

# Rapid SAW Sensor Development Tools

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## ABSTRACT

The lack of integrated design tools for Surface Acoustic Wave (SAW) devices has led us to develop tools for the design, modeling, analysis, and automatic layout generation of SAW devices. These tools enable rapid development of wireless SAW sensors. The tools developed have been designed to integrate into existing Electronic Design Automation (EDA) tools to take advantage of existing 3D modeling, and Finite Element Analysis (FEA). This paper presents the SAW design, modeling, analysis, and automated layout generation tools.

**Keywords:** Design automation, modeling, simulation, software prototyping, surface acoustic waves.

## 1. INTRODUCTION

Integrated Vehicle Health Monitoring (IVHM) of aerospace vehicles requires rugged sensors with reduced volume, mass, and power, to measure a variety of phenomena. Wireless systems are preferred when retrofitting sensors onto existing vehicles [1]. Surface Acoustic Wave (SAW) devices are capable of sensing: temperature, pressure, strain, chemical species, mass loading, acceleration, and shear stress. SAW technology is low cost, rugged, lightweight, and extremely low power. For these reasons new SAW sensors are being investigated for wireless aerospace applications.

The lack of currently available tools made it necessary to develop tools for the design, modeling, analysis, and automatic layout generation of SAW devices. The Impulse Response method was used to implement the models. The model is first order and calculates the frequency response, the insertion loss, the admittance, and the electrical parameters. Operational characteristics of the SAW device are visualized using plots that are generated for each of the parameters. In addition to the plots, several parameters are calculated and stored for use as inputs for the automatic layout of the device in a layout editor.

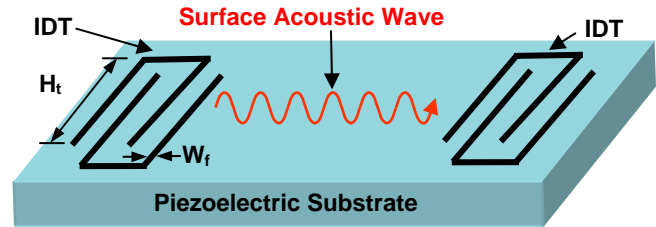


Figure 1. Basic SAW Delay line Device.

## 2. BACKGROUND

The SAW Delay line structure is composed of two sets of InterDigitated (IDT) metal fingers on a piezoelectric substrate (Figure 1). This configuration finds application as a bandpass filter [2], or a sensor. Sensors are created by adding a sensing medium between the two IDTs. When one of the IDTs is excited by a sinusoidal electrical signal, the piezoelectric effect generates mechanical waves. The waves propagate to the other IDT and re-generate an electrical signal through the inverse piezoelectric effect. SAW devices have been designed to minimize dispersion, attenuation, and diffraction [3].

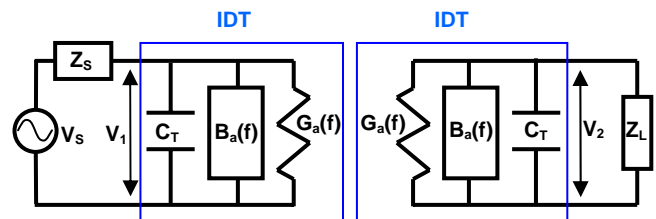


Figure 2. Mason equivalent circuit model.

## 3. MODEL IMPLEMENTATION

The SAW device was modeled with the Impulse Response method [4]. This method was implemented using a variety of software tools including Hardware Description Languages (HDL) [5] and mathematical modeling tools. This is a primarily a first order model; however, it captures the piezoelectric, mechanical and electrical behaviors. The model assumes that the finger overlap or aperture is constant and that the metallization ratio between the fingers and spaces is 0.5. The Impulse Response method is based upon the Mason equivalent circuit (Figure 2). The figure shows the source voltage and both the source and load impedances which are not part of the model. For each IDT

the model is comprised of the radiation conductance  $G_a(f)$ , the acoustic susceptance  $B_a(f)$ , and the total capacitance  $C_T$ . The model calculates the wavelength ( $\lambda$ ), and the number of finger pairs ( $N_p$ ) using the following equations:

$$\lambda = \frac{v}{f_0} \quad (1)$$

$$N_p = \text{round} \left( \frac{2}{NBW} f_0 \right) \quad (2)$$

where  $v$  is the acoustic velocity in the media,  $f_0$  is the center or synchronous frequency, and NBW is the null bandwidth or fractional frequency.

