Surface Acoustic Wave Bidirectional Filter Synthesis and Analysis

1984

Raymond L. Yap

University of Central Florida

Find similar works at: http://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

Part of the Engineering Commons

STARS Citation


http://stars.library.ucf.edu/rtd/4705

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
SURFACE ACOUSTIC WAVE BIDIRECTIONAL FILTER
SYNTHESIS AND ANALYSIS

BY

RAYMOND L. YAP
B.S.E., University of Central Florida, 1981

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Fall Term
1984
ABSTRACT

Surface Acoustic Wave (SAW) devices are manufactured using standard metallization and photolithographic techniques that have been established by the semiconductor industry. The facilities in the newly developed Microelectronics laboratory at the University of Central Florida will be utilized in the fabrication of a SAW device.

This thesis will outline the complete procedure beginning with the initial design from given specifications, up to mask generation, fabricating and testing of the device. This will serve to calibrate the fabrication process for future work in SAW device and semiconductor fabrication.

The models that are used in the SAWCAD design software will be verified by comparing the theoretical and experimental results.
ACKNOWLEDGEMENTS

I would like to thank Dr. Donald Malocha and members of my graduate committee for their suggestions and assistance in the writing of this thesis. Special thanks to the past and present members of the Solid State Devices Laboratory for the many ways in which they have assisted in this endeavor.

To my parents and all those close to me who have supported and encouraged me, thank you.
# TABLE OF CONTENTS

## LIST OF TABLES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>vi</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>vii</td>
</tr>
</tbody>
</table>

## I. BACKGROUND OF PREVIOUS WORK

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to SAW devices and SAW theory</td>
<td>1</td>
</tr>
<tr>
<td>Physical Description</td>
<td>1</td>
</tr>
<tr>
<td>Transversal Filter Implementation</td>
<td>3</td>
</tr>
<tr>
<td>Apodization</td>
<td>4</td>
</tr>
<tr>
<td>Sampling Theory</td>
<td>5</td>
</tr>
<tr>
<td>Time Impulse Response and Frequency Response of SAW Devices</td>
<td>7</td>
</tr>
<tr>
<td>Second-Order Effects</td>
<td>8</td>
</tr>
<tr>
<td>Pulse Shaping Techniques</td>
<td>9</td>
</tr>
<tr>
<td>Introduction to SAWCAD</td>
<td>10</td>
</tr>
<tr>
<td>Impulse Response Design Procedure</td>
<td>10</td>
</tr>
<tr>
<td>Introduction to SAWCAD Facilities</td>
<td>10</td>
</tr>
</tbody>
</table>

## II. OBJECTIVE OF PROPOSED WORK

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
</tr>
</tbody>
</table>

## III. METHODS, PROCEDURES AND EXPERIMENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Impulse Response and Frequency Response Design</td>
<td>14</td>
</tr>
<tr>
<td>Device Structured Layout</td>
<td>27</td>
</tr>
<tr>
<td>Fabrication Process</td>
<td>35</td>
</tr>
<tr>
<td>Test and Analysis</td>
<td>40</td>
</tr>
<tr>
<td>Theoretical and Experimental Data</td>
<td>40</td>
</tr>
</tbody>
</table>

## IV. CONCLUSION AND SUMMARY

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
</tr>
</tbody>
</table>
APPENDICES ................................................................. 57

A. General Design Rules for Transducer Layout ........................................ 57
B. Substrate Preparation ................................................................. 58
C. Procedure for Flash Evaporation .................................................. 60
D. Photoresist Processing ............................................................... 61
E. Effect of Apodization on Conductance ............................................. 63

REFERENCES ................................................................. 67
LIST OF TABLES

1. Design Specifications  .................. 14
2. Layout Dimensions  .................... 29
3. Experimental and Theoretical Results . . . . . 55
# LIST OF FIGURES

1. Typical SAW Device .................................................. 1
2. Transversal Filter Schematic ........................................ 3
3. Amplitude Weighting and Apodization .............................. 4
4. Time and Frequency Representation of a RF Gated Signal ...... 6
5. Sampled Time Impulse Response and its Frequency Spectrum . 6
6. Flowchart for Time Impulse Response and Frequency Response Determination ...................................................... 15
7. Fortran Program to Create Data File of $2f_0$ Sampled Time Impulse Response of the Eigen Function .................. 17
8. Data File of $2f_0$ Sampled Time Impulse Response of the Eigen Function ...................................................... 18
9. Data File of $4f_0$ Sampled Time Impulse Response of the Eigen Function ...................................................... 19
10. Sampled Time Impulse Response of Input Transducer at $4f_0$ Sampling ....................................................... 20
11. Frequency Response of Input Transducer at $4f_0$ Sampling ....................................................... 21
12. Fortran Program to Create Data File of $2f_0$ Sampled Time Impulse Response of the Output Transducer ............ 22
13. Data File of $2f_0$ Sampled Time Impulse Response of the Output Transducer ....................................................... 22
14. Data File of $4f_0$ Sampled Time Impulse Response of the Output Transducer ....................................................... 23
15. Sampled Time Impulse Response of Output Transducer at $4f_0$ Sampling ....................................................... 24
16. Frequency Response of Output Transducer at 4f₀ Sampling .......................... 25
17. Overall Frequency Response of Device .......................... 26
18. Flowchart for Creating Transducer Geometry .......................... 27
19. Device Floor Plan .......................... 30
20. Device Geometry from STRUCTURE Program (with magnified sections) .................. 32
21. 10X Reticle (actual size) .......................... 33
22. Device Mask .......................... 34
23. Flowchart for Fabrication Process .......................... 35
24. Device Package (internal view) .......................... 37
25. Test Fixture for Device .......................... 38
26. Material Design Definitions .......................... 41
27. Predicted Frequency Response Showing Third Harmonic (Theoretical) .................. 41
28. Measured Frequency Response Showing Third Harmonic (Experimental) .................. 42
29. Frequency Response (Theoretical) .......................... 43
30. Frequency Response (Experimental) .......................... 43
31. Passband Response (Theoretical) .......................... 44
32. Passband Response (Experimental) .......................... 44
33. Group Delay (Theoretical) .......................... 46
34. Group Delay (Experimental) .......................... 47
35. Input Transducer Impedance (from Design Information reflecting parasitics) .................. 48
36. Input Transducer Impedance (Experimental) .......................... 48
37. Output Transducer Impedance (from Design Information reflecting parasitics) .................. 49
38. Output Transducer Impedance (Experimental) .......................... 49
39. Time Impulse Response (Experimental) .................. 51

40. Enhanced Frequency Response (from time impulse response modification) .......................... 52

41. Undamped Frequency Response .......................... 53

42. Damped Response ........................................ 53

43. Frequency Response (bulk modes removed) .............. 54

E1. Amplitude Weighted Transverse Cosine Function .......... 63

E2. Apodized Transverse Cosine Function ..................... 65
CHAPTER I

BACKGROUND OF PREVIOUS WORK

Introduction to SAW Devices and Theory

Physical Description of a SAW Device.

