J. Environ. Nanotechnol.
Volume 3, No.3 pp. 106-115
ISSN (Print): 2279-0748
ISSN (Online): 2319-5541
doi: 10.13074/jent.2014.09.143101

SAW Devices – A Comprehensive Review

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Received:03.05.2014 Accepted:05.08.2014

Abstract

Surface Acoustic Waves (SAWs) are elastic waves travelling along the surface of solid piezoelectric materials with amplitude that decays exponentially with depth. Using an Interdigital Transducer (IDT), these waves can be demonstrated and reproduced in the laboratory in devices called SAW devices. Such devices find many applications as delay lines, filters, resonators and sensors. The present paper provides a snapshot review and description of the functioning, operation and latest technical advancements seen in these devices over the period from 2003-2012. For improvement in design, development, fabrication and characterization of these devices, computational modeling plays a prominent and pivotal role. Employing unique custom made software algorithms based on well established principles of physics, these devices are accurately modeled and simulated and a short review and description of the strategy adopted for the same is also provided.

Keywords: *Surface Acoustic wave; Interdigital Transducer.*

1. INTRODUCTION

The existence of surface acoustic waves (SAW) was highlighted in by(Lord Rayleigh in 1885). Subsequently in the days to come, a major factor in the emergence of SAW technology was the invention of the Interdigital Transducer (IDT) by (White and Voltmer in 1965). An IDT is a device which consists of two interlocking comb-shaped metallic Aluminium coatings which are fixed on to a piezoelectric substrate such as Quartz or Lithium Niobate to effectively convert applied RF electrical pulses to mechanical energy and vice versa. Such a transducer forms the basis for the design of a wide variety of SAW devices like delay lines, band pass filters, resonators and sensors. One of the most striking properties of SAWs is their extremely low velocity-about 10^5 times less than EM waves and over a wide spectrum of operating frequencies ranging from approximately 10 MHz to 12 GHz. Traditional usage of these devices has been primarily in the telecommunications industry and in mobile phones and related base stations. Emerging applications include SAW sensors for a variety of measurements like torque and tyre pressure sensors biosensors for medical applications (Ballantine. D. S et al., 1997;), gas sensors (Levit. N et al., 2002) and industrial and commercial applications such as: vapor, humidity, temperature, and mass sensors (Bowers. W et al., 1991, Vetelino. K. A et al., 1996, Weld. C. E et al., 1999). The present paper reviews the physics underlying a majority of these devices.

2. SAW DELAY LINE

The simplest and the earliest of SAW devices is the SAW delay line consisting of two simple IDT structures (Figure 1). One IDT acts as the input or the transmitting IDT which converts electrical signal to acoustic energy that propagates on the surface of the piezoelectric substrate to the output transducer which converts acoustic energy back to an electric signal creating a delay equivalent to the time taken by SAW to travel between the two IDTs. Variation of the SAW travel length between the IDTs can be manipulated to get delays of different magnitude typically in the range of 1-50 μsec. To streamline the direction of flow of SAW and confine it to only one direction, absorbers are used at the end of the device to attenuate it.

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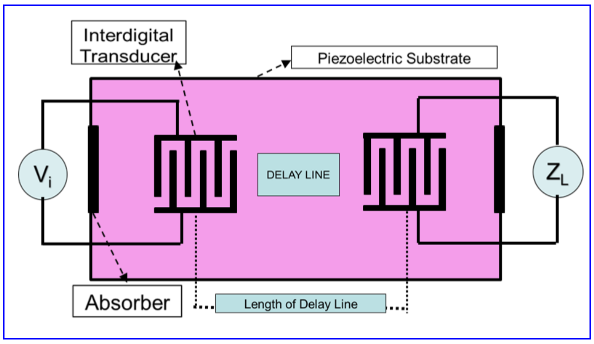

Fig. 1: Schematic of a delay line with uniform IDTs

The delay produced by a SAW device can be expressed as $\tau = L/\upsilon_0$ ---------------(1)

where τ is the delay time, L is the mean spacing between input and output IDTs and υ_0 is the SAW propagation speed.

