DESIGN OF AN RF BAW RESONATOR

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भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Department of Electrical Engineering

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Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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Approval Sheet

This thesis entitled "Design of an RF BAW Resonator" by R.Vijay Kumar is approved for the degree of Master of Technology from IIT Hyderabad.

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I would also like to thank my parents and friends for their all around support.

Abstract

Band pass filters for microwave frequencies realized with thin film bulk acoustic wave resonators (FBAR) are a promising alternative to current dielectric or surface acoustic wave filters for use in mobile telecommunication applications. With equivalent performance FBAR filters are significantly smaller than dielectric filters and allow for a larger power Operation than SAW filters . In addition FBARs offer the possibility of on-chip integration which will result in substantial volume and cost reduction.

First part of the thesis consists of an overview of different types of resonators and their advantages and disadvantages, followed which the design of film bulk acoustic wave resonator (FBAR) and its characterization .

Second part of thesis consists of the design of ladder filter from the designed series and shunt resonators and its characterization.

Nomenclature

BAW	Bulk Acoustic Wave Resonator
CRF	Crystal Resonator Filters
FBAR	Film Bulk Acoustic Wave Resonator
Linbo$_3$	Lithium Niobate
Knbo$_3$	Potassium Niobate
K_{eff}^2	Electromechanical Coupling Coefficient
Q	Quality Factor
RF	Radio Frequency
SAW	Surface Acoustic Wave Resonator
SMR	Solidly Mount Resonator
SCF	Stacked Crystal Filters

Contents

Declaration ii

Approval Sheet iii

Acknowledgements iv

Abstract v

Nomenclature vi

1 Introduction 1

1.1 Introduction 1

1.2 Aim and Motivation 1

1.3 Literature Survey in brief 1

1.4 Contribution of the Thesis 2

1.5 Brief overview of Thesis 2

1.5.1 Resonators 2

1.5.2 Filters 3

1.5.3 Knbo$_3$ 3

1.6 Thesis Organization 3

2 Resonators 4

2. 1 Different types of resonators 4

2.1.1 Advantages of BAW over SAW 4

2.1.2 Different types of BAW resonators 5

2.1.3 Equvalent (Electrical) of a rasonator 6

2.1.4 Key Parameters of the resonator 6

2.1.5 Different ways of creating an air gap 7

2.2 Design of FBAR by making use of Knbo$_3$ 7

2.2.1 Specifications of the Design 7

2.2.2 Process steps for the Design 8

2.2..3 Results 11

2.2.4 Equivalent Electrical circuit for the Design 12

2.2.5 Comparison of Results 13

2.3 Design of Shunt Resonator (FBAR) by making use of Knbo3 13

2.3.1 Specifications of the Design 13

2.3.2 Process steps for the Design 14
2.3.3 Results and Conclusion..14
2.3.4 Equivalent Electrical circuit for the design..15

3 Filters.. 16

3.1 Different types of filters 16

3. 2 Design of ladder filter by making use of FBAR 17

3. 3 Conclusion 20

3.4 Applications 20

4 Knbo$_3$ 21

4.1 Properties of Knbo$_3$ 21

5 conclusion and future work 22

5.1 Conclusion 22

5.2 Future work 22

References 23

Chapter 1

Introduction

1.1 Introduction

Traditional filters have some disadvantages so that they cannot be operated beyond certain frequencies. For example multistage filters cannot be operated beyond 100 KHz, mechanical filters cannot be operated beyond 500 KHz and crystal filters cannot be operated beyond 20MHz. Moreover to process a signal in the GHz frequency range we need a device whose dimensions are comparable with the wavelength of the signal. For example to process a 2GHz signal we need a device dimensions of almost 15cm, similarly for 4GHz it is almost 7.5cm. so if we convert an electromagnetic signal into an acoustic signal by making use of piezoelectric effect , where the speed of acoustic is far less than the speed of light , so that the device dimensions are now comparable .

This mechanism is used in RF BAW /SAW filter technologies. In which the key element is the resonator and its performance.

1.2 Aim and Motivation

The aim of this work is to design a Film Bulk Acoustic Wave Resonator (FBAR) with high Quality factor, large band width and moderate electromechanical coupling coefficient for potential S band applications.

Film Bulk Acoustic Wave Resonator (FBAR) and their performance are key in the design of filters for GHz range applications and sensor applications. This is the driving force behind this work.

1.3 Literature Survey in Brief

Recently in the RF and microwave frequency control and signal processing fields, thin film bulk acoustic wave resonators (FBARs) have received great attention because of their small size, low insertion loss, and low power consumption [1]–[3]. For example, filters based on AlN FBARs which can be operated in the low and medium gigahertz range have been fabricated for signal processing and communication devices [4]–[5]. Having gone through all the presented papers it is found that the resonator and its performance is the key in filter design. In the literature one can find so many resonators designed for different applications by using different materials, of such Zno based SMR with specially designed bragg reflector for 2.7GHz with high quality factor [6]. Tilt in the c-axis of a material can be needed in certain special applications, which alters the mode of operation of the resonator from longitudinal/ quasi longitudinal/ shear modes. C-aixs tilted Zno with quasi shear mode of operation designed for liquid applications[7].c-axis Aln with shear mode using lateral electric field excitation for 2GHz applications[8]. FBAR`s can also be designed by using ferroelectric materials like Linbo$_3$ with CVD deposition was tested[9]. Apart from this reconfiguration of resonators is also possible by making use use of passive elements[10]. Resonators can also be used for sensing applications like humidity sensor, Viscosity sensor, label free **B**iomolecular sensors and many other sensing applications.

1.4 Contribution of this thesis

This work focuses on the design of RF BAW Resonator, following which the design of a filter by making use of above Resonator.

- Design of RF BAW Resonator by making use of Knbo$_3$.
- Design of Ladder Filter by making use of Resonator.

1.5 Brief Overview of Thesis

A brief overview of the thesis presented here

1.5.1 Resonators

Resonators are MEMS devices where you will find an active element (piezoelectric material) and metal electrodes. In BAW the piezoelectric material is sandwiched between the two electrodes, when an electric field or voltage is applied an acoustic wave is generated. Where the resonant frequency depends on the thickness of the piezoelectric material and to some extent on the electrode thickness.

