Mixed Modeling of a SAW Delay Line using VHDL

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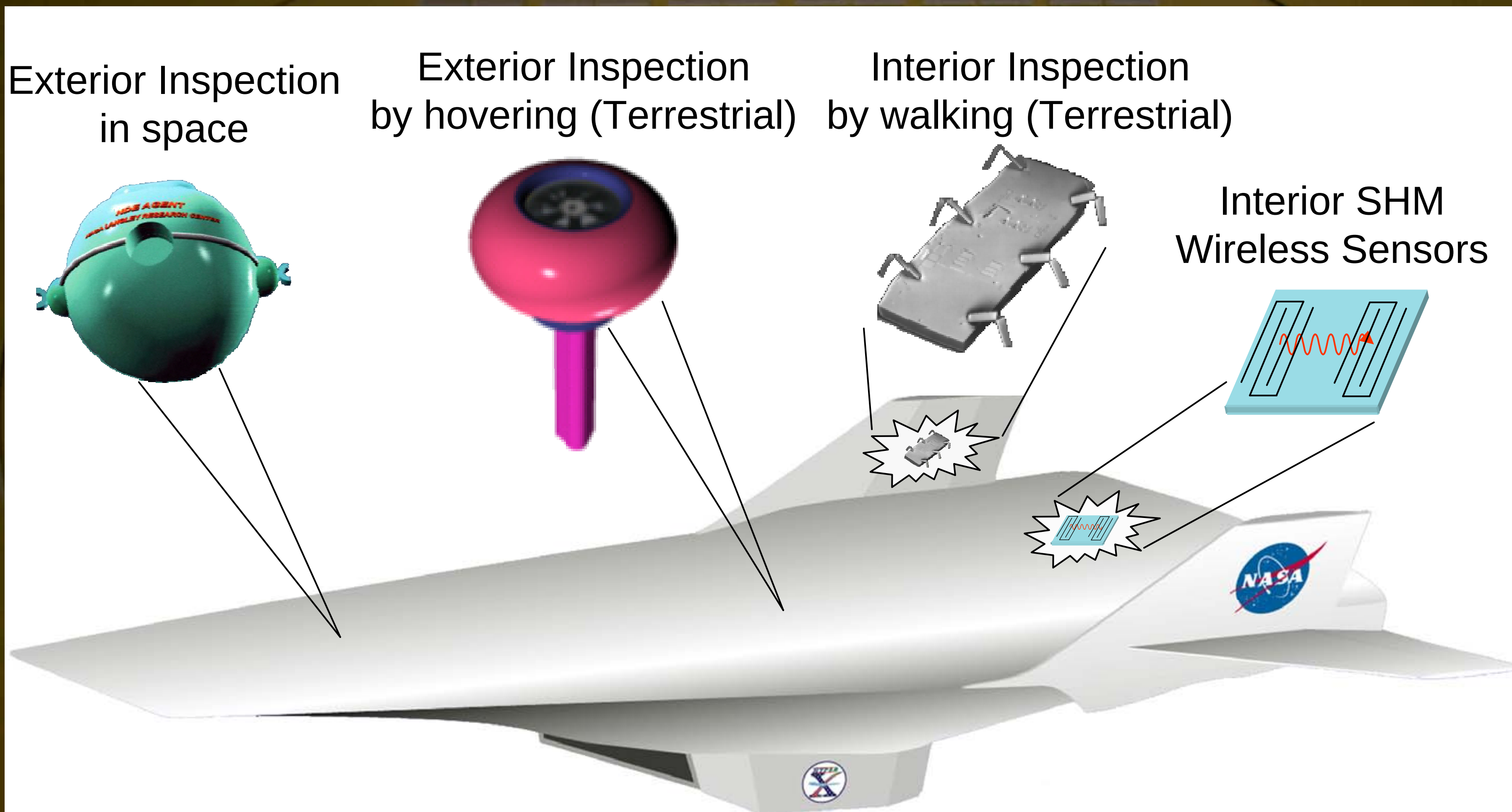
Outline

- Motivation
- Introduction to Surface Acoustic Wave Devices
- Impulse Response Method
- VHDL Implementation
- Model integration into existing EDA Tools
- Results
- Conclusions

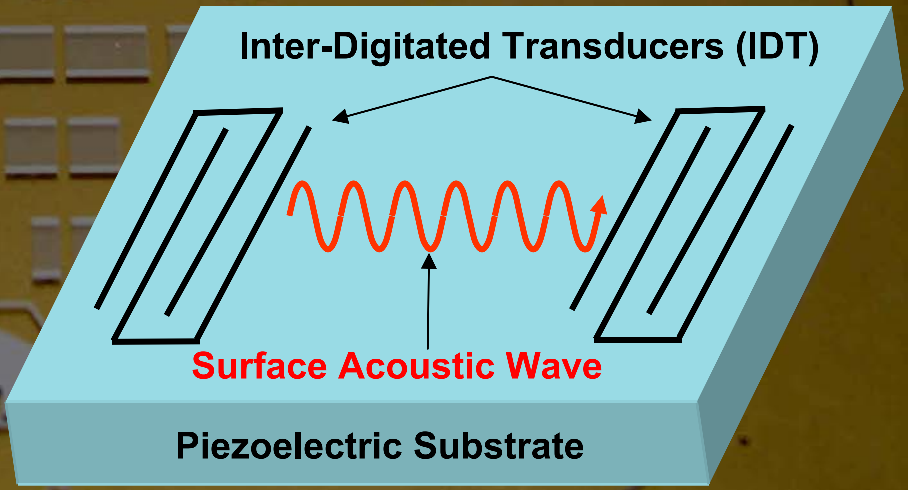
Motivation



Non-Destructive Evaluation (NDE) of Aerospace Vehicles

Surface Acoustic Wave (SAW) Devices

- Inexpensive
- Small (low mass and low volume)
- Extremely Low power (RF or Ambient)
- Versatile
  - Temperature sensors
  - Pressure sensors
  - Strain sensors
  - Ultrasonic sensors
  - Chemical sensors
  - Filters
  - Resonators
  - Signal Processing



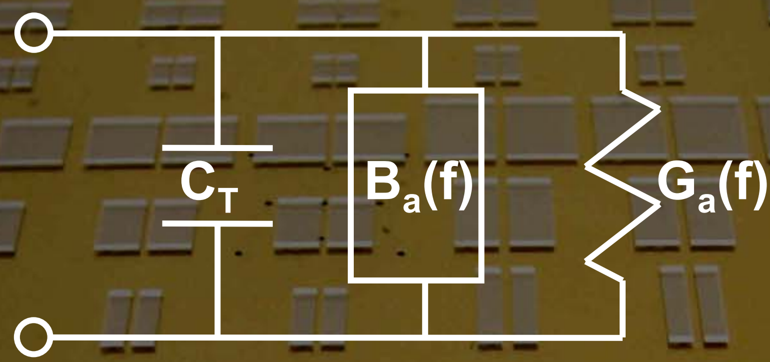
Basic SAW Delay line Device.

Impulse Response Method

- The SAW device was modeled using the Impulse Response method[1].
- This is a first order model only and does not take into account second order effects such as reflections, and Triple Transit Echoes (TTE).
- Simulates the mechanical, piezoelectric and electrical behavior.
- The model calculates the
  - Frequency response
  - Loss of the system
  - Admittance & Conductance
  - Electrical parameters such as the matching inductor.
- This model is valid only for transducers where at least one of the two IDTs is un-weighted.
- Assumes a constant metallization ratio of 0.5, and uniform finger overlap or aperture.