3. SAW FILTERS

SAW filters are electromechanical devices commonly used in radio frequency applications. These devices are similar to the delay lines in their structure (Figure 2). The delayed outputs from the IDTs are recombined to produce a direct

analog implementation of a finite impulse response filter. The frequency and phase response of a Band pass filter is shown (Figure 3).Table 1 & 2 summarizes recent work done by different researchers on SAW delay lines and SAW filters.

Table 1. Recent Research in SAW Delay Lines

Reference	Substrate	Orientation	Centre Frequency	Insertion Loss[dB]	Result
R.T.Webster (1985)	GaAs	[100], [110]	1.5 GHz	-30	Low TCF Calculated*
J. Enderlein et al., (1995)	$GaAs/SiO_2/Au$	[100], [110]	-	-	TCD & TCF Calculated*
Waldmer Solouch (1998)	$LiNbO_3$	128° YX	70 MHz	-15	Triple Transit Signals effectively suppressed
Tooru Nomura & Atsushi Saitoh (2002)	$LiTaO_3$	36 ° YX	40 MHz	- 33	High Sensitivity and Linear result obtained
J.Hechner & W.Soluch (2005)	$LiNbO_3/SiO_2/Al$	41° YX	80 MHz	-15	Measured Liquid Viscosity and Conductivity
J. Xu et al., (2005)	AlN/Al_2O_3	0001/1120	260 MHz	-	Minimum mass of SAW 23 pg/cm ^{2} & SH-SAW 31 pg/cm ^{2} detected
W.Soluch& E.Brzozowski (2007)	$GdCa_4O(BO_3)_3$	XZ, YX, ZX	100 MHz 110MHz 101 MHz	-17.3, -15, -18.7	Obtained Low Insertion Loss in the temperature range 20-200 ^{0} C
Ville Viikari et al., (2009)	$LiNbO_3$	YX	245 MHz	~ 40	Relative Time Delay 2.8 µs calculated
Hoang-Si-Hong et al., (2012)	AlN/Si, ZnO seed layer/AlN/Si, ZnO nano rod/ZnO seed layer/AlN/Si	002/100	129.1 MHz 125.56 MHz 123.53MHz	-26.99, -27.50, -27.92	Humidity (RH) range from 10% to 90% at 25 ^{0}C obtained

***TCD** - Temperature co-efficient of delay ***TCF** - Temperature co-efficient of frequency

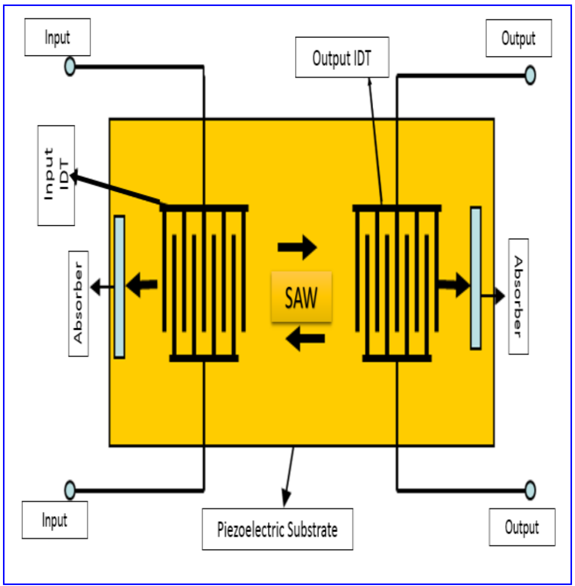

Fig. 2: Schematic diagram of a SAW Filter

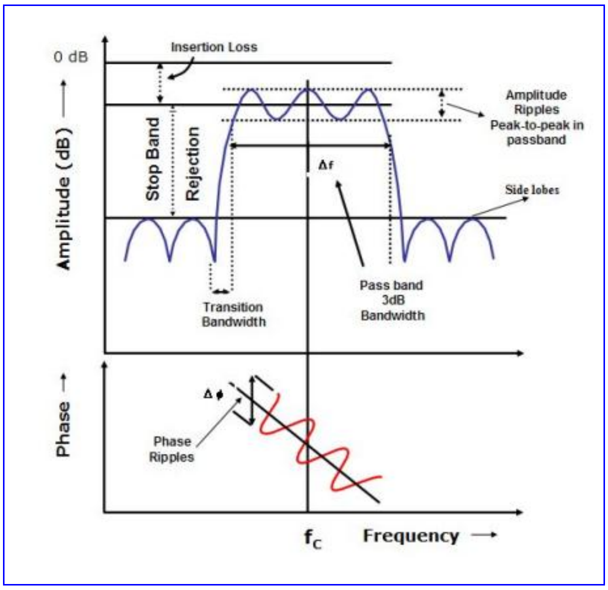

Fig. 3: Schematic frequency & phase response of a SAW band-pass filter.