1.5.2 Filters

Filters are generally meant to pass certain frequencies and reject other frequencies. Filters are designed by treating resonators as an electrical element. If we connect the resonators electrically then we will have an either a ladder or lattice filters. If we connect the resonators acoustically then we end up in having either SCF or CRF filters. This is entirely based on the design requirements.

1.5.3 Knbo3

Over half a decade or so much of the research work is focused in using the Aln, Zno as active elements in resonators design. Very recently the focus is shifted to study the usage of ferroelectric elements as active elements in resonators, because of their high acoustic velocities and high piezoelectric coefficients. Their compatibility with silicon is big hurdle it seems. Here we are using $knbo_3$ as an active element which is a ferroelectric material, it is because all ferroelectric`s are piezoelectric`s .

1.6 Thesis Organization

This Thesis is organized in the fallowing way

- Chapter1: is the introduction describing the motivation behind the work , literature survey, objectives and contribution of the work.
- Chapter2: describes about the basic working principals of resonators, different types of resonator technologies, their advantages and disadvantages, design specifications of resonator using $knbo_3$, results and conclusion.
- Chapter3: describes about different types of filter configurations, design of ladder filter using resonator`s and its characterization.
- Chapter4: describes about the properties of $knbo_3$
- Chapter5: presents the conclusion of this work as well as future directions of this work.

Chapter 2

Resonators

2.1 Different Types of Resonators

There are two resonator technologies 1.SAW (surface acoustic wave) and 2.BAW (bulk acoustic wave). As the name signifies SAW is the one in which the acoustic wave travels along the surface of the piezoelectric material, BAW is the one in which the acoustic wave travels along the thickness of the material. These are known for their high performance small size and low cost.

2.1.1 Advantages of BAW over SAW

Among these two BAW offers advantages over SAW in terms of low insertion loss, better Selectivity, high power handling, high operating frequency and better electrostatic discharge protection. The temperature coefficient (TCF) of BAW can also be better than SAW (-20ppm/◦c verses -45ppm/◦c) good TCF makes the selectivity of BAW even better, since the filter has less frequency drift over temperature makes the designer easier since less guard band is needed. SAW suffers from diffraction losses along the inter digital transducer (IDT) losses and mode conversion losses when surface acoustic wave is reflected by so many fingers along the long cavity. ohmic losses of large electrodes are smaller than the IDT which makes Q even better. BAW can operate at much higher frequencies because the thickness of the piezoelectric layer which is deposited by VLSI process is not an issue for at least up to 20GHz. While in SAW frequency is limited by IDT pitch or finger width or gap. The cycle time of design is less for SAW when compared to BAW.

2.1.2 Different types of BAW Resonator

BAW Resonator consists of a piezoelectric material sandwiched between the top and the bottom electrodes. The voltage or electric field excites the acoustic wave whose resonant frequency is given by $f = v*N/2*d$ where v is the acoustic velocity, N is the integer multiple, d is the thickness of the piezoelectric material. Acoustic velocity is strong dependent on the piezoelectric material properties and is given by $v = \sqrt{(c/\rho)}$ where ρ density of the piezoelectric material c is the elastic constant of the material.

There are two types of BAW resonator technologies 1.FBAR (film bulk acoustic resonator) and 2.SMR (solidly mount resonator). Each has got its own advantages and disadvantages. The major difference between them is the way the acoustic energy is trapped at the bottom electrode. In FBAR an air gap is created at the interface of the bottom and the carrier wafer so as to ensure the main mode of interest is effectively trapped. While in SMR a Bragg reflector under the bottom electrode serves this purpose. The Bragg reflector is generally constructed by materials of alternating low and high acoustic impedances of thickness λ/4. FBAR gives better coupling coefficient than SMR because the air/electrode interface traps more acoustic wave between the electrodes than Bragg reflector. FBAR gives better Q than SMR due to lack of additional reflecting layers in which the acoustic wave may attenuate and escape. While SMR offers mechanical robustness and better TCF over FBAR .

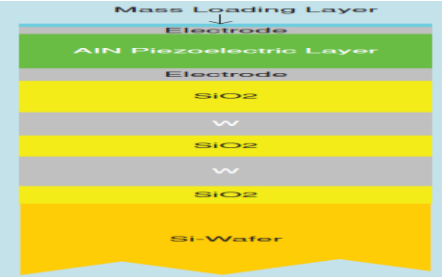


Fig 1: SMR

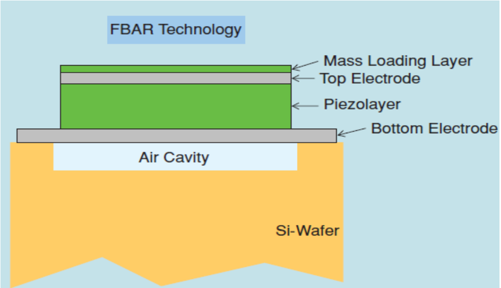


Fig 2: FBAR

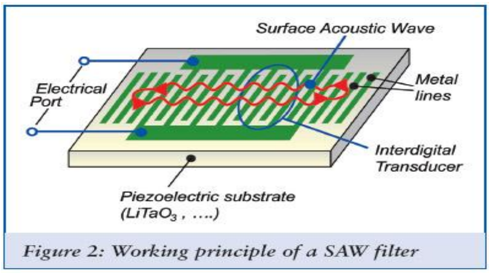


Fig 3: SAW

2.1.3 Equivalent (Electrical) circuit of a resonator

The electrical equivalent model of the resonator is the Butterworth van dyke model (BVD model). Where the capacitance C_0 represents the parallel plate capacitance formed by the piezoelectric material together with the top and bottom electrodes, L_1 represents the motional inductance, C_1 represents the motional capacitance, and R1 represents the motional resistance (acoustic losses) .The expressions for all the circuit parameter are as follows.

