Department of Technology and Built Environment

Modeling of a Tunable Thin Film Bulk Acoustic Resonator and Bandpass Filter design based on Ferroelectric Film

Master’s Thesis in Electronics/Telecommunication

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To

My Parents
This thesis is a result of my research at Tera Hertz and millimeter wave laboratory of Chalmers University of Technology, Sweden to fulfill the requirement for the Master degree in Electronics/Telecommunication Engineering at University of Gavle, Sweden.

Professor Spartak Gevorgian, Professor in Chalmers University of Technology and senior specialist at Ericsson, supervised me and guide me during the whole period of research. The thesis work is examined by Dr. Jose Chilo at University of Gavle.

The main purpose of the thesis is to design a tunable bandpass filter. A single tunable film bulk acoustic resonator (TFBAR) is the building block to design the bandpass filter. The simulations of single FBAR resonator are based on measurements, taken by John Berge, the PhD Student at Chalmers University of technology. Advance Design System (ADS) by Agilent technology is used for simulations. The measurement data is reproduced in ADS simulations by using MASON and Butterworth Van Dyke model and by using this data a tunable bandpass filter for 5GHz applications is designed.
Abstract

Filters having smallest size, high power handling capability, high Q factor, operating frequency up to several gigahertz’s (GHz) and low cost are the demand of the market to use in front end wireless/radio communication systems. In this regard several filter technologies have been introduced and utilized commercially. The increasing demand of such type of filters has opened a new challenge for filter designers.

The purpose of this thesis is to design of a Tunable Bandpass Filter based on Barium Strontium Titanate (BSTO) Ferroelectric Film. A single Film bulk acoustic resonator (FBAR) is measured. MASON and Butterworth Van-Dyke (BVD) model are studied and implemented to reproduce the measurements. Simulations are performed by using the Advance Design System (ADS) by Agilent technologies. Simulations and measured data are used to exactly extract the physical and electrical parameters of a single FBAR.

FBAR filter topologies are being studied and implemented. Ladder filter topology is selected to design the bandpass filter. The extracted physical and electrical parameters are used to investigate the performance of the filter. The area and the top electrode thickness of the series and shunt resonators are optimized to achieve the bandpass response with maximum out of band rejection, minimum insertion loss and sharper roll off near the pass band.

A 3rd order T-type bandpass filter for 5GHz applications is designed. The insertion loss of -2.925 dB is achieved. The filter exhibits the 3dB bandwidth of 176 MHz and out of band rejection of -10 dB. DC bias of 0-25 V is used to analyze the tuning behavior of the filter. The electromagnetic co-simulation is also done in momentum to analyze the parasitic effects between the resonators. The results show the good agreement between the schematic and momentum simulation.

Layout and masks are also designed on a 10*10 mm wafer that will be used later to fabricate the filter and further investigations.

Keywords: BSTO, FBAR, BVD, Ferroelectric Bandpass filter
Acknowledgements

I would like to express my sincere gratitude to my supervisor Prof. Spartak Gevorgian for giving me the opportunity to work in the Tera Hertz and Millimeter Wave Laboratory. His continuous support and valuable advices has made it possible for me to complete the task within the time frame and achieving the desired goals.

John Berge, the PhD student, who helped me in understanding the fabrication process to design the layout and masks. I am thankful to him by sharing his experience regarding fabrication.

My special thanks to Dr. Jose Chilo for accepting the responsibility as an examiner. Prof Edvard Nordlander and Dr. Niclas borjell who helped me in accepting the proposal.

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Finally my special thanks to my beloved parents for always encouraging and guiding me throughout my life.
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</tr>
<tr>
<td>BAW</td>
<td>Bulk Acoustic Resonator</td>
</tr>
<tr>
<td>FBAR</td>
<td>Film Bulk Acoustic Resonator</td>
</tr>
<tr>
<td>SMR</td>
<td>Solidly Mounted Resonator</td>
</tr>
<tr>
<td>BSTO</td>
<td>Barium Strontium Titanate</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>ZnO</td>
<td>Zinc Oxide</td>
</tr>
<tr>
<td>AIN</td>
<td>Aluminum Nitride</td>
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<tr>
<td>BVD</td>
<td>Butterworth Van-Dyke</td>
</tr>
<tr>
<td>MBVD</td>
<td>Modified Butterworth Van-Dyke</td>
</tr>
<tr>
<td>KLM</td>
<td>Krimholtz, Leedom and Matthae</td>
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<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
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<tr>
<td>ADS</td>
<td>Advance Design System</td>
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<td>GSG</td>
<td>Ground-Signal-Ground</td>
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# 1 Introduction

Filters based on Lumped elements, Ceramic and Surface acoustic wave (SAW) technologies are being used commercially. Lumped elements and ceramic based filters were bulky. So SAW technology is introduced to cope with the market demand as smart components. But SAW filters are difficult to fabricate at frequency above 3 GHz due to very thin electrodes and short distance between the fingers of interdigital transducer. In that case filters based on thin film bulk acoustic resonators (FBAR) introduces low insertion loss, high power handling capability, low cost and smallest size [5, 6]. There are many piezoelectric films that are being used to design FBAR filters i.e. Aluminum Nitride (AlN), Lead Zirconate Titanate (PZT), Zinc Oxide (ZnO), Strontium Titanate (STO) and Barium Strontium Titanate [6-9]. The FBAR filters based on AlN and ZnO has been used with external tuning element to tune the resonance frequency. The use of external tuning elements introduces the parasitic and degrades the quality factor [2]. To avoid these parasitic and external tuning elements the materials that exhibit the electric field dependency i.e. BSTO and PZT are used. The materials i.e. BSTO and PZT are related to the family of ferroelectric materials in which the piezoelectric constant are dependent on the applied electric field. When the electric field is varied these ferroelectric materials exhibits variable piezoelectric constants that enables the ferroelectric materials to be used to design the tunable bandpass filters.

