

1.45GHz-1.55GHz Tunable RF Band-pass Filter

By

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FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
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for the Degree
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Department of Electrical & Electronic Engineering
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MAY 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Omnia AdilMohamed Idriss

ABSTRACT

RF signals are used in the communication field in general. It has special band called microwave band which is the focus of this project. The idea of filtering comes from the need to transmit certain frequency of ranges of interest and block others. In this project the focus is on tunable filters using MEMS idea to solve the problem of complexity and price of the conventional tunable filters. The project focuses on L band to get the range from 1.45GHz to 1.55 GHz. The project starts by designing the low pass prototype and convert it to comb-line filter to find the capacitance range for the design of the tuneable capacitor using CMOS-MEMS technology. The tunable capacitor has to be modelled and designed. Theoretical modelling and ADS simulation determined the tuning range required for the capacitor is from 1.72pF to 1.84pF. A CMOS-MEMS fixed and tuneable capacitors were designed and simulated to achieve this range of capacitance and requires a voltage of 20V for tuning. Thus the objectives of the study have been achieved successfully and recommendations are made to achieve a wider frequency range for the filter and for integration of the filter with the tunable capacitor.

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CHAPTER 1: INTRODUCTION

1.1 Background of study

Radio Frequency (RF) signals are electromagnetic waves in the range from 3 kHz to 300 GHz; this range is used in the communication applications. There is a special range from 1GHz to 100GHz which is known as microwave range and includes bands with different ranges such as the L band with a range of 1-2GHz, S band with a range of 2-4 GHz, Q band with a range of 30-50 GHz and many other bands.

The microwave applications are confined to three main regions and these applications are military systems, measurement equipment and communication systems. Microwave signals are mostly used in the communication system applications such as sending and receiving text and pictures using computer, mobile or any of the communication devices.

Each application has a specific range to work properly; filter is used to get the range needed for the application which used RF filter. The first RF filter was generated in 1915 by integrating between Germany and United States and it has been grown in 1940 by using transfer function in filtering the signals. The tunable filter uses different stop and band pass range to tune and can be designed using a different band pass filter or by adjusting the components. There are many types of tunable filters: magnetic filter, optical fiber and MEMS tunable filters [1].

This project will be focusing on microelectronic mechanical system (MEMS) fabricated using standard complementary metal oxide semiconductor (CMOS) technology. The applications of MEMS are numerous and include sensors and actuator switches and these applications have been used in many fields. The early

device of MEMS was transistor which it had been used to measure the pressure of the machines and recently used in controlling communication system [2].

MEMS have been integrated with RF filter to get a filter with small loss and a wide tunable range. The RF-tunable filter is standard for radio frequency filter and integrated with a MEMS tunable capacitor for designing the variable element.

This project focuses on the L band with a range of 1-2 GHz which has many useful applications and include military use in the range of 1.452-1.492 GHz, Global positioning system carriers (GNSS) which is used in GPS, telecommunications use in GSM mobile phones, amateur radio is allowed in this range of frequency and its digital audio broadcasting (DAB) which is used in world space satellite have the range of 1.457-1.492 GHz.

1.2 Problem statement

The conventional tunable Band-pass filter is complex and it is expensive to buy the components of the circuit. There are many ways to design tuning filter: optical fiber is one way to design it but it has many disadvantages such as high cost, a finite lifetime. Another is ferromagnetic tunable filter which also has disadvantages such as high power consumption, high cost and low tuning speed.

1.3 Objective and Scope of studies

1.3.1 Objectives

- Modeling and simulation of Band pass RF filter.
- Modeling and simulation of MEMS tunable capacitor switch.

1.3.2 Scope of studies

This project aims to model a tunable band pass filter and a CMOS-MEMS tunable capacitor to use for the filter in order to reduce cost and complexity of the circuit components. This project is

1. To design and simulate RF band-pass filter conventional circuit in the range of 1.45-1.55GHz to determine the tunable capacitor range.
2. To design and simulate a CMOS-MEMS tunable capacitor meeting the determined specifications.

1.4 Project Feasibility

This project has been considered feasible since all needed facilities such as simulation and modeling software are available at the place of study “university technology PETRONAS , UTP” and based on the proposed method and Gantt chart , it will be able to complete all the activities within the time frame .

CHAPTER 2: LITERATURE REVIEW

2.1 Band pass Filter

Many researches have been done in the communication area to design a band pass filter. One of the interest areas is filters the second order low band pass filter circuit as shown in figure 2.1. Each order of the filter has a capacitor connected to it with a resistor in parallel to pass the low frequencies (DraženJuriši. et, 2001)[3].

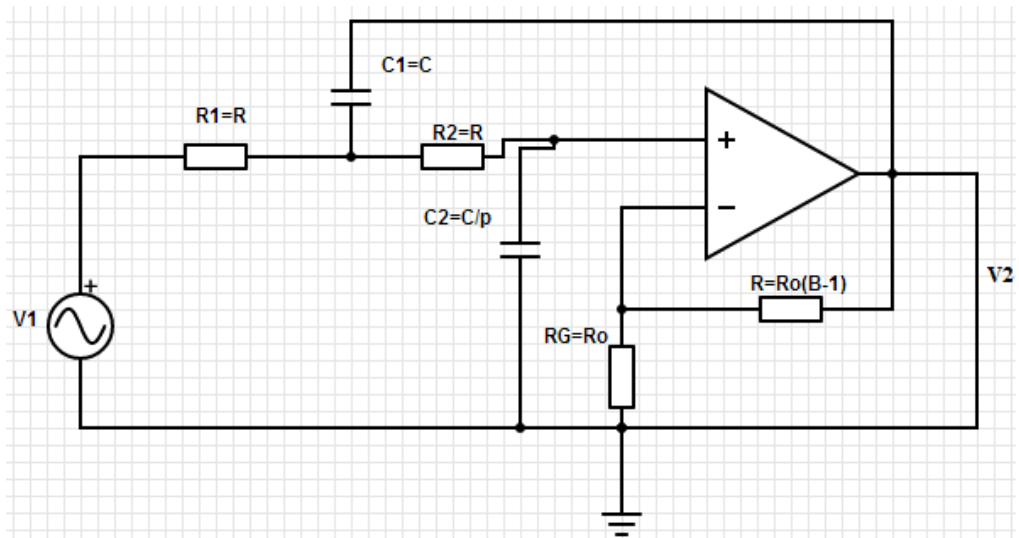


Figure 2.1: Second Order low pass filter [3]

To convert the low pass filter to band pass filter the resistor transforms to the resistor and capacitor in the series and the capacitor transforms into parallel resistor and capacitor combination and this called a “lossy” LP-BP transformation and it produces the circuit in Figure 2.2 .