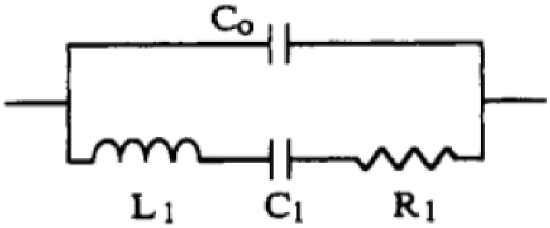


Fig 4: Electrical Equivalent circuit of a resonator

$$C_1 = C_0 * \left[\left(\frac{f_p}{f_s}\right)^2 - 1 \right] \qquad L_1 = \frac{1}{(f_p{}^2 - f_s{}^2) * 4\pi^2 C_0} \qquad C_0 = \frac{\epsilon_0 * A}{d}$$

$$Q = \frac{2\pi * L_1 * f}{R_m} \qquad f_s = \frac{1}{2\pi * \sqrt{(L_1 C_1)}} \qquad f_p = \frac{1}{2\pi * \sqrt{\left(L_1 \left(\frac{C_0 C_1}{C_1 + C_0}\right)\right)}}$$

Where f_s , f_p represents the series and parallel resonant frequencies of the resonator, ε_0 represents the dielectric constant of the piezoelectric material, A represents the electrode area, d represents the thickness of the piezoelectric material, Q is the quality factor of the resonator.

2.1.4 Key Parameters of the resonator

The key parameters of a resonator are the electromechanical coupling coefficient ($K_{eff}{}^2$), band width and quality factor are depends mainly on the piezoelectric material and the electrode material and the conditions on which the piezoelectric material is deposited.

Electromechanical coupling coefficient is given by $K_{eff}{}^2 = \frac{\pi^2 * (f_p - f_s)}{4 \quad f_p}$.

2.1.5 Different ways of creating an air gap

There are two different ways of creating an air gap so that acoustic losses are going to be minimized. 1. Front etched FBAR (Fig 2) and 2. Back etched FBAR. It is difficult to precisely control the performance of film bulk acoustic wave resonator fabricated using the front etch process. So the idea is to use inductive coupled plasma (ICP) for back etching process, since high aspect ratio structures are can be realized using ICP etching process. Because ICP etching has a characteristics of dry etching and larger selectivity between substrate and thin films.

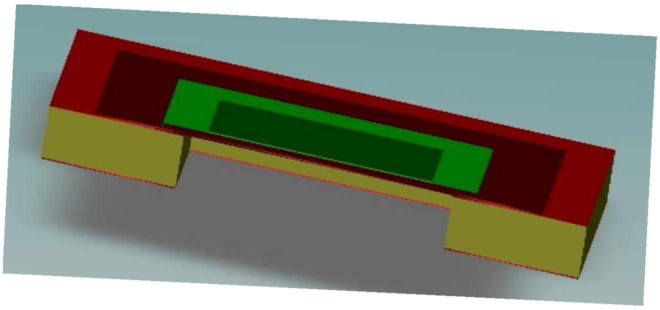


Fig 4: Back etched FBAR

2.2 Design of FBAR by making use of $Knbo_3$

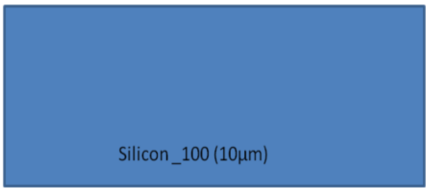
By making use of $Knbo_3$ as a piezoelectric material, we designed a backed etched FBAR with the following design specifications.

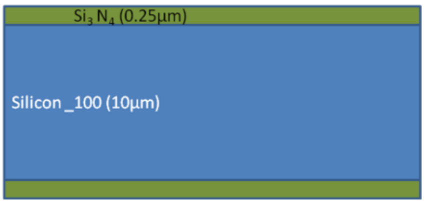
2.2.1 Specifications of the Design

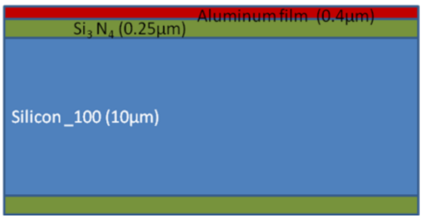
Layer Name	**Material Name**	**Thickness in (µm)**
substrate	Silicon_100	10
nitride	Si_3N_4	0.25
Bottom electrode	Aluminum film	0.4
Piezoelectric	$Knbo_3$	1
Top electrode	Aluminum film	0.32

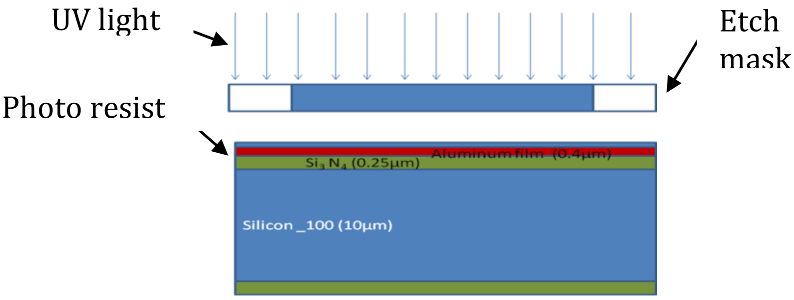
2.2.2 Process Steps for the Design

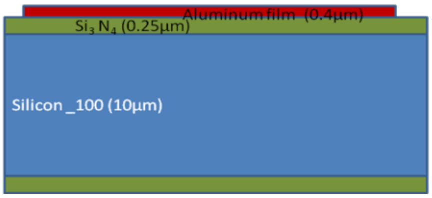
Process steps for the Design are as follows