Table 2. Recent Research in SAW Filters

Reference	Substrate	Orientation	Centre Frequency [MHZ]	Band width	Insertion Loss [dB]	Result
Mitsutaka Hikita et al., (1985)	$LiTaO_3$	36º, YX	830 MHz	(25-27) MHz	-(3.5 to 4)	Designed 800 MHz high performance SAW filters for mobile phones
James.W.Culver et al., (1988)	$LiNbO_3$	YX	300 MHz	100 MHz	-	Reduction in size of DCPTF * compared to PTF *
Paul.T.M.Van Zeiji (1992)	$LiNbO_3$	YZ	100 MHz	5 MHz	-1.5	Noise & Dynamic range of a filter amplifier Calculated
Hiromi Yatsuda et al., (1995)	$LiNbO_3$	64º, YX	0.8MHz 1.9 MHz 2.4 MHz	~ 40 MHz	-16, -19, -26	Designed Miniature SAW filters in the range 1to 3 GHz for wireless application
OU Hok Huor et al., (1995)	$LiTaO_3$	36º, YX	800 MHz	~ 30 MHz	- 2.5	Developed a super high Power SAW Filter by ordinary SAW filter
Hiroyuki Odagawa et al., (1998)	$LiNbO_3$	128º, YX	10 GHz	200 MHz	-3.4	Investigated 10 GHz range low loss ladder type Saw filters
Andreas Springer et al., (1999)	$LiTaO_3$	YX	3.15 GHz	128 MHz	-1.7	Designed and fabricated a ladder type filter at 3.15 GHz
Jingze Tian et al., (2005)	$LiTaO_3/Si_3N_4/$ DLC	YX	922 MHz	59 MHz	-4.7	Si_3N_4 and DLC† passivation layers on characteristics of SAW filters studied
King-Yuen Wong & Wai-Yip(2005)	ZnO/Al(IDT)/ Diamond	YX	1198 MHz 1500 MHz	31.9 MHz 32.2 MHz	-12.84, -7.09	Analyzed Frequency Response using Finite Difference Time Domain method
Marija F.Hribsek et al., (2010)	$LiNbO_3$	ST, Quartz	72 MHz	2 MHz	-12	Designed Algorithms and measured Frequency Response
Satoshi Fujii & Jian (2012)	SiO_2/IDT/AlN/ Diamond structure	(001),[100]	5.2 GHz	30 MHz	-0.76	Resolved interference in Wireless LAN by developing a 5.2 GHz Bandstop filter

* **DCPTF** - Digitally controlled programmable transversal filter, **PTF** - Programmable transversal filter

† **DLC** – Diamond like Carbon

Kiyoharu Tagawa et al., (2005) presented an optimum design approach to tackle the structural design of SAW filters. The frequency response of such SAW filters are governed by configurations of IDT's and grating reflectors fabricated on piezoelectric substrates. Besides optimization methods, computer aided design technique utilized the equivalent circuit model of IDT to evaluate frequency response in SAW filters through computer simulation. In order to lessen the effect of design imperfections, causing dispersion of certain parameters the Taguchi method was employed.

T. Wang et al., (2007) have reported employing the concept of neural networks to extract the lumped element parameters of bonding pads and internal arrangements for ladder-type SAW filters.

4. SAW RESONATOR

SAW Resonator employs surface acoustic wave, and is able to be applied to high frequency circuit where conventional crystal, ceramic resonators are not available, as SAW Resonator oscillates stably with its fundamental mode over frequency range from 200 MHz to around 1 GHz (http://www.token.com.tw/) Resonance can be generated by placing a grating at the propagation direction of a SAW excited by IDT. A one-port SAW resonator consists of one IDT with reflective gratings on either side (Figure 4).