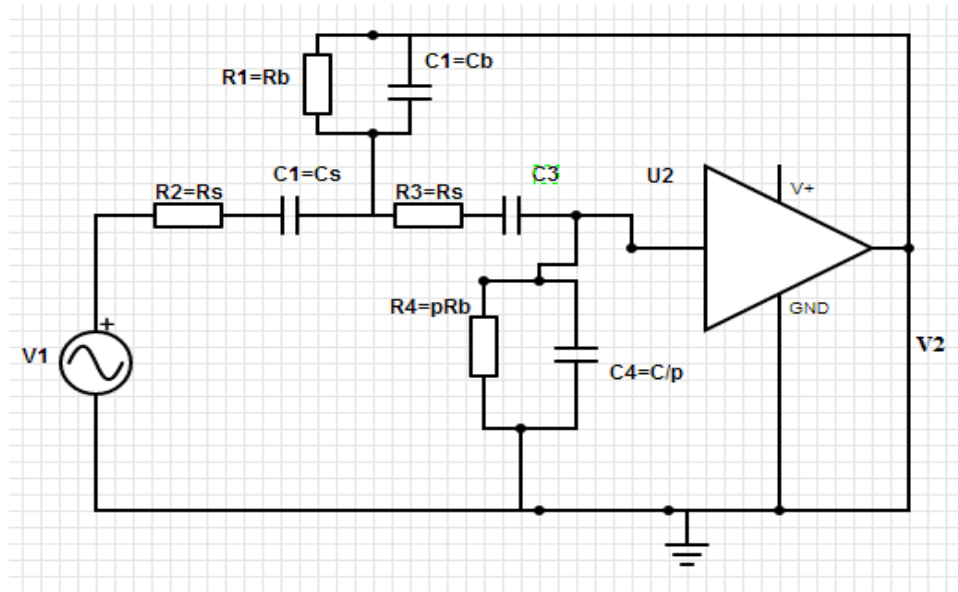


Figure 2.2: Fourth order BP filter circuit [3]

With the circuit shown in figure 2.2 which is the fourth order of band pass filter that gives the output response as shown in Figure 2.3 gives the pass band range from 100 KHz-300 KHz with 200 KHz bandwidth.

In addition this process can be extended to the sixth order or higher but it has to be even order.

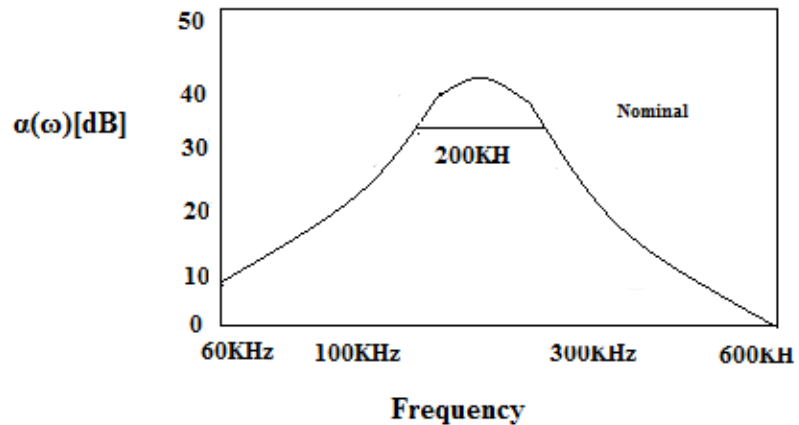


Figure 2.3: Magnitude of 4th-order BP filter [3]

2.2 RF-MEMS devices

RF-MEMS devices are devices using MEMS techniques used for microwave signals. There are many advantages of MEMS devices that include [1]:

1. Low power consumption :

Normally switches desire 30-80V but RF-MEMS uses a small amount of current and reduces the power to 10-100nJ.

2. High Isolation:

Devices have high isolation under two conditions; first if there is low off state and the frequency range is 0.1-60 GHz or the capacitance ratio is 60-160 and the frequency range is 8-100 GHz.

3. Low insertion loss:

RF-MEMS devices have insertion loss of 0.1dB when the frequencies range up to 100GHz.

4. Linearity and Intermodulation Products :

MEMS switches are linear devices; normally the performance of these switches is (30-50) dB

5. Low cost :

RF-MEMS switch modeling using surface micromachining make it cheap.

Moreover, there are disadvantages of the RF-MEMS:

1. Relatively Low Speeds:

There are three types of RF MEMS switches, which are thermal, magnetic and electrostatic. The speed of these filters is the range from (2-40) μ s if that is electrostatic switch and for the magnetic /thermal the speed of the switch range from (200-3000) μ s. However, all the RF-MEMS application requires faster switches.

2. High Voltage or High Current Drive:

As it mentioned the RF-MEMS have low power consumption that result for low current in the electrostatic switch and it will have high voltage at the same time, for the thermal/magnetic it will have high current with low voltage .

3. Power Handling

RF-MEMS cannot take over 200mW of power and there are some switches have 500mW.

4. Reliability

Normally the systems need switches with 20-200billion cycles and MEMS switches is 0.1-40 Billion cycles. [4]

2.2.1 Tunable Capacitors

A tunable capacitor is a device that uses MEMS techniques to enable the tuning of its capacitance. The insertion loss of poly-silicon MEMS capacitor was measured to be -4dB at 40GHz and this tunable range has been achieved by small value of voltage of about 0.1V [20].

2.3 Tunable filters

Electronically tunable filter is type of filter which can use in the project because it can cover a wide range and it has a compact size. The perfect way to use this filter is by using tunable capacitor and for this type there are three technologies that can be used:

- (a) Semiconductor Gallium Arsenide (GaAs), Silicon (Si) or Silicon-Germanium (SiGe) varactors
- (b) Ferroelectric thin film tunable capacitors
- (c) Radio frequency micro-electromechanical systems (RF MEMS) switches and varactors [6].

2.4 RF- tunable Band pass filter

This part will focus on some researches for the tunable capacitor which are:

2.4.1 Optical fiber tunable band pass filter

Optical fiber is used for designing the tunable band pass filter and there is research done to design and demonstrate a widely tunable wavelength filter, which is realized by lateral bending of a fiber Bragg grating mounted on a substrate. Fiber Bragg

Grating (FBG) is the best solution for the sharp spectral filtering characteristics and low insertion loss.

This device fabricated on a hydrogen-loaded dispersion fiber gives the center wavelength of **1551nm** and it is tunable for the range from **1525nm** to **1565nm** that is used in many researches such as sharp spectral filtering characteristics and low insertion loss (Chee S. Goh et. 2002)[21].

2.4.2 Ferromagnetic tunable band-pass filter

One of the important researches compares between different types of filters and these filters are: Mechanically tunable filter, varactor tuned Filter , E-planed filter , magnetic static wave (MSW) and Yttrium iron garnet(YIG) filter which functions as magnetically tuned and the research compares the important parameters of the different types of these filters such as insertion loss and power consuming as is done in the research of Uher and Hofer (1991) [10] and after they designed the filters it gets the research has shown in table 2.1 [1]

Table 2.1 shows the MSW and YIG filters have less insertion loss but compared with insertion loss of the E-plane or varactor using MEMS. Mechanical filters have high power consumption while the magnetic filters have low power consumption; the tuning speed is lower for the mechanical filter, YIG filter and Magnetic. Moreover, the tuning speed of E-plane and varactor is very high.