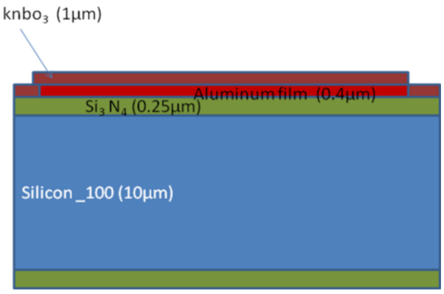












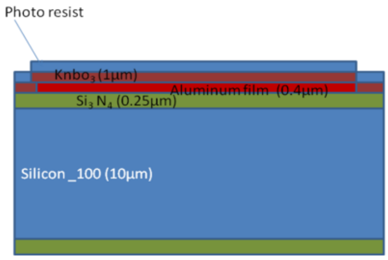
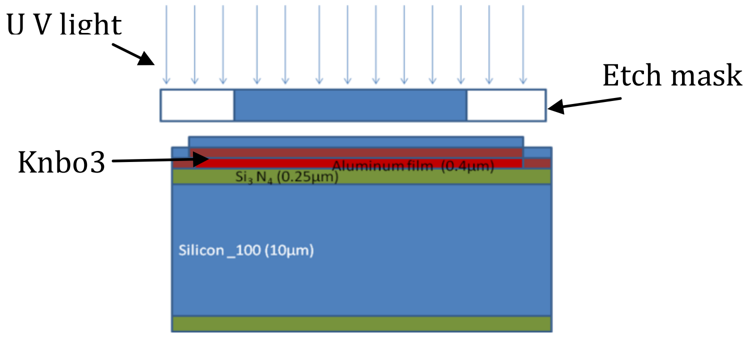
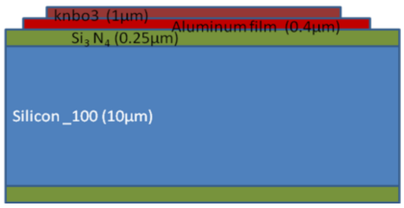
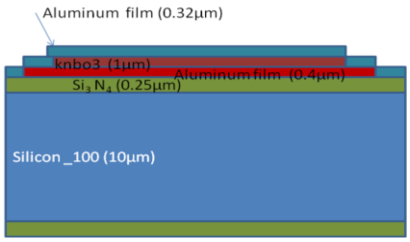


Photo resist
Knbo$_3$ (1µm)
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)


U V light
Etch mask
Knbo3
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)


knbo3 (1µm)
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)


Aluminum film (0.32µm)
knbo3 (1µm)
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)

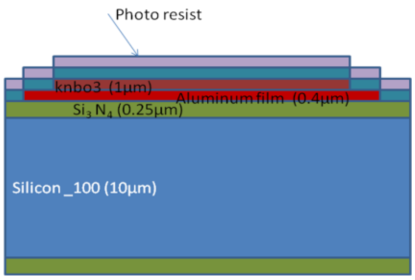
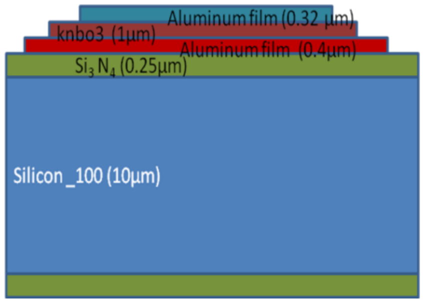
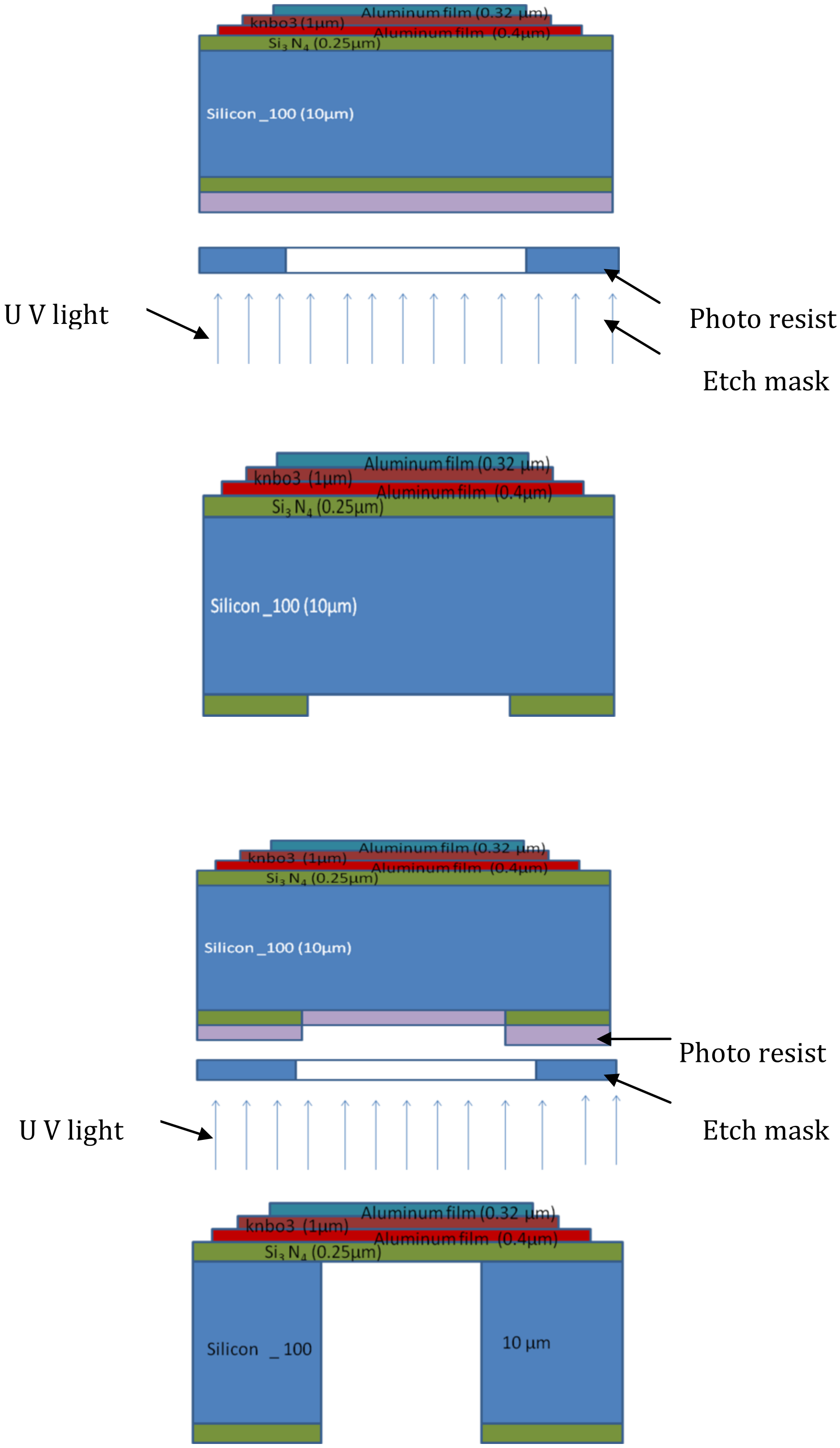


Photo resist
knbo3 (1µm)
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)


Aluminum film (0.32 µm)
knbo3 (1µm)
Aluminum film (0.4µm)
Si$_3$N$_4$ (0.25µm)
Silicon _100 (10µm)