## 1.1 Thesis Objectives and implementation

This thesis focuses on the FBAR bandpass filter design based on BSTO ferroelectric film. The main objective is to design, model and extract physical parameters of a single FBAR and then by using these parameters to design a tunable bandpass filter for 5GHz applications.

The procedure that is implemented to achieve the objective is summarized below

1. Measurement of a single BSTO FBAR
2. Modeling of FBAR by using MASON and Butterworth Van-Dyke Model
3. Extraction of BSTO parameters by using the models named above
4. Study and implementation of FBAR filter topologies
5. Selection of the best filter topology regarding insertion loss, out of band rejection, steeper roll-off and fabrication
6. Layout design
7- Electromagnetic Co-simulation
8- Mask set design of each layer for fabrication

1.2 Thesis Organization

Chapter 1 introduces the different filter technologies to indicate the importance of FBAR based filters in current and future radio/wireless communication. This chapter also introduces the objectives and the procedure to achieve those objectives.

Chapter 2 introduces the basic theory about acoustic waves, DC field dependent parameters and tunable thin film bulk acoustic resonator. This chapter also introduces the types of FBAR regarding fabrication.

Chapter 3 includes the measurement of a single TFBAR. In this chapter different models has been described and simulations are done by using two of these models to extract the piezoelectric parameters of fabricated TFBAR.

Chapter 4 describes the design of a bandpass filter by using the extracted parameters from modeling. Different topologies of FBAR filter design are discussed and simulated. Ladder topology is selected to design the filter. This chapter also includes the electromagnetic co-simulation of bandpass filter. For electromagnetic co-simulation first the layout is designed that is the result of discussion with supervisor and John Berge, responsible for fabrication. The main purpose of this electromagnetic co-simulation is to analyze the parasitic effect between the resonators used to design the bandpass filter.

The conclusion and future work is presented in chapter 5. The conclusion is the result of work that finally describes the achievement of a bandpass filter. The suggestions and improvements, which are analyzed during the thesis, are presented in future work.
2 Basic Acoustic Wave Theory and FBAR

This chapter introduces the basic theory about acoustic waves to understand the acoustic resonator. The basic working principle of FBAR is also explained. As this thesis utilizes the ferroelectric film of BSTO so DC field dependent parameters are presented with their appropriate numerical values taken from [13]. The types of FBAR regarding fabrication are discussed. The fabricated FBAR, which is used for measurement, is also presented with the thickness of each layer.

2.1 Acoustic Waves
Acoustic waves in solids, also known as elastic waves, involve mechanical deformation strain ($S$) of a material and the associated internal forces, which are known as stresses ($T$). The stress ($T$) and strain ($S$) are related to each other by means of Hook’s law [1].

$$T = cS$$  \hspace{1cm} (2.1)

where ‘c’ is the elastic stiffness constant [1].

2.2 Piezoelectricity
Piezoelectricity is the property of a piezoelectric material to produce electrical charge under mechanical stress. The acoustic waves are generated and detected by using this piezoelectric effect. When a piezoelectric material is subjected by an external mechanical force or stress the acoustic waves are propagated in the material. The propagation velocity depends on the material properties [5].

2.3 Acoustic Velocity
Acoustic velocity, also known as the phase velocity of acoustic wave, is dependent on the material density and elastic stiffness of the material as described by [1].

$$vac = \sqrt{\frac{c^2}{\rho}}$$  \hspace{1cm} (2.2)

where

$vac$=acoustic velocity

c= elastic stiffness

$\rho$=material density
2.4 Quality Factor

The quality factor is the ratio of the energy stored and energy dissipated per cycle as given in equation [1]

\[ \text{Quality Factor} = \frac{\text{Energy Stored}}{\text{Energy dissipated per cycle}} \quad 2.3 \]

The Q factor defines the limitation of achievable insertion loss and steeper roll off, to design a bandpass filter based on FBAR. By utilizing the high Q resonators a rapid change from bandpass region to out of band rejection region and lower insertion loss can be achieved. So the measure of Q factor is an important factor. The Q factor of an FBAR resonator can be calculated by [10]

\[ Q = \frac{f}{2} \left| \frac{d \phi_x}{df} \right| \quad 2.4 \]

where

\( \phi_x \) = Impedance Phase

\( f \) = resonance frequency (series/parallel)

2.5 Electromechanical Coupling Coefficient \( k_t^2 \)

Electromechanical coupling coefficient determines the percentage of energy conversion from mechanical to electrical and vice versa. It is denoted by \( k_t^2 \) and is expressed as [11]

\[ k_t^2 = \frac{h^2}{\varepsilon \varepsilon_0} \quad 2.5 \]

where

\( h \) = piezoelectric constant

\( \varepsilon \) = dielectric constant of piezoelectric material

subscript \( (E) \) and \( (S) \) indicates that stiffness constant and the dielectric constant are measured under constant electric field and constant strain respectively.

2.6 Generation of Acoustic Waves in Acoustic wave resonators

There are two types of acoustic wave resonators.