Table 2.1: performance comparison between different filters [10]

Performance	Mechanical	YIG	MSW	E-Plane	Varactor
Bandwidth	0.3-3	0.2-3	0.2-0.5	1-10	2-20
Insertion Loss	0.5-2.5	3-8	6-10	0.7-2.5	0.3-2.5
Selectivity	12-24	12-36	24	12-24	12-24
Rejection att.	>50	40-60	>45	>50	>30
Power	100-500	0.1-1	0.05	5-200	0.05-0.1
Tuning range	5-20	Multi-	Multi-	60-70	Octave

Tuning speed	Very low	05-2	05-2	$0.5-10^3$	10^3
BW variation	10-20	10-40	10-40	5-10	1-2
Tuning	+/- 15	+/-10	+/-10	+/- 15	+/-35
Temp.	20	15	15	25	25
Millimeter-	No	Yes	No	Yes	No

2.4.3 RF-tunable Band pass filter

There are many researches in the RF-MEMS tunable band pass filter. An earlier research by Zhao et al [8] had designed the range of (10-14 GHz) of an RF-MEMS tunable band pass filter based on elliptic functions of low pass filter. It was designed by integrating a low pass filter and a high pass filter.

For tunable filters, the higher cutoff frequency can be achieved by transfer of the cutoff frequency of the low pass filter and also achieved by tuning low pass filter by setting the first transmission zero (FTZ). The tunable band pass is then obtained by setting the last transmission zero (LTZ) to have the RF-tunable Band pass filter cascaded from the low pass filter that have the cutoff frequency 13GHz with high pass filter that have cutoff frequency 10GHz. The bandwidth that could be cover by this filter is in the range 10.4-24.2GHz and the insertion loss is about 0.5dB but it has ripple result from elliptic function.

Moreover, Pillans et al [9] used the same technology of the cascade of tunable low pass filter as shown in Figure 2.4 with a tunable high pass filter that is shown in Figure 2.5 to have the tunable pass band filter. They tested this method in the range of 6-15 GHz and the result was a low pass filter with an insertion loss in the range 2-4 dB with rejection of more than 60 dB as shown in Figure 2.6. For the high pass filter, they obtained an insertion loss in the range of (3-5dB) with rejection of more than 60 dB also as shown in Figure 2.7.

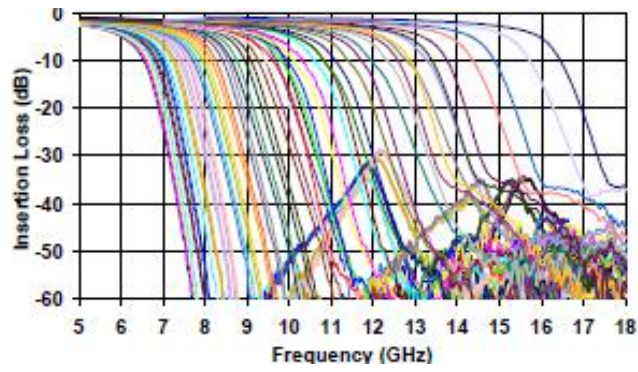


Figure 2.4: Insertion loss plot of 56 low-pass filter element states [9]

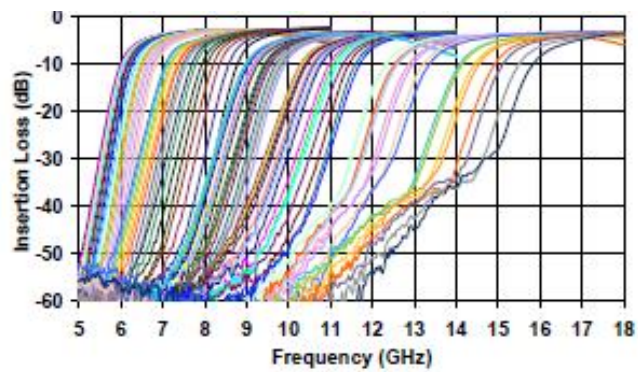


Figure 2.5: Insertion loss plot of 80 high-pass filter element states [9]

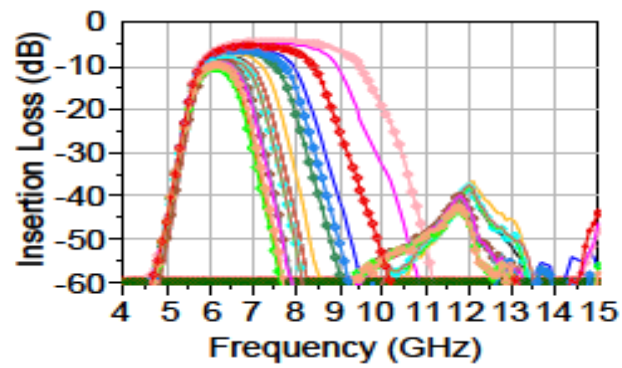


Figure 2.6: 6-9 GHz tunable bandwidth demonstration [9]

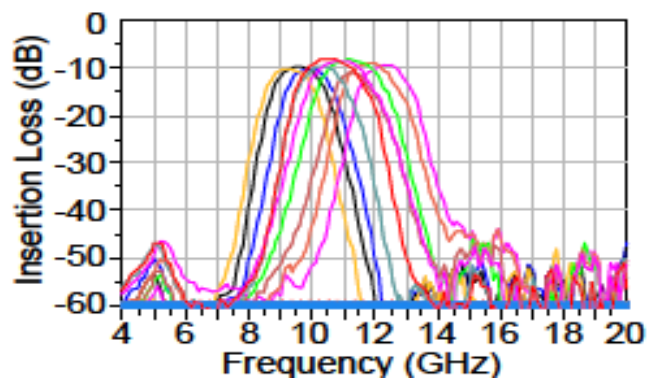


Figure 2.7: 9-12 GHz tunable center frequency demonstration [9]

Shim et al [11] discusses the band pass filter using properties of electrostatically actuated capacitors in the range of (0.6-1GHz). They use two technologies utilizing PCB (Print Circuit Board) and MEMS. The MEMS filter has a size of 10.2 mm × 14.9 mm and the size of PCB filter is 44.7 mm × 59.2 mm. Therefore as the table (2) shows, the MEMS filter has a smaller size compare to PCB.