Film bulk acoustic Wave

2.2.3 Results and Conclusion

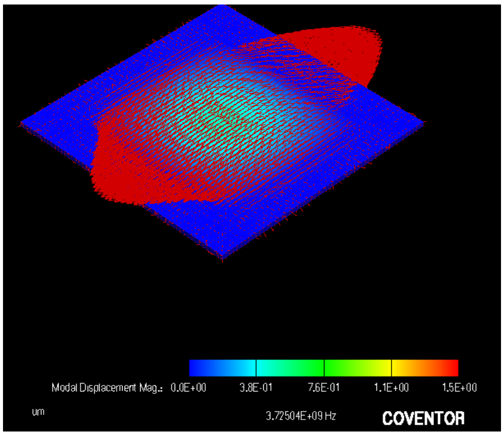


Fig 5: series resonant frequency @3.72504GHz

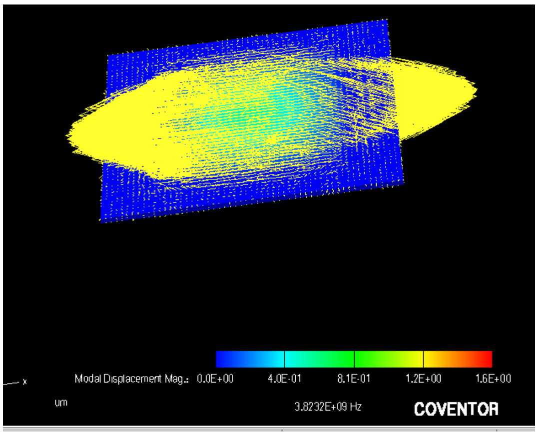


Fig 6: parallel resonant frequency@3.8232GHz

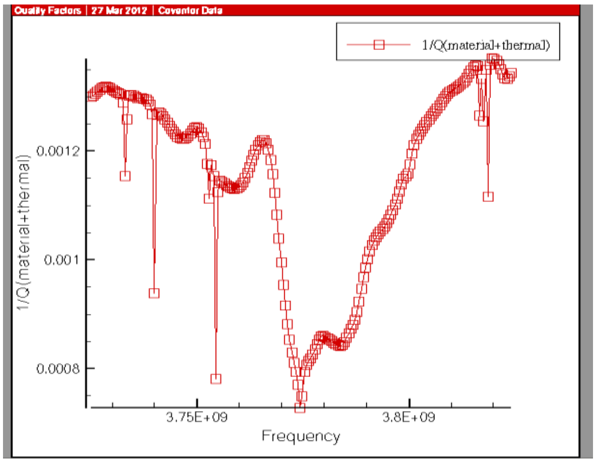
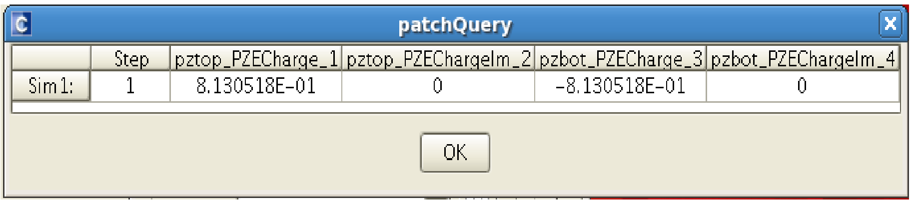


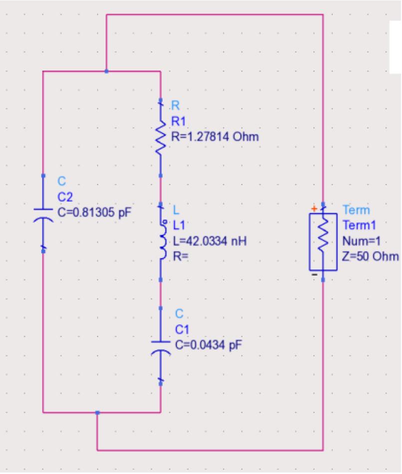
Fig 7: 1/Q vs frequency



patchQuery

	Step	pztop_PZECharge_1	pztop_PZEChargeIm_2	pzbot_PZECharge_3	pzbot_PZEChargeIm_4
Sim1:	1	8.130518E-01	0	-8.130518E-01	0

2.2.4 Equivalent Electrical circuit for the Design



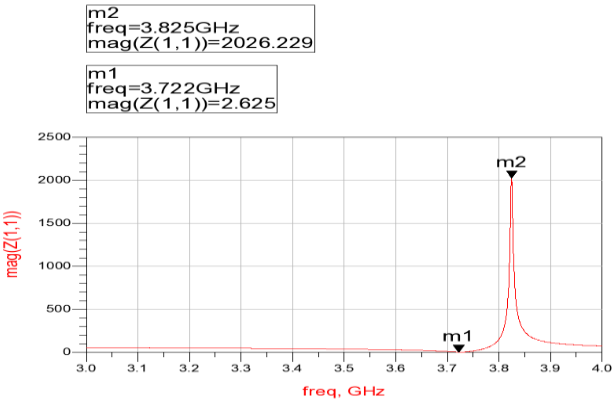


Fig 8: Impedance vs Frequency

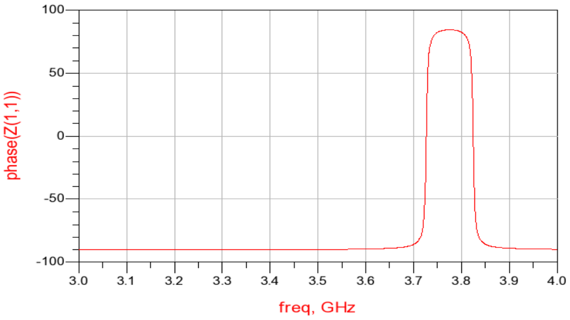


Fig 9: phase vs Frequency

The resonator behaves as a mere capacitor for all the frequencies except at the resonant frequencies it behaves as an inductor. This resonator is exhibiting a series and parallel impedances of 2.6ohm and 2K ohm. The electromechanical coefficient of the resonator is 6.5%. For most of the mobile applications electromechanical coupling coefficient lies between 6% to 9% .