### 3.1 Frequency Response

The frequency response (transfer function) of a SAW device (Fig. 2) is the ratio of  $V_2$  over  $V_1$ , and is shaped by the sinc function. It is represented by [4]:

$$H(f) = 4k^2 C_s f_0 N_p^2 \left( \frac{\sin(X)}{X} \right)^2 e^{-j \left( \frac{N_p + D}{f_0} \right)} \quad (3)$$

where  $f$  is the frequency,  $k$  is the piezoelectric coupling coefficient,  $D$  is the delay between IDTs in wavelengths, and  $C_s$  is the capacitance for a finger pair per unit length. The variable  $X$  is defined as

$$X = N_p \pi \frac{(f - f_0)}{f_0} \quad (4)$$

Often the frequency response is normalized by the log equation:

$$H_n(f) = 20 \log(|H(f)|) \quad (5)$$

### 3.2 Radiation Conductance

The real part of the IDT admittance is called the radiation conductance. The radiation conductance is also shaped by the sinc function [4] and is found by

$$G_a(f) = 8k^2 C_s H_a f_0 N_p^2 \left| \frac{\sin(X)}{X} \right|^2 \quad (6)$$

where  $H_a$  is the aperture or overlap height of the fingers. The radiation conductance is normalized by the following equation:

$$G_n(f) = \frac{G_a(f)}{G_a(f_0)} \quad (7)$$

### 3.3 Acoustic Susceptance

The third element of the model is the imaginary part of the IDT admittance and is called the acoustic susceptance. It is the acoustic wave phenomena modeled as an electrical

parameter. The Hilbert transform of the radiation conductance gives the acoustic susceptance [4]:

$$B_a(f) = G_a(f_0) \frac{\sin(2X) - 2X}{2X^2} \quad (8)$$

The acoustic susceptance is normalized using the radiation conductance since the acoustic susceptance at the synchronous frequency is zero:

$$B_n(f) = \frac{B_a(f)}{G_a(f_0)} \quad (9)$$

### 3.4 Admittance and Impedance

The total admittance is found by combining the radiation conductance, the acoustic susceptance and the total capacitance [8]. The total admittance is given by

$$Y = G_a + j(2\pi f C_T + B_a) \quad (10)$$

The total static capacitance ( $C_T$ ) for the IDT is found by multiplying the capacitance per unit length for a pair of fingers ( $C_s$ ) times the finger overlap or aperture ( $H_a$ ) times the number of finger pairs ( $N_p$ ).

$$C_T = C_s H_a N_p \quad (11)$$

If equation (10) is inverted it will yield the impedance of the IDT [8]:

$$Z(f) = \frac{1}{(G_a + j(2\pi f C_T + B_a(f)))} \quad (12)$$

### 3.5 Insertion Loss

It is very useful to calculate the insertion loss of electrical systems. For SAW devices the insertion loss is a function of frequency, and is calculated from the conductance, susceptance, and the load resistance  $R_g$  [9]:

$$IL(f) = -10 \log \left[ \frac{2G_a(f)R_g}{(1 + G_a(f)R_g)^2 + [R_g(2\pi f C_T + B_a(f))]^2} \right] \quad (13)$$

The minimum insertion loss occurs when  $f = f_0$  the synchronous frequency.