Table 2.2: Performance comparison of filters between different researches [11]

	Brown'00 [12]	Borwick'03 [13]	Lee'09 [14]	PCB [11]	This [11]
f_c(MHz)	700-1330	225-400	510-910	559-988	602-1011
Insertion	2-6	4.7-6.2	1.8-2.5	4.6-5.3	3-3.6
BW_{30dB}/BW_{3dB}	8-22% of f _c	4% of f _c	20% of f _c	8-15% of f _c	13-4% of f _c
BWdB	2-3	5-6	4.5-6.5	2.8-3.6	3.2-4.7
Tuning Speed	N/A	<600μs	N/A	< 1 μs	40-80μs
IIP3	18-4dBm	30-38dBm	N/A	>30dBm	20-0dBm
Technology	PCB	PCB+MEMS	PCB	PCB (SMT)	MEMS
Size (mm²)	31 × 40	30× 44.5	4.4× 3.4	44.7× 59.2	10.2× 14.9

2.5 RF MEMS tuned comb-line filter

Comb-line filter is coupled line filter and in these designs all the lines are short-circuits at one end and at the other end are terminated in capacitor to ground.

This type of filter is used to design the RF tunable filter for the range of 8.2 GHz-11.3 GHz and this is an X band as reported by Nordquist et al [17]. Specific parameters are used such as resonator impedances of 50 ohm, physical length of the

resonators of 2 mm, loading capacitance ranging from 150-300 pF and the resonators was 45° at 10 GHz.

The result for this design was measured and shows a pass band return loss of 7dB and insertion loss ranging from 4.5 dB to 6 dB for the tuning states for which the center of frequencies are 8.9 GHz, 9.2 GHz, 10.2 GHz and 11.3 GHz. Therefore the filter has low insertion loss and low return loss and this type of filter will be used in this project in the range from 1.45-1.55 GHz.

CHAPTER 3: METHODOLOGY

3.1 Procedure Identification

The main steps in the methodology are: literature search for information on the tunable band-pass filter and the MEMS tunable capacitor, design and simulate of the tunable band-pass filter and design and simulate the MEMS tunable capacitor. Figure 3.1 shows the flow chart of the project.

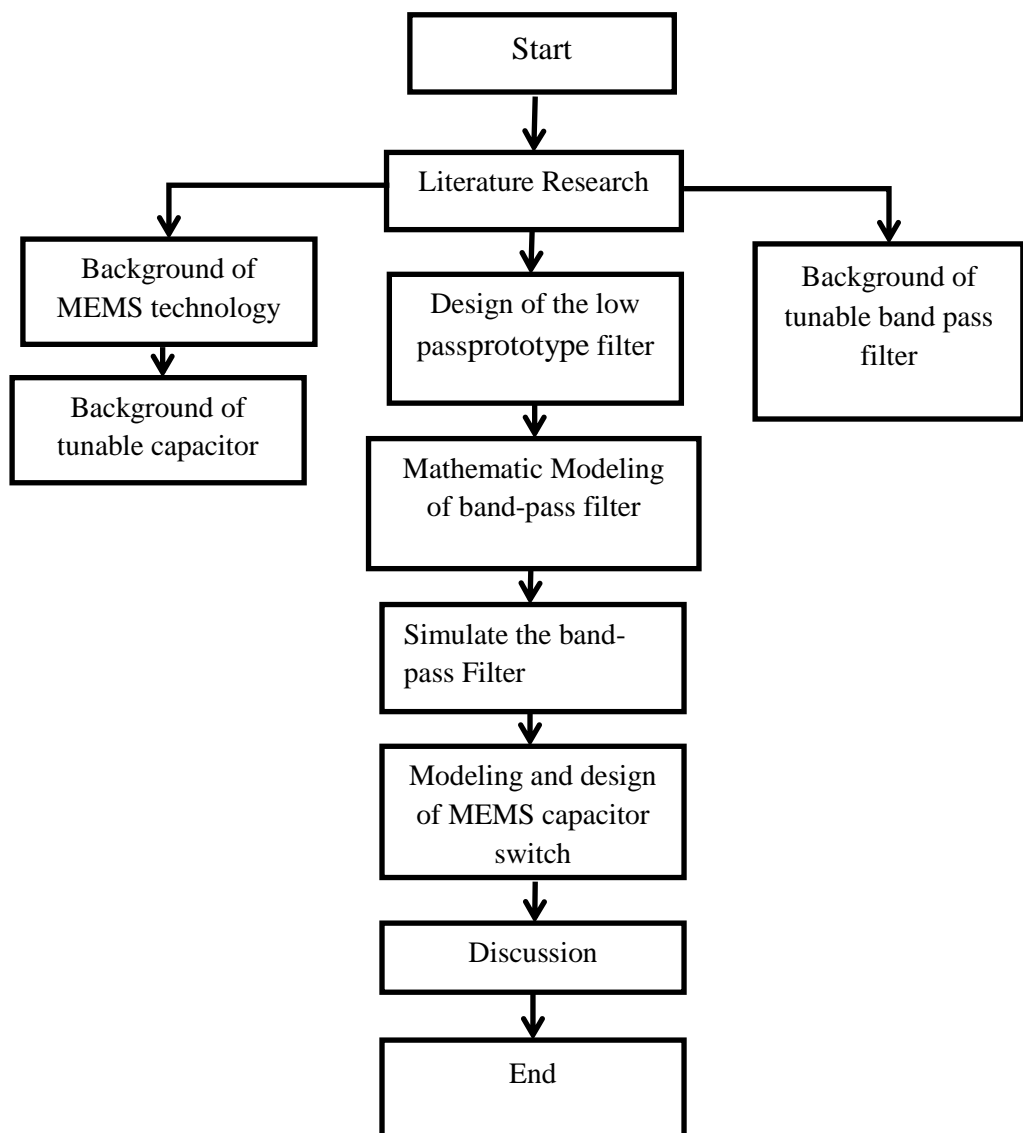


Figure 3.1: Flow chart of the project

3.2 Background study of MEMS and tunable band pass filter

Elements of projects involved in this stage include the study of RF tunable band pass filter. The conventional band-pass filter requires different filters to have the range of tuning which makes the circuit complex. Figure 3.2 shows how to design conventional tunable band-pass filter.