A Surface Acoustic Wave (SAW) device is an electroacoustic device that converts electrical energy into an acoustic wave, which may be manipulated to perform certain signal processing functions. The acoustic wave is then received and converted back into an electrical signal.

A typical SAW device is shown in Figure 1 and consists of an input and output transducer on a highly polished

![Figure 1. Typical SAW Device.](image-url)
piezoelectric substrate. Crystalline quartz and lithium niobate are two commonly used piezoelectric substrates, and all the magnetic dipoles in the crystal structure are orientated in the same direction. The input and output transducers are a series of interdigital metal electrodes, which are laid down using standard metallization and photolithographic techniques. Each adjacent electrode or "finger" is connected to busbars of opposite polarity. When a voltage is applied to the input transducer, the voltage appearing between adjacent fingers torques the dipoles in the crystal. The dipoles then snap back to their original orientation thereby generating an acoustic wave which emanates from both ends of the transducer and propagates along the surface of the crystal. The wave that is generated towards the edge of the crystal is damped out by the acoustic absorber. SAW devices are reciprocal devices and as the surface wave travels under the output transducer it is converted back into an electrical signal. Various signal processing functions may be implemented depending on the particular pattern on the transducers, the width and periodicity of the electrodes.

The velocity of the acoustic wave is on the order of 3000 m/s. This results in an operating range of 10 MHz to 1 GHz because the corresponding wavelengths are 300 um to 1.5 um. At present, these limits are due to the resolution limitations of photolithographic processing for high
frequency devices and physical size limitations for low frequency devices.

Transversal Filter Implementation

The interdigital transducer structure approximates an ideal transversal filter. A transversal filter, as shown in Figure 2, is a tapped delay line consisting of a series of delay paths, each weighted by a coefficient, and a summer to sum the delayed signals. In the time domain, filtering is performed because the delayed signals add constructively and destructively under different conditions. In an interdigital transducer, the gap between electrodes act as delay paths and the electrodes sample or tap the signal as it propagates through it. The busbars act as the summing junction. Weighting coefficients may be implemented by amplitude weighting each individual electrode or more commonly by using a technique called apodization [1].
Apodization

Figure 3 shows both amplitude weighting and apodization implementations and note that they essentially carry the same information. For an apodized transducer, wherever there is an overlap between electrodes of opposite polarity, surface waves are generated. Where no overlap exists, no surface waves are generated. The amplitude weighting information is indirectly contained in the spatial extent of the acoustic wave generated. A large overlap results in a spatially larger surface wave and a small overlap results in a spatially smaller surface wave [1].
Sampling Theory

From Fourier transform theory, an RF gated signal is composed of a carrier wave multiplied by a window function. This is equivalent to the spectrum of the window function being translated around the frequency of the carrier. (See Figure 4.) If the finite time impulse time response is sampled by a train of impulses, the spectrum will consist of the spectrum of the finite time impulse response being repeated at every multiple of the frequency of the impulse train, as shown in Figure 5. The sampling theorem requires that sampling be performed at twice the highest frequency of interest or higher to avoid aliasing. If this condition is met then the sampled finite time impulse response will contain sufficient information about the frequency response [2].

The RF carrier is usually the highest frequency of interest and sampling at twice and four times the carrier frequency will be referred to as $2f_0$ and $4f_0$ respectively.
Figure 4. Time and Frequency Representation of a RF Gated Signal.

Figure 5. Sampled Time Impulse Response and its Frequency Spectrum.
Time Impulse Response and Frequency Response of SAW Devices.

Due to the uniqueness of Fourier transform pairs, every time impulse response will yield a unique frequency response and vice-versa.

SAW devices implement different frequency responses by apodizing the transducers with the sampled time impulse response patterns. A typical SAW device consists of a transmitting transducer and a receiving transducer separated by a finite distance which provides a delay factor. Therefore, the overall time impulse response is given by the convolution of the input and output time impulse responses.

\[ h_T(t) = h_1(t) \ast h_2(t - t_d) \]

From Fourier transform theory, this corresponds to an overall frequency transfer function of the multiplication of the frequency responses of the input and output transducers.

\[ H_T(w) = H_1(w) \times H_2(w) \times e^{-j\omega t_d} \]

In the design of a SAW device, the overall frequency response has to be decomposed into two transfer functions in order to implement the transmitting and receiving transducers.
Second-Order Effects

There exist some second-order effects in a SAW device that serve to degrade its performance. Surface wave generation also causes bulk waves to be produced, and they propagate down into the crystal and reflect off the bottom. Those bulk waves that reflect into the receiving transducer add undesired signal levels causing signal degradation, usually appearing as ripple in the frequency response. This effect is minimised by roughing the back surface of the crystal and coating it with an absorbing material to scatter the bulk waves.

Triple-transit echo (TTE) occurs due to device bidirectionality and regeneration. As a surface wave travels through the output transducer, it induces a voltage across the busbars. It in turn regenerates another acoustic wave which propagates back to the input transducer. The portion of this signal that undergoes a similar process upon reaching the input transducer and that is received by the output transducer, constitutes triple-transit echo. It appears as an attenuated image of the time impulse response at three times the delay time. Triple-transit echo can be suppressed by mismatching the transducer's load impedance.

RF feedthrough occurs when the signal at the input port is transmitted to the output port via electromagnetic radiation through the air. Instead of going through the delayed acoustic path, the signal is transmitted to the
output instantly. Proper packaging techniques that shield the input and output ports, and proper grounding of the device minimizes RF feedthrough.

Mechanical edge loading occurs at the electrode edge interface and results in acoustic reflections off the edges. This causes distortion of the frequency response because the reflected wave is in phase with the incident wave. The split-finger configuration used in $4f_0$ sampling greatly reduces internal reflections.

Diffraction is due to the wave spreading out as it propagates along the crystal surface. In apodized transducers, where there may be areas of small overlap, diffraction effects are greater. However, the degree of diffraction depends on the crystal used and LiNbO$_3$ tends to be self-compensating [1,3].

**Pulse Shaping Techniques**

Window functions are used for pulse shaping in signal processing and communication systems. The Eigen function was introduced by Vasile [4] for the synthesis of SAW bandpass filters, and is a combination of cosine weighted functions. It was selected because its frequency spectrum has low sidelobe levels, typically below 60 dB, and small inband ripple. The theoretical sidelobe level is difficult to
achieve in practice and superior bulk wave suppression and RF shielding is necessary. The Eigen function lends itself readily for analysis and will be used in the design.