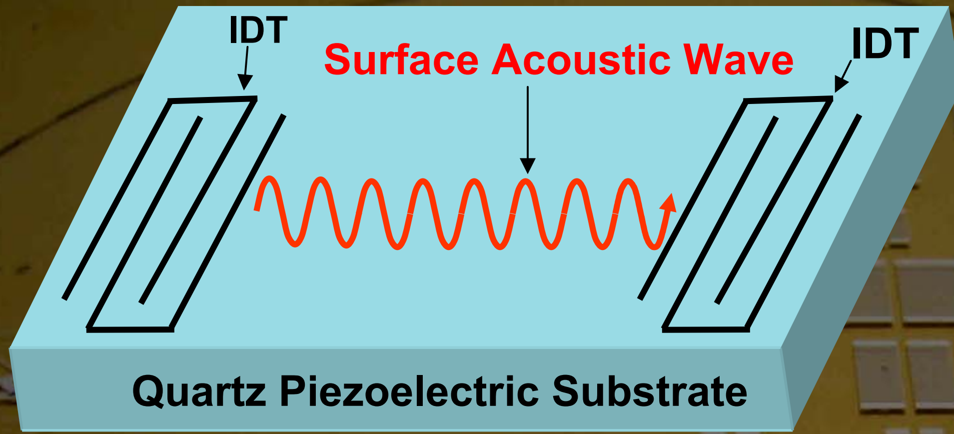
[1] Hartmann, C.S., Jr.; Bell, D.T.; Rosenfeld, R.C.; "Impulse Model Design of Acoustic Surface-Wave Filters", Microwave Theory and Techniques, IEEE Transactions on, Volume 21, Issue 4, Apr 1973, pp. 162 – 175

Circuit model used in the Impulse Response Method



- **Uses the Mason equivalent circuit model.**
  - **Based on Crossed field model.**
  - **C_T is the total capacitance for an IDT.**
  - **$B_a(f)$ is the acoustic susceptance.**
  - **$G_a(f)$ is the radiation conductance.**

Example Parameters



Basic SAW Delay line.

- SAW delay line that consists of two identical IDTs.
- The synchronous frequency is 52.563 MHz.
- The substrate is ST cut Quartz.
  - Cs = 0.503385 pf/cm (capacitance per finger pair, per cm)
  - k = 0.04 (piezoelectric coefficient)
  - v = 3158 m/s (acoustic velocity)
- NBW = 1.5 MHz (null bandwidth, or fractional bandwidth)
- The delay length between the two IDTs is 5 wavelengths.
- The source and load resistances are assumed to be 50 Ω.

Parameter Optimization

Optimization of finger pairs

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

$$N_p = 70$$

```
Np <= round(2.0/NBW*f0);
```

Aperture width optimization

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

$$W_a = \frac{1}{R_{in}}\left(\frac{1}{2 f_0 C_s N_p}\right)\frac{\left(4k^2 N_p\right)}{\left(4k^2 N_p\right)^2 + \pi^2}$$

$$W_a = 2399.0\mu m$$

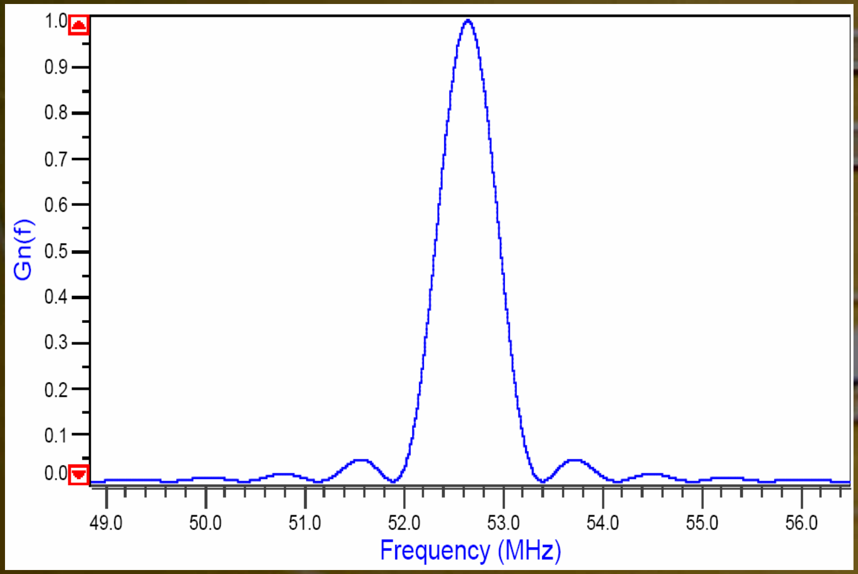
```
function Wa_Optimized (f0,Np,Cs,k : real) return real is
    variable Wa_opt1 : real := 1.0;
      begin
          Wa_opt1  := (1.0/(2.0*Rin*Np*f0*Cs))*
          (4.0*Np*k*k)/(((4.0*Np*k*k)**2)+(math_pi**2));
    return Wa_opt1;
end function Wa_Optimized;
```

Conductance and Susceptance

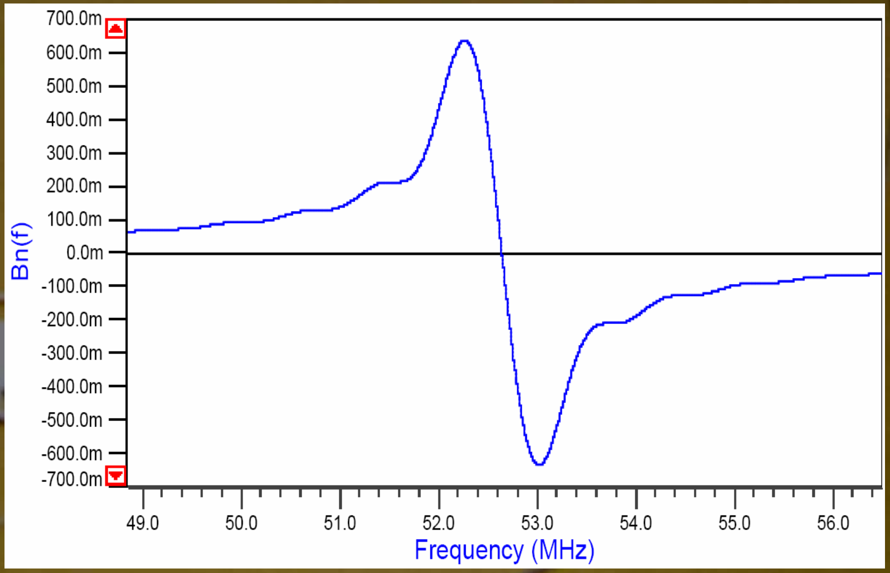
$$X = N_p \pi \frac{(f - f_0)}{f_0}$$

$$G_a(f) = 8k^2 C_s W_a f_0 N p^2 \left| \frac{\sin(X)}{X} \right|^2 \qquad B_a(f) = \frac{G_a(f_0)\sin(2X) - 2X}{2X^2}$$