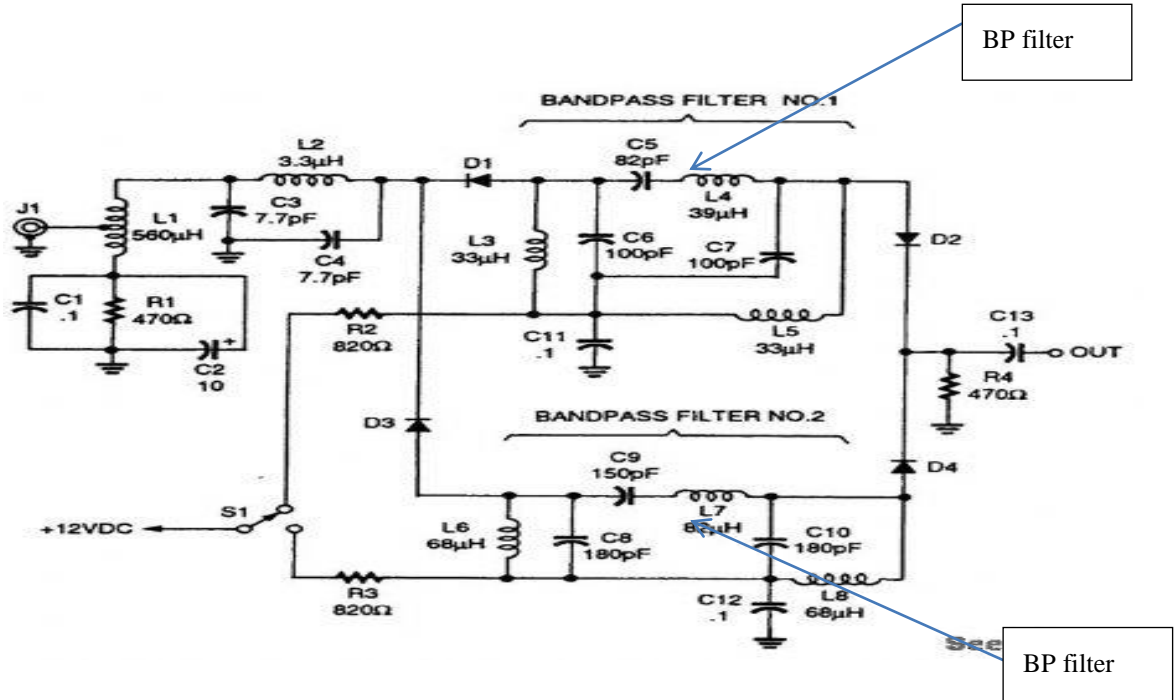


Figure 3.2: conventional band pass filter

The conventional band pass filter uses two band-pass filters or more to get the range of frequencies specified. MEMS have been integrated for applications in RF filter to reduce losses from the filter and to make the circuit simpler compared to conventional circuits.

3.3 Design and simulation of the RF band pass filter

After doing the literature review it is found that it has to design RF band pass filter by designing the low pass prototype filter and transfer it to the band pass filter which is a comb-line band pass filter that have number of capacitors with fixed value depending on the order of the filter.

3.3.1 Design and theoretical modeling the Band-pass filter

Design the band pass filter with parameters is shown in table 3.1

Table 3.1: band-pass filter parameters

Parameters	Values
Band pass frequency (GHz)	1.45-1.55
The center frequency	$f_0 = 1.499GHz$
Pass-band return loss	$L_R \geq 20dB$
Stop-band insertion loss	$L_A \geq 40dB$ at $f_0 \pm 200MHz$
System impedance	50Ω
θ	50°

There are 3 main steps in the design and theoretical model will be shown next.

3.3.1.1 Low pass prototype

Low pass prototype is the basic of the designing any filter .in designing it first, we have to get the order of the filter (which determines the least number of transfer function to be used) by using equation 3.1 after calculating the selectivity of the filter using equation 3.2 starting with a passive low pass prototype and selecting a normalized frequency of $\omega= 1$, and by determining the band pass frequency BW , stop band frequency, insertion loss L_A and return loss L_R , the order of the filter can be calculating using equation 3.1 [15].

$$N \geq \frac{I_L + L_R + 6}{20 \log \left[S + \sqrt{(S^2 - 1)} \right]} \quad (3.1)$$

$$S = \frac{\text{stopband}}{\text{passband}} \quad (3.2)$$

Each order of the filter or transfer function represent by LC circuit as shown in figure 3.3 to get the low pass prototype it connect the LC circuit depends on the number of

order which shown in figure 3.4 .

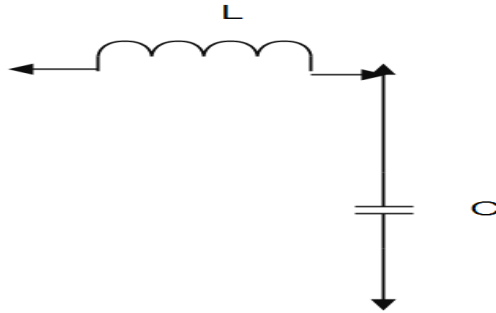


Figure 3.2: LC circuit

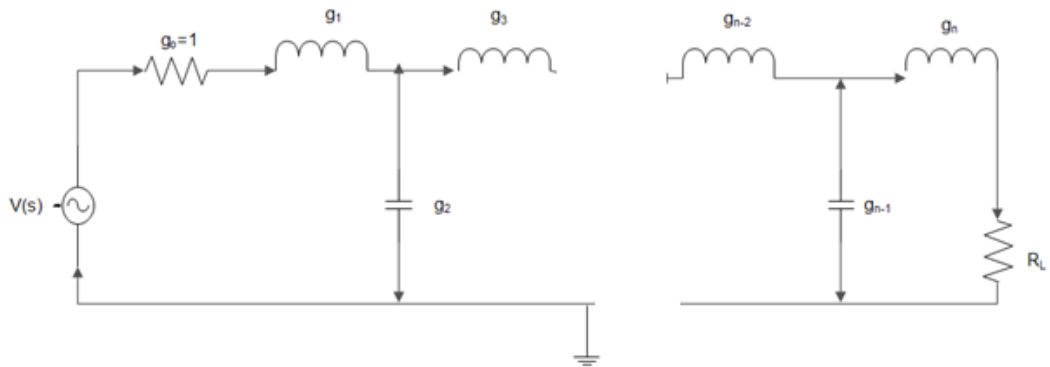


Figure 3.3: Low pass prototype circuit

However, the S parameters and the ripple need to be calculated to be used in the calculation of the low pass filter parameters and to determine the loss in the filter. The S parameters are calculated using the insertion loss specified in table 3.1 using equation 3.3 for S₁₁ and 3.4 to obtain S₁₂.

$$L_R = 10 \log \frac{1}{|S_{11}|^2} = s_{11} \quad (3.3)$$

$$|S_{12}|^2 = 1 - |S_{11}|^2 \quad (3.4)$$

By using S₁₂ value obtained from equation 3.4 the ripple of the filter is obtained using equation 3.5:

$$(1 + \varepsilon^2) = \frac{1}{|S_{12}|^2} \quad (3.5)$$

Next, it is required to calculate the values of the low pass filter elements to be used in the circuit such as the capacitances values C_{Lr} (where $r = 1, 2, 3 \dots N$) N is order of filter that had been calculated and admittance K Equation 3.6 is used to obtain the values of the capacitors C_{Lr} . to calculate the parameters of the low pass filter .

$$C_r = \frac{2}{\eta} \sin \left[\frac{(2r-1)\pi}{2N} \right] \quad (3.6)$$

However, we need to first calculate the parameter η the equation meter used in the equation (3.6) and it calculated by using equation 3.7:

$$\eta = \sinh \left[\frac{1}{N} \sinh^{-1} \left(\frac{1}{\varepsilon} \right) \right] \quad (3.7)$$

Lastly, characteristic admittance is calculated using equation 3.8:

$$K_{r,r+1} = \frac{\left[\eta^2 + \sin^2 (r\pi/N) \right]^{1/2}}{\eta} \quad (3.8)$$

For the circuit in figure 3.4 the characteristic admittance $K_{r,r+1}$ represent the inductor and the capacitor represent by C_{Lr} , but in this circuit all these element represent by g .