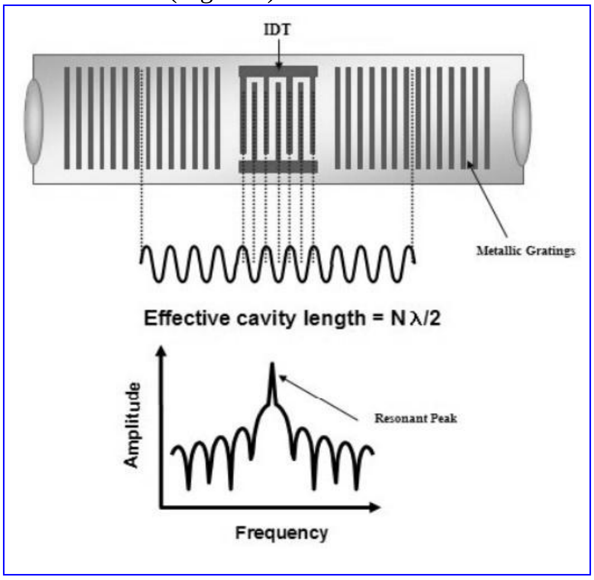

Fig. 4: One port SAW resonator & its frequency response.

These reflective metallic gratings are placed in an array such that their spacing is λ/2, where

$$\lambda = v/f_0 \text{ ----------- } (2)$$

ν is the phase velocity, f_0 is the centre frequency and λ is the SAW wavelength. The reflective gratings can be used to produce moderately high Q (Quality factor) resonators as these can be used to form a resonant cavity around an IDT source-receiver pair. Since the grating is sharply resonant compared to the IDT, it gives rise to a sharp resonant spike superimposed on the broad maximum IDT insertion loss curve. Moreover, as SAW devices are inherently small and rugged, high operating frequencies limited to the present day's micro fabrication facilities, can also be achieved. Review of recent developments in SAW resonator technology is provided below.

Tooru Nomura et al., (1998) have reported investigations on a one-port surface acoustic wave (SAW) resonators incorporating Langmuir-Blodgett (LB) films. LB method is suitable to produce a uniform and thin coating film, which is important for stability and reproducibility of SAW sensors. LB films have the advantage that they can be deposited accurately down to monomolecular thickness. A 90 MHz SAW and a one-port resonator configuration was used as the sensing element. Ultra-thin monolayer of arachidic acid and arachidic acid ethyl ester were deposited. Experimental results showed that the Q values and the resonant frequencies of the resonator device varied with film mass loading on the SAW device surface.

P. Smole et al., (2003) demonstrated the tuning of the center frequency of a one-port resonator as a basic filter element by changing the propagation velocity underneath the IDT. A tunability in center frequency of –1.2 % at 1.21 GHz was demonstrated by this fabrication technique in comparison to -0.26% achieved with samples realized with a conventional layer by layer deposition technique. The difference in tunability was demonstrated with TEM and XRD investigations.

Ji Wang et al., (2006) analyzed the periodic structure of electrodes on a substrate of SAW resonators with two dimensional equations. Xiangwen Zhang et al., (2007) have highlighted key techniques in research, such as coding and decoding of the sensor nodes, signal frequency measurement of the sensor nodes, intelligent signal processing, measurement error compensation and network security techniques. Marc Loschonsky et al., (2008) presented the results of fabrication and measurement of Metal-Organic-Vapour-Phase-Epitaxy (MOVPE) grown on a-plane and c-plane Gallium Nitride based SAW resonators on r-plane

Sapphire substrates. The devices showed quality factors of higher than 800 at 3 GHz for a-plane Gallium Nitride and higher than 3000 for c-plane oriented thin films. Both types of materials were used to buildup resonators and their scattering parameters, temperature co-efficient up to 200^{0}C and wave velocities were measured. Roland Salut et al., (2009) reported the design of single and double port SAW resonators operating near 5GHz and measured their characteristics.