$$G_n(f) = \frac{G_a(f)}{G_a(f_0)} \qquad B_n(f) = \frac{B_a(f)}{G_a(f_0)}$$



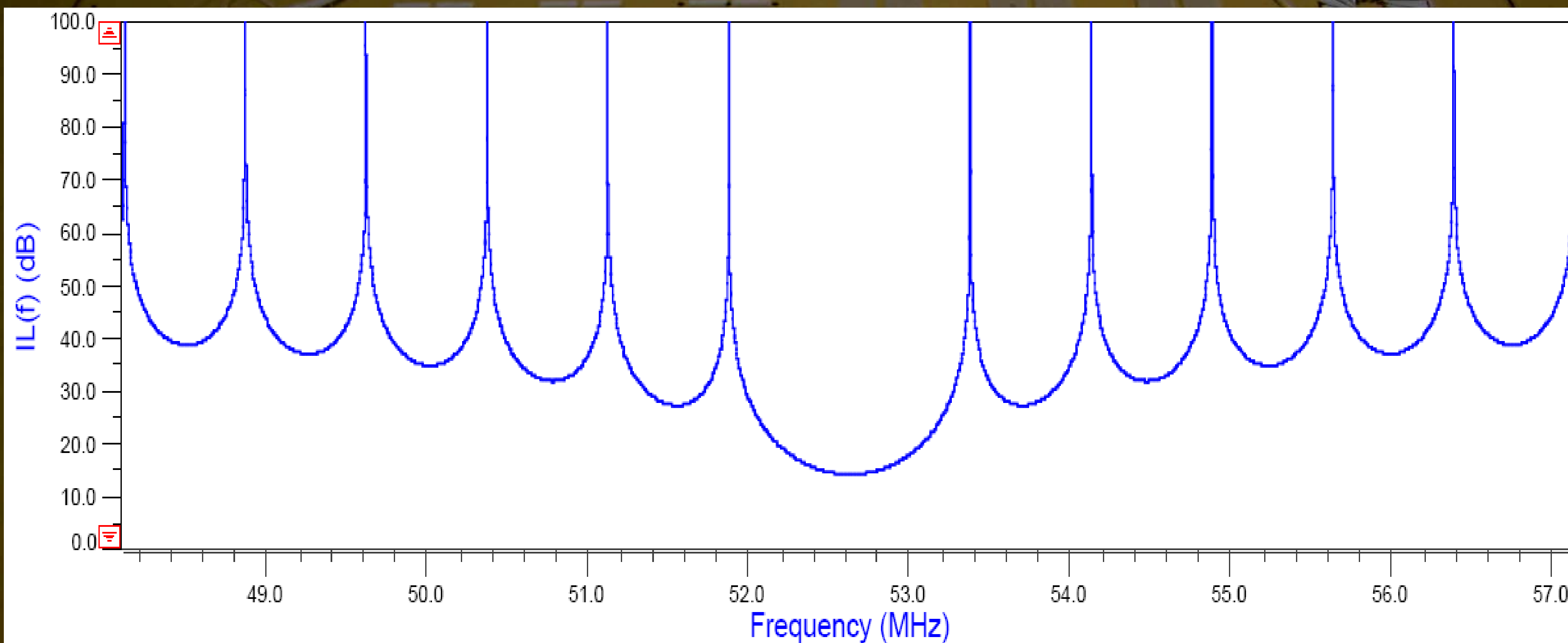
Radiation conductance of the SAW delay line.



Acoustic susceptance of the SAW delay line.

Insertion Loss

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



Insertion Loss of the SAW delay line.

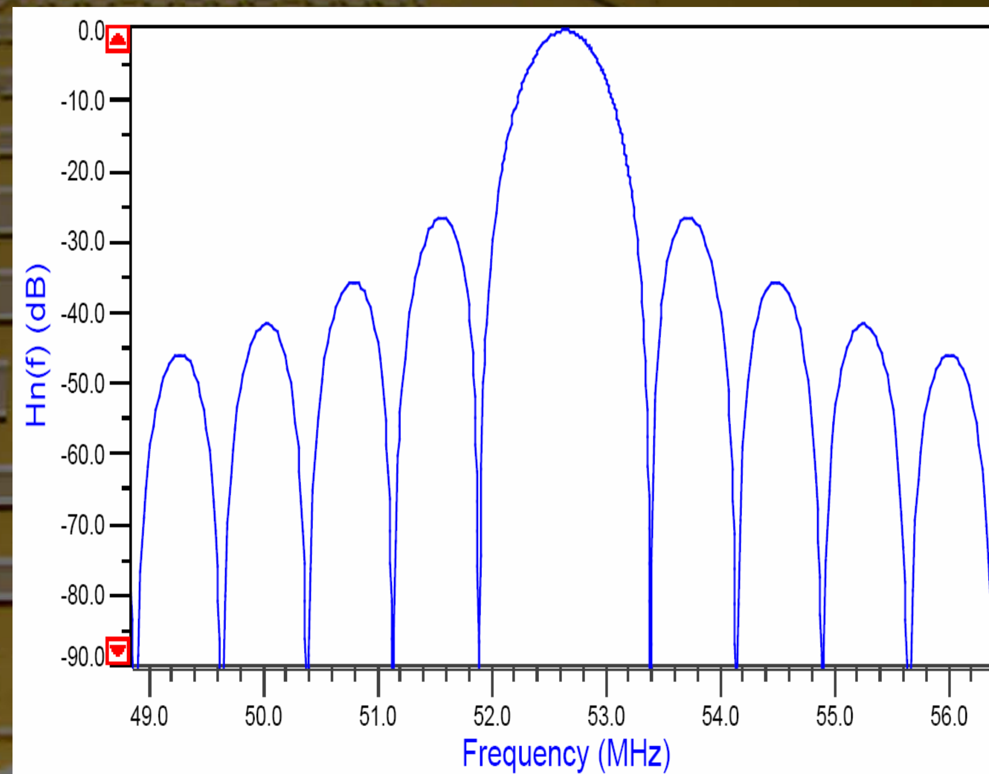
Frequency Response

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

$$\left| H(f) \right| = 2k\sqrt{(C_s f_0)}\,Np\,\frac{\sin(X)}{X}$$

$$H_T(f) \cong H_1(f) \cdot H_2(f)$$

$$H_n(f) = 20\log\left(\left| \frac{H_1(f)H_2(f)}{H_1(f_0)H_2(f_0)} \right| \right)$$