3.3.1.2 Comb-line filters

A band-pass filter is constructing by modifying the low pass prototype. The first step is to modify the low-pass prototype to comb-line band-pass filter by calculating the α and β parameters values using the equation 3.9 and 3.10, respectively [15].

$$\alpha = \frac{2\omega_0 \tan(\theta_0)}{\Delta\omega \left\{ \tan(\theta_0) + \theta_0 \left[1 + \tan^2(\theta_0) \right] \right\}} \quad (3.9)$$

$$\beta = \frac{1}{\omega_0 \tan(\theta_0)} \quad (3.10)$$

Where θ_0 is electrical length of the transmission line that used in the designing the band-pass comb-line filter and its equal 50° which is equal to 0.8726 mm .The capacitor values may then be calculated by using equation 3.11.

$$Y_{rr} = \frac{C}{\beta} \quad (3.11)$$

The circuit in figure 3.5(a) shows the circuit of comb line filters when design using micro strip line which show admittance is built using transmission line which is open. The equivalent circuit in figure 3.5(b) shows that the equivalent of admittance which is inductor and the resistor for this circuit is the resistor in the wire.

In the replacing the values of elements in the circuit that will be simulated will replace the inductor values with the resistor in the wire by impedance and the capacitor as it found.

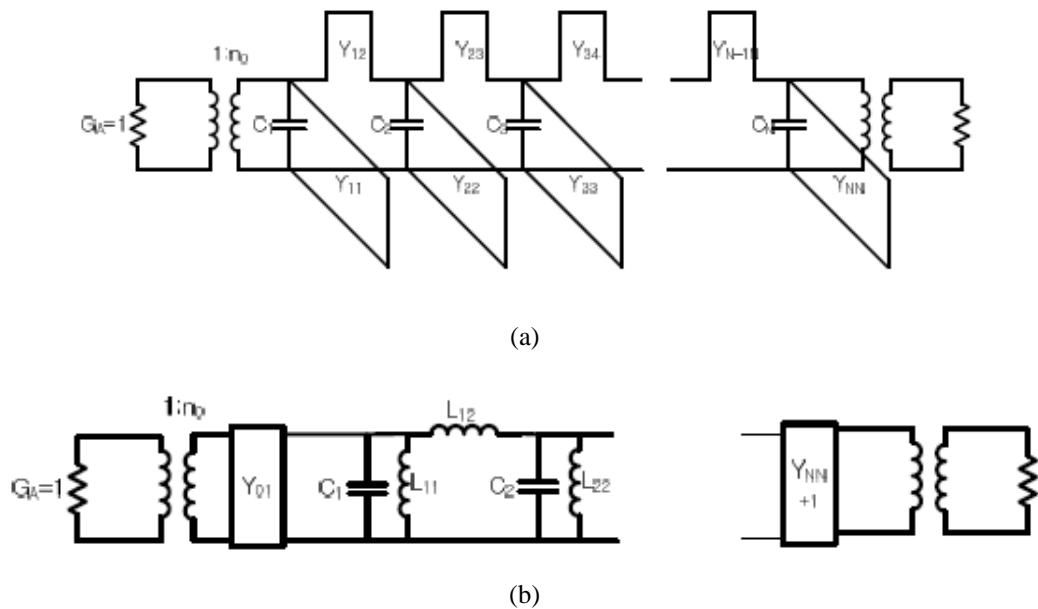


Figure 3.4: (a) the comb line filter (b) the equivalent circuit of the comb line filter

The values of the parameter n_r and therefore admittance $Y_{r,r+1}$ may then be calculated using equations 3.12, 3.13, 3.14, 3.15, 3.16 and 3.17 respectively.

$$n_r = \left[\frac{\alpha C_{Lr} \tan(\theta_0)}{Y_{rr}} \right]^{1/2} \quad (3.12)$$

$$Y_{r,r+1} = \frac{K_{r,r+1} \tan(\theta_0)}{n_r n_{r+1}} \quad (3.13)$$

$$Y_1 = Y_N = Y_{11} - Y_{12} + \frac{1}{n_1^2} - \frac{1}{n_1 \cos(\theta_0)} \quad (3.14)$$

$$Y_r = Y_{rr} - Y_{r-1,r} - Y_{r,r+1} \quad (3.15)$$

$$Y_0 = Y_{N+1} = 1 - \frac{1}{n_1 \cos(\theta_0)} \quad (3.16)$$

$$Y_{0,1} = Y_{N,N-1} = \frac{1}{n_1 \cos(\theta_0)} \quad (3.17)$$

When find all the normalized values of the admittances and capacitor it has to denormalized the admittance by multiplying each value by 50 to obtain the resonator impedance. The capacitance is divided by 50 to obtain the denormalized capacitance which completes the theoretical derivations. These theoretical values are validated by simulation using the ADS software to obtain the response of the filter.

3.3.1.3 Determination of the other Parameters of the comb line band-pass Tunable Filter

a) The Quality Factor

The Quality factor of the band-pass filter can be calculated using 3.18.

$$Q = \frac{f_r}{\Delta f} \quad (3.18)$$

Where the f_r is the resonant (or central) frequency of the circuit and Δf is the bandwidth.

3.3.2 Simulation RF band pass filter

ADS is system and high speed data links. It is used in this study to design the RF comb-line filter in order to obtain the output response. ADS is the world's leading electronic design automation software for RF, microwave and high speed digital applications. It provides an integrated design environment for designers of RF electronic products such as mobile phones, pagers, wireless network, satellite communication and radar.

In the designing the band-pass filter will use two ports of the S parameter with start frequency 1GHz and stop frequency 2 GHz with steps 100 MHz, The figure 3.6 shows the functions of the ADS simulation software.