Roshan Kshetrimayum et al., (2011) illustrated polymer coated (SAW) resonators by combining Coupling-of-Mode (COM) description of SAW resonators and perturbation calculation of SAW propagation under polymer loading. The Coupling-of-Modes (COM) (Pierce. J. R., 1954) theory is a refined method that was developed to describe the phenomenon of coupling of waves in microwave tubes. COM theory has been widely used to analyze different types of SAW devices, such as resonators and single phase unidirectional transducers. Simulation results were presented for one-port and two-port resonator devices coated with visco-elastic thin polymer film. The influence of polymer film on resonator response is studied with regard to variations in film thickness and shear modulus. This model simplifies understanding of polymer-coated SAW sensors.

A.N.Nordin et al., (2011) described the design and implementation of RF CMOS SAW resonator. The resonators were fabricated using standard IBM 0.18 micrometre technology to achieve desired resonant frequency and subsequently based on these measurements, an associated equivalent circuit model was developed to make an in-depth study of the physics and dynamics of these devices.

Dong Chen et al., (2011) compared traditional piezoelectric substrates for design of SAW devices. For design of the SAW stress sensor, Sezawa mode is considered in comparison with Rayleigh mode. The reason being Sezawa mode exhibits higher phase velocity and electromechanical coupling co-efficient for frequency thickness (f_h) ranging from 0.75 to 3.5 GHz.µm. SAW devices in ZnO/Si structures exhibit excellent mechanical properties of silicon, higher electromechanical coupling coefficient, higher SAW phase velocity, compatibility with MEMS batch process etc.,. The results conclusively showed that the stress sensitivity of the senor is high, adjustable, and the relative frequency shift exhibits good linearity, which makes the sensor a suitable choice for stress measurement in thin gap. The uniform contact stress sensor was used in the calculation range from 0 Mpa to 6 Mpa with step 1 Mpa.

5. SAW SENSOR

Acoustic wave sensors are extremely versatile devices that are just beginning to realize their commercial potential for transduction of physical and chemical quantities. Figure 5 depicts a SAW sensor having sensing element coated with thin polymeric material for detection and monitoring of vapor and gases. Due to the sensitivity of the surface acoustic wave to even the slightest perturbations, small effects caused by different phenomena can be detected. Almost all physical quantities like surface mass, stress (Jerzy Filipiak et al.,2007), strain, temperature (Donald C.Malocha et al.,2013), pressure (M.Benneti et al.,2008) etc., can be measured by SAW sensors. In addition, SAW sensors are miniaturized, rugged, highly sensitive, reliable, cost-effective and fast real time response.

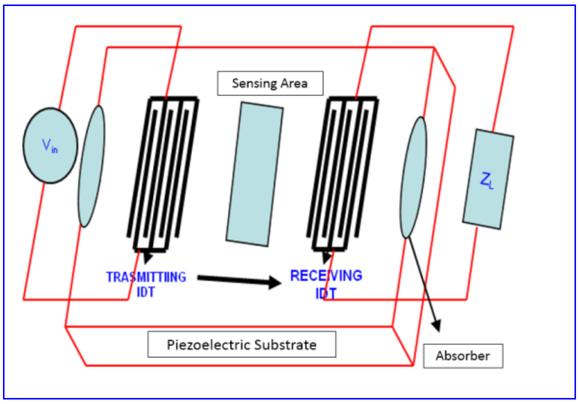

Fig. 5: Schematic diagram of a SAW sensor

In most SAW sensors, the mass loading effect is predominantly employed. Under the assumption that the mass layer adsorbed on the surface is thin or rigid, the mass-induced change in SAW velocity can be written as

$$\frac{\Delta v}{v_o} = -c_m f_o \rho_s,$$

Where C_m is called the mass sensitivity factor.

$$c_m = \frac{\pi v_o}{2}\left(\frac{v_{xo}^2}{\omega P} + \frac{v_{yo}^2}{\omega P} + \frac{v_{zo}^2}{\omega P}\right).$$

Where, v_{xo}, v_{yo}, and v_{zo} are the SAW particle velocities at the surface and ρ_s is the surface mass density, $\Delta v/v_o$ is the fractional velocity change and f_o is the operating frequency (Moises Levy 2008).

Dominique Rebiere et al., (1994) have compared two acoustic propagation modes-(SAW and SH-APM). The sensitivity of these configurations to flow rate at various heating power levels were presented and discussed. Experiment shows that for the SAW mode, sensitivity equals 7 KHz and for SH-APM mode sensitivity equals 30 KHz was achieved.