**Introduction to SAWCAD**

Impulse Response Design Procedure.

SAW devices have been analysed and models introduced to aid in their design. One of the first models was a transmission line model conceived by Smith and Gerard [5]. This model was complex, difficult to implement for analysis and even more difficult for synthesis.

The impulse response design procedure was first introduced by Hartmann, et al. [6]. It is a simple first-order model that assumes weak coupling, approximates the electrodes as impulses, and ignores electrical loading and second-order effects. This model proves to be fairly accurate in spite of these assumptions, and knowing the sampled time impulse response configuration and apodizing it on a SAW transducer, will result in the frequency response of that impulse response being realized. Hence, any frequency response can be defined.
Introduction to the SAWCAD Facilities.

The SAWCAD software developed at the University of Central Florida is computer-aided design programs for bidirectional SAW transducers [7]. Program development was done on a VAX 11/750. SAWCAD is a user-friendly system that is completely menu driven. There are three main menus, the main menu, the device analysis menu, and the graphics menu, that execute the options of the system.

The main menu provides access to the graphics and device analysis menus. In addition, it employs system disk file read and write subroutines for time and frequency data files, a Fast Fourier Transform subroutine, and a subroutine to multiply data files and/or system resident data.

The graphics subroutine allows magnitude plots of time and frequency data, as well as plots of phase and group delay. It also allows rescaling of the window of displayed data and redefining of the screen viewport.

The device analysis subroutine determines the equivalent circuit model of the transducer from its time domain data, provides relevant electrical parameters and allows for matching to be performed. The complete broadband frequency response can be calculated and a graphics option allows the electrical network to be displayed.

Parallel with the development of SAWCAD, a STRUCTURE program was created to generate the transducer geometry from the time sampled impulse response data. The STRUCTURE
program is also menu driven and functions by drawing rectangles for the electrodes, busbars, and bond pads, given their dimensions. Data files for input and output transducers may be worked on separately and merged to give two transducer layouts. There are also options for complete rescaling of the layout.

The graphics subroutine will plot the transducer structure geometry and has the capability of zooming and magnifying the displayed layout for closer viewing.
CHAPTER II

OBJECTIVE OF PROPOSED WORK

The main objective of this thesis is to describe the entire design, fabrication, and test process for the development of research SAW devices. It will begin with the initial device design from given specifications, mask generation, fabrication using standard metallization and photolithographic techniques and finally testing of the device. This will serve to calibrate the fabrication facilities in the Microelectronics laboratory at the University of Central Florida.

This thesis will also endeavor to verify the models used and determine deficiencies in the design software, SAWCAD, developed at UCF. SAWCAD assumes amplitude weighting but the actual implementation will be through apodization. Verification will be accomplished by comparing the device performance data with theoretically predicted data.
CHAPTER III

METHODS, PROCEDURES AND EXPERIMENTS

Time Impulse Response and Frequency Response

The following design specifications for an arbitrary SAW device are given in Table 1.

TABLE 1.
DESIGN SPECIFICATIONS.

Center frequency, $f_0 = 79$ MHz.
Sampling rate, $f_s = 4f_0$.
Substrate: $128^\circ$ YX LiNbO$_3$.

Input transducer: Apodized with Eigen Function.

At baseband the Eigen function is given by,

$$ h(t) = 0.44 + 0.5\cos\left(\frac{2\pi t}{\tau}\right) + 0.07\cos\left(\frac{4\pi t}{\tau}\right) $$

Impulse response length, $\tau_1 = 0.266$ usec.

Output transducer: Unweighted.

Impulse response length: 4 finger pairs at 2$f_0$ sampling for wide bandwidth.
The flowchart that outlines the procedure for using SAWCAD to determine the overall time impulse and frequency response for the device is shown in Figure 6.

![Flowchart for Time Impulse Response and Frequency Response Determination.](image-url)
Some preliminary calculations at $2f_0$ sampling are necessary before going into SAWCAD. The Eigen function on the input transducer and the rectangular window function on the output transducer have to be converted into discretely sampled time impulse functions. This is done by substituting discrete time values $t_n$ for $t$ in the Eigen function, where $t_n = n \cdot \Delta t$ and $n$ is an integer. For $2f_0$ sampling, the time impulse response length, $\tau_1 = N \cdot \Delta t$. Therefore the conversion is performed as shown below.

\[
h_1(t) = \left[ 0.44 + 0.5 \cos \left( \frac{2\pi t}{\tau_1} \right) + 0.07 \cos \left( \frac{4\pi t}{\tau_1} \right) \right] \cos(2\pi f_0 t) \quad |t| \leq \frac{\tau_1}{2}
\]

$2f_0$ sampling: $t_n = n \cdot \Delta t$, $\Delta t = (2f_0)^{-1}$

\[
\tau_1 = N \cdot \Delta t
\]

\[
h_1(t_n) = \left[ 0.44 + 0.5 \cos \left( \frac{2\pi t_n}{\tau_1} \right) + 0.07 \cos \left( \frac{4\pi t_n}{\tau_1} \right) \right] \cos(2\pi f_0 t_n) \quad |t_n| \leq \frac{\tau_1}{2}
\]

\[
h_1(n) = \left[ 0.44 + 0.5 \cos \left( \frac{2\pi n}{N} \right) + 0.07 \cos \left( \frac{4\pi n}{N} \right) \right] \cos(n \pi) \quad |n| \leq \frac{N}{2}
\]

\[
N = \frac{\tau_1}{\Delta t} = 2f_0 \tau_1 = (2)(79 \text{ MHz.})(0.266 \text{ usec.}) = 42
\]

\[
h_1(n) = \left[ 0.44 + 0.5 \cos \left( \frac{n \pi}{21} \right) + 0.07 \cos \left( \frac{2n \pi}{21} \right) \right] \cos(n \pi) \quad |n| \leq 21
\]

The results of the above computations show that there will be 42 time intervals and 43 time samples.
Figure 7 shows the Fortran program that was written to create a data file of the $2f_0$ sampled time impulse response of the Eigen function. The program was compiled, linked with a write data to disk subroutine and executed to give the data file shown in Figure 8.

```fortran
common/file/ amp(4096),phase(4096),nfft,itype
common/dat/ fo,tflo,tfhi,num

itype=-1
nfft=43
num=43
fo=79
tflo=-1.3291139
tfhi=1.3291139
icont=18
pi=3.14159

10 i=-1,21
   amp(i+22)=(.44+.5*cos(i*pi/21)+.07*cos(i*2*pi/21))*cos(i*pi)
   phase(i+22)=0.0
   continue
   call writeo(icont)
   stop
end
```

**Figure 7.** Fortran Program to Create Data File of $2f_0$ Sampled Time Impulse Response of the Eigen Function.
Figure 8. Data File of \(2f_0\) Sampled Time Impulse Response of Eigen Function.