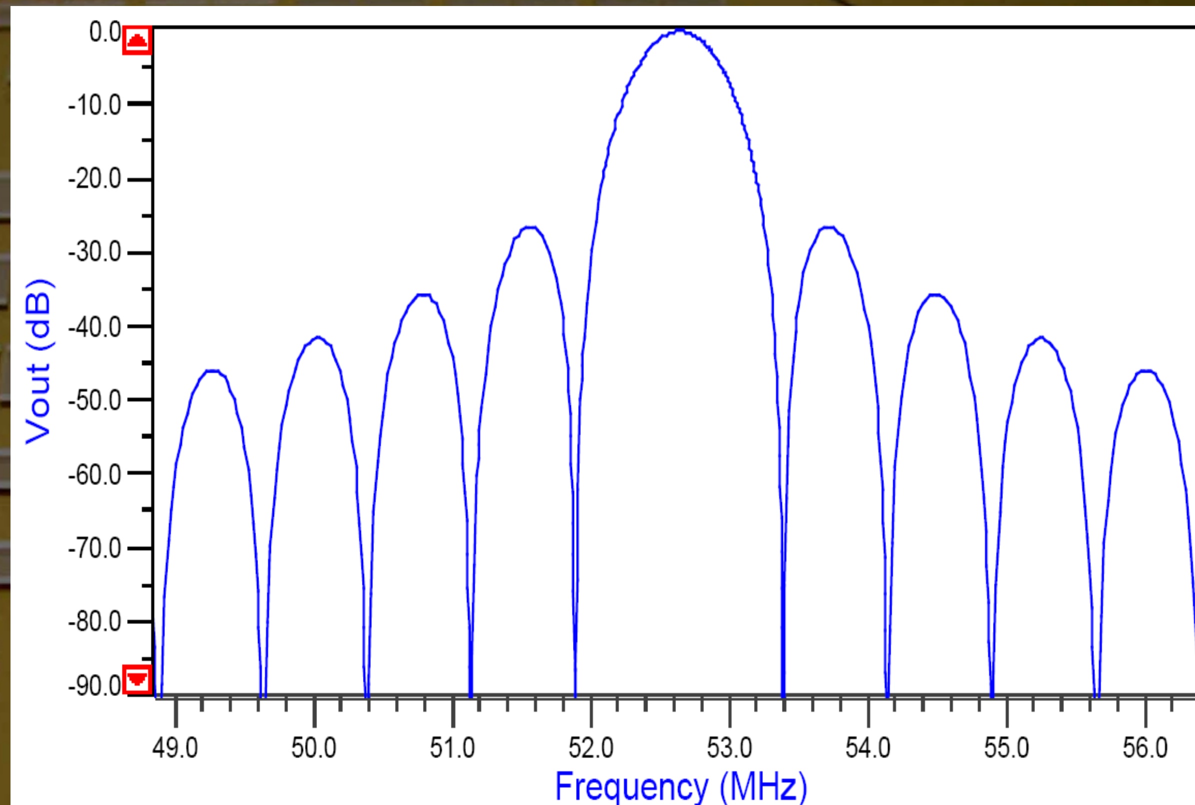
Frequency response of the SAW delay line about the center frequency.

VHDL code for modeling an IDT

```
Library IEEE;
Use IEEE.Math_Real.all;
Use IEEE.Fundamental_Constants.all;
Entity Freq_Response is
  Port (Signal f0,Np,Cs,k : in real;
        Signal HT : out real);
  End Freq_Response;

Architecture Freq_Domain of
  Freq_Response is
    Signal f,fmax,fmin : real := 1.0;

Function x (f,f0,Np : real) return real is
  Variable result : real := 0.0;
    Begin
      If f = f0 then
          result := 1.0e-12;
      Else
          result := math_pi*Np*((f-f0)/f0);
      End If;
   Return result;
End Function x;
```

```
Function H (f,f0,Np,Cs,k : real) return real is
  Variable result : real;
  Begin
    result := 2.0*k*sqrt(Cs*f0)*Np*((sin(x(f,f0,Np))) / (x(f,f0,Np)));
  Return result;
 End Function H;

Begin
  FR1: process is
    Begin
      Wait for 1fs;
       f <= f0*0.5;
       fmax <= f0*1.5;
       fmin <= f0*0.5;
       HT <= 20.0*log10(abs((H(f,f0,Np,Cs,k)**2.0) / H(f0,f0,Np,Cs,k)**2.0));
       Wait for f0*0.5*1.0e-6;
       While f <= fmax loop
         HT <= 20.0*log10(abs((H(f,f0,Np,Cs,k)**2.0) / H(f0,f0,Np,Cs,k)**2.0));
         Wait for f0*1.0e-10;
          f <= f+(f0*1.0e-4);
    End Loop;
  End Process FR1;
End Architecture Freq_Domain;
```

Example VHDL-AMS code for modeling an IDT




```
library IEEE;
use IEEE.electrical_systems.all;
library ieee;
use ieee.math_real.all;
use ieee.math_complex.all;
use work.SAW_Pack1.all;

entity Freq_Response2 is
  generic (f01,Np1,Cs4,k4:real);
  port ( terminal input1 : electrical;
         terminal output1 : electrical );
end entity Freq_Response2;

architecture behavior of Freq_Response2 is
 quantity vin  across input1 to electrical_ref;
 quantity vout across iout through output1 to electrical_ref;

begin
     vout == 20.0*log10(abs((hh((vin),f01,Np1,Cs4,k4)**2.0)/hh(f01,f01,Np1,Cs4,k4)**2.0));
end architecture behavior;
```

Automated Report
(VHDL Code Output)

<<< SAW Delay Line Summary Report >>>

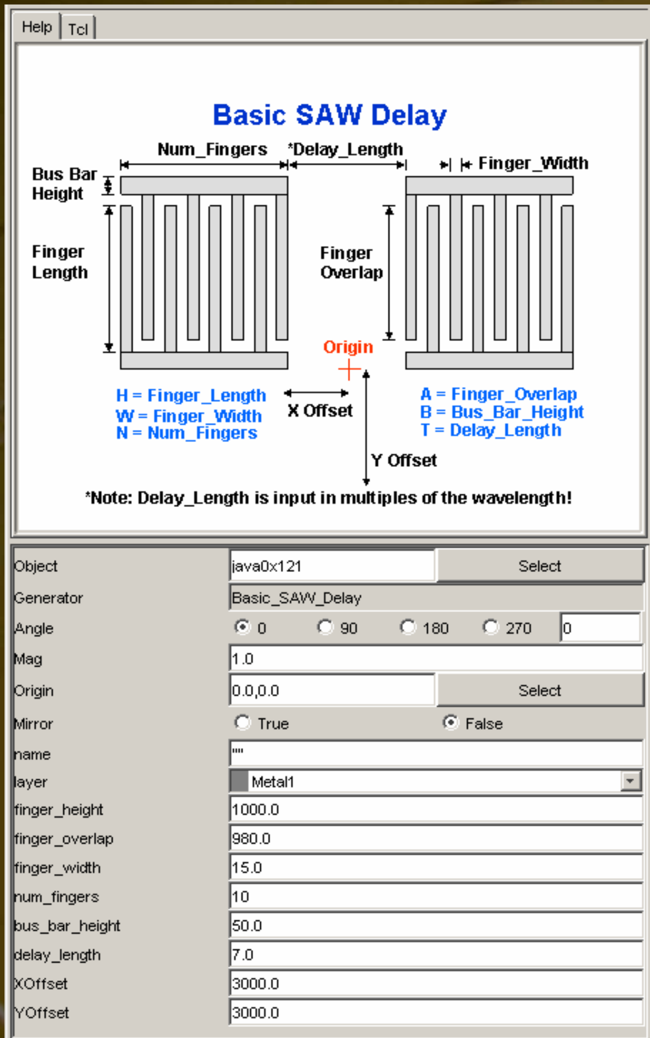
Finger Height	=	2.499000e-003 m
Aperture Height	=	2.399000e-003 m
Finger Width/Spacing	=	1.500009e-005 m
Number of Finger Pairs	=	7.000000e+001
Bus Bar Height	=	2.000000e-004 m
Delay Length (in wavelengths)	=	5.000000e+000
X Offset	=	0.000000e+000 m
Y Offset	=	0.000000e+000 m