W.Welsch et al., (1997) presented the utilization of horizontally polarized SAW for immunosensing in liquids. A dual delay-line device on a $LiTaO_3$ substrate working at 345 MHz to detect immunoglobulins of type G in phosphate buffer was used. From the experimental results a sensitivity of 112.5 kHz (nano gram $mm^{-2})^{-1}$ and detection limit of 35 pico gram for the absolute mass was detected to find a quadratic frequency dependence of the sensor signal thereby indicating the presence of a mass-loading effect.

Xiaojun Tong and De Zhang., (1999) have reported the propagation properties of a Quasi-Longitudinal Leaky Surface Acoustic Wave (QLLSAW) sensors with higher phase velocity and small propagation attenuation. Sensors with this Acoustic Wave mode can achieve higher work frequency than normal SAW sensors. QLLSAW propagates with large propagation attenuation of about 1.5 dB/λ and normal SAW sensors can be absorbed by liquid, however, QLLSAW can propagate along liquid/solid interface with small propagation attenuation. Experimental evidences showed that Quasi-Longitudinal Leaky QLLSAW may be applied to liquid-sensing application directly. designed and implemented three SAW oscillators for sensor applications. Two of them were designed for two-port resonator SAWs at 315 MHz and 915 MHz and the third was designed for two-port delay line SAWs at 260 MHz.

Demonstrated four-sensor passive wireless Orthogonal Frequency Coding (OFC) SAW system at 915 MHz., and they have reported that both software and hardware improvements are necessary to increase accuracy and reduce spurious noise. This approach provides enhanced code collision immunity, higher processing gain and lower losses which provide a robust multi-sensor system.

Fabio Cenni et al., (2010) designed a microelectronics interface for a SAW chemical sensor aimed at gas detection. Such a sensor interacts with a gas, identifies its unique breakdown voltage and thereby detects the concentration of the gas. Even minute concentrations of trace gases can be identified. Gas sensors find applications in Process control industries, Environmental monitoring, Boiler control etc., The microelectronics front end architecture was designed at transistor level with 0.35μm CMOS technology and the device was embedded in a phase locked loop (PLL) that converted the change of concentration of gaseous mercury into a frequency shift of the loop frequency.

6. SAW DEVICE MODELLING

Computational device modeling oflate has become an inseparable and essential part of scientific research and from a device designer's point of view, if the device model is able to accurately predict device performance in varied situations, then such a procedure comes as a handy cost and time cutting tool to derive optimum benefits from a device.

Modeling of SAW devices is resorted to achieve two primary objectives: (i) to comprehend propagation, generation and detection of acoustic waves in piezoelectric materials and (ii) to analyze and design structures such as IDTs, delay lines, filters, resonators etc., to achieve desired frequency responses. Modeling techniques need to deliver fast and accurate results, be easy to compute and distinctly offer connections between modeled parameters and device performance.

Generation and transduction of acoustic waves on a piezoelectric substrate has led to the development of several different models. Numerous modeling approaches have been presented over the years and to name the important i) Impulse Response Model ii) Equivalent Circuit Model iii) Coupling of Modes Model iv) Transmission Matrix Model etc .,

The Impulse Response Model (White. R.M., 1967) is primarily a first order model that can be used as a fast tool to obtain information on the piezoelectric, mechanical and electrical behavior of a SAW transducer as well as additional details regarding circuit impedances, conductance, matching networks and frequency scaling. The analysis and design of SAW transducers by an impulse response description has been discussed by several authors in detail (R. H. Tancrell et al., 1971, C. C. Tseng., 1968, T.Venkatesan 2013 et al.,). This is a first order model that does not take into account any second order effects such as reflections, spurious bulk acoustic wave (BAW) generation, wave diffraction, beam steering due to anisotropy of substrate, electromagnetic feed through between IDTs, mechanical loading, to name a few relevant phenomena. Finite impulse response filters have lower selectivity than IIR (infinite impulse response filters) filters.