2.2.5 Comparison of Results

	From IEEE paper	Results obtained	From IEEE paper
Electromechanical coupling coefficient	5.8%	6.5%	6.9%
Band width	71.34 MHz	98.2MHz	60MHz
Impedance ratio	40 dB	57.8 dB	45 dB
Quality factor	70	760	1200

2.3 Design of Shunt Resonator by making use of knbo3

Shunt Resonator is designed by placing a loading layer on the top electrode of the above designed FBAR.

2.3.1 Specifications of the Design

Layer Name	**Material Name**	**Thickness in (µm)**
substrate	Silicon_100	10
nitride	Si_3N_4	0.25
Bottom electrode	Aluminum film	0.4
Piezoelectric	$Knbo_3$	1
Top electrode	Aluminum film	0.32
Mass loading layer	copper	0.001

2.3.2 Process Steps for the Design

Process steps are same as the above design except a loading layer is deposited on the top electrode.

2.3.3 Results and Conclusion

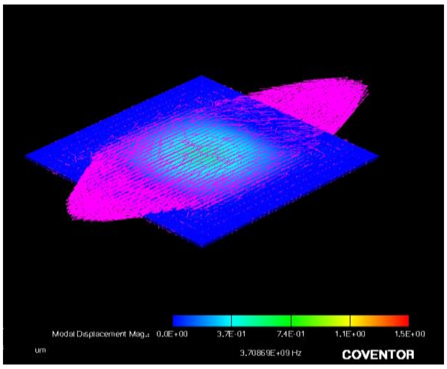


Fig 10: Series Resonant frequency @ 3.70869GHz

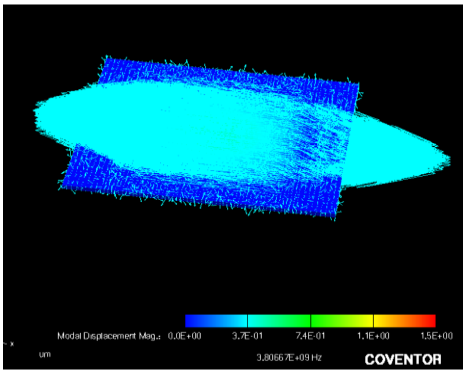


Fig 11: Parallel Resonant frequency@3.80667GHz

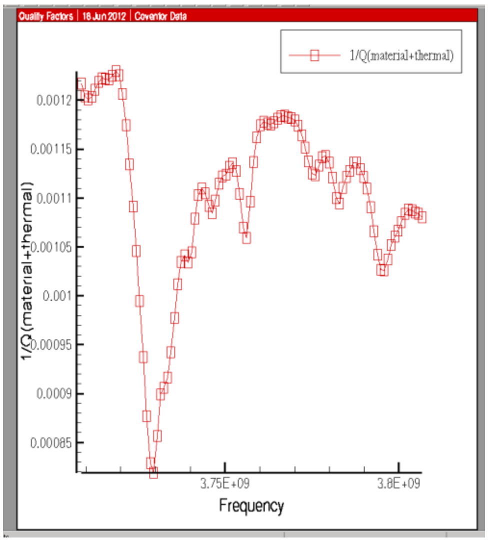
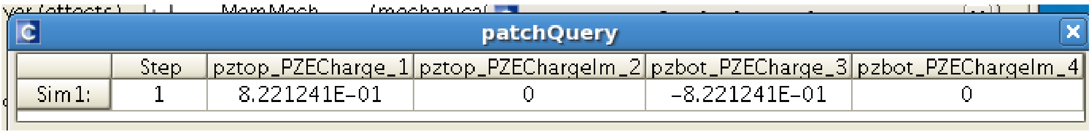
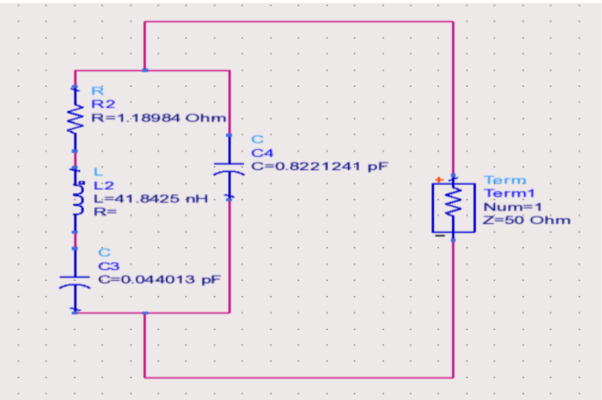


Fig 12: 1/Q vs frequency



	Step	pztop_PZECharge_1	pztop_PZEChargeIm_2	pzbot_PZECharge_3	pzbot_PZEChargeIm_4
Sim1:	1	8.221241E-01	0	-8.221241E-01	0

2.3.4 Equivalent Electrical circuit for the Design



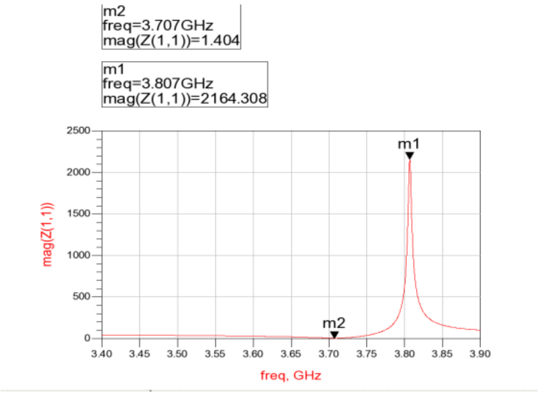


Fig 13: Impedance vs Frequency

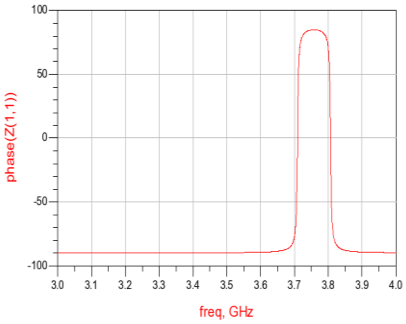


Fig 14: Phase vs Frequency

This resonator is exhibiting a series and parallel impedances of 1.4ohm and 2.1K ohm. The electromechanical coefficient of the resonator is 6.5%**.**

Chapter 3

Filters

3.1 Different Types of filters

Filters are generally intended to pass a certain band of frequencies and exclusion of all other interfering ones. Depending on how the BAW Resonators interconnected there are four different types of filter configuration are possible 1.ladder 2.lattice 3.coupled resonator filter (CRF) 4. Stacked crystal filters (SCF). The main difference between them is, in ladder and lattice filters the resonators are electrically connected while in CRF and SCF the resonators are acoustically connected.