To convert to \(4f_0\) sampled data, the \(2f_0\) sampled data file was edited to double each sampled data point, giving a total of 86 time samples. The new time interval, \(\Delta t\) is calculated for \(4f_0\) sampling.

\[
\Delta t = 1/4f_0 = 6.3291 \text{ nsec.}
\]
Values of \( t_{fhi} \) and \( t_{flo} \) were recalculated and updated in the file to account for 4f₀ sampling.

\[
t_{fhi} = (\Delta t \times 42) + (\Delta t/2) = 0.1345 \text{ usec.}
\]

and

\[
t_{flo} = -[(\Delta t \times 42) + (\Delta t/2)] = -0.1345 \text{ usec.}
\]

The resulting 4f₀ sampled data file is shown in Figure 9.

<table>
<thead>
<tr>
<th>( t_{fhi} )</th>
<th>( t_{flo} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7361687</td>
<td>0.7361687</td>
</tr>
<tr>
<td>0.6550005</td>
<td>0.6550004</td>
</tr>
<tr>
<td>0.5713574</td>
<td>0.5713574</td>
</tr>
<tr>
<td>0.4881932</td>
<td>0.4881932</td>
</tr>
<tr>
<td>0.4081475</td>
<td>0.4081475</td>
</tr>
<tr>
<td>0.3334174</td>
<td>0.3334174</td>
</tr>
<tr>
<td>0.2656723</td>
<td>0.2656723</td>
</tr>
<tr>
<td>0.1958005</td>
<td>0.1958005</td>
</tr>
<tr>
<td>0.1126790</td>
<td>0.1126790</td>
</tr>
</tbody>
</table>

Figure 9. Data File of 4f₀ Sampled Time Impulse Response of Eigen Function.
The graphics subroutine was then invoked to plot the $4f_0$ sampled data. Figure 10 is the plot of the $4f_0$ sampled time impulse response of the Eigen function.

![Sampled Time Impulse Response](image)

**Figure 10.** Sampled Time Impulse Response of Input Transducer at $4f_0$ Sampling.

To determine the frequency response of the input transducer, the $4f_0$ sampled time data file was read into the system and the Fast Fourier Transform subroutine called to perform the transformation. The number of data points needed in the Fast Fourier Transform has to be an integer power of 2. Augmenting zeros were added to the data file to give 1024 data points. Frequency response data was written to disk and Figure 11 shows the frequency response obtained.
The time impulse response and frequency response for the output transducer were determined following the same procedure. Specifications given indicate that the transducer is unweighted, and that four finger pairs are required. The conversion for $2f_0$ sampling follows.

$$h_2(t) = \cos(2\pi f_0 t) \quad |t| \leq \frac{T_2}{2}$$

$$N = \frac{T_2}{\Delta t} = 2f_0 T_2 = (2)(79 \text{ MHz})(0.051 \text{ usec.}) = 8$$

$$h_2(n) = \cos(n\pi) \quad |n| \leq 4$$

There are 8 time intervals and 9 time samples.
Figure 12 is the Fortran program that created the $2f_0$ sampled time impulse response of the output transducer, and it produced the data file shown in Figure 13.

common/file/ amp(4896),phase(4896),nfft,itype
common/dat/ fo,tflo,tphi,num

      itype = -1
      nfft = 9
      num = 9
      fo = 73
      tflo = -0.025316455
      tphi = 0.025316455
      icont = 10
      pi = 3.14159
      do 11 i=-4, 4
         amp(i+5)=cos(i*pi)
         phase(i+5)=0.0
      continue
      call write(i,cont)
      stop
      end

Figure 12. Fortran Program to Create Data File of $2f_0$ Sampled Time Impulse Response of the Output Transducer.

1.000000
-1.000000
1.000000
-1.000000
0.999999
-0.999999
0.999999
-0.999999
0.999999

Figure 13. Data File Of $2f_0$ Sampled Time Impulse Response of Output Transducer.
Converting to $4f_0$ sampled data gave a total of 18 time samples. The new time interval, $\Delta t$ was also 6.3291 nsec. The new values of tfhi and tflo were computed for $4f_0$ sampling.

$$tfhi = (\Delta t \times 18) + (\Delta t/2) = 0.0269 \text{ usec.}$$

and

$$tflo = -[(\Delta t \times 18) + (\Delta t/2)] = -0.0269 \text{ usec.}$$

The resulting $4f_0$ sampled data file is shown in Figure 14.

```
type= -1
fo = 0.7999999900E+02
flo = -0.26688734E-01
tfhi = 0.26688734E-01
num = 18
0.9999999
0.9999999
-0.9999999
-0.9999999
1.0000000
1.0000000
-1.0000000
-1.0000000
1.0000000
1.0000000
-1.0000000
-1.0000000
1.0000000
1.0000000
-0.9999999
-0.9999999
0.9999999
```

Figure 14. Data File of $4f_0$ Sampled Time Impulse Response of Output Transducer.
The graphics subroutine plot of the $4f_0$ sampled time impulse response is shown in Figure 15.

Figure 15. Sampled Time Impulse Response of Output Transducer at $4f_0$ Sampling.

The Fast Fourier Transform subroutine was called again to transform the time file and augmenting zeros were added to give 1024 data points. Frequency response data was written to disk and shown in Figure 16.
Finally, to obtain the total frequency response of the device, the multiplication option of SAWCAD was used to multiply the frequency response data files of the input and output transducers. The overall frequency response was written to a disk file and the plot is shown in Figure 17.
Figure 17. Overall Frequency Response of Device.
Device Structured Layout.

The device structured layout refers to the actual transducer geometry that will be implemented on the device. The STRUCTURE program will be used to create the device geometry by producing the apodization pattern, busbars, and any other desired SAW components. Figure 18 is the procedure followed for creating the device layout.

Figure 18. Flowchart for Creating Transducer Geometry.
The initial floor plan layout is necessary to give an overall view of the device's dimensions and the relation of the components with respect to each other. Input and output transducers will be designed separately and then combined to give the total layout. STRUCTURE does all design in terms of the center frequency wavelength, $\lambda_0$, and therefore all dimensions used in the program must be in terms of $\lambda_0$.

