has led to the development of several different models. Modelling of SAW devices is resorted to achieve two important objectives:

- To comprehend propagation, generation and detection of acoustic waves in piezoelectric materials and
- To analyze and design structures such as IDTs, delay lines, filters, resonators etc., with desired frequency responses.

Of the models that were introduced in the early stages to gain basic and rapid insight on device performance were the one developed by Feldmann [15], the *Delta Function Model* [16] and the *Impulse Response Model* [17], [18], all based on signal theory analysis.

3. IMPULSE RESPONSE MODEL AND ITS EQUATIONS

The Impulse Response model was first presented by Hartmann et al in 1973 as an improvement over the earlier Delta Function model. It is derived from the impulse response of a nondispersive transducer [17] and is primarily a first order model that can be used as a fast tool to obtain information on the piezoelectric, mechanical and electrical behaviour of a SAW transducer as well as additional details regarding circuit impedances, matching networks and frequency scaling.

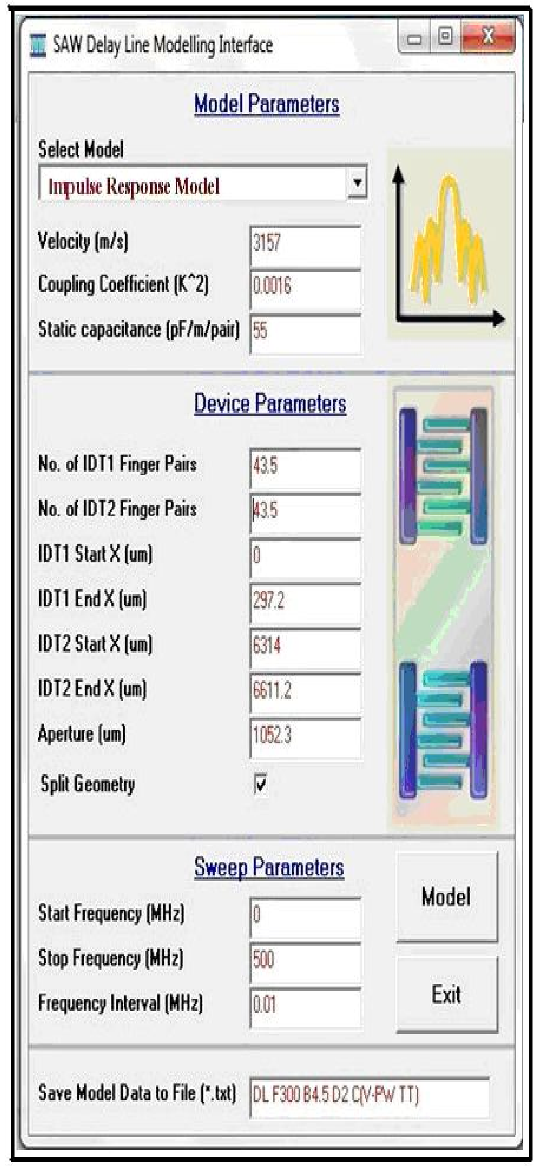

Fig. 2: SAW Delay Line Modelling Interface Screen Shot

Accordingly, the total energy is found from the impulse response and is equated to the radiation conductance. Moreover, the Fourier transform of the SAW device's frequency response ***H(f)*** is the device impulse time response ***h(t)***.