### 3.6 Aperture Optimization

An optimal design must match the IDT resistance (real impedance) to the source resistance. The IDT finger overlap or aperture height ( $H_a$ ) is often adjusted so that the IDT design achieves the correct IDT resistance. The following equation is used to optimize the aperture in terms of the input resistance ( $R_m$ ):

$$H_a = \frac{1}{R_m} \left( \frac{1}{2f_0 C_s N_p} \right) \frac{(4k^2 N_p)}{(4k^2 N_p)^2 + \pi^2} \quad (14)$$

### 3.7 Matching Network

If impedance matching is required, then a series inductor can be used to cancel out the static capacitance at the synchronous frequency. The series inductor can be calculated from [10]:

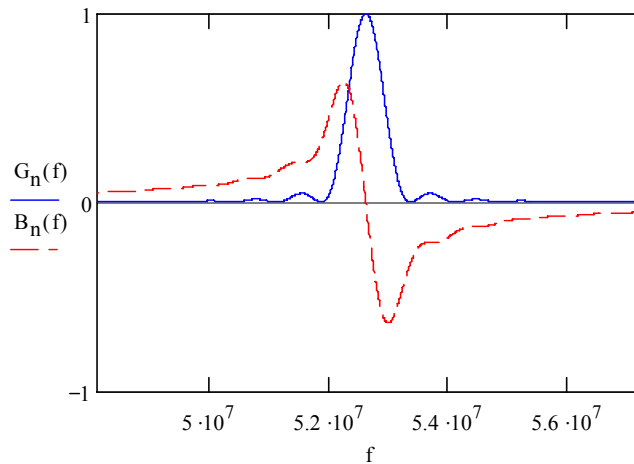
$$Inductor = \frac{1}{(2\pi f_0)^2 C_T} \quad (15)$$

### 4. SAW DELAY LINE EXAMPLE

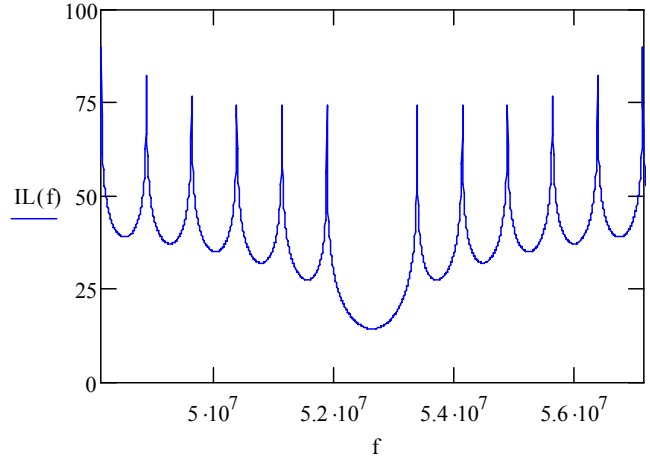
A simple SAW delay line consisting of two identical IDTs demonstrates the model. The synchronous frequency is 52.633 MHz. The substrate is ST cut Quartz. The Null Bandwidth (NBW) is 1.5 MHz. The delay length between the two IDTs is 5 wavelengths. Both the source and load resistances are assumed to be 50 Ω. The selection of a substrate material determines the capacitance,  $C_s = 0.503385$  pf/cm, the piezoelectric coefficient,  $k = 0.04$ , and the acoustic velocity,  $v = 3158$  m/s for the SAW device [11]. Using these values in equation (14) yields an optimized aperture of 2399.0 μm.

### 5. ANALYSIS

The model results are visualized in plots of the frequency response, the insertion loss, the radiation conductance, and the acoustic susceptance. Figure 3 shows both the normalized radiation conductance, and the normalized acoustic susceptance. Figure 4 shows the insertion loss. Both figures are calculated from the parameters of the SAW delay line example in the previous section.



**Figure 3. The normalized radiation conductance and acoustic susceptance.**



**Figure 4. Insertion loss of the SAW delay line.**

Several parameters are calculated and written into a summary report to aid in analyzing the design. The parameters can be used in a circuit simulator such as SPICE, but since this is a stand alone application it is unnecessary. The plots allow complete analysis of the SAW device and the parameters written to the file are used to automatically synthesize the layout for the device in a layout editor [12]. As shown in Figure 5 the width of the fingers is 15 μm, the number of fingers is 70, aperture height is 2399.0 μm, there is a 5 wavelength delay, and the bus bar height is 500 μm. The first eight parameters are required for automatic layout generation. The aperture height ( $H_a$ ) is optimized to match 50Ω, since most test equipment has input and output impedances of 50Ω [13]. Manual intervention is necessary during the analysis phase to examine the plots, however, future improvements will incorporate automatic checking of the parameters and automatic optimization tools to further reduce the amount of human interaction that is needed.