For 128° LiNbO₃, the wave velocity, $v_a$, is 3936 m/sec. Center frequency wavelength can then be calculated. For 4fo sampling, derivations show that the electrode width is equal to the gap width and comes out to be $\lambda_0/8$.

$$\lambda_0 = \frac{v_a}{f_0} = 49.83 \text{ um.}$$

Electrode/gap width = $\lambda_0/8 = 6.23 \text{ um.}$

The input transducer's impulse response length is 0.2658 usec. Therefore the transducer length is 1.046mm. With 18 fingers in the output transducer, the transducer length is 0.2118 mm.

The subroutine that creates the structure geometry requires layout dimensions pertaining to the SAW components on the device, and will prompt the user for them. Appendix A shows some of the general layout design guidelines that are followed, Table 2 shows the dimensions that were selected for this design.
TABLE 2.

LAYOUT DIMENSIONS.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Busbar height</td>
<td>10 mils. = 5.097 λ₀</td>
</tr>
<tr>
<td>Busbar extension</td>
<td>0</td>
</tr>
<tr>
<td>Acoustic beamwidth</td>
<td>50 λ₀</td>
</tr>
<tr>
<td>Electrode-busbar gap</td>
<td>0.8028 λ₀</td>
</tr>
<tr>
<td>Finger width</td>
<td>0.125 λ₀</td>
</tr>
<tr>
<td>Electrode gap</td>
<td>0.25 λ₀</td>
</tr>
<tr>
<td>Electrode-dummy break distance</td>
<td>0.25 λ₀</td>
</tr>
<tr>
<td>Bond pad: center</td>
<td></td>
</tr>
<tr>
<td>Bond pad width</td>
<td>5.097 λ₀</td>
</tr>
<tr>
<td>Bond pad height</td>
<td>7.646 λ₀</td>
</tr>
<tr>
<td>Electrodes: Unsplit</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0</td>
</tr>
</tbody>
</table>

With the above information the floor plan of the device was drawn and is shown in Figure 19.
Figure 19. Device Floor Plan.
Before beginning to create any transducer geometry, the time sampled impulse response data file has to be accessible by the STRUCTURE program. The data files of the input and output transducers, that were shown in Figures 9 and 14, were transferred to the STRUCTURE directory.

To create the input transducer geometry, the time impulse response data file of the Eigen function was first read into the system. The subroutine to create transducer geometry was invoked and the design dimensions of Table 2 were entered when prompted. All the structure data was then written to a disk file.

The ground plane was created next by simply invoking the modify structure manually subroutine and specifying the starting point of the rectangle, its width and height. These dimensions were taken from the device floor plan, and the starting point referenced to the lower left-hand corner of the input transducer which was taken to be (0,0). Ground plane structure data was then written to disk.

The transducer geometry for the output transducer was created following the same procedure for the input transducer, and using the appropriate time data file. In addition, the starting coordinates were offset to give 50 mils between the transducers.

The final step was to create a structure data file that would contain structure data on both transducers and the ground plane. This was accomplished by executing STRUCTURE
and reading the respective data files consecutively, thereby combining all the data, and writing the data to disk. The overall device geometry from the STRUCTURE program is shown in Figure 20.

Figure 20. Device Geometry from STRUCTURE Program (with magnified section).
The main purpose of obtaining the transducer geometry is to generate a mask that will be used to fabricate the device. The total structure data file was downloaded from the VAX 11/750 onto an IBM PC. A SAW MASK DRAW program was developed on the IBM PC for plotting masks, and it was used to plot a 100X reticle of the device. An HP7580B plotter driven by the PC drew the 100X reticle with India ink on a mylar sheet.

To produce the mask, the 100X reticle was taken to the mask making facilities at the Microelectronics Division of Martin Marietta, Orlando, Florida and a 10X reduction, shown in Figure 21, was made. It was then stepped and repeated nine times onto a photographic transparency, and reduced another 10X to give an overall reduction of 100X. This final transparency was contact printed onto a chrome blank to produce a chrome mask to be used in the device fabrication. The mask is shown in Figure 22.

Figure 21. 10X Reticle (actual size).
Figure 22. Device Mask.
Fabrication Process

The fabrication process for the SAW device is outlined in Figure 23.

Figure 23. Flowchart of Fabrication Process.
A $128^\circ \text{YX LiNbO}_3$ wafer was prepared according to the procedure in Appendix B, and an aluminium film deposited onto the surface by flash evaporation. Any metal deposition method may be used as long as the film is uniform and sufficient thickness is attainable. The flash evaporation procedure outlined in Appendix C yields a film thickness of approximately 2000 Å.

The photoresist process of Appendix D was performed to transfer the transducer patterns onto the aluminium film. After the process was completed, the wafer was examined under a microscope and checked for processing flaws.

Prior to scribing the wafer a reasonably thick layer of photoresist was spun onto the etched wafer and softbaked for about 30 min. This is a necessary step that prevents the abrasive slurry of the wire saw from scratching and removing any aluminium. The stage was heated and a small amount of wax melted onto it to hold the wafer. This wax can be removed with trichloroethylene. The wafer was then scribed, and normally it takes about 10 seconds for the wire saw to cut through. Large wafers may be difficult to scribe due to their size and more cuts may be necessary to get it down to size. After scribing, each device was mounted upside down and cross-hatch lines were scribed onto the back surface by contacting the moving wire saw with the surface repeatedly, at small intervals. The time of contact need only be for a half second or less, or until a deep groove is cut into the
crystal. Cross-hatching reduces reflections off the crystal bottom by scattering the bulk waves.

A 16-pin metal DIP package was used to mount three good devices. A small amount of silicone rubber sealer was placed on the back of the devices and then attached to the header, and allowed to cure over a 24 hour-period.

The devices were then wire bonded using 1 mil gold wire. Figure 24 shows the configuration of the devices on the header and the wire bond connections. The ground planes were bonded to separate header pins to allow for the flexibility of reversing the connections to the terminals of the transducers.

![Figure 24. Device Package (internal view).](image)

Finally, an acoustic absorber material was very carefully spread onto the outside area of the transducers to prevent edge reflections. Slightly viscous photoresist proved to be adequate for this purpose. Fresh photoresist was drawn into the grooves under the crystal through capillary action to help reduce bulk mode reflections even more.
To test the devices, the header had to be mounted onto a PC board. A hole was cut into a single-sided copper board and the header inserted into it so that the bottom of the header was resting on the board surface. (See Figure 25.) Ground pins were soldered to the ground plane of the board, and OSM type semi-rigid connectors used to connect to the input and output terminals of the devices.

Figure 25. Test Fixture for Device.
The input and output connectors were soldered at right-angles to each other so that their magnetic fields would be orthogonal thus preventing cross coupling. In addition, a ground plane which was simply a thin sheet of copper board was placed in the space between the input and output pins of the header. This shields the inputs from the outputs and minimizes any RF feedthrough.
Test and Analysis.