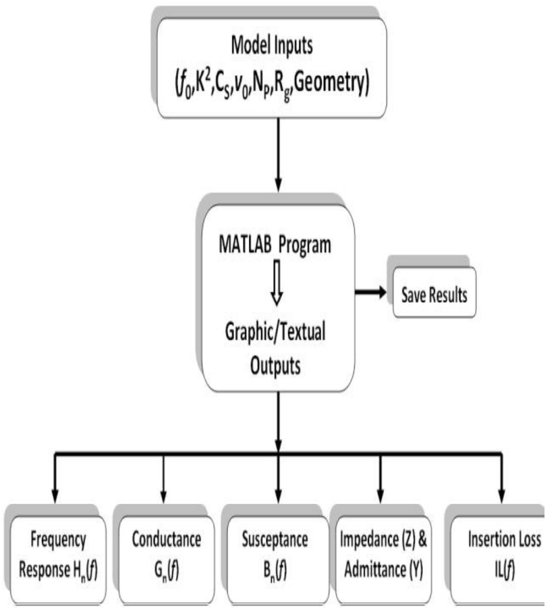

Fig. 3 : MATLAB Program Flow Chart

Table 1. MATLAB Program Input Modelling Parameters

S. No.	Parameter	Symbol	Value Used
1.	Coupling Coefficient	K^2	0.0016 (Quartz)
2.	Capacitance of finger pair/unit length	C_S	0.55×10^{-10} farad/m (Quartz)
3.	SAW Free velocity on Quartz	v_0	Modelling parameter varied around 3157 m/s
4.	Centre Frequency	f_0	300 MHz
5.	IDT Geometry	single or split	Split geometry
6.	Width of finger/gap in IDT	width	131.49×10^{-8} m,
7.	IDT Aperture or finger overlap	W	105233×10^{-8} m,
8.	IDT Electrode pairs in input & Output	$M=N=N_p$	43.5
9.	X dimensions of input & output IDT	idt1s, idt1e, idt2s, idt2e	$3621179.0331 \times 10^{-8}$ m, $3666805.9978 \times 10^{-8}$ m, $4252578.9993 \times 10^{-8}$ m, $4298205.9961 \times 10^{-8}$ m,
10.	Load Resistance	R_g	50 Ohms

Hartmann was able to establish that the time response of a SAW IDT transducer [4] is given by

$$h(t) \propto \sqrt[4]{(K^2 C_S)}\ \mathrm{Z}\ f_0^{3/2} \sin(2\pi f_0 t) \quad \text{for} \quad 0d\text{” } t\ d\text{” } N/f_0 \qquad (1)$$

$$= 0 \qquad \textit{otherwise}$$

Where $\boldsymbol{K^2}$ is the electromechanical coupling coefficient, $\boldsymbol{C_S}$ is the electrode pair capacitance per unit length (*pf/cm-pair*) and $\boldsymbol{f_0}$, the centre frequency of operation. This expression relates the IDT impulse time response to the physical device parameters like coupling coefficient and electrode capacitance of the piezoelectric substrate. To convey the basic elements of this model, a simple Mason equivalent circuit [24] as shown in (Fig. 4) is normally used. $\boldsymbol{C_T}$ represents the total capacitance of an IDT, and $\boldsymbol{B_a(f)}$ and $\boldsymbol{G_a(f)}$ their susceptance and conductance respectively. Source voltage $\boldsymbol{V_S}$, the source impedance $\boldsymbol{Z_S}$ and the load impedance $\boldsymbol{Z_L}$ (equivalent to $\boldsymbol{R_g}$) which are excluded in the model are also displayed in (Fig. 4). Both the load and input resistance are assumed to be 50 Ω.

The frequency response of such a delay line is the ratio of the voltages $\mathbf{V_2}$ over $\mathbf{V_1}$ and is obtained by performing the Fourier transform of ***h(t)*** for both the IDTs and convoluting them in the frequency domain. It is found that the shape of the frequency response has a ***sinc*** function dependence [25] and is represented as

$$H(f) = 20 \log \left\| 4K^2 C_S W f_0 N_P^2 \left(\frac{\sin X}{X}\right) e^{-j\left(\frac{D+N_P}{f_0}\right)^*} \right\| \qquad (2)$$

Where ***W*** is the aperture or finger overlap in the IDT, $\boldsymbol{N_P=M=N}$ are the number of IDT finger pairs and ***D*** is the delay length in wavelengths between the IDTs. The variable defined as ***X*** in equation 2 is $N_P \pi \left(\frac{f-f_0}{f}\right)$ where ***f*** is the instantaneous frequency at any instant of time ***t.*** The other parameters that are modelled are given by the expressions