Wavelength	=	6.000038e-005 m
Synchronous Frequency	=	5.263300e+007 Hz
Acoustic Velocity	=	3.158000e+003 m/s^2
Series Matching Inductor	=	1.081672e-006 H
Minimum Insertion Loss (@f0)	=	1.424679e+001 dB
Total Capacitance (single IDT)	=	8.453344e-012 F

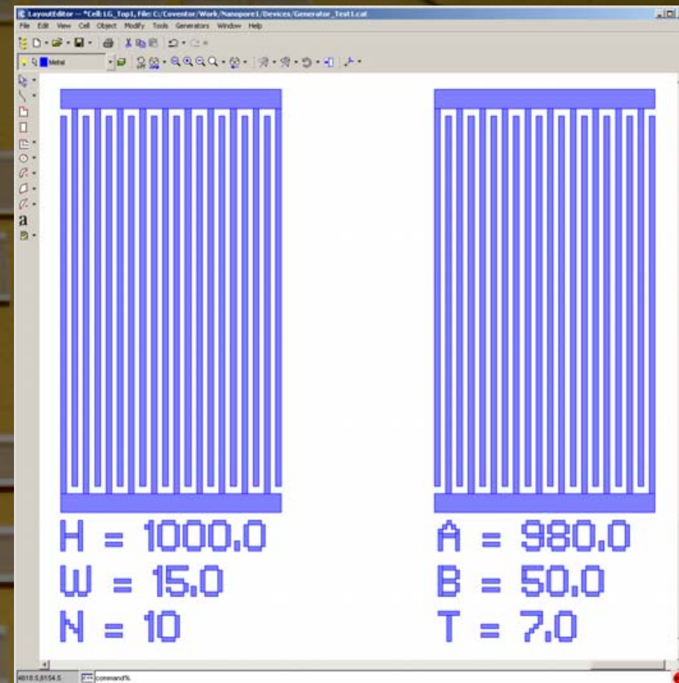
Integration of the models into existing EDA Tools

- Interface to *existing* layout tools.
  - Integrate VHDL models with layout software.
  - Parameterizable libraries of SAW devices using scripting language Tcl.
  - We integrated the tools into commercial Electronic Design Automation (EDA) Layout software for MEMS devices.
- The tools allow us to rapidly create, model, analyze and automatically generate device layouts (fabrication netlist).
- Enables a higher level of abstraction in the design process thus reducing the development time while increasing productivity.
- Allows access to existing tools
  - 3D Modeling
  - Finite Element Analysis (FEA)

Parameterizable Library



Layout Generator dialogue box.
This dialogue box is where the parameters for the basic SAW delay line are input.



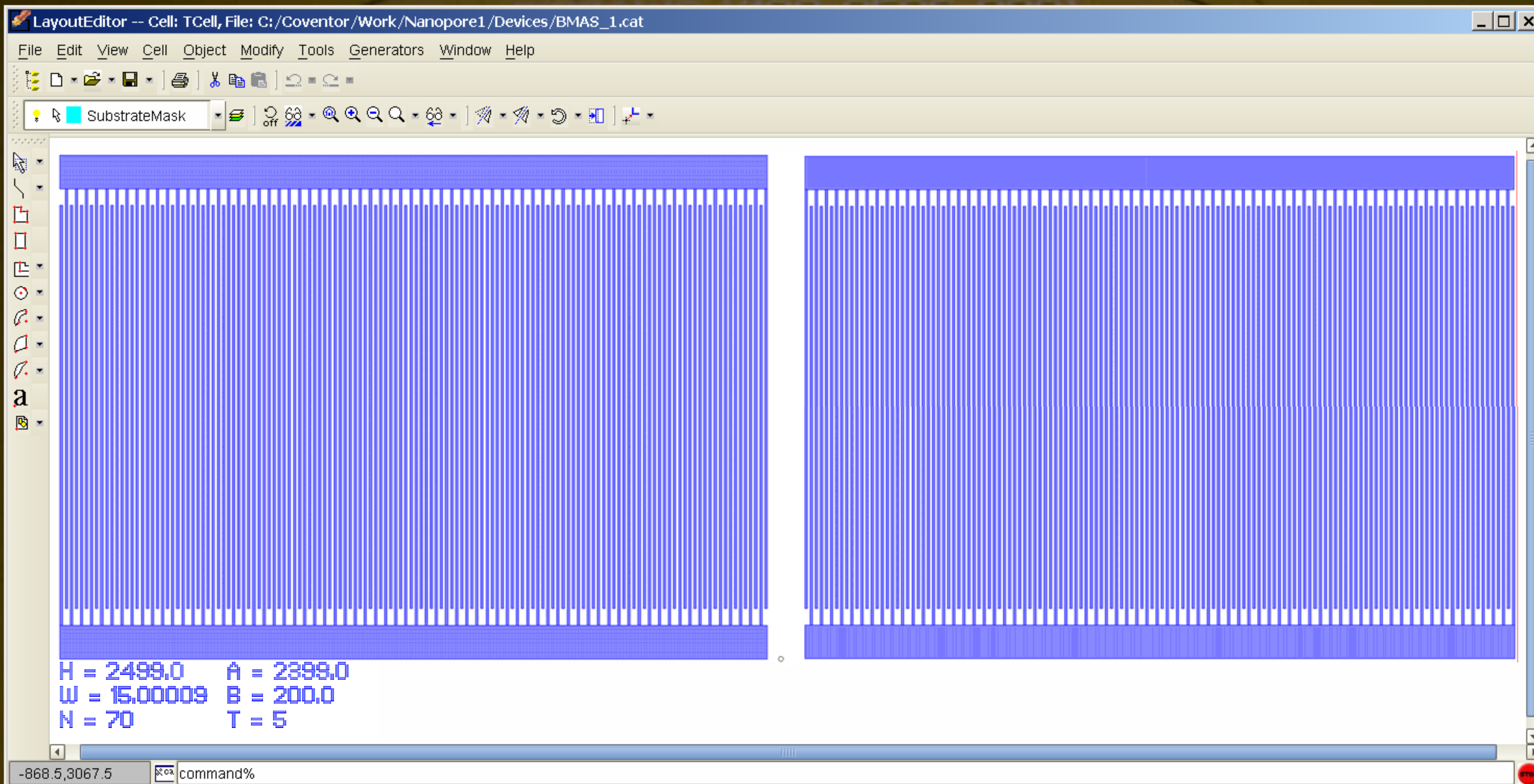
Layout of a basic SAW delay line.