"Finger Height (m)	= " 0.002499
"Aperture Height (m)	= " 0.002399
"Finger Width/Spacing (m)	= " 1.5e-005
"Number of Finger Pairs	= " 70
"Bus Bar Height (m)	= " 0.0005
"Delay Length (wavelengths)	= " 5
"X Offset (m)	= " 0
"Y Offset (m)	= " 0
"Wavelength (m)	= " 6e-005
"Synchronous Frequency (MHz)	= " 52.63
"Acoustic Velocity (m/s)	= " 3158
"Series Matching Inductor (H)	= " 1.082e-006
"Minimum Insertion Loss (@f0 in dB)	= " 14.25
"Total Capacitance (Single IDT) (F)	= " 8.452e-012

**Figure 5. Example of a SAW Summary Report**

**6. PARAMETERIZABLE LIBRARY**

This library is similar to the standard cell libraries found in digital design packages. The library is implemented in an existing layout editor to reduce software development time. The library allows the user to automatically generate detailed layouts of SAW components, such as delay lines, resonators and sensors.

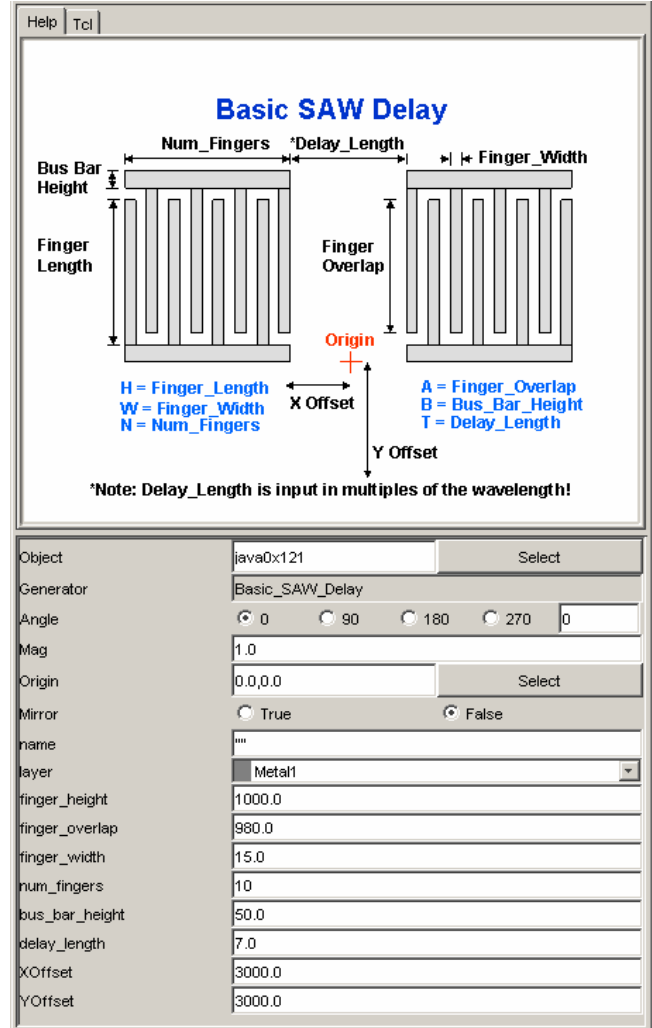
Tool Control Language (Tcl) is a common scripting language [14]. Most commercial EDA tools include a provision for the creation and execution of macros using the Tcl language. The layout generator utilizes the Tcl language to create macros that automatically generate layouts of SAW devices. We created generators for the basic SAW IDT structures, reflectors, delay lines, and both one and two port resonators.

A SAW delay line layout generator was developed with Tcl. The code includes both transmit and receive IDTs. Error checking ensures the parameters input are within bounds. The code includes annotation of the layout with the design parameters. The flexibility was increased by adding a way to change the X and Y offset of the device. A dialog box is automatically created for the input parameters from the Tcl code. An html graphic was linked to the layout generator using the help feature to assist in minimizing the ambiguity as to what the input variables represented. The graphic is located within the dialog box above the parameter entry area. These enhancements are all included in the layout generator we named Basic\_SAW\_Delay. The inputs for the Basic\_SAW\_Delay generator are; the length of the fingers, the amount of overlap between the fingers, the width of the fingers, number of finger pairs, the height of the bus bars, and the length of delay between the two SAW devices. Once the parameters have been entered into the dialogue box (Figure 6), a layout is generated. 3D models of the device and netlists which can be used to create fabrication masks can be created from the layout.