Ladder filters has an advantage in terms of selectivity. But a poor out of band rejection due to its natural capacitor voltage divider, out of band rejection can be improved by increasing the order of the filter. Increasing the order of the filter leads to increase in the in band insertion losses and gives rise to ripples in the pass band and spikes at the limits of band pass. Lattice filters has an advantage in terms of out of band rejection and band width. But the disadvantage lies in converting balanced to unbalanced transition. A hybrid configuration such as a ladder- lattice has advantages of both in terms of selectivity and out of band rejection.

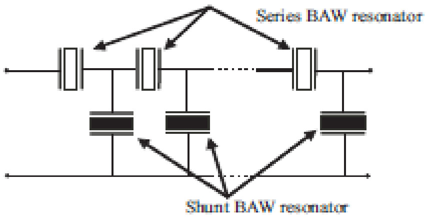


Fig 15 : ladder filter

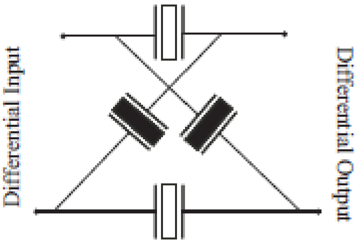


Fig 16 : lattice filter

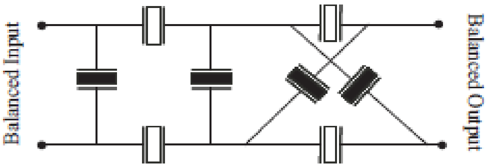


Fig 17: ladder - lattice

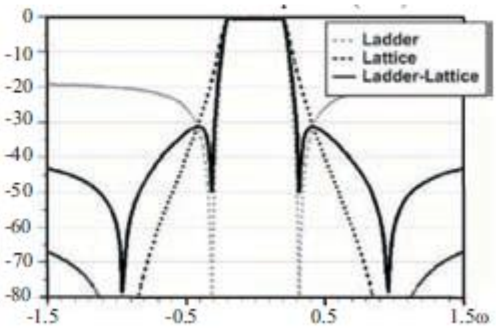


Fig 18: Transmission response of different filters

Applications above 5 GHz can be found in [11], in which a 5/3 Ladder filter with doubled resonators is manufactured at 5.2 GHz, with a 4 dB relative bandwidth of W = 3.2%, exhibiting a minimum insertion loss of L = 2.0 dB, and an OoB rejection of more than 24dB.

3.2 Design of ladder filter by making use of FBAR

The resonators which are discussed in the 2nd chapter are connected in ladder configuration with filter order of 1/1 ,2/2,3/3,4/4,5/5.

