Research Article

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A Comparison of Surface Acoustic Wave (SAW) Delay Line Modelling Techniques for Sensor Applications

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ABSTRACT

This paper describes a comparative modelling study of Surface Acoustic Wave (SAW) devices. The Surface Acoustic Waves (SAWs) are generated and received by the interdigital transducer (IDT) on a piezoelectric substrate. SAW device design parameters like piezoelectric substrate, structure of IDT, number of finger pairs, device frequency and etc., are optimized and its frequency responses achieved by using three models, namely, Impulse response Model, Crossed-field Equivalent Circuit Model and Coupling-of-Modes Model. The modelling of ST-X Quartz based SAW Delay line with 40 finger pairs operating at a centre frequency of 300 MHz has been undertaken and its modelled frequency response studied via three models. Employing a custom made MATLAB® algorithm, the device is modelled by varying its design parameters. The modelled results are analyzed and compared for attaining better performances for potential applications in a SAW sensor.

Keywords: Impulse Response Model; Equivalent Circuit Model; Coupling of Modes Model; SAW delay lines; MATLAB®.

1. INTRODUCTION

In recent scenario, the investigations are focused on sensing technologies and in our daily lives, we interact with a type of sensor and may not realize it. Basically, sensor is a device that converts a physical quantity into a measurable and recognizable signal. The sensors must be sensitive to a desired physical or chemical change while being insensitive to environmental influences (Durdag, 2008). Hence, sensors have become emerging technology and currently being investigated in wide-variety of technological areas (Priya *et al.* 2015). Nowadays, many sensors are available in practice, most promising device is Surface Acoustic Wave (SAW) based sensors, exhibit a high sensitivity to various physical and chemical parameters (Karthikeyan *et al.* 2015). They offer innovative and very promising solutions in a wide range of sensing applications (Elhosni *et al.* 2016). Moreover, it gives timely alert and shows predicting characteristics for the detection of toxic and harmful gases (Raj *et al.* 2013) with desired accuracy.

Surface Acoustic Waves propagates on piezoelectric substrate are excited and detected by inter digital transducers (IDTs). IDT forms the basis for the design of wide variety of SAW devices like delay line, filters, resonators, sensors etc., (Venkatesan and Pandya 2013). One of the most striking properties of SAW is their extremely low velocity about 10^5 times less than EM waves, it operates at a wide range of frequencies from several MHz to few GHz (Banu Priya *et al.* 2014). They possess various frequency characteristics. As passive devices, they introduce losses of several decibel (dB). The insertion loss value depends on SAW device design and piezoelectric substrates (Shen *et al.* 2002).

SAW sensors, can be defined as a transducer that converts an unknown physical quantity using known electromechanical mechanisms into measureable data. The sensor operation consists in measuring time delay changes alteration of SAW propagation in SAW device caused by a parameter that is being measured (Sharma *et al.* 2014; Venkatesan *et al.* 2015). SAW delay line plays the important role of SAW sensors. The travel length between transmitter and receiver IDT is called delay time (fig.1) (Haresh M *et al.* 2013). The delay time produced by a SAW device can be expressed as, $\tau = L/v_0$, where, L is the distance between the centre of the input and output IDT's and v_0 is the velocity of selected piezoelectric substrate.

Modelling of SAW delay line is carried out using three different types of models namely, Impulse Response Model, Crossed-field Equivalent Circuit Model (ECM) and Coupling of Modes (COM) model, each having its own limitations. This paper describes and compares the results obtained from selected models.