Theoretical and Experimental Data.

The device was tested on an HP8507A Network Analyzer and data acquisition was performed through an HP9845B. Frequency response, group delay and impedance plots of the device fabricated are presented.

Theoretical data was determined from SAWCAD. The device analysis subroutine, which calculates the equivalent circuit model of each transducer, was executed. The material parameter definitions of the device, and which are required by this subroutine is shown in Figure 26. However, the theoretical data up to this point does not incorporate external parasitic effects. Bond wires contribute about 0.1 μH of inductance and the header capacitance is approximately 0.5 pF. These parasitic component values were added to the equivalent circuit models of the transducers and the complete frequency response determined. Impedance measurements were obtained from the transducer design information calculated by the device analysis subroutine. Frequency response and group delay plots reflecting the added parasitic effects are shown below with the experimental data.
<<< Material Parameter Definitions >>>

ENTER coupling coefficient : [PU= 0.0000E+00] => 0.055
ENTER substrate velocity (m/sec) : [PU= 0.0000E+00] => 3927
ENTER beam width (fo wavelengths) : [PU= 0.0000E+00] => 50
ENTER substrate capacitance (p/cm) : [PU= 0.0000E+00] => 5.4
ENTER electrode duty factor : [PU= 0.0000E+00] => 0.2
ENTER metal resistivity (Ohms/sq) : [PU= 0.0000E+00] => 0

ENTER:
1 for 1/4 lambda electrodes
2 for 1/2 lambda electrodes
3 for 1/6 lambda electrodes
4 for arbitrary electrode pattern

[PU=4] : => 2

Figure 26. Material Design Definitions.

Figure 27. Predicted Frequency Response Showing Third Harmonic (Theoretical). Does not reflect 6 dB bidirectional transducer loss.
Figure 28. Measured Frequency Response Showing Third Harmonic (Experimental).

The plots show that the first and third harmonic responses occur at 79 MHz and 237 MHz respectively, in theory and in practice. However, the theoretical third harmonic response peak is 2.43 dB below the main response while experimentally it is 2.75 dB above the main response. Bulk mode energy tends to mask the low sidelobes, although the "ears" on either side of the main response are evident in both plots. Significant differences in out-of-band sidelobe levels are due to second-order effects which are not accounted for in theory.
Figure 29. Frequency Response (Theoretical).

Figure 30. Frequency Response (Experimental).
The passband shape is accurately predicted by the SAWCAD model, and the insertion loss, 3dB and 40 dB bandwidths correlate well. SAWCAD predicts 17.2 dB insertion loss and 17.1 dB was measured. The measured 3 dB and 40 dB bandwidths were 6.5 MHz. and 18.5 MHz. respectively, compared with 5.5 MHz. and 18.3 MHz. predicted. Experimental center frequency is 78.7 MHz. which is close to the predicted 79 MHz. The sidelobes adjacent to the passband are significantly higher than predicted. This is caused by tap weight inaccuracies due to implementation in the structure of the apodized transducer. Diffraction and tap end effects are believed to be the principle cause. In addition, bulk and plate mode energy is spread across the frequency band; setting the base level at approximately -75 dB. Finally, RF feedthrough is also apparent and contributes substantially to the base level at the third harmonic and higher frequencies.
Figure 31. Passband Response (Theoretical).

Figure 32. Passband Response (Experimental).
The passband response of the device shows a ripple not predicted by SAWCAD. This passband ripple is due to triple-transit echo, and has a period given by the inverse of twice the delay time. The period of the ripple, from Figure 32, is measured to be 0.9 MHz. The delay time measured from the group delay plot of Figure 34 is 481 nsec., and twice this value gives 0.96 usec or 1.04 MHz. The correlation is not exact, however, because peak-to-peak ripple is difficult to measure due to the rounded response.

Figure 33. Group Delay (Theoretical).
The predicted and measured group delay, shown in Figures 33 and 34, exhibit the same characteristic shape, although at the edges of the passband they roll off at different rates. One major error that occurred is that theoretical data predicted 720 nsec. peak-to-peak group delay while 26 nsec. peak-to-peak was measured. Further verification of the model parameters in SAWCAD seem to be necessary.
<<< Electrical Network >>>
<<< Design Information >>>
[Does not include bidirectional loss]

Frequency = 79.0 MHz

Input Impedance, Zin = (44.80, -86.41)

S11 = (-0.4238, 0.5252)

|S11|*|S11| = 0.4554

|S21|*|S21| = 0.5446

Total Insertion Loss = 2.771 dB

Parasitic & other Dissipative Losses = 0.1315 dB

Mismatch Loss = 2.639 dB

Figure 35. Input Transducer Impedance (from Design Information reflecting parasitics).

Figure 36. Input Transducer Impedance (Experimental).
 electrical network
<< Design Information >>
[Does not include bidirectional loss]

Frequency = 79.0 MHz

Input Impedance, Zin = (49.15, -228.6)
S11 = (-0.8403, 0.3682)
|S11||S11| = 0.8416
|S21||S21| = 0.1584

Total Insertion Loss = 8.407 dB

Parasitic & other Dissipative Losses = 0.4034 dB

Mismatch Loss = 8.003 dB

Figure 37. Output Transducer Impedance (from Design Information reflecting parasitics).

Figure 38. Output Transducer Impedance (Experimental).
Theoretical impedances were calculated from the transducer equivalent circuit and is composed of the thin-film resistance, acoustic conductance and the electrode capacitance. Experimental impedances were measured from the network analyzer. The following measurements, normalized to 50 ohms, were taken.

**Theoretical**

- $Z(\text{input}) = 0.9 - j1.7$
- $Z(\text{output}) = 1.0 - j4.6$

**Experimental**

- $Z(\text{input}) = 2.0 - j1.9$
- $Z(\text{output}) = 3.1 - j7.5$

The theoretical and experimental reactance term of the input impedance were well correlated although the resistance term was not. This difference in the resistance term may be due to the effect of apodization, and Appendix E shows calculations necessary to account for it. For the output transducer, poor correlation was evident.

The time impulse response of the device, shown in Figure 39, was obtained by data acquisition of the frequency response data and performing an inverse Fast Fourier Transform. Note that RF feedthrough occurs at $t=0$ and the main time response occurs after a delay time of 0.48 usec. This correlates well with the measured group delay of Figure 34.
The triple-transit echo occurs at three times this delay, i.e. 1.44 usec, as noted in the plot. An approximate relationship for the ratio of the TTE power to the main signal power is as follows:

\[
\frac{\text{TTE power}}{\text{Main signal power}} = 6 \text{ (dB)} + 2\text{IL(dB)} = 40.2 \text{ dB}
\]

From Figure 32, this value was measured to be 42.4 dB.