1. Surface Acoustic Wave Resonator (SAW)
2. Bulk Acoustic Wave Resonator (BAW)

Both SAW and BAW resonators utilize the piezoelectric material to generate the acoustic waves. Acoustic waves are generated by direct and converse piezoelectric effect. In SAW resonators the acoustic waves propagate on the surface of the material due to which these types of resonators are known as surface
acoustic wave resonators. In BAW resonator technology the piezoelectric material is sandwiched between the two electrodes that confine the energy within the resonator as expressed in [12].

2.7 FBAR Basic Principle
A simple FBAR consists of a piezoelectric thin film sandwiched between two electrodes as shown in figure 2.1 [1].

When an alternating voltage is applied to the electrodes the piezoelectric film expands and contracts due to which mechanical waves or acoustic waves are generated. This generation of acoustic waves under the electric field is called the converse piezoelectricity [2]. The resonance condition occurs when the thickness of the piezoelectric layer becomes equal to the integer multiple of a half of wavelength as described by [1]

\[
f = \frac{v_{ac}}{2d}
\]

where

\( v_{ac} \) = Acoustic Velocity
\( d \) = Piezoelectric film thickness

The resonance behavior of an FBAR is shown in figure 2.1 There are two resonances, one is the series resonance and the other is known as parallel resonance. The series resonance occurs when the polarization vector of thin film is in-phase with the applied electric field and when the polarization vector is out of phase with applied electric field the parallel resonance condition occurs [1]. A.A. Shirakawa et al and R. Lanz et al in [3, 4] describes that at parallel resonance the FBAR exhibits high electrical impedance while at series resonance the electrical impedance is minimum. Beyond all these frequencies the FBAR behaves like a capacitor as there is a dielectric in between two electrodes.
2.8 DC field dependent piezoelectric parameters

The DC field dependency of acoustic velocity, dielectric constant of ferroelectric film and electromechanical coupling coefficient results to obtain a tunable FBAR as described by Spartak Gevorgian et.al in [14] and implemented by X.Zhu et.al in [16]. The stiffness constant of BSTO is electric field dependent so by virtue of this field dependency the acoustic velocity is also electric field dependent. The field dependent stiffness constant is given by [13, 14].

\[
c_{33} = c_{11} \left[ 1 + \lambda^{(1)} T + \lambda^{(2)} (T-T_a)^{1/2} E \right]^{2/3}
\]

where

\[
E = \frac{V}{L}
\]

and

\[
V = \text{DC biasing voltage}
\]

\[
L = \text{thickness of piezoelectric layer}
\]
$c_{11}$, $c_{33}$ and $\lambda$ are some constants and are given in the table 2.1 with their nominal values taken from G.Rupprecht and W.H.Winter in [13]. The subscripts indicate the direction of acoustic wave propagation.

Table 2-1 Nominal values of constants used in equation 2.7 [13]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{11}$ (N/m²)</td>
<td>$3.25*10^{11}$</td>
</tr>
<tr>
<td>$\lambda^{(1)}$ (°K⁻¹)</td>
<td>$-2.69*10^{-4}$</td>
</tr>
<tr>
<td>$\lambda^{(2)}$ (°K)</td>
<td>$-0.102$</td>
</tr>
<tr>
<td>$\lambda^{(3)}$ (°K¹/²m²/V²)</td>
<td>$-1.1*10^{-15}$</td>
</tr>
<tr>
<td>$T$ (°K)</td>
<td>$300$</td>
</tr>
<tr>
<td>$Ta$ (°K)</td>
<td>$103$</td>
</tr>
</tbody>
</table>

The DC field also changes the dielectric constant of BSTO i.e. by increasing the DC bias the dielectric constant turns lower and vice versa. At 0V the BSTO exhibits the highest dielectric constant. The DC bias dependent dielectric constant is given by [14]

$$\varepsilon(E, T) = \frac{\varepsilon(T)}{1 + (A/CK)e^{3(T)/E^2}} \quad 2.9$$

where $A$ and $CK$ are constants that can be tuned for the curve fitting of measured data. The nominal values of $A$ and $CK$ are $0.15*10^{-17}$ (Km²/V²) and 32100 (K) respectively.

Similarly the DC bias also changes the electromechanical coupling properties and is given by [14]

$$kt^2 = \frac{d_{33}^2}{\varepsilon_0\varepsilon_{33}s_{33}} \quad 2.10$$

where

$$d_{33}^2 = d_{33}^2 + 2g_{33}E_{33} \quad 2.11$$

And

$$s_{33} = s_{33}(0) \left[ 1 + \lambda^1 T + \lambda^2 (T - Ta) - 1 + \lambda^4 (T - Ta) - 1/2E^2 \right] \quad 2.12$$

where

$s_{33}$, $d_{33}$ and $g_{33}$ are elastic compliance and piezoelectric constants. The nominal values of these constants are given in the table 2.2 [14].
Table 2-2 Nominal values of Piezoelectric constant [14]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{33}$ (m/V²)</td>
<td>$5.08 \times 10^{-13}$</td>
</tr>
<tr>
<td>$g_{33}$ (m²/V²)</td>
<td>$2.08 \times 10^{-20}$</td>
</tr>
<tr>
<td>$s_{33}(0)$ (m²/N)</td>
<td>$6.13 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\varepsilon_0$ (F/m)</td>
<td>$8.85 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\lambda^1$ (K⁻¹)</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\lambda^2$ (K)</td>
<td>5.7</td>
</tr>
<tr>
<td>$\lambda^4$ ($0.4 \times 10^{13} m^2/V^2$)</td>
<td>$0.9 \times 10^{-15}$</td>
</tr>
</tbody>
</table>

2.9 Tunable Thin Film Bulk Acoustic Resonator

A Tunable Thin Film Bulk Acoustic Resonator is the type of resonator that can be electrically tuned by varying the applied DC electric field. There is no need of any external element to tune the resonance frequency of TFBAR, as the reason is described in chapter 1. The DC field dependent parameters of some piezoelectric materials help to electrically tune the resonance frequency of FBAR [17]. Two types of FBAR are being used now a day.