In the Equivalent Circuit Model, (W. R. Smith et al., 1969) SAW propagation is modeled as EM signal propagation in a transmission line and includes signal generation due to an applied voltage, current generation in the load as well as losses and energy storage effects as shown in Figure 6. A SAW delay line is modeled as a device possessing two acoustic ports and one electrical port. The acoustic ports represent mechanical waves traveling into and out of the IDT whereas the electrical ports represent the current and voltage of the IDT. The greatest advantage this model offers is that it can be easily implemented in circuit simulation tools (W. F. P. W. R. Smith, 1975). The equivalent circuit model is a cross field model where the electric fields are considered to be normal to the piezoelectric substrate as shown in Figure 7. This model is technically robust but difficulties are faced while trying to incorporate certain second order effects like diffraction, backscattering, charge distribution and electrical / mechanical perturbations in the model and certain other wave types like Leaky waves or Surface transverse waves.

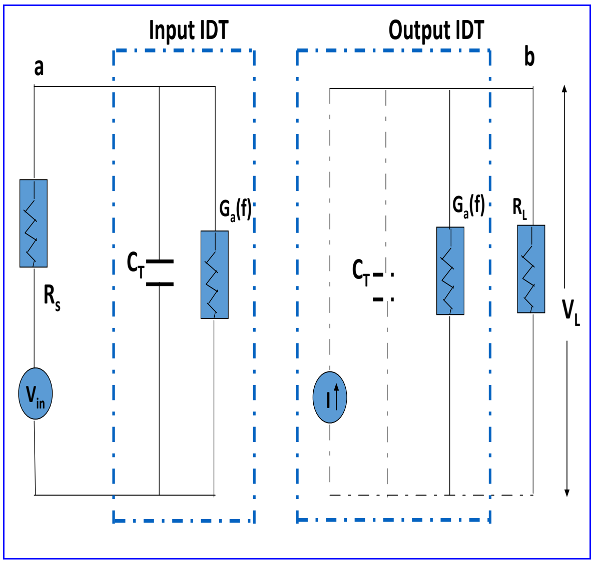

Fig. 6: Equivalent circuit for SAW delay line in crossed-field model

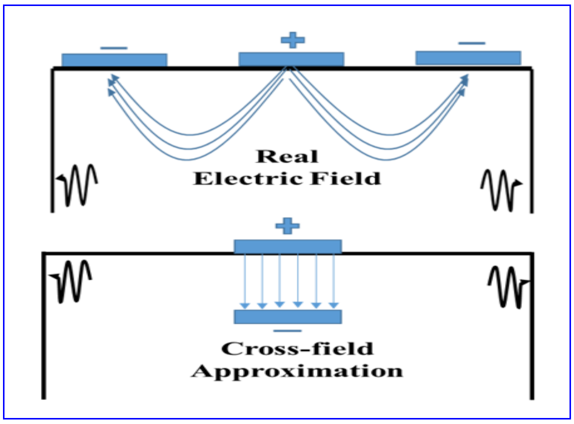

Fig. 7: E field direction in cross-field ECM model

The Coupling-of-Modes (COM) theory by (Pierce.J.R., 1954) is a refined method that was developed to describe the phenomenon of coupling of waves in microwave tubes, and subsequently has been successfully applied in analyzing a wide range of devices including holograms and waveguide couplers in opto electronics. COM theory has been used to effectively analyze different types of SAW devices, such as resonators and single phase unidirectional transducers. In this model, accurate results are obtained in narrow frequency range. For wide frequency range, phenomena like generation of bulk waves, coupling to bulk modes and the spatial harmonics at higher frequencies influence the device characteristic but they are excluded from COM model.

One of the successful implementation of modeling strategies and techniques for SAW devices has been studied and carried out in which a 300 MHz SAW delay line fabricated on ST-X quartz crystal with 28.5 IDT finger pairs and split geometry was first modeled, simulated and then the results obtained from such a process was validated with experimental results. And the results have been found to be very satisfactory. The simulations were performed using a combination of software programming using Visual Basic as a front end tool and MATLAB®, as the main back end tool. In the above study, graphic results were imported to Microsoft Excel for viewing, analysis and comparison of the plots obtained and modeled results have been experimentally validated too. Equivalent Circuit Modeling results in the above study are presented below.

