Rapid SAW Sensor Development Tools

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Outline

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• Approach
• Impulse Response Method
• Modeling and Analysis Tool
• Integration into existing EDA Tool
• Automated Layout Generation Tool
• Prototype Results
• Conclusions
Motivation

Exterior Inspection in space
Exterior Inspection by hovering (Terrestrial)
Interior Inspection by walking (Terrestrial)

Non-Destructive Evaluation (NDE) of Aerospace Vehicles

Interior SHM Wireless Sensors
Surface Acoustic Wave (SAW) Devices

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

SAW Modeling Tools

Layout Editor

Automatic Layout Generation

Fabrication

3D Modeling

Finite Element Analysis

New Tools

Existing Tools
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.

Circuit model used in Impulse Response Modeling

- 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

- 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.
Optimal number of finger pairs

Aperture width optimization

\[ Z(f) := \frac{1}{G_a(f) + j \left( 2 \cdot \pi \cdot f \cdot C_T + B_a(f) \right)} \]

\[ H_a := \frac{1}{R_{in}} \left( \frac{1}{f_0 \cdot 2 \cdot C_s \cdot N_p} \right) \cdot \frac{4 \cdot k^2 \cdot N_p}{\left( 4 \cdot k^2 \cdot N_p \right)^2 + \pi^2} \]

\[ N_p := \text{round} \left( \frac{2}{\text{NBW}} \cdot f_0 \right) \]

\[ N_p = 70 \quad H_a = 2399.0 \mu m \]
Conductance and Susceptance

Acoustic susceptance of the SAW delay line.

Radiation conductance of the SAW delay line.

\[ x(f) := N_p \cdot \pi \cdot \left( \frac{f - f_0}{f_0} \right) \]

\[ G_a(f) := 8 \cdot k^2 \cdot C_s \cdot H_a \cdot f_0 \cdot N_p \cdot 2 \left( \frac{\sin(x(f))}{x(f)} \right)^2 \]

\[ B_a(f) := \frac{G_a(f_0)}{G_a(f_0)} \cdot \frac{(\sin(2 \cdot x(f))) - 2 \cdot x(f)}{2 \cdot x(f)^2} \]

\[ G_n(f) := \frac{G_a(f)}{G_a(f_0)} \]

\[ B_n(f) := \frac{B_a(f)}{G_a(f_0)} \]

Radiation conductance of the SAW delay line.

Acoustic susceptance of the SAW delay line.

\[ G_n(f) \]

\[ G_n(f) \]
Insertion Loss

\[ IL(f) := -10 \log \left( \frac{2 \cdot G_a(f) \cdot R_g}{\left(1.0 + G_a(f) \cdot R_g\right)^2 + \left[R_g \cdot \left(2 \cdot \pi \cdot f \cdot C_T + B_a(f)\right)\right]^2} \right) \]
Frequency Response

\[ x(f) := N_p \cdot \pi \cdot \left( \frac{f - f_0}{f_0} \right) \]

\[ Z_r := v \cdot \lambda \cdot H_a \cdot \rho \]

\[ H_n(f) := 20 \cdot \log \left[ 4 \cdot k^2 \cdot C_s \cdot H_a \cdot Z_r \cdot f_0 \cdot N_p \cdot \frac{2 \cdot \sin(x(f))}{x(f)} \right]^{2} \cdot e^{-j \left( \frac{N_p + 5}{f_0 \cdot s} \right)} \]
MathCad Worksheet
for modeling an IDT

\[ \lambda := \frac{v}{f_0} \]

\[ W_f := \frac{\lambda}{4} \]

\[ N_p := \text{round} \left( \frac{2}{\text{NBW}} f_0 \right) \]

\[ H_a := \frac{1}{R_{\text{in}}} \left( \frac{1}{f_0 2 \cdot C_s \cdot N_p} \right) \left[ \frac{4 \cdot k^2 \cdot N_p}{(4 \cdot k^2 \cdot N_p)^2 + \pi^2} \right] \]

\[ H_t := H_a + H_b \]

\[ x(f) := \begin{cases} f_0 & \text{if } f = f_0, \ 0 & \text{if } f = 0 \end{cases} \cdot N_p \cdot \pi \cdot \left( \frac{f - f_0}{f_0} \right) \]

\[ G_a(f) := 8 \cdot k^2 \cdot C_s \cdot H_a \cdot f_0 \cdot N_p \cdot \left( \frac{\sin (x(f))}{x(f)} \right)^2 \]

\[ C_T := N_p \cdot C_s \cdot H_a \]

\[ B_a(f) := G_a(f_0) \cdot \frac{\left( \sin (2 \cdot x(f)) \right) - 2 \cdot x(f)}{2 \cdot x(f)^2} \]

\[ H_n(f) := 20 \cdot \log \left[ 4 \cdot k^2 \cdot C_s \cdot H_a \cdot Z_r \cdot f_0 \cdot N_p \cdot \left( \frac{\sin (x(f))}{x(f)} \right)^2 \cdot e^{-j \left( N_p + \frac{5}{f_0} \right)} \right] \]

Wavelength

Electrode Finger Width

Number of Finger pairs

Finger Aperture

Finger Height Total

Radiation Conductance

Total IDT Capacitance

Acoustic Susceptance

Frequency Response
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/s²
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 MathCad® 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)
This dialogue box is where the parameters for the basic SAW delay line are input.

- 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.
Finite Element Analysis available from existing tools.
Surface Acoustic Wave Research

Stress (XZ) in a Quartz substrate caused by changing the voltage on alternating metal fingers.
Device Results

Frequency response of the SAW delay line device.
Conclusion

- Developed models for a SAW delay line.
  - First order models only which use the Impulse Response Method.

- 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.
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;
2nd Order Model

\[ \frac{\lambda_0}{8} \]
\[ \frac{\lambda_0}{4} \]
\[ \frac{\lambda_0}{8} \]

Piezoelectric Substrate

Metal Finger

\[ jZ_u \tan\left(\frac{\theta_u}{2}\right) \]
\[ jZ_u \tan\left(\frac{\theta_u}{2}\right) \]
\[ jZ_m \tan\left(\frac{\theta_m}{2}\right) \]
\[ jZ_m \tan\left(\frac{\theta_m}{2}\right) \]
\[ jZ_u \tan\left(\frac{\theta_u}{2}\right) \]
\[ jZ_u \tan\left(\frac{\theta_u}{2}\right) \]

\[ jZ_u \csc(\theta_u) \]
\[ jZ_m \csc(\theta_m) \]
\[ jZ_u \csc(\theta_u) \]

1:1

1:1

1:1

1:1

1:1

\[ \lambda_0 \]

\[ \frac{\lambda_0}{4} \]

\[ \frac{\lambda_0}{8} \]

\[ \frac{\lambda_0}{8} \]

\[ \frac{\lambda_0}{4} \]

\[ \frac{\lambda_0}{8} \]
Rapid Integrated Prototyping of SAW Sensors (RIPSAWS)