1- Air Gap FBAR

2- Solidly Mounted FBAR (SMR-FBAR)

In air gap FBAR an air interface is used with membrane structure for free vibration of acoustic waves. While in SMR structure a membrane of alternative high and low acoustic impedance, also known as Bragg reflector, is used along with the piezoelectric film as shown in figure 2.1 [12]. In this thesis SMR-FBAR is used. The resonator is fabricated on a silicon substrate with three pairs of hafnium oxide (HfO2) and silicon dioxide (SiO2). Aluminum is used as the top electrode while the platinum is used as the bottom electrode. The active layer of BSTO is sandwiched between top and bottom electrodes. The fabricated SMR FBAR is shown in figure 2.4. The thickness of each layer is given in the table 2.3. Titanium (Ti) and Titanium Oxide (TiO₂) layers are used to support the fabrication.

![Figure 2-3 Types of FBAR a) Air Gap FBAR (b) Solidly Mounted FBAR [12]](image)
### Table 2-3 Layers thicknesses of fabricated FBAR

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Top electrode)</td>
<td>100 nm</td>
</tr>
<tr>
<td>Titanium (Top Electrode)</td>
<td>10 nm</td>
</tr>
<tr>
<td>Platinum (Bottom Electrode)</td>
<td>100 nm</td>
</tr>
<tr>
<td>Titanium Dioxide (Bottom Electrode)</td>
<td>25 nm</td>
</tr>
<tr>
<td>Titanium (bottom Electrode)</td>
<td>20 nm</td>
</tr>
<tr>
<td>Hafnium Oxide (Bragg Reflector)</td>
<td>260 nm</td>
</tr>
<tr>
<td>Silicon Dioxide (Bragg Reflector)</td>
<td>284 nm</td>
</tr>
<tr>
<td>Silicon (Substrate)</td>
<td>0.37 mm</td>
</tr>
</tbody>
</table>

![Fabricated SMR FBAR](image)

The basic principle of a simple FBAR has been described in section 2.7. The resonance behavior of an FBAR is shown in figure 2.5. There are two resonant frequencies. The intersections of real axis of the smith chart and impedance circles determine these resonant frequencies. ‘fs’ represents the series resonant frequency and ‘fp’ represents the parallel resonant frequency. These resonance frequencies are also known as the resonance frequency ‘fr’ and antiresonance frequency ‘fa’. The difference between these resonance frequencies is due to the electromechanical coupling coefficient \((kt^2)\) as described by S.Sherrit et.al in [11].

\[
kt^2 = \frac{\pi}{2} \frac{fs}{fp} \tan\left(\frac{\pi}{2} \frac{fp-fs}{fp}\right)
\]

2.13
The electromechanical coupling coefficient described in equation 2.13 can be calculated by taking the measurement data from Vector Network Analyzer (VNA), after fabrication of single TFBAR. If piezoelectric constants of the material are known then it can also be calculated from simulated data by using the MASON equivalent circuit. The equation 2.10 gives the measure of electromechanical coupling coefficient when the piezoelectric constants of the material are known.
3 Measurement, Modeling and Simulation of FBAR

The design of a bandpass filter based on FBAR requires the piezoelectric constants of the material used. If the piezoelectric constants are not known then there must be a measurement of single FBAR resonator. This chapter first presents the measurement of a single BSTO FBAR. Fitting of measured data with simulations, to extract the physical and electrical parameters of a single TFBAR, are described. Different acoustic and electrical equivalent circuits like MASON and Butterworth Van Dyke Model have been used to model the single FBAR.

3.1 Measurement

Fabricated single FBAR using the BSTO thin film is measured. The S-parameter data is taken directly from VNA and plotted in ADS. The plot of impedance from measured data is shown in figure 3.1. It can be clearly seen that at series resonance frequency the FBAR has low electrical impedance while high electrical impedance occurs at parallel resonance frequency. When 0V DC bias is applied to FBAR it behaves like a capacitor, as there is a dielectric between the electrodes. But when the DC bias is applied a resonance condition occurs and exhibits two resonances.

Figure 3-1 Impedance behavior when the switch is ON & OFF
The measurements are taken on different biasing voltages, as well, to analyze the tuning behavior of FBAR. A DC bias of 0V to 25V is swept. The plot of S11 is shown in Figure 3.2. At different biasing voltages the FBAR is exhibiting different resonances. This resonance frequency shift is due to the field dependent acoustic velocity as described in section 2.8. Similarly the Figure 3.3 shows the bias dependent electromechanical coupling coefficient. When the bias is decreased the loop gets smaller and the frequency spacing i.e. electromechanical coupling coefficient gets lower and at 0V the device behavior is in capacitive region and there is no resonance i.e. switched OFF. At 25 V the device has the highest percentage of energy conversion and maximum spacing between series and parallel resonance frequency.