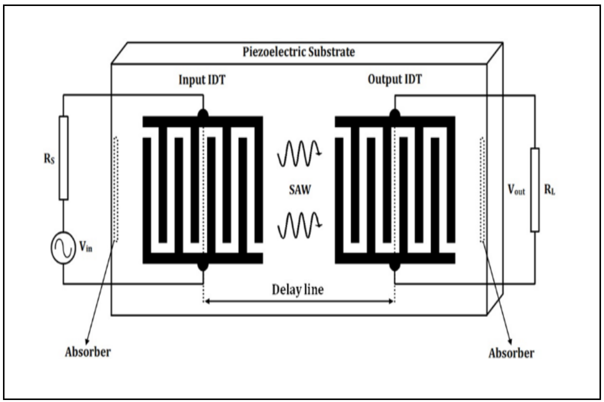

Fig. 1: SAW delay line

2. THEORETICAL ANALYSIS

2.1 Impulse Response Model (IRM)

The Impulse Response Model (IRM) was first introduced by Hartmann *et al.* 1973 as an improvement over the delta function model and is derived from the impulse response of a non-dispersive transducer. This is a first order model that can be used as modelling tool to get data on the piezoelectric materials, includes electro-mechanical behaviour of a SAW transducer as well as additional details about circuit impedances, matching systems and frequency ranges. The Impulse response method was used as the starting position for modelling the SAW delay line (Campbell, 1989).

According to this model, the total energy is found from the impulse response and is equated to the radiation conductance through the Hilbert transform. This model assumes constant and equal spacing and finger widths. A simple mason equivalent circuit model (fig. 2) can be used to convey the basic elements of the Impulse Response Model.

Hartmann was able to establish that the time response ***h(t)*** of a SAW IDT transducer (Campbell, 1989)is given by

$$h(t)\ \alpha\ 4\sqrt{K^2C_S}f_0^{3/2}(t)\,(\sin 2\pi f_0\,t) \qquad (1)$$

where, $K^2$is the electromechanical coupling coefficient, $C_S$is the electrode pair capacitance per unit length (pf/cm-pair) and $f_0$is the center frequency of operation.

Taking Fast Fourier Transform (FFT) of (1) we get,

$$H(f) = 20log\left|\left[4K^2C_sWf_0N^2\left(\frac{sinX}{X}\right)^2 e^{-i\left(\frac{N+D}{f_0}\right)}\right]\right| (2)$$

Where, *H(f)* is frequency response of IDTs, *W* is aperture or finger overlap in the IDT, *Np* = *M* = *N* are the number of IDT finger pairs of input and output IDTs and *D* is the delay length in wavelengths between the IDTs. The variable defined as *X* in equation (2) is, $N_p\pi\left[\left(\frac{f-f_0}{f_0}\right)\right]$, where *f* is the instantaneous frequency at any instant of time t.

Insertion loss of the SAW delay line which is a function of frequency,

$$\mathrm{IL(f)} = -10\log\left[\frac{2\mathrm{G_a(f)R_g}}{\left(1+\mathrm{G_a(f)R_g}\right)^2+\left[\mathrm{R_g}(2\pi\mathrm{fC_T}+\mathrm{B_a(f)})\right]^2}\right] \qquad (3)$$