- **Finger heights of 1000 µm.**
- **Finger widths of 15 µm.**
- **10 finger pairs**
- **aperture of 980 µm.**
- **Bus bar heights are 50 µm.**
- **Delay between the two IDTs is 7 λ.**

Example Tcl code for a simple IDT structure

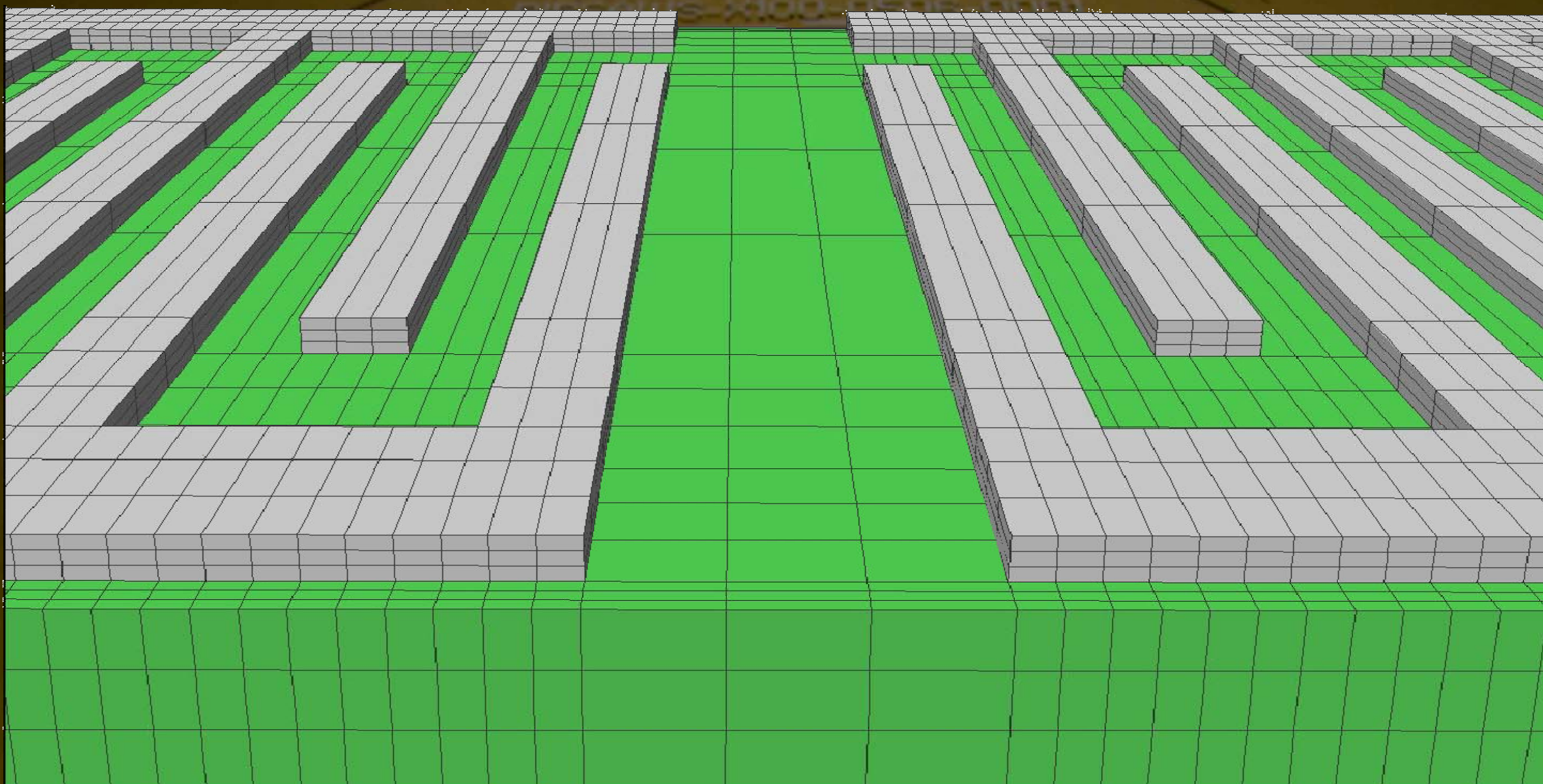
```
proc Basic_IDT { obj sname llayer dfinger_L dfinger_O dfinger_W inum_fingers dbus_bar_h}
{
global error_count
set Length [expr ($inum_fingers*4*$dfinger_W-$dfinger_W)]
set Gap [expr ($dfinger_L-$dfinger_O)]

 # Top comb fingers
 #======================
 # Finger origin of the first finger
 set FOx [expr 0]
 # Loops over all movable fingers
 for {set i 1} {$i <= $inum_fingers} {incr i} {
  # Draws the movable comb finger
  set finger [cat:rectangle -layer $llayer $FOx  [expr ($Gap+$dbus_bar_h)] [expr ($FOx+$dfinger_W)]  [expr ($Gap+$dbus_bar_h+$dfinger_L)]]
  $obj addObject $finger
  # Next finger origin
  set FOx [expr $FOx + 4*$dfinger_W]
 }
 # Bottom comb fingers
 #====================
 # Finger origin of the first finger
 set FOx [expr (2*$dfinger_W)]
 # Loops over all fixed fingers
 for {set i 1} {$i <= [expr $inum_fingers]} {incr i} {
  # Draws the fixed comb finger
  set rect [cat:rectangle -layer $llayer $FOx $dbus_bar_h [expr $FOx+$dfinger_W]  [expr ($dbus_bar_h+$dfinger_L)] ]
  $obj addObject $rect
  # Next finger origin
  set FOx [expr $FOx + 4*$dfinger_W]
 }
 # Top Electrode
 #================
  set rect [cat:rectangle -layer $llayer 0  [expr ($dbus_bar_h+$Gap+$dfinger_L)] $Length  [expr ((2*$dbus_bar_h)+$Gap+$dfinger_L)] ]
  $obj addObject $rect
 # Bottom electrode
 #=================
 set rect [cat:rectangle -layer $llayer 0 0 $Length $dbus_bar_h]
 $obj addObject $rect
 return
}
```

IDT Layout from Tcl



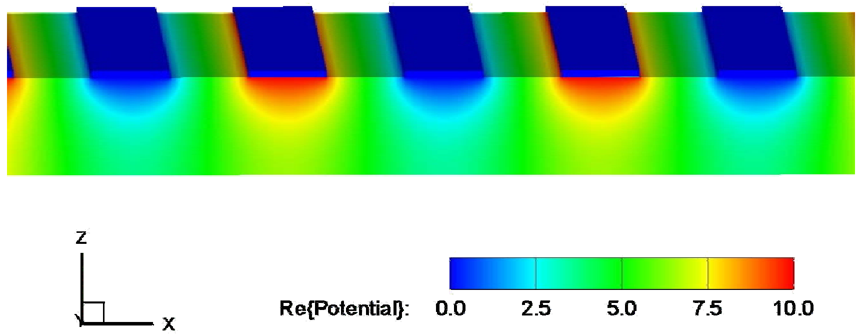
Automatically generated layout of the SAW delay line from the example.

3-D Modeling

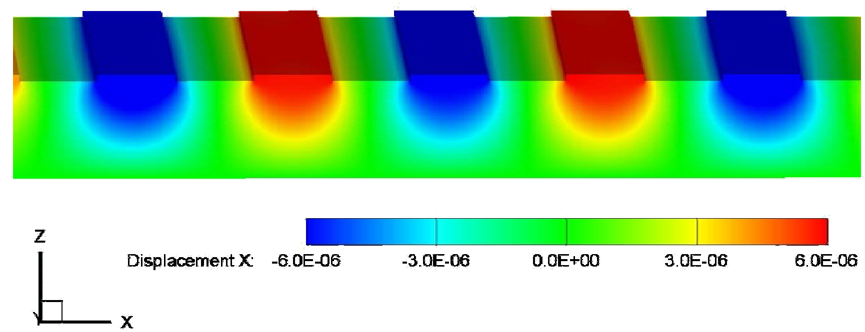


Exaggerated 3-D Model of a SAW delay line.
The model has been meshed using Manhattan bricks.