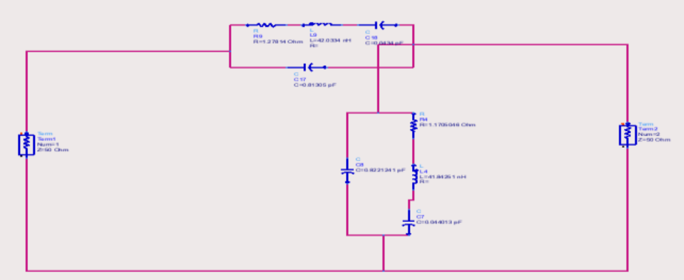


Fig 19: “first order” ladder filter

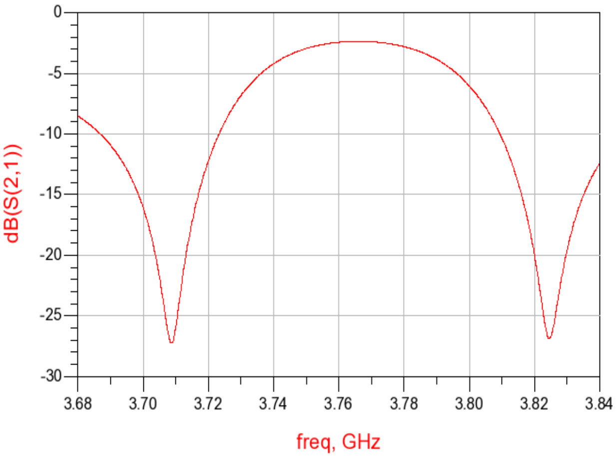


Fig 20: transmission response of first order

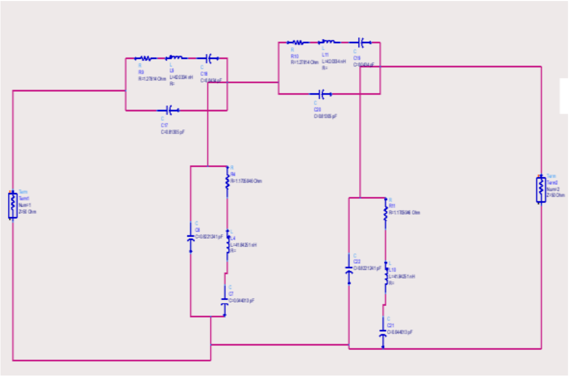


Fig 21: “second order” ladder filter

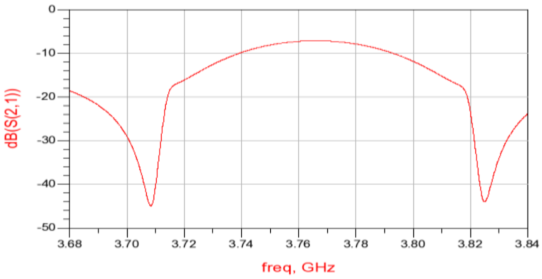


Fig 22: transmission response of second order

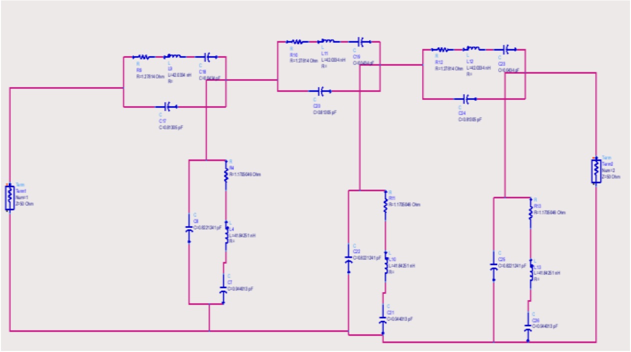


Fig 23: “third order” ladder filter

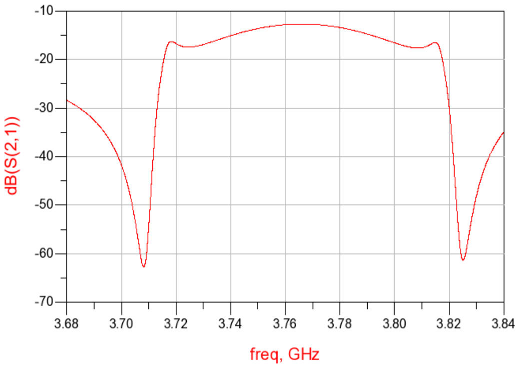


Fig 24: transmission response of third oder

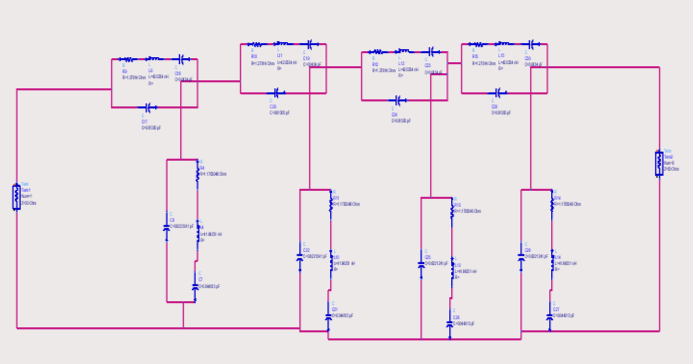


Fig 25: “fourth order” ladder filter

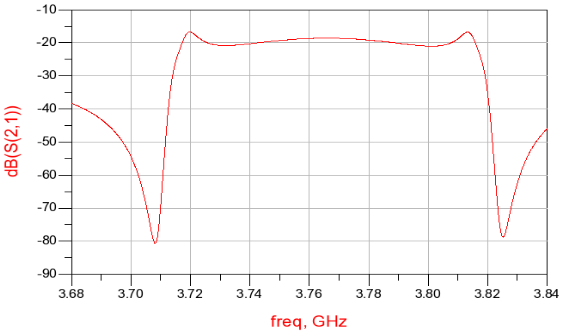


Fig 26: transmission response of fourth order

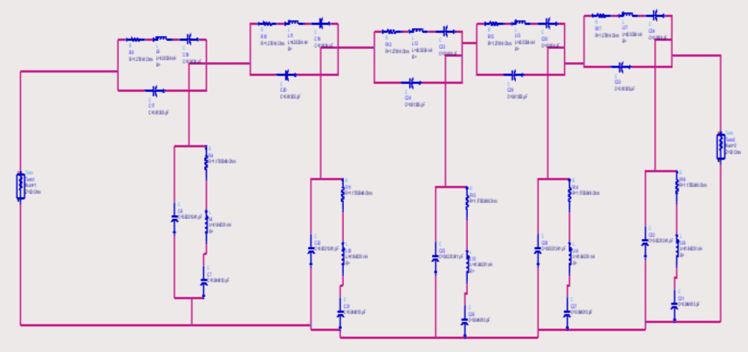


Fig 27: “fifth order” ladder filter

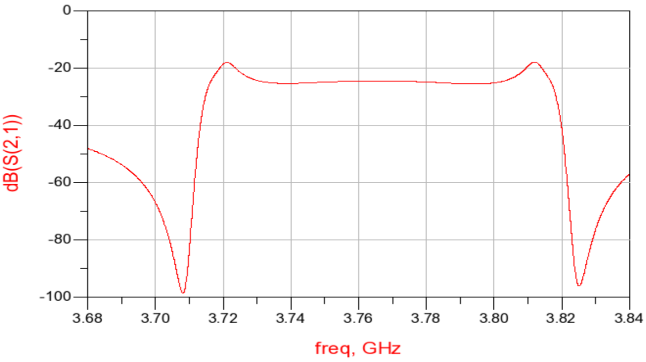


Fig 28: transmission response of fifth order

3.3 Conclusion

As described earlier ladder filters are highly selective and have poor out of band rejection. Which one can find by looking at first order response. As the filter order increases pair of spikes at resonant frequencies, increase in “ in band insertion losses” and increase in out of band rejection . Fifth order offers an insertion loss of -22dB, Quality factor of around 760, band width 75MHz, out of band rejection is about -50dB and electromechanical coupling coefficient of 6.5%.

3.4 Applications

These filters can be used for potential S- band applications (2 to 4 GHz). In specifically for wi- max applications.

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Chapter 4

KNbo$_3$

4.1 Properties of Knbo$_3$

Knbo3 is a ferroelectric material, all ferroelectrics are piezoelectric`s converse is not true. Advantages of this material are it is lead free, it has high piezoelectric coefficients and high acoustic velocity. If one wants to work at higher frequencies, high acoustic velocity materials allows us to deposit films of reasonable thickness when compared to low acoustic velocity materials. The dielectric, piezoelectric and elastic properties of knbo3 are taken from this paper[12]. In order to properly characterize piezoelectricity, the constitutive equations are considered. The constitutive equations describe the relationship electric field and mechanical stress.

$$T = c * S - e^{t} * E$$

$$D = e * S + \varepsilon * E$$

Where T represents stress vector, S represents strain vector, E represents the electric field vector, D represents the electric displacement vector, e represents the piezoelectric stress matrix, c represents elasticity matrix and ε represents dielectric matrix.

Chapter 5

Conclusion and Future work

5.1 Conclusion

As a part of this thesis work we designed and simulated the resonator by making use of knbo3 (both shunt and series resonators) and design of ladder filter by making use of the above resonators.

5.2 Future work

This work can be future carried out as future scope in order to develop duplexers / reconfigurable filters as follows:

- Reconfiguration is possible by making use of passive elements.
- Resonators can be used to build a duplexer.

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