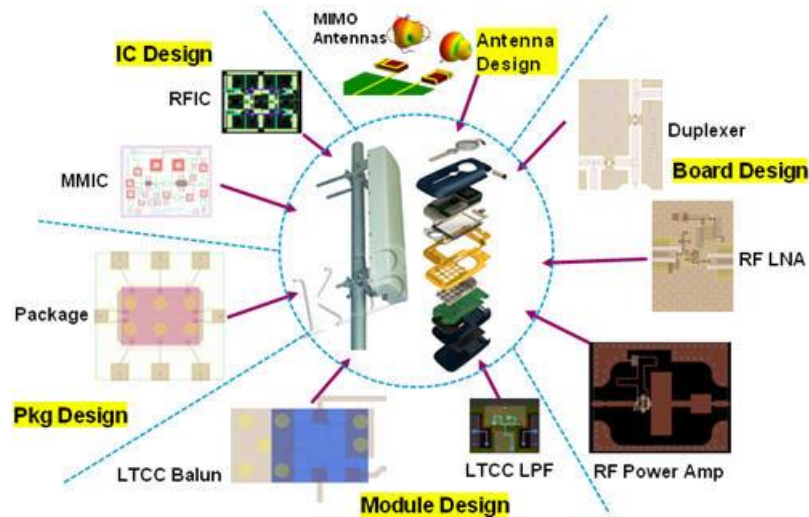


Figure 3.5: The ADS functions

3.4 Tunable MEMS capacitor design and modeling

3.4.1 General modeling for the tunable MEMS capacitor

Finding the comb-line band-pass filter parameters give a fixed value for the capacitor. The capacitor consists of two metal plates with a gap between them. In this study the design comb finger capacitors will be used. First, the range of capacitance values required is calculated using equation 3.18:

$$X_c = \frac{1}{2\pi f C} \quad (3.18)$$

Where X_C is the impedance for the capacitor, C the capacitance of the capacitor and f is the frequency of the filter, here can adjust the tunable range by replacing the range of the frequency to determine the range of tunable capacitor. Equation 3.20 is used to calculate the capacitance:

$$C = \frac{Q}{V} \quad (3.20)$$

Where Q is the charge stored on the plates and V is electrostatic potential. The electric field, E , is given by equation 3.21.

$$E = \frac{Q}{\varepsilon A} \quad (3.21)$$

Where ε is the electric permittivity of free space and A represent the cross-sectional area of the plates. The capacitance C when the distance between the two plates is d is therefore given by

$$C = \frac{Q}{V} = \frac{Q}{Ed} = \frac{Q}{\frac{Q}{\varepsilon A} d} = \frac{\varepsilon A}{d} \quad (3.22)$$

3.4.2 Design of the CMOS-MEMS Tunable comb-finger capacitor

The schematic of the tunable comb-finger capacitor is as shown in Figure 3.7. There will be two capacitor one tunable and one fixed to get the big value for the capacitance, each capacitor has a length of 1060 μm and a width of 1880 μm . There are 70 fingers on both the stator and rotor fingers. The length of the fingers are 790 μm , their width 10 μm and have a thickness of 2.1 μm considering the Aluminum layers as will be explained later The overlapping area of the fingers is 770 μm and the distance between two adjacent stator and rotor fingers is 1 μm and the from the stator and rotor that away from each other's is 8 μm . The comb-finger capacitors are designed according to 0.35 μm CMOS technology following by a post-CMOS micromachining process to release the structure.

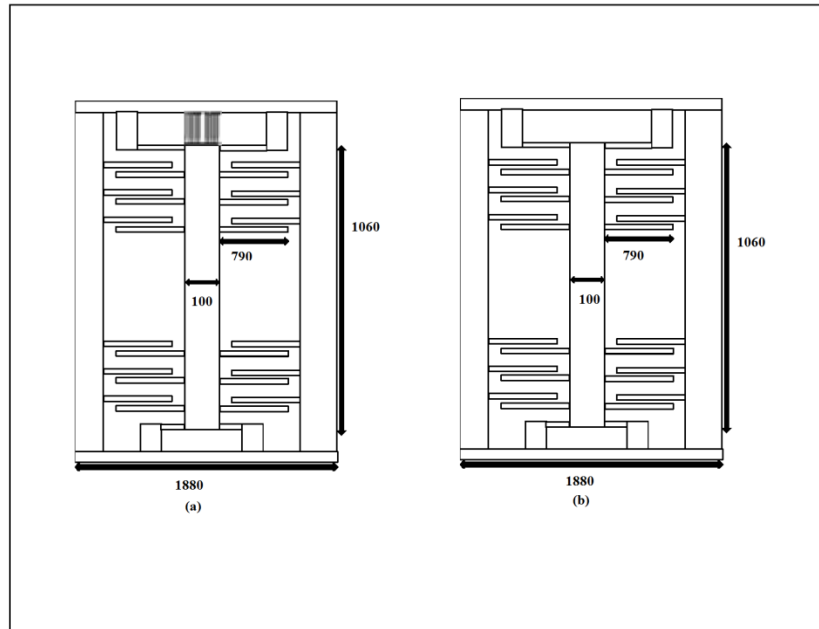


Figure 3.6: Shows the top view of the interdigitated comb-finger capacitors with (a) showing the tunable capacitor design and (b) the fixed capacitor design

In this project, it used the CMOS technology where the thin film has thickness of $5\mu\text{m}$ which is combination of Aluminum is the metal and silica for the oxide. If the finger is long there will be silicon on the finger to protect it from breaking, Figure 3.8 shows (a) top view of a set of interdigitated comb fingers and (b) cross-section view across A and A' of a set of interdigitated comb fingers showing the layers composing the fingers.

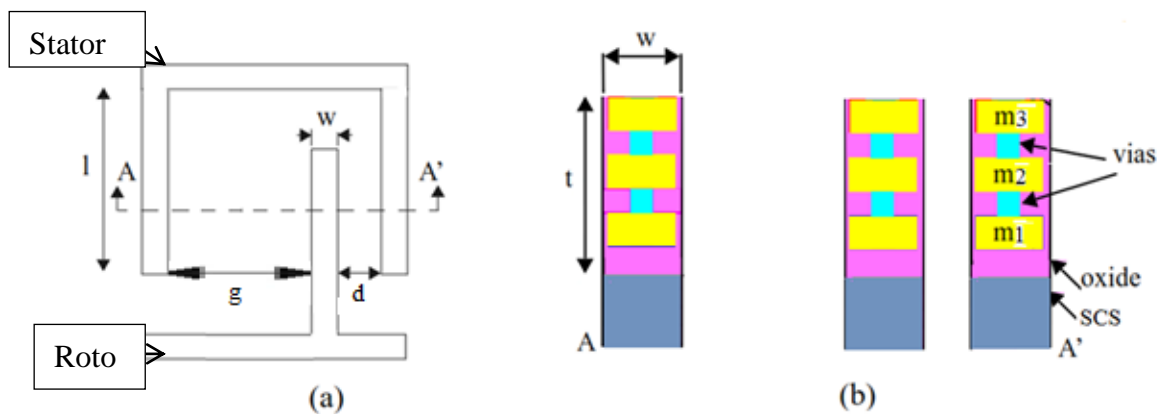


Figure 3.7: (a) top view of a set of interdigitated comb fingers and (b) cross-section view across A and A' of a set of interdigitated comb fingers

In the derivation of the capacitance between the rotor and stator beams, the parallel plate capacitance expression (neglecting the fringing effect) is derived in terms of the physical dimensions of the interdigitated beams as shown in Figure 3.8(b). The derivation of the capacitance formula assumes that the beams are a single metal layer instead of stacked metal-oxide composite with via layers as shown in Figure 3.8(a).