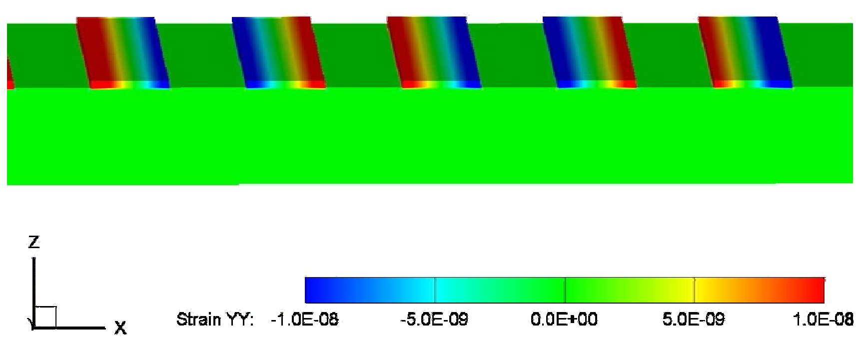
FEA Analysis



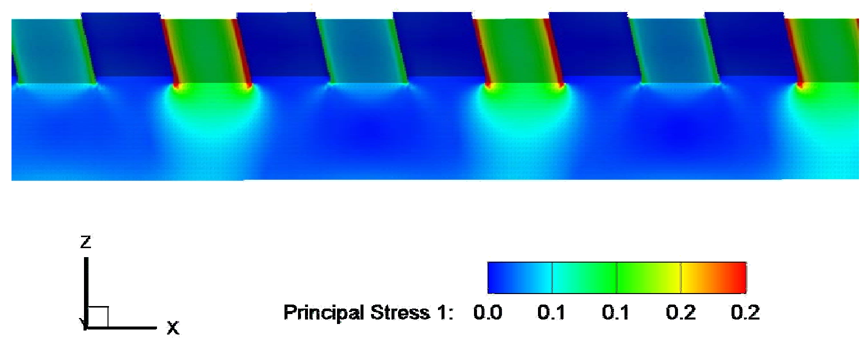
Potential



Displacement in X



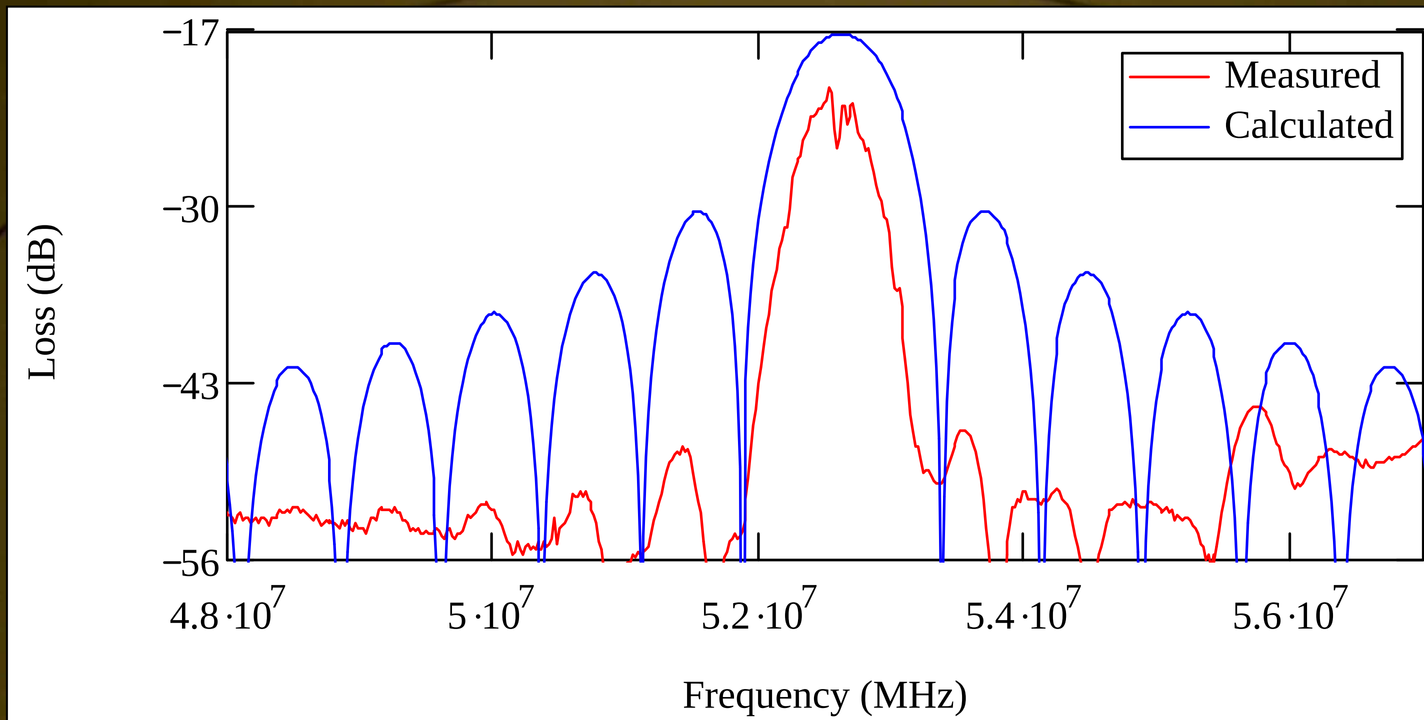
Strain_{YY}



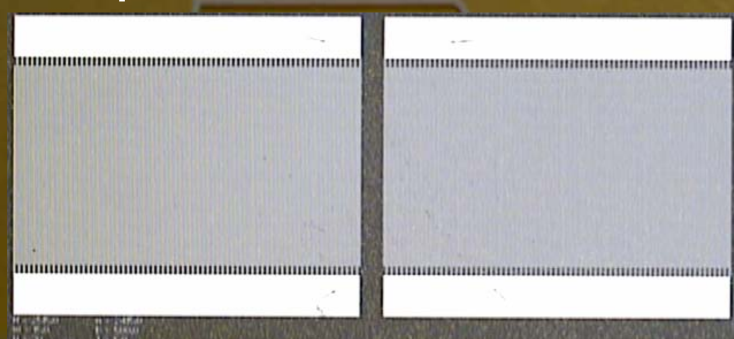
Principal Stress 1

Finite Element Analysis available from existing tools.

Device Results



Frequency response of the SAW delay line device.