To demonstrate the capability of the layout generator we used the generator and the Basic\_SAW\_Delay component (Figure 6) to generate the layout of a SAW delay line with a wavelength of 60  $\mu\text{m}$ . The fingers are 15  $\mu\text{m}$  wide with 15  $\mu\text{m}$  wide spacing between them. The number of finger pairs per IDT is 10, and alternate fingers are attached to bus bars (electrodes) that are 50  $\mu\text{m}$  high. The aperture or finger overlap is 980  $\mu\text{m}$  out of the 1000  $\mu\text{m}$  finger height. The delay length is input in multiples of the wavelength (seven in this case), but is calculated as  $(7-1/4)\lambda$  or 405  $\mu\text{m}$ , where  $\lambda$  is the wavelength. The delay length is the spacing between the fingers of the two separate IDTs. The subtraction of  $1/4\lambda$  is necessary to maintain the phase relationship between the first and second IDTs so no unwanted phase shifts occur. Figure 7 is the output of the layout generator using the parameters that are shown in

Figure 6. The layout is automatically annotated with all of the device parameters except for the X and Y offset values. The text used for annotation utilizes a low flash count font and is created on the same layer as the IDT fingers. This self documentation feature is useful when placing numerous devices on a wafer with different parameters.

We have also implemented one and two port SAW resonators [15]. The one port SAW resonator component consists of a single IDT in between two reflectors. The two port SAW resonator device consists of two IDTs sandwiched between two reflectors.



**Figure 6. Layout Generator dialog box.**

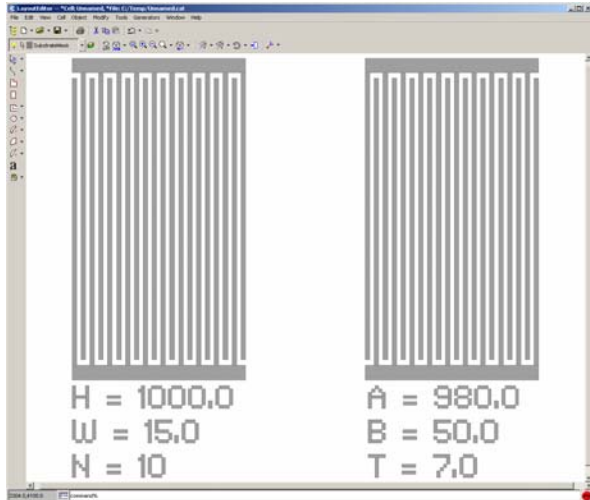


Figure 7. Layout of a basic SAW delay line.

### 7. FINITE ELEMENT ANALYSIS

The modeling, analysis and layout generator tools have been integrated into commercially available Electronic Design Automation (EDA) software. This was done to take advantage of existing tools such as netlist generation, 3D modeling and Finite Element Analysis (FEA). After a layout is created using the parameterizable library components that layout can be used to generate a 3D model. Figure 8 is an exaggerated 3D model of a SAW delay line. The model has been meshed using Manhattan bricks.

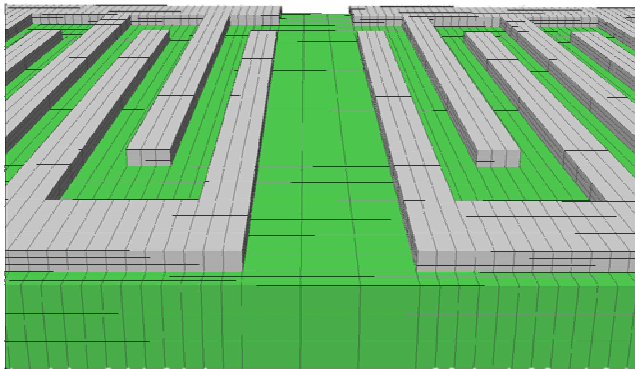


Figure 8. Exaggerated 3D Model of a SAW device.