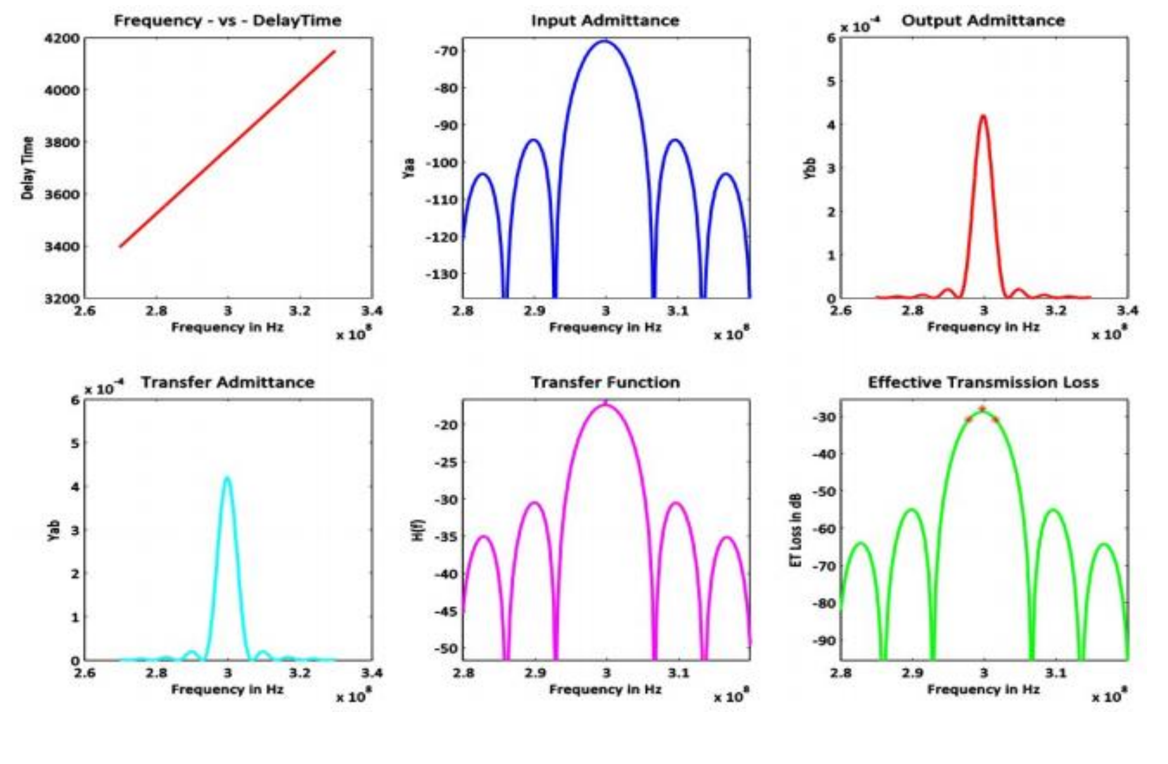

Fig. 8: Crossed-Field ECM MATLAB Graphic Output.

Table 3. MATLAB® input and output modeling parameters.

S.No	Input Parameters	Value used	Output Parameters
1.	Coupling Co-Efficient (k^2)	0.0016(quartz)	Effective velocity of SAW (V_s)
2.	Capacitance of finger pair/unit length (C_s)	$0.05x10^{-10}$ farad/m(quartz)	Centre Frequency(f_0)
3.	SAW free velocity on quartz (v_0)	Modeling parameter varied around 3157 m/s	Delay time (τ)
4.	Centre Frequency (f_0)	300MHz	Total Input & output IDT Capacitance (CT_i & CT_0)
5.	IDT Geometry	Split Geometry	Electrical admittance of single period IDT (G_0)
6.	IDT Electrode pairs in input and output ($M=N=N_P$)	43.5	Insertion loss I_L (f)
7.	Load Resistance (R_g)	50 ohms	3 dB Bandwidth BW

7. CONCLUSION

An attempt has been made in this paper to highlight and describe the physics of SAW devices and their different types with their corresponding principles. Recent research work done in these areas from 2003-2012 has also been reviewed and listed. Additionally the paper also highlights how the above devices are computationally modelled and simulated. The authors feel that there still remains a large scope for device effects that can be incorporated for obtaining greater accuracy during modelling and simulation purposes.

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