Figure 3-2 Resonance frequency shift by changing DC bias
3.2 Modeling

There are different models that can be used to model the FBAR. MASON, Krimholtz, Leedom and Matthae (KLM) and BVD models are the most widely used equivalent circuits. MASON and KLM are the physical models of FBAR but BVD model is the electrical model that consists of lumped elements. MASON and BVD model has been used in this thesis to extract the parameters and further design of bandpass filter. Both of the models are described below.

3.2.1 MASON MODEL

Mason is the most commonly used physical equivalent circuit to model an FBAR [19]. It can be used to analyze the pre-fabrication behavior of the device. It converts the FBAR into two acoustic ports and one electrical port connected to the acoustic part by an electromechanical transformer. The electromechanical transformer determines the conversion of electrical energy into acoustic energy and vice versa as expressed by S.Sherrit et al in [11]. The MASON model is shown in figure 3.4.
The parameters for the MASON model are given by [11]. $Z_a$ and $Z_c$ model the acoustic impedance of the piezoelectric layer. $C_0$ is the static capacitance between the top and bottom electrode. While ‘$n$’ is the turn ratio of the electromechanical transformer that determines the energy transformation from electrical to mechanical and vice versa.

\[
\begin{align*}
C_0 &= \frac{\varepsilon_0 \varepsilon_r A}{d} \\
n &= C_0 h_{33} \\
Z_a &= iZ_0 \tan \left( \frac{\Gamma t}{2} \right) \\
Z_c &= -iZ_0 \csc(\Gamma t)
\end{align*}
\]

where

$\varepsilon_0$ = free space dielectric constant

$\varepsilon_r$ = Dielectric constant of piezoelectric film

$d$ = Thickness of piezoelectric film

$A$ = Area of the resonator

while $h_{33}, n, \Gamma, t$ and $C_0$ are treated as complex constants and are manipulated to program the schematic design.
3.2.2 Extraction of Parameters by using MASON Model

The Mason model described above is used to extract the physical parameters of the piezoelectric thin film. The Bragg reflector is cascaded by using the acoustic transmission lines with appropriate length, impedance and propagation constant and is given in table 3.1. Generally no losses are included in the original mason model but in this program the losses are introduced to exactly model the device behavior. The dielectric loss has been introduced in terms of ‘$G_0$’. While ‘$R_s$’ is introduced to model the electrode losses in the electrical part of the circuit. The losses in the active layer are also introduced. The mason model including the Bragg reflector is shown in figure 3.5.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Q Factor</th>
<th>Acoustic Impedance (Kg/m$^2$ s)</th>
<th>Acoustic Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>500</td>
<td>16.98e6</td>
<td>6290</td>
</tr>
<tr>
<td>Platinum</td>
<td>100</td>
<td>80.2e6</td>
<td>3737</td>
</tr>
<tr>
<td>Titanium</td>
<td>100</td>
<td>27.3e6</td>
<td>6070</td>
</tr>
<tr>
<td>Titanium oxide</td>
<td>500</td>
<td>33.9e6</td>
<td>8477</td>
</tr>
<tr>
<td>Silicon Dioxide</td>
<td>500</td>
<td>12.55e6</td>
<td>5972</td>
</tr>
<tr>
<td>Hafnium Oxide</td>
<td>500</td>
<td>52.77e6</td>
<td>5451</td>
</tr>
<tr>
<td>Silicon</td>
<td>500</td>
<td>19.7e6</td>
<td>8433</td>
</tr>
<tr>
<td>Air</td>
<td>500</td>
<td>400</td>
<td>360</td>
</tr>
</tbody>
</table>
Figure 3-5 MASON Model with Bragg reflector
Tuning and optimization procedure is adapted to exactly reproduce the measured data. The highest DC bias of 25V is selected, to first extract the physical parameters. Figure 3.6 compares the measurement and simulation results by utilizing the MASON equivalent circuit. Figure 3.6 (a) indicates that the extracted electromechanical coupling coefficient is in favorable comparison with measurement. Similarly figure 6.3 (b) indicates that extracted combination of piezoelectric thickness and acoustic velocity of table 3.2 can reproduce the measured data. The extracted physical parameters of ferroelectric thin film are given in table 3.2.

(a) Extracted ‘$kt^2$’ vs. measured ‘$kt^2$’

(b) Extracted S11 (dB) vs. Measured S11 (dB)

Figure 3-6 Comparison of measured data with MASON simulated data
Table 3-2 Extracted parameters of single BSTO FBAR

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Extracted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Electrode Area</td>
<td>314 µm²</td>
</tr>
<tr>
<td>BSTO Thickness</td>
<td>285 nm</td>
</tr>
<tr>
<td>Acoustic Velocity of BSTO</td>
<td>6978 m/s</td>
</tr>
<tr>
<td>Dielectric Constant of BSTO</td>
<td>102.5</td>
</tr>
<tr>
<td>Electromechanical Coupling Co-efficient</td>
<td>7%</td>
</tr>
</tbody>
</table>

3.2.3 BVD Model

Butterworth and Van Dyke presented a lumped element electrical model, also known as BVD, which models FBAR near resonance. It converts the FBAR into four equivalent lumped elements i.e. $R_m$, $C_m$, $L_m$ and $C_0$. $R_m$, $C_m$ and $L_m$ are known as motional parameters, motional branch or motional arm. $C_0$ determines the capacitance between the two electrodes with piezoelectric film sandwiched between them. $L_m$ represents the acoustic mass; while $C_m$ and $R_m$ represent the compliance and acoustic loss respectively [2]. The BVD electrical equivalent circuit and its parameters are presented here given by [1].