Once a layout has been meshed it can be analyzed using FEA techniques. This allows for detailed stress and strain analysis during sensor operation. The EDA tool suite includes solvers for potential, charge, displacement, and a variety of stress and strains. To demonstrate this capability the Principle Stress 1 is shown in Figure 9. In the figure, stress within the substrate is created by the piezoelectric effect when adjacent fingers are at opposite polarities.

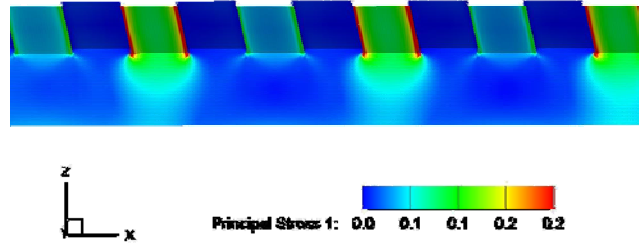


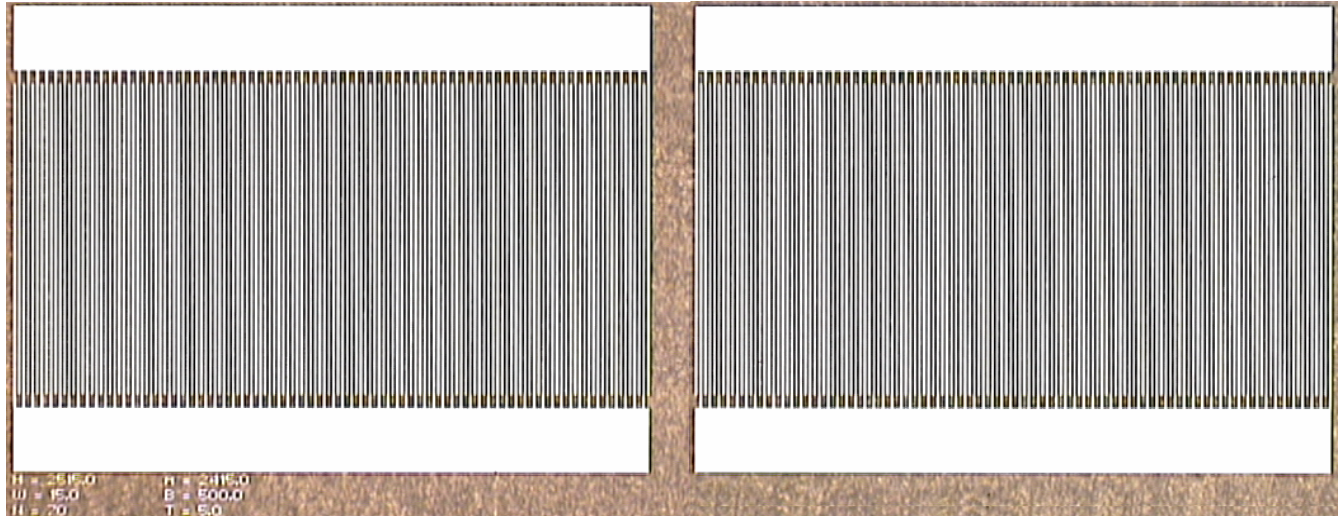
Figure 9. Principle Stress 1.