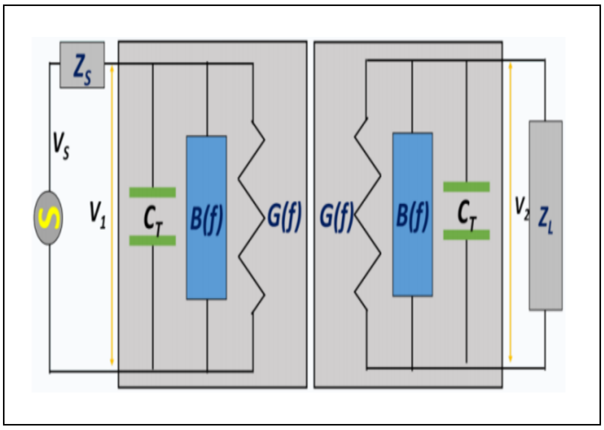

Fig. 2: Mason equivalent circuit for mpulse response model

2.2 The Crossed-field Equivalent Circuit Model (ECM)

For a selected piezoelectric material, the ‘crossed-field’ model is made by evaluating the contribution to SAW excitation due to the electric field components is perpendicular to the surface. The advantage of ECM model is straight forward execution of circuit. In crossed-fieldcircuit model the distribution of electric field under the electrodes of IDT is normal to the piezoelectricsubstrate andis similar to the electric fielddistribution of a parallel plate capacitor as shown in fig. 3 (Smith *et al.* 1969). ECM model may be considered as modified Mason model as shown in fig. 4. In ECM model, the voltage is applied to the electrode of IDT in order to calculate the frequency response H(f), admittance of device, the Effective Transmission Loss (ETL) by improved Impulse response model.

By utilizing circuit theory analysis for the current voltage relations on the input and output side of the equivalent circuit, the parameters like radiation conductance G_a(f), input admittance y_{aa}, output admittance y_{bb}, transfer admittance y_{ab}, voltage transfer function and effective transmission loss are calculated. The corresponding equations are as follow.

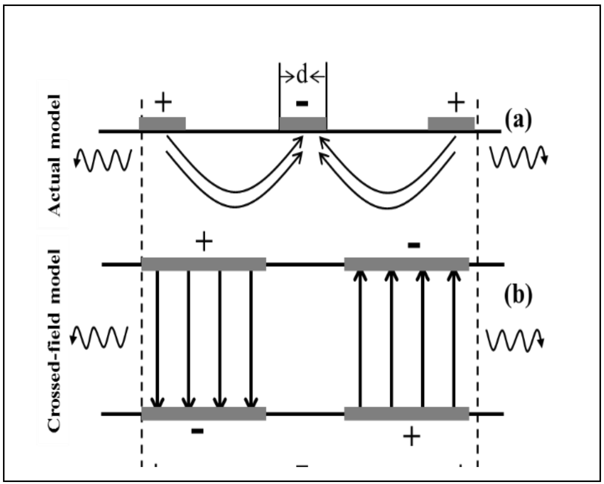

Fig. 3. Electric Field Direction in ECM

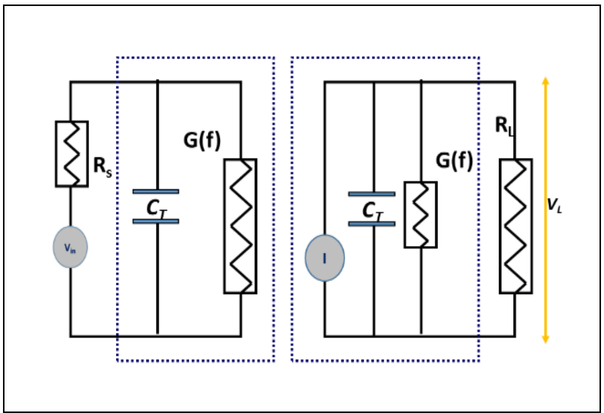

Fig. 4: Mason equivalent circuit for crossed-field equivalent circuit model

The input-output voltage transfer function H(f) is

$$H(f) = \left\{ \frac{Y_{ab} R_L}{[(1 + Y_{aa} R_S) + (1 + Y_{bb} R_L) - Y_{ab}^2 R_S R_L]} \right\}$$

Effective transmission loss(ETL) in decibels as defined by (Devries, 1977).

$$ETL = -20 log_{10} \left| \frac{[(1 + y_{aa} R_s)(1 + y_{bb} R_L) - y_{ab}^2 R_s R_L]\sqrt{R_L / R_S}}{2 R_L y_{ab}} \right|$$

2.3 The Coupling-of-Modes (COM) Model

The Coupling-of-Modes (COM) approach to modelling SAW devices is a refined method that was developed to describe the phenomenological model. Haus (Haus 1977a; Haus and Schmidt 1977; Haus 1977b) first introduced the COM theory in SAW field. The COM theory has the advantage of modelling response of SAW device such as internal transducer reflection analysis (Mathews 1977; Dong-Pei Chen and Haus 1985; Thorvaldsson and Nyffeler 1986)when half wavelength finger spacing is used (Brown *et al.* 1989) and Single Phase Unidirectional Transducer (SPUDT) devices (Hartmann *et al.* 1982). The modelling parameters here is to model a SAW device by calculating the transfer function by applying appropriate boundary conditions (Haus and Huang 1991). In fig. 5, the building blocks of SAW delay line can be divided in to 3 segments namely, input IDT, output IDT and the gap or delay length between them.