Data enhancement was attempted in an effort to obtain a purer frequency response free of second-order effects. One method was to modify the time impulse response to remove the RF feedthrough, triple-transit echo and bulk wave energy, and then perform a Fast Fourier Transform. The frequency
response of such an attempt is shown in Figure 40. Although it appears that the frequency response is cleaner, the sidelobe level has been raised and the windowing effect has produced the sidelobe response. The deficiency in this method may be due to too much bulk mode energy being present within the SAW passband.

Figure 40. Enhanced Frequency Response (from time impulse response modification)

Another attempt was made by placing photoresist between the transducers, to damp out the SAW response, and taking data on just the bulk modes. Theoretically, by subtracting the damped response from the undamped response, the bulk modes would be reduced. Figures 41, 42 and 43 show the results of such an attempt.
Figure 41. Undamped Frequency Response.

Figure 42. Damped Response.
This method was unsatisfactory mainly because the bulk modes were at such a low level that they did not subtract out significantly. Very little enhancement was obtained.
CHAPTER IV

CONCLUSION AND SUMMARY

Experimental and Theoretical Results.

The results of the measurements of both the theoretical and experimental data are tabulated for comparison in Table 3.

TABLE 3.

EXPERIMENTAL AND THEORETICAL RESULTS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency, f0 (MHz.)</td>
<td>79.0</td>
<td>78.7</td>
</tr>
<tr>
<td>Insertion Loss (dB)</td>
<td>-17.2</td>
<td>-17.1</td>
</tr>
<tr>
<td>3dB Bandwidth (MHz.)</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td>40dB Bandwidth (MHz.)</td>
<td>18.3</td>
<td>18.5</td>
</tr>
<tr>
<td>Sidelobe Level (dB)</td>
<td>&lt; 85</td>
<td>&lt; 46</td>
</tr>
<tr>
<td>Group Delay (p-p, nsec.)</td>
<td>720</td>
<td>26</td>
</tr>
<tr>
<td>Input Impedance (normalized to 50 ohms)</td>
<td>0.9 - j1.7</td>
<td>2.0 - j1.9</td>
</tr>
<tr>
<td>Output Impedance (normalized to 50 ohms)</td>
<td>1.0 - j4.6</td>
<td>3.1 - j7.5</td>
</tr>
</tbody>
</table>
The design and fabrication of the bidirectional surface acoustic wave device was successfully accomplished. Slight problems with contamination were encountered in fabrication but this was minimized by performing the entire fabrication sequence in one session and by avoiding prolonged exposure of the substrate to the open air during processing. The equipment in the Microelectronics Laboratory proved to be adequate for SAW device fabrication.

Results of theoretical and experimental data show that there is a close correlation between frequency response data in the passband. Data enhancement techniques were unsuccessfully attempted in an effort to reduce bulk wave and spurious responses, proving that as mentioned previously, in practice it is difficult to obtain the theoretical sidelobe levels. The scales of the group delay were in error although the characteristics were similar.

The resistance of the input transducers impedance was not correlated although the reactance term was almost identical. This difference may have been due to the apodization losses that were not accounted for in the design.

The output impedance measurements were severely uncorrelated and further analysis will be necessary to determine the cause of this discrepancy. Some parasitic effects may have been overlooked in the design, or the small transducer size may have led to large errors.
APPENDIX A

GENERAL DESIGN RULES FOR TRANSDUCER LAYOUT

1- Busbar height is typically 5-20 mils wide.

2- Bond pads typically 5 mils square or larger to accommodate bond wire.

3- Gap to busbar distance typically \( \leq \lambda_0 \).

4- Dummy electrode to electrode gap distance typically \( 0.5 \lambda_0 \) to \( \lambda_0 \).

5- Acoustic beamwidth typically between 50 - 100 \( \lambda_0 \).

6- Distance between transducers typically around 50 mils to prevent RF feedthrough.
APPENDIX B

SUBSTRATE PREPARATION

1- Turn on the tap water in the fume hood. Water should be left running in order to flush away all chemicals.

2- Put on lab. coat or apron and PVC gloves.

3- Fill a glass petri dish with a solution of concentrated sulphuric acid and hydrogen peroxide (95:10) and immerse the substrate for about 10 minutes. The solution is a strong oxidizer and care should be exercised when using it.

4- Wash the substrate with tap water and detergent to remove bulk contaminants from the surface.

5- Rinse the substrate in tap water.

6- Hold the substrate with tweezers such that the tip of the tweezers are at the bottom part of the substrate and as close to the edge as possible.

7- Rinse the substrate with trichloroethylene to remove the detergent residue. Spray from the top of the substrate so that the residue drips down towards the tweezers. This also prevents contaminants from the tweezers migrating onto the substrate surface.

8- Rinse the substrate with acetone to remove the trichloroethylene residue.

9- Rinse the substrate with methanol to remove the acetone residue.

10- Rinse the substrate with deionized water to remove the methanol residue.
11- Construct a vapor degreaser by putting trichloroethylene in a glass beaker and boiling it on a hot plate. Set the temperature of the hot plate such that the vapor condenses near the top of the beaker and drips back into solution. Suspend the substrate in the beaker so that the vapor condenses on the surface and sheets down it. This removes any remaining contaminants. Slowly withdraw the substrate and place in a clean petri dish.
APPENDIX C

PROCEDURE FOR FLASH EVAPORATION

1- Prepare substrate according to Appendix B.

2- Vent the flash evaporation chamber (Chamber 3) of the vacuum system, and lift the chamber head.

3- Replace the tungsten boat if necessary and place an aluminium pellet in it.

4- Mount the substrate(s) onto the sample holder, and lower the chamber head. The samples should be at a distance of 115 cm. above the source.

5- Rough the chamber down to 20 mTorr, which can be read from the gauge on the control panel.

6- Close the roughing valve, wait two seconds and open the high vacuum valve.

7- Cryo pump the chamber down to $2 \times 10^{-5}$ torr, which can be read from the ionization gauge controller.

8- Switch off the ionization gauge when the desired vacuum has been reached.

9- Set rotation of sample holder to 100%.

10- Slowly bring up power supply to the 40 mark for about 15 seconds, until the aluminium pellet has evaporated.

11- Shut down the power supply.

12- Vent the vacuum chamber and remove the metallized substrate(s).
APPENDIX D

PHOTORESIST PROCESSING

1- Prepare substrate as outlined in Appendix B and C.