### 8. PROTOTYPE RESULTS

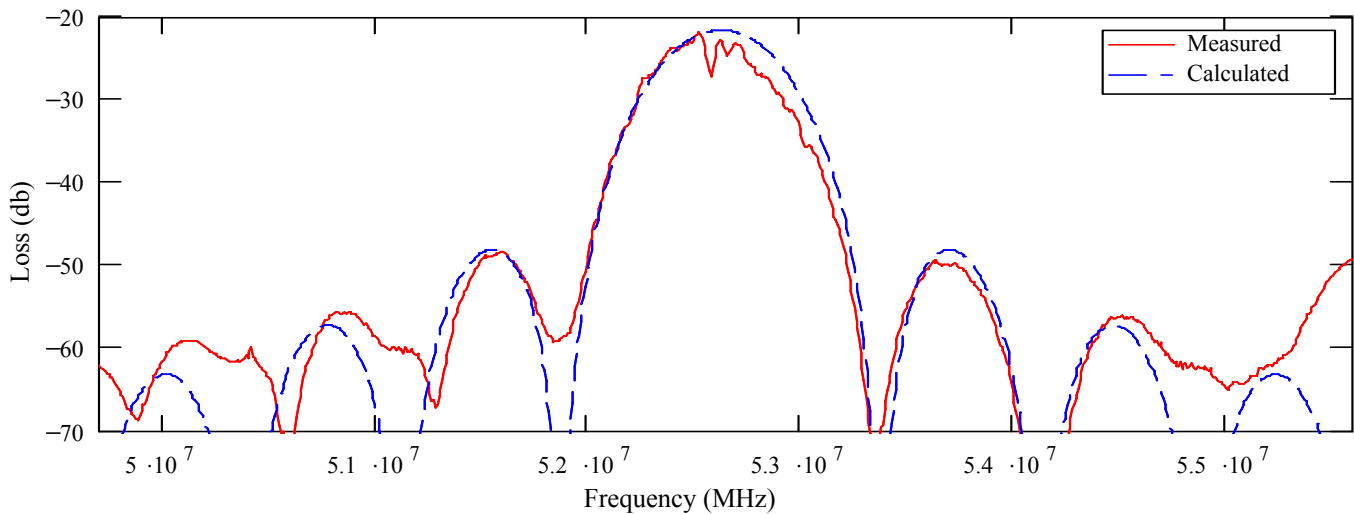
A number of choices must be made before the parameters that have been calculated can be used to realize a layout. These values are the height of the bus bars on the top and bottom of the fingers, the length of the fingers that are not overlapped (not part of the aperture), and the X and Y offset values. From the earlier example (section 4) the following parameters are used; a bus bar height (BBH) of 500  $\mu\text{m}$ , and un-overlapped finger length ( $H_b$ ) of 100  $\mu\text{m}$ , and for simplicity an offset of (0.0, 0.0). Using the values from Figure 5, an automatic layout can be performed to create the layout and netlist of the device. The netlist has been used to fabricate the prototype device (Figure 10).

To demonstrate the capability of the library components, the layout of a SAW delay line with the parameter values from Figure 5 was generated. Fabrication masks are created from this layout. The fabrication masks can be used to construct the prototype SAW device shown of Figure 10. This device is comprised of two identical IDTs, each with 70 finger pairs. The finger widths and spacings are both 15  $\mu\text{m}$ , which corresponds to a synchronous frequency of 52.663 MHz.





**Figure 10. Surface Acoustic Wave Delay Line.**



**Figure 11. Calculated and Measured Results of a SAW Delay Line.**

## 9. RESULTS

The frequency response of the system is plotted in (Figure 11) along with the measured frequency response from the device in Figure 10. A comparison between the calculated frequency response and the measured frequency response demonstrates that the first order model captures the main characteristics of the central lobe and the first side lobes. However, it does not correctly model the second or subsequent side lobes. It also does not accurately represent the ripples seen on the main lobe caused by second order effects such as triple transit echoes, and internal reflections.

## 10. CONCLUSIONS

An implementation of rapid SAW sensor development tools has been presented. These tools are currently being used to investigate new wireless sensors for Integrated Vehicle Health Monitoring (IVHM) of aerospace vehicles.

The tools consist of first order models, analysis, plots, and parameterizable library components for automatic layout generation. The first order model has been presented, along with the results from a typical SAW delay line. Optimization was performed to match the RF impedance parameters of the IDT to standard test equipment, and a report was generated with all of the salient design parameters. A prototype SAW delay line device was created from the design parameters. A layout was automatically generated of the prototype design. The layout was used to create fabrication masks from which the prototype device was fabricated. Both the calculated and measured results from the prototype design were presented.

Future work will include second order effects such as reflections, triple transit echoes, and temperature effects. Transmission line theory will be the basis of these higher order SAW device models, and should give more accurate results.

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