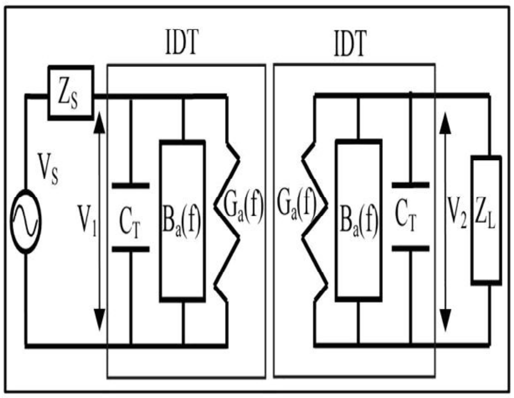

Fig. 4: Equivalent Circuit for SAW Delay Line in Impulse Response Model

1. Radiation conductance $G_a(f)$ (real part of IDT admittance)

$$G_a(f) = 8\,K^2 C_S W f_0 N_P^2 \left|\frac{\sin X}{X}\right|^2 \quad (3)$$

2. Acoustic susceptance (imaginary part of IDT admittance) is obtained by performing Hilbert transform of $G_a(f)$. It is usually normalized using radiation conductance as acoustic susceptance disappears at the synchronous centre frequency f_0

$$B_a(f) = G_a(f_0)\left[\frac{\sin(2X) - 2X}{2X^2}\right] \quad (4)$$

3. Total static capacitance C_T of the IDT (with a factor 1.44 added to include split geometry) is

$$C_T = C_S W N_P \quad (5)$$

4. Total admittance of the IDT

$$y = G_a + j(2\pi f\, C_T + B_a) \quad (6)$$

5. Impedance of the IDT is obtained by inverting the above admittance equation[139]

$$Z_f = \left(\frac{1}{G + j(2\pi f\, C_T + B_a)}\right) \quad (7)$$

6. Transmission loss of the delay which is a function of the frequency [72] is

$$IL(f) = -10\log\left[\frac{2\,G_a(f) R_g}{\left(1 + G_a(f) R_g\right)^2 + \left[R_g\left(2\pi f C_T + B_a(f)\right)^2\right]}\right] \quad (8)$$

4. RESULTS & CONCLUSION

In this model, it is assumed that SAW velocity under metallized IDT is different from the free surface SAW velocity $\boldsymbol{v_0}$ and that the actual SAW velocity, referred to as effective velocity $\boldsymbol{v_s}$ as given below by equation (9) in [4] determines the device frequency shift.

$$v_s = v_0 - \left[\frac{K^2 v_0}{2}\right] \quad (9)$$

The modelling algorithm was run several times by varying the free surface SAW velocity $\boldsymbol{v_0}$ for Quartz substrate around ***3157 m/s*** and every time the modelled results with shift in centre frequency and wave velocity $\boldsymbol{v_0}$ were graphically analyzed as well as imported to Microsoft Excel for comparison with the measured results. The best fit was obtained when the parameter $\boldsymbol{v_0}$ was equal to ***3153.5 m/s***. The MATLAB algorithm was codified to generate plots of modelled parameters as a function of frequency so as to infer their behaviour directly. In addition to the above, algorithm also had the flexibility to simulate device parameters for various sets of SAW delay lines simul-taneously. The modelled graphic output of various parameters corresponding to a value of v_o = 3153.5 m/s are depicted in Figure 5(A, B, C, D, E). These five plots display the parameters transfer function '$H_n(f)$', delay time, acoustic susceptance '$B_n(f)$', radiation conductance '$G_n(f)$' and insertion loss 'IL(f)', wherein the subscript 'n' denotes that the parameter has been normalized. A comparison of the modelled parameters and their measured values is shown in (Fig. 6) and is summarized in Table 2.