2- Before beginning the PR process make the following preparations:
   a) Switch on Blue M oven and set for 90°C. Allow 30 minutes for oven to stabilize.
   b) Obtain aid from the lab. assistant to fill the photoresist syringe with Shipley AZ 1470 positive photoresist. Put a filter in the filter holder for the syringe and insert it on the syringe. This is to remove microscopic contaminants out of the photoresist.
   c) Make up a solution of photoresist developer (Shipley developer and deionized water in a 1:1 solution.)
   d) Make up a solution of aluminium etch if there is none available.
      Aluminium etch: 380 ml. Phosphoric acid.
      75 ml. Acetic acid.
      15 ml. nitric acid.
      25 ml. deionized water.
   e) Make sure that the mask to be used is free of contaminants and finger marks. Chrome masks can be cleaned by gently scrubbing with detergent, rinsing with tap water and then methanol, and drying with the air gun. Emulsion masks scratch easily and must be cleaned in an ultrasonic cleaner with a solution of detergent and water. DO NOT SCRUB THE EMULSION!. Spray with methanol and dry with the air gun.

3- Switch on the spinner control and the vacuum pump for the spinner table.

4- Set the time and speed of rotation by using a dummy substrate on the stage and pressing the foot switch. Set rotation for 4000 rpm and time for 30 seconds.
5- Place the substrate on the spinner and apply photoresist to the substrate using the syringe. It usually requires some force to pump the photoresist through the micron filter. Begin at the center of the substrate and move out to the edges. Make sure that there is enough photoresist to cover the entire surface upon spinning.

6- Start the spinner by using the foot switch.

7- After the spinner has stopped, check if the substrate surface is fully coated with photoresist. If it is not fully covered, remove all photoresist with acetone and go back to step 1.

8- Place the substrate in the 90°C oven for 15 minutes. Substrates used for SAW devices are susceptible to thermal shock and may fracture if heated too rapidly. Exercise care when placing them in the oven.

9- Obtain assistance from your lab. instructor on the operation of the Karl Suss Mask Aligner.

10- Mount the mask in the mask holder of the aligner. The emulsion or chrome side must face the substrate.

11- Mount the substrate on the chuck, bring into contact mode and make sure that the direction of propagation on the substrate is aligned with the transducer pattern on the mask.

12- Expose for 2 seconds.

13- Develop the exposed photoresist in the developer for approximately 4-5 minutes. It is possible to periodically check the developing rate by removing the substrate, rinsing with deionized water to cease the developing, drying with air and examining the substrate under a microscope. Developing can be continued by returning the substrate to the developer.

14- After developing is completed, immerse the substrate in aluminium etch. The exposed aluminium should etch away after approximately 5-10 minutes.

15- Rinse with deionized water to remove aluminium etch.

16- Rinse with acetone to remove baked on photoresist, methanol and deionized water.

17- Blow dry using the air gun.
APPENDIX E

EFFECT OF APODIZATION ON CONDUCTANCE.

Figure E1 shows an amplitude weighted transverse cosine function.

Figure E1. Amplitude Weighted Transverse Cosine Function.

The acoustic conductance at center frequency is given by:

$$G_a(f_0) = 2 |H(f_0)|^2$$

The procedure for determining the acoustic conductance is outlined as follows:

$$h(t) = A e(t) \cos(2\pi f_0 t) \quad 0 < t < \frac{T}{2}$$

where amplitude, $A = 4k \sqrt{C_T f_0^{3/2}}$

$k^2 =$ substrate coupling coefficient(%)  

$C_T =$ electrode pair capacitance(pF/pair)

envelope, $e(t) = \frac{2}{\pi} \cos^{-1} \left( \frac{2t}{T} \right) \quad 0 < t < \frac{T}{2}$
From Fourier Transform theory,

\[ H(f_0) = \frac{A}{2} \int_{-\tau/2}^{\tau/2} e(t) \, dt \]

\[ = \frac{2A}{\pi} \int_0^{\tau/2} \cos^{-1} \left( \frac{2t}{\tau} \right) \, dt \]

\[ = \frac{AT}{\pi} \]

Hence,

\[ G_a(f_0) = 2 |H(f_0)|^2 \]

\[ = \frac{2A^2 \tau^2}{\pi^2} \]

\[ = \frac{2A^2 N_p^2}{f_0^2 \pi^2} \]

\[ = \frac{2(16k^2 C_T f_0 N_p^2)}{f_0^2 \pi^2} \]

\[ = 8k^2 C_T f_0 \frac{N_p^2}{(\pi^2/4)} \]

\[ = G_o \frac{N_p^2}{(\pi^2/4)} \]

\[ = 0.4053 G_o N_p^2 \]

but \( \tau = N_p/f_0 \)

where \( G_o = 8k^2 C_T f_0 \)
Figure E2 shows an apodized transverse cosine function.

![Figure E2. Apodized Transverse Cosine Function.](image)

The acoustic conductance at center frequency is given by:

\[ G_a(f_o) = 2|H(f_o)|^2 \]

To determine the center frequency conductance, the transducer will be divided up into tracks, and the conductance evaluated for each track. The total conductance will then be determined by summing the conductances of each track. The summation becomes an integral if the tracks are small. An expression for the apodized transducer is given by:

\[ h(t,x) = A \cos \omega_0 \text{t.rect} \left| \frac{t}{\tau \cos (\pi x/W_a)} \right| \]

where amplitude, \( A = 4k\sqrt{C_s f_o} \)

\( k^2 = \) substrate coupling coefficient

\( C_s = \) electrode pair capacitance/cm

(pF/pair-cm).

From Fourier Transform theory,

\[ H(f_o,x) = \frac{A}{2} \left[ \frac{\tau \cos (\pi x/W_a)}{W_a} \right] \]
Hence,

\[ G_a(f_o, x) = 2|H(f_o)|^2 \]

\[ = 2 \int_{-W_a/2}^{W_a/2} |H(f_o, x)|^2 \, dx \]

\[ = 2 \int_{-W_a/2}^{W_a/2} \frac{A^2 \pi^2}{4} \cos^2 \frac{\pi x}{W_a} \, dx \]

\[ = \frac{A^2 \pi^2 W_a}{4} \]

\[ = \frac{(16k^2C_s f_o N_p^2)W_a}{4} \]

\[ = 8k^2C_T f_o \frac{N_p^2}{2} \]

\[ = G_o \frac{N_p^2}{2} \quad \text{where } G_o = 8k^2C_T f_o \]

\[ = 0.5 \, G_o N_p^2 \]

Therefore the difference in conductance due to apodization weighting over amplitude weighting is;

\[ \frac{G_a(\text{apodized})}{G_a(\text{amplitude weighted})} = \frac{0.5 \, G_o N_p^2}{0.4053G_o N_p^2} = 1.2337 \]
REFERENCES