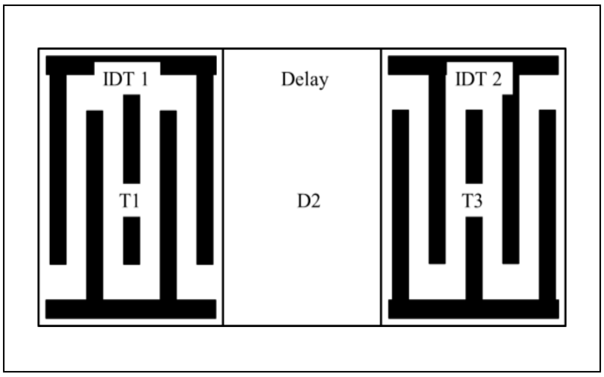

Fig. 5: COM model based SAW delay line

These segments are represented by their transmission matrices and then finally the total device transmission matrix [M] is written as

$$[M] = [T_1][D_2][T_3]$$

The scattering matrix of an IDT is represented as

$$[T] = \begin{bmatrix} s(1 + t_0)e^{j\theta_t} & -st_0 & t_{13} \\ st_0 & s(1 - t_0)e^{-j\theta_t} & t_{13}e^{-j\theta_t} \\ st_{13} & -st_{13}e^{-j\theta_t} & t_{33} \end{bmatrix}$$

$[D_2]$ represents the 2x2 matrix of the gap in between the IDTs and is given by

$$[D] = \begin{bmatrix} e^{j\beta d} & 0 \\ 0 & e^{-j\beta d} \end{bmatrix}$$

Where β=2π/λ is called phase constant, d is the gap length and λ is the wavelength at the given frequency f.

3. MODELLING STRATEGY

In the present study, a SAW delay line of 300 MHz is modelled for analyze the frequency response using a custom made algorithm have been developed in MATLAB®. SAW delay line was fabricated on piezoelectric substrate with the IDTs wereemployed synchronously and the input parameters are listed in table 1. We will employ all of these designing parameters in our modelling study adapting the selected three models through the flow chart as shown in fig. 6.

Table 1. Input parameters for modelling of SAW device

S. No	Parameter (Symbol)	Values
1	Coupling coefficient (K^2)	0.0016 (ST-X Quartz)
2	SAW velocity (v_s)	3158 m/s (ST-X Quartz)
3	Operating frequency (f_0)	300 MHz
4	IDT geometry	Single Geometry Double Geometry
5	Finger width (d)	2.6317 µm (Single Geometry) 1.3159 µm (Double Geometry)
6	Wavelength (λ)	10.5267 µm
7	Aperture (W)	100 λ
8	Number of finger pairs ($N_P = N = M$)	40 finger pairs
9	Load and Source resistance (R_L *and* R_s)	50 Ω

4. RESULTS & DISCUSSION

The MATLAB® algorithm was generated, where the basic input parameters are taken from table 1 and the output results were then obtained in graphically as well as numerical values were exported in *.xls* formats and successively saved on to Excel files for future analysis and comparison. The output parameters and their values are listed in table 2.