![BVD Model](image)

Figure 3-7 Butterworth Van-Dyke Model (BVD)

\[
C_0 = \frac{\varepsilon_0 \varepsilon_r A}{d} \quad 3.5
\]

\[
C_m = \frac{8\varepsilon_0 \varepsilon_r A \omega_r}{\pi^3 \nu_a} kt^2 \quad 3.6
\]

\[
L_m = \frac{\pi^3 \nu_a}{8\varepsilon_0 \varepsilon_r A \omega_r kt^2} \quad 3.7
\]

\[
R_m = \frac{\alpha_r L_m}{Q} \quad 3.8
\]

where

$Q$= Quality factor of piezoelectric film
3.2.4 Extraction of Parameters by using MBVD Model

The original BVD model does not account the dielectric losses so another model based on the BVD model is presented and known as Modified Butterworth -Van Dyke (MBVD) model. In this model the dielectric loss is introduced in series of the static capacitor. The MBVD model is shown in figure 3.8 in which ‘R₀’ is representing the dielectric loss and ‘Rs’ is representing the electrode losses [20]. Cm and Lm provides the series resonant frequency while the shunt resonant frequency is provided by Cm and Lm in series with C₀ as described by [21, 22].

![Figure 3-8 Modified Butterworth Van-Dyke Model (MBVD)](image)

The physical parameters, which were extracted by using the mason model, are used to simulate and extract the motional parameters. By using the tuning and optimization procedure the simulation is performed to reproduce the measurements. Figure 3.9 shows that the MBVD simulations and measurements are in good agreement.

![Figure 3-9 Comparison between MBVD simulation and measured data](image)
Simulations are also performed on different biasing voltage to extract the motional parameters. Table 3.3 presents the numerical values obtained after a good agreement between simulations and measurements. The data for 0V is not given in the table because at 0V DC bias the device behaves as a capacitor and there is no conversion of energy from one form to another. Figure 3.10 show that when the switch is OFF i.e. 0V then for all the applied range of frequencies the device behavior is in capacitive region of smith chart. At this point the FBAR has no motional component in parallel with $C_0$ so there is no resonance. The FBAR exhibits an extracted dielectric constant of 286 at 0V.

Table 3-3 Extracted parameters by using MBVD model

<table>
<thead>
<tr>
<th>DC Bias (V)</th>
<th>$C_0$(pF)</th>
<th>$C_m$(fF)</th>
<th>$L_m$(nH)</th>
<th>$R_m$(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>2.25</td>
<td>135.471</td>
<td>6.06529</td>
<td>2.209</td>
</tr>
<tr>
<td>20</td>
<td>2.5</td>
<td>135.97</td>
<td>5.9839</td>
<td>2.193</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>137.45</td>
<td>5.8512</td>
<td>2.056</td>
</tr>
<tr>
<td>10</td>
<td>3.75</td>
<td>128.75</td>
<td>6.1519</td>
<td>2.203</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>80.5</td>
<td>9.62</td>
<td>2.45</td>
</tr>
<tr>
<td>2</td>
<td>5.95</td>
<td>23.85</td>
<td>32</td>
<td>6.96</td>
</tr>
</tbody>
</table>
Filters are the key components for separating the desired frequency from the spectrum in mobile/radio communication systems. High data rates, greater mobility, cost effectiveness, lighter weight, smaller size and high performance is the demand for advance mobile communication systems [23-25]. Introduction of new frequency bands for wireless communication system i.e. from 500 MHz to 6 GHz has put the challenges on filter technology. Surface acoustic wave (SAW) filters and Ceramic filters have been used previously. SAW filters have high selectivity and small size [4] but low power handling capability, poor insertion loss and limited frequency operation up to 3 GHz has limited the applications of SAW filters in advanced mobile communication systems [27]. On the other hand Ceramic filters have high power capability and good selectivity. But their large size is the major drawback for miniaturized front end applications [26, 28].

This chapter focuses on an Electrically Tunable Bandpass filter based on BSTO Ferroelectric Film, filter topologies, design, simulations and layout/mask design for the proposed Bandpass filter.

### 4.1 TFBAR Bandpass Filter
TFBAR based Bandpass filter is the promising technology for the current miniature and future smart and compact front end applications in radio communication. TFBAR filters can operate up to several GHz range with high quality factor, high power handling capability, low insertion loss and smallest size as compared to SAW, Lumped and ceramic filters [29-31]. DC field dependent parameters of BSTO enable to design the tunable bandpass filters which allow agile communication [31-35].

### 4.2 Design Principle
To design a simple bandpass filter based on FBAR it requires at least two FBARs, one is connected in series and other is in parallel as shown in figure 4.1.
The resonance frequency of shunt resonator is kept lower than the series resonator. The difference between the series resonance frequency of shunt resonator and the parallel resonance frequency of series resonator determines the bandwidth. Larger the difference between these resonance frequencies, larger the bandwidth but a dip can appear in pass band when the gap between these resonance frequencies is increased as described by [16, 33, and 34].

4.3 Filter Topologies
There are three different topologies currently being used to design bandpass filters.

1. Ladder Type
2. Lattice Type
3. Ladder-Lattice Type

4.3.1 Ladder Type
A simple ladder type filter is shown in figure 4.1 [19]. It can consist of at least two FBARs. Ladder type filters have very sharp roll off but out of band rejection is rather poor [4]. The area of the resonators can be optimized to get better out of band rejection. It can also be improved by cascading more stages but this will increase the insertion loss [29, 36, and 38]. In general the ladder type filters have low insertion loss, low out band rejection and high filtering sharpness [25, 26].