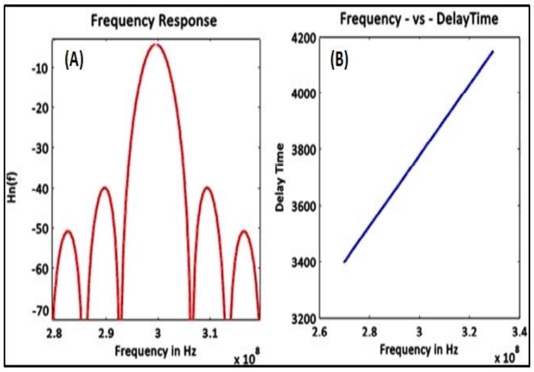

Fig. 5(i) : Impulse Response Model MATLAB Output

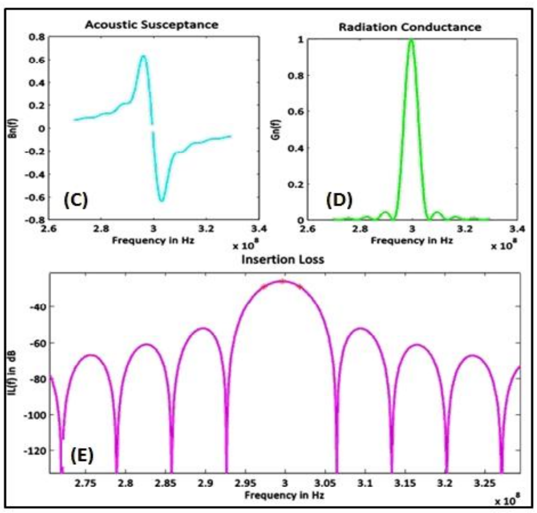

Fig. 5(ii) : Impulse Response Model MATLAB Output

A comparison of the modelled frequency response with the measured values (figure 8) demonstrates for the first time (hitherto never reported for a 300 MHz device) how this first order model replicates in an excellent manner, the main characteristics of the central lobe and the subsequent side lobes taking in to effect the second order effects such as EMF, TTE and circuit parasitics. All important parameters like ***observed frequency shift, time delay and insertion loss*** are accurately modelled and predicted. The only mismatch is in the ***insertion loss*** (around ~3 dB) observed between the modelled value of insertion loss ***(-25.7924 dB)*** *and its measured value* ***(-29.2029 dB).***

Table 2. Comparison of Modelled and Measured Values

S. No.	Parameter		Modelled Result	Measured Result
1	Centre Frequency	f_0	2.9955e+008 Hz	2.995625e+008 Hz
2	Delay Time	τ	2.0038e-006 sec	2-01e-006 sec
3	Insertion Loss	$IL(f)$	-25.7924 dB	-29.2029 dB
4	3dB Bandwidth	BW	4.4834e+006 Hz	4.4975 e+006 Hz
5	Effective Velocity of SAW	v_s	3.151e+003 m/s	Not Measured
6	Total Static Capacitance	C_T	3.6255e-012 f	Not Measured

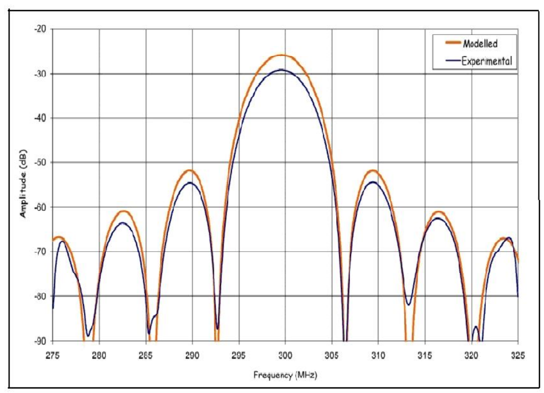

Fig. 6 : Comparison of Modelled and Measured Values

5. ACKNOWLEDGEMENTS

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