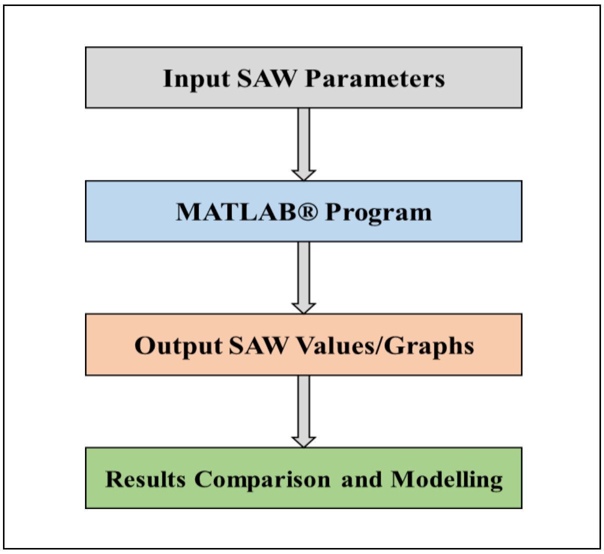

Fig. 6: Flow chart

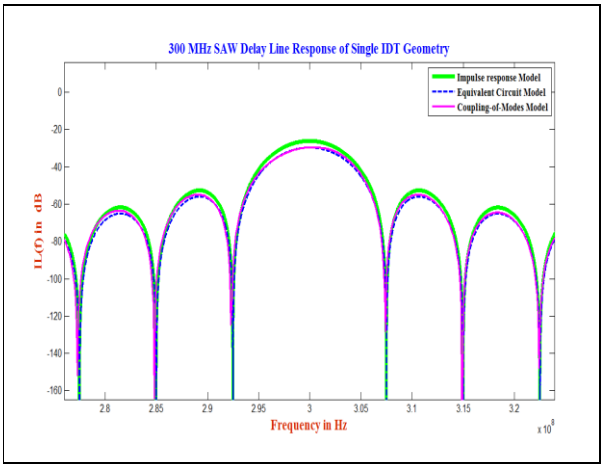

Fig. 7: Modelled responses of 300 MHz SAW delay line for single IDT geometry

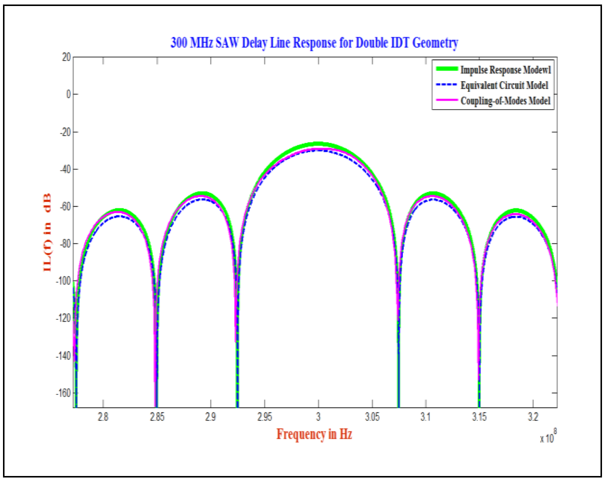

Fig. 8: Modelled responses of 300 MHz SAW delay line for double IDT geometry

Table 2. Modelled output values of 300 MHz SAW delay line

Model	Single IDT Geometry		Double IDT Geometry	
	Insertion Loss (dB)	3dB Bandwidth (MHz)	Insertion Loss(dB)	3dB Bandwidth (MHz)
IR Model	-26.22	4.9	-26.63	5.0
EC Model	-29.67	4.8	-30.08	4.8
COM Model	-29.62	5.1	-29.14	5.1

5. CONCLUSION

The SAW delay line device was modelled using the Impulse Response model, Crossed Field Equivalent circuit model and COM model with 40 finger pairs operating at a frequency of 300 MHz. SAW device design parameters were optimized and its frequency responses were obtained by employing a custom made MATLAB® algorithm.A comparision of graphical results wereachievedconveniently from the selected three models. The deviceresponses realisationfor attaining better performances for potential applications in a SAW sensor with validation in the future experimentally.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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