4.3.2 Lattice Type
The topology by using lattice technique for filter design is shown in figure 4.2 [19].

![Lattice type filter](image)

Figure 4-2 Lattice type filter [19]

Lattice type filters have high out of band rejection but lower roll off near pass band. To improve the roll off more resonators can be cascaded but it will increase the insertion loss. Another approach that can be used to get sharper roll off is to optimize the static capacitance of the two arms of the lattice filter [16].
Generally the lattice filters have high out of band rejection, lower filtering sharpness and medium insertion loss as compared to ladder type filters.

4.3.3 Ladder-Lattice Type

The topology that combines both the ladder and lattice type in one filter is called the ladder-lattice topology. This kind of filter can be optimized to have both the high out of band rejection and sharper roll off near pass band [26]. An example of a ladder-lattice filter is shown in figure 4.3 [35].

![Image of Ladder-Lattice Filter](image)

Figure 4-3 Ladder-Lattice filter [19]

4.4 Design of a 3rd Order T-type Ladder filter

Different filters have been studied and simulated including the π-Type and T-type techniques in ladder topology. As the ladder type filters are being mostly used because of straightforward implementation, lower insertion loss and high out of band rejection [17, 24, 27, and 28] so a 3rd order T-type ladder filter, as shown in figure 4.4, has been selected to work further and optimize it to get the best performance. The order of the filter indicates the total number of resonators in the filter. The series resonators are identical to each other in terms of resonator area, BSTO layer thickness and electrode thicknesses. Both series resonators also have the same resonance frequency. While the shunt resonator is tuned at lower frequency than the series resonator. To get the different resonant frequency the thickness of the piezoelectric film can be optimized [24] or the mass loading of the top electrode can be processed during fabrication [13, 21]. In this work the mass loading of the top electrode is used to tune the resonant frequency of the shunt resonator. Each resonator has been modeled by using the MBVD model and then these MBVD equivalent circuits are used to design and simulate the bandpass filter. The loading layer thickness has been achieved by using the MASON model.
4.4.1 Schematic Simulation and Results

4.4.2 Schematic Simulation

A 3\textsuperscript{rd} order T-Type ladder filter by using MBVD equivalent circuit is shown in figure 4.5. There are three resonators in the circuit. Each MBVD circuit is representing an FBAR. The series resonators have the same resonant frequency. But the shunt resonator has been tuned to have the resonance frequency lower than the series resonator. The filter is designed to operate on a 50 Ω system. To achieve the maximum bandwidth the resonance frequency of shunt resonator has been optimized. As described earlier that a dip can appear in the pass band if the difference between the resonance frequencies is continuously increased so the optimization of resonance frequency of shunt resonator is kept limited to avoid the dip in pass band. The area of the resonators is tuned to achieve the minimum insertion loss and high out of band rejection. A trade off in between insertion loss and out of band rejection has been observed so after optimization the size of the resonators providing the minimum achievable insertion loss and out of band rejection is given in the table 4.1. The table also includes the calculated values of motional arms, top electrode thicknesses and resonance frequency of each resonator.
Figure 4-5 MBVD equivalent circuit of bandpass filter

Table 4-1 Calculated MBVD and physical parameters of designed bandpass filter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Series Resonator</th>
<th>Shunt Resonator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (μm²)</td>
<td>12*12</td>
<td>17*17</td>
</tr>
<tr>
<td>Series Resonance Frequency(GHz)</td>
<td>5.723</td>
<td>5.552</td>
</tr>
<tr>
<td>C0(pF)</td>
<td>0.4976</td>
<td>0.8474</td>
</tr>
<tr>
<td>Rm (Ω)</td>
<td>9.477</td>
<td>5.913</td>
</tr>
<tr>
<td>Cm(fF)</td>
<td>28.044</td>
<td>47.76</td>
</tr>
<tr>
<td>Lm(nH)</td>
<td>27.577</td>
<td>17.205</td>
</tr>
<tr>
<td>Top electrode Thickness (nm)</td>
<td>78</td>
<td>100</td>
</tr>
</tbody>
</table>
The simulation result of a 3rd order ladder type TFBAR bandpass filter is shown in figure 4.6. The designed filter has the insertion loss of –2.925 dB. The out of band rejection of -10dB and a 3dB bandwidth of 176MHz have been achieved. Both the resonators have two resonant frequencies. The pass band depends on the difference between the series resonant frequency of the series resonator and the parallel resonant frequency of shunt resonator. While beyond these frequencies each resonator behaves like a capacitor. Maximum transmission occurs when the series resonance frequency of the series FBAR equals or near to the parallel resonance frequency of the shunt FBAR. At series resonance frequency of shunt FBAR and parallel resonance frequency of series FBAR, the transmission is blocked thus results in a bandpass filter as demonstrated in figure 4.7. Due to the field dependent parameters of BSTO the filter can be switched OFF and ON by changing the bias voltages. Also the center frequency of the filter can be tuned by varying the DC bias.

Figure 4-6 Simulation result for a 3rd order T-Type Ladder Filter
The figure 4.8 compares the transmission and reflection coefficients when the switch is OFF & ON respectively. Figure 4.8 (a) indicates that when the switch in OFF there is no resonance but at 25V DC bias i.e. the highest selected voltage the filter exhibits a resonance. Similarly at 0V bias there is no transmission of frequencies but at 25 V the device is ON and gives a bandpass response with some transmission loss while beyond this pass band the filter exhibits the high transmission loss.
As it is mentioned that the ferroelectric film has electric field dependent parameters so principally the filter should have the resonance frequency shift by changing electric field. To analyze the tuning behavior of the bandpass filter the bias voltages has been varied and the tuning of the center frequency is achieved. The tuning behavior of the bandpass filter on different biasing voltages is shown in figure 4.9.