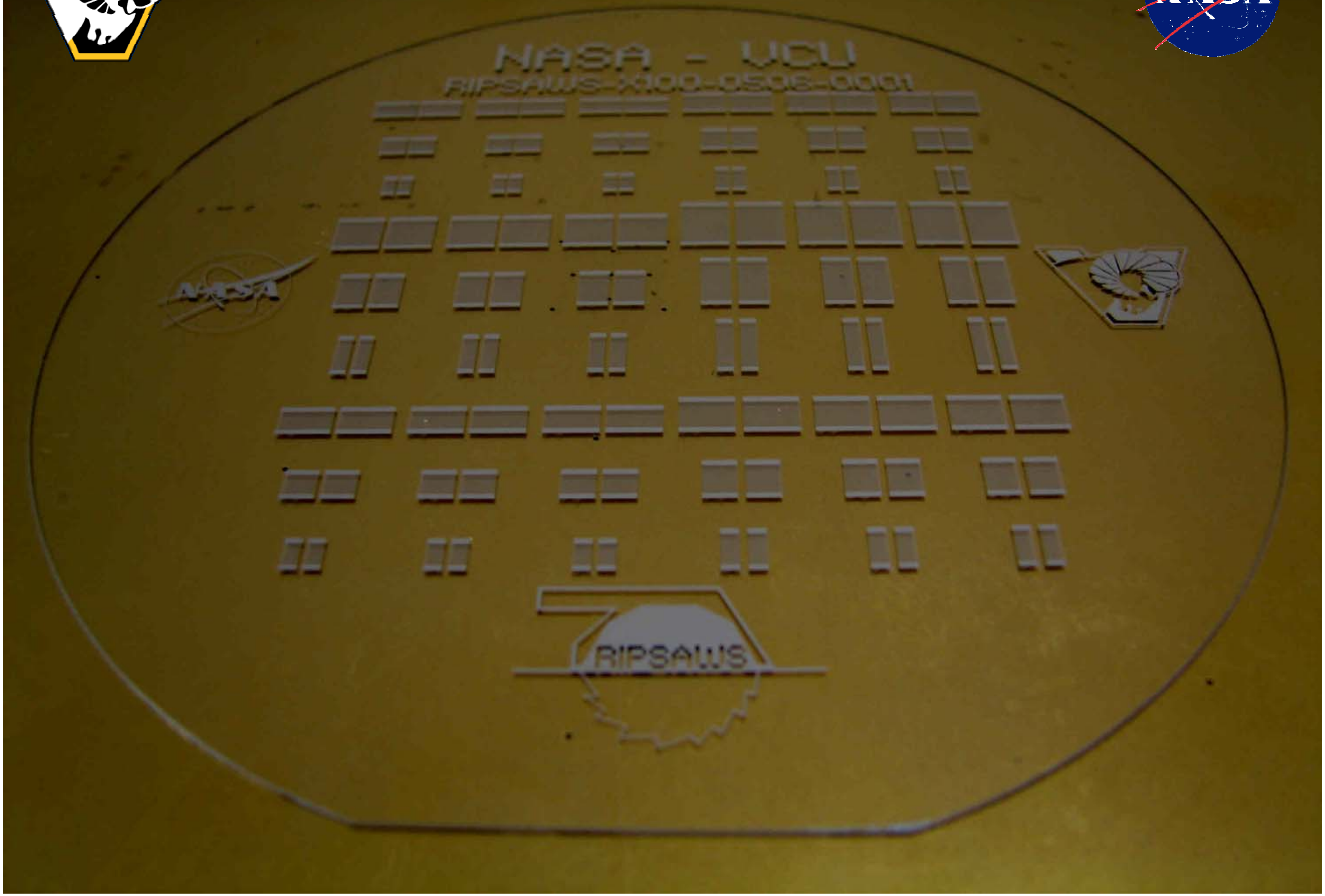


Picture of the device.

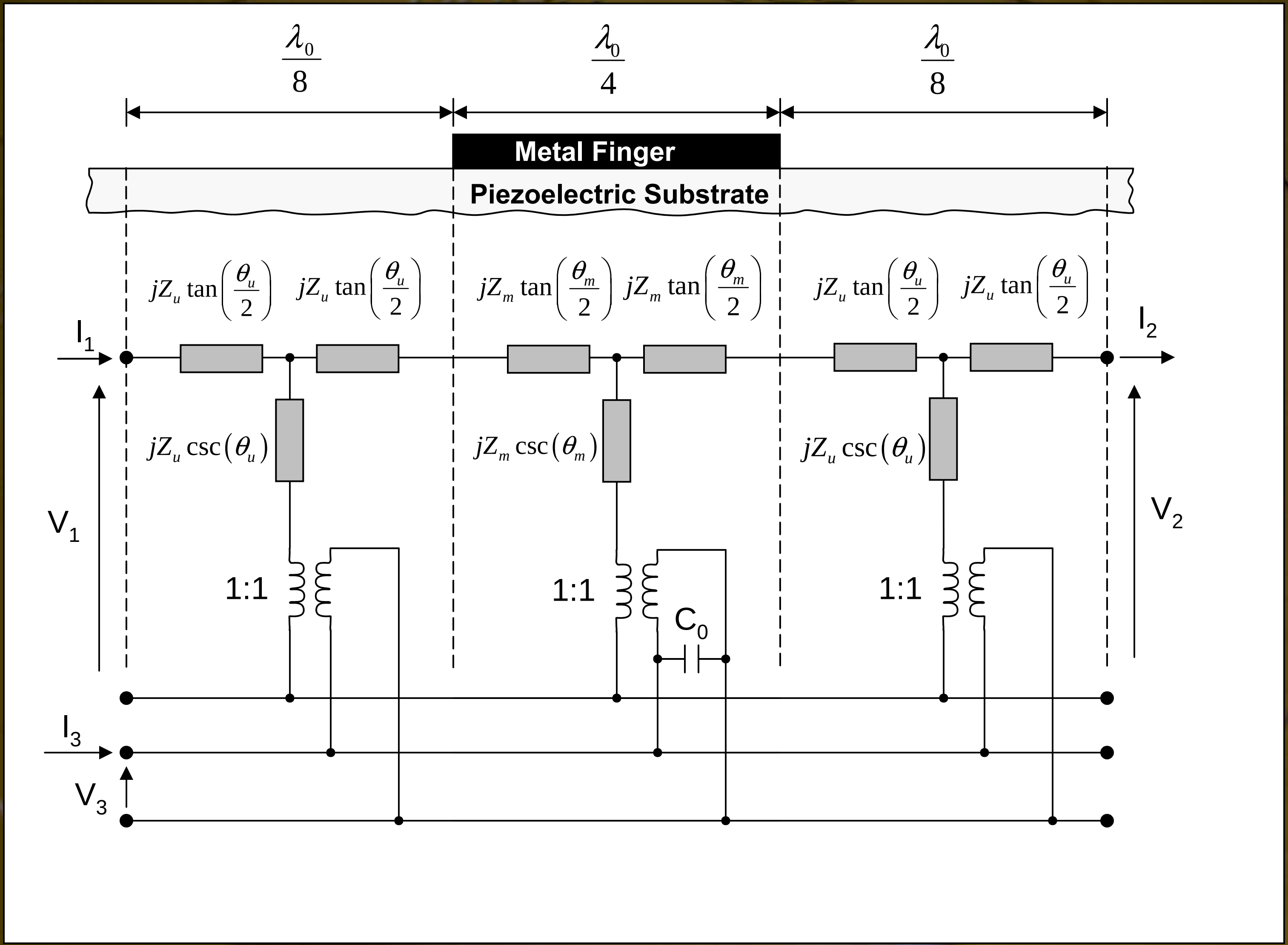
Conclusion

- **Developed models for a SAW delay line.**
  - **First order models only which use the Impulse Response Method.**
  - **Frequency response models in VHDL time domain analysis.**
- **Integrated the Models into existing EDA tools.**
  - **Parameterizable Library components using Tcl scripting language.**
  - **Automatic Layout Generation w/Annotation.**
- **Future work will include second order effects such as reflections, triple transit echoes, and temperature effects.**
- **We will continue to look for ways to model SAW devices in the frequency domain using the VHDL-AMS language.**

Auxiliary Slides



2nd Order Model



Passive Wireless SAW Sensor System