![Figure 4-9 Tuning behavior of FBAR bandpass Filter](image-url)
4.5 Layout Design and Electromagnetic Co-Simulation

When the simulation results are achieved and physical parameters i.e. area and thickness of each layer is known then it comes to design the layout. This section will provide the details about the designed layout of the filter. Later this layout will also be used for electromagnetic co-simulation.

4.5.1 Layout Design

Different layout patterns were designed and discussed regarding fabrication and finally a layout is presented here in figure 4.10 which is designed by using the ADS momentum. The total area of the filter including grounds and pads for measurements is 550*400 µm². The layout is designed to measure by using ground-signal-ground (GSG) probes with the size of 150 µm. As the filter contains multiple set of layers so at some points it is needed to pattern some layers. It is also necessary to pattern the layers because the area that will be sandwiched between top and bottom electrode will be the active area therefore it can be seen that three resonators are obvious in layout. The pattern of each layer is presented in Appendix. The layout is marked with some text and points which describes the each part of the layout. Part of the layout marked with ‘A’ and ‘B’ will be used to connect the ground and signal probes respectively. DC bias will be applied to the point marked with ‘C’. The point ‘D’ is indicating the isolation layer between top and bottom electrode.

![Figure 4-10 Layout of the filter](image-url)
4.5.2 Electromagnetic Co-Simulation

To analyze the effect of parasitic capacitances between FBARs momentum simulation is performed. For momentum simulation the layout that is presented above is updated with layer thicknesses and substrate definition. After defining the layers and substrate the MBVD motional parameters are connected to the layout in the schematic window. To connect the motional parameters it is necessary to define the ports in momentum. So after defining the ports in momentum the layout is imported in schematic window and motional arm is connected. Normally the layout without the motional branch is just a capacitor as there is a dielectric between electrodes so it is necessary to introduce the motional arm in schematic. The complete layout with motional parameters connected is shown in figure 4.11.

Figure 4-11 Layout with motional branch for Electromagnetic Co simulation
DC bias will be applied by using external bias tee. The result for electromagnetic co-simulation in comparison with the schematic simulation is shown in figure 4.12. Simulations show that both the results are identical to each other in terms of insertion loss, bandwidth and reflection coefficient. The difference in the out of band rejection is due to parasitic capacitance between the resonators causing to decrease the static capacitance of each resonator.

Figure 4-12 comparison between schematic and momentum simulation of bandpass filter
4.5.3 Masks Design for Fabrication

Masks are designed in ADS momentum. A silicon substrate of 10*10mm\(^2\) has been chosen. Masks contain the filters and resonators, both series and parallel, separately. Some test structures are inserted for future measurements and de embedding. Masks for each patterned layer are shown in Appendix. Each layer will be deposited as it is patterned and piezoelectric layer will be deposited all over the substrate. The final structure of the mask designed on a 10*10mm\(^2\) wafer is shown in figure 4.13.

Figure 4-13 Final Mask on 10*10 mm2 wafer
5 Conclusion and future work

5.1 Conclusion
This thesis work utilized the electric field dependent parameters of BSTO ferroelectric film and successfully designed and simulated an electrically tunable bandpass filter.

A single FBAR based on BSTO ferroelectric film is measured and modeled by using MASON and MBVD model. Piezoelectric constants are extracted. Different FBAR filter topologies are studied and simulated. A 3\textsuperscript{rd} order T-Type ladder based tunable bandpass filter is designed and simulated by using the extracted piezoelectric constants and MBVD model. Mass loading of top electrode is used to change the resonant frequency of series resonators from shunt resonator.

The insertion loss of -2.925 dB is achieved. The designed filter exhibits 3dB bandwidth of 176 MHz and out of band rejection of -10.807 dB. Momentum simulation is also performed and comparable results have been achieved in layout design and schematic simulation.

5.2 Future work
The study and simulations has shown that electrically tunable bandpass filters can be achieved by using the ferroelectric films so first the future work will involve the manufacturing of the designed bandpass filter. The resonators used to design the bandpass filter will be measured separately for de-embedding. Electrode materials can be changed to get higher coupling coefficient. Filter design by using two different piezoelectric thicknesses can also be implemented. Mass loading of bottom electrode can be suggested which will decrease the processing of layer depositions on the ferroelectric film. Ladder-lattice filter topology can be used to achieve the goals for particular bandwidth, insertion loss and out of band rejection.
6 References


7 Appendix

This section shows the MBVD parameters, electromechanical coupling coefficient and Q-factor plots with respect to applied DC bias. Also the pattern of the masks for each layer is given here. The complete layout for a bandpass filter is presented. Finally the filter and test structure mask is shown to fabricate on 10*10 mm wafer.

Figure 7-1 Coupling Coefficient vs. DC Bias

(a)Motional Capacitance vs. DC Bias
(b) Motional Inductance vs. DC Bias

(c) Motional Resistance vs. DC Bias
Figure 7-2 Motional Parameters vs. DC Bias

Figure 7-3 Extracted Q factor vs. DC Bias
Figure 7-4 MASK set for Fabrication

Figure 7-5 Final Design of the Filter