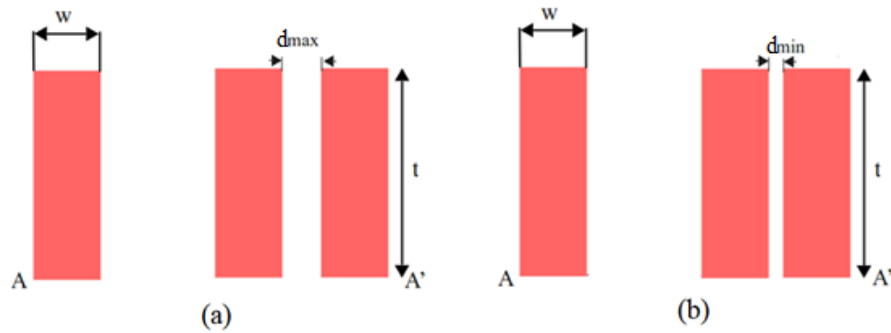


Figure 3.8: cross-section of modeled set of interdigitated comb fingers (a) for minimum capacitance case and (b) for maximum capacitance case

As it shown in figure 3.9 to obtain the difference in the calculation and the distance between the maximum capacitance with minimum distance d_{min} and the minimum capacitance with For the maximum distance d_{max} , in this figure the distance labeled in the figure, with neglecting the big gap as shown in figure 3.9 (b).

With finding the range of the capacitance for the comb line band-pass filter, the maximum capacitance of the interdigitated comb fingers can be calculated using equation 3.23 and the minimum capacitance using equation 3.24.

$$C = \frac{n\epsilon t l}{d} \quad (3.23)$$

$$C = \frac{n\epsilon t l}{d + \Delta d} \quad (3.24)$$

Where d is the distance between the two plates(the minimum distance), n the number of comb fingers, Δd is the change in the distance to the maximum distance, t thickness of the layers, l length of the layers and cross-sectional area, A , of two adjacent plates facing each other is $A = t \times l$.the parameters used for the design

adopted for the study is shown in table 3.2.

Table 3.1: Parameters used in the CMOS-MEMS capacitor design

Parameter	Symbol	Value
Permittivity of free space (C^2/Nm^2)	ϵ_0	8.85×10^{-12}
Length of comb fingers (μm)	l	790
Thickness of comb fingers (μm)	t	2.1
Gap between comb fingers (μm)	d	1.0
Maximum gap (μm)	d_{max}	1.39
The minimum distance (μm)	d_{min}	1.0
Number of fingers	n	70

3.4.3 Modeling of the CMOS-MEMS tunable capacitor

To get the capacitor there is signal path of current will be in to the stator part and out from the rotor part by that it gets the value of the capacitance. To find the tunable range for the tunable capacitor in the figure 3.10(a) by using the heater showing in the figure, when the current go in the heater to heat the plate will expand the rotor from the minimum to the maximum distance to get the from maximum to minimum capacitor, for the signal path will be the same for the fixed capacitor.

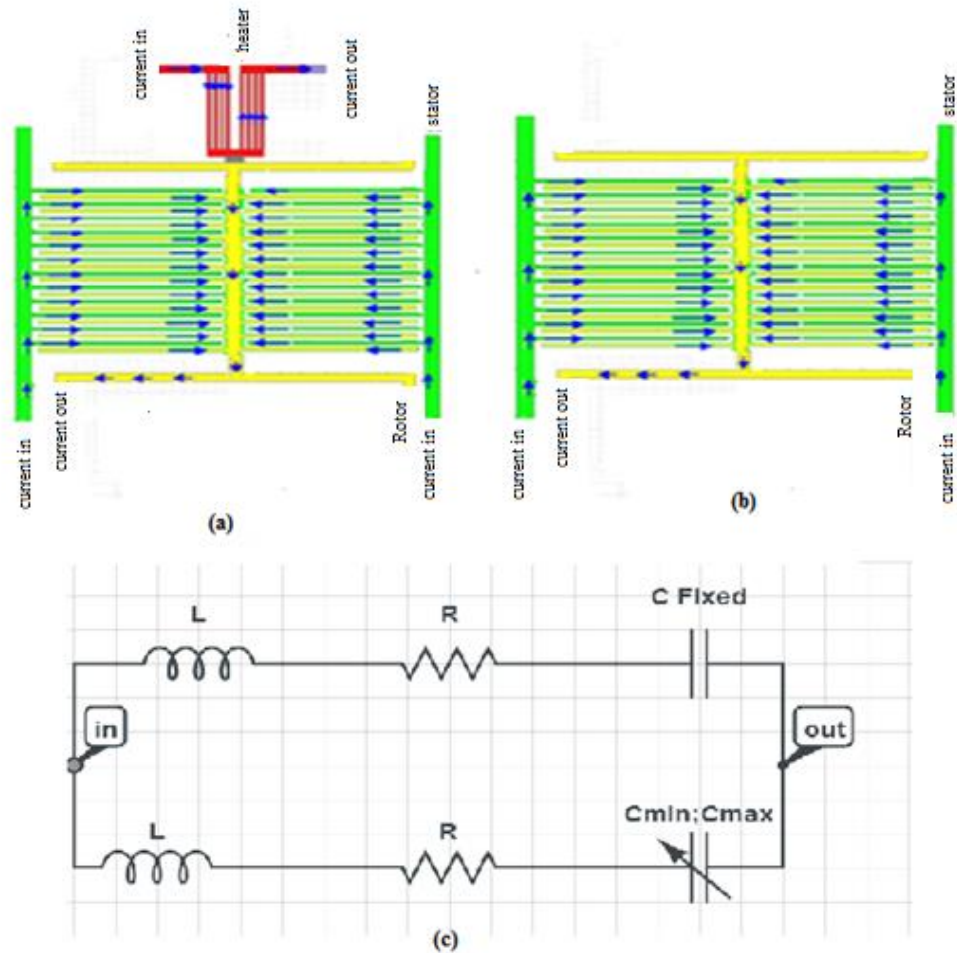


Figure 3.9:(a) Tunable capacitor, (b) Fixed value capacitor and (c) equivalent circuit model of the interdigitated comb fingers.

The interdigitated comb finger have equivalent circuit which show in the figure 3.10 (c) which is inductor and resistor connect in series with the capacitor , for the two capacitors shows in 3.10(a), 3.10(b) will be connected in parallel to get the big value for the capacitance.

3.4.3.1 Equivalent resistance of the interdigitated beams

The total resistor for the comb fingers ,calculating the equivalent resistance of the interdigitated beams, since all the metal layers are parallel to each other, the equivalent sheet resistance of one beam, R_s , is calculated using all of sheet resistances of metal layers, these vias are neglected to calculate the worst case resistance. Here there are three metal layers so the equivalent resistors which are connecting in parallel this for one finger after that calculate for the n number of fingers, the figure 3.11 shows how the resistance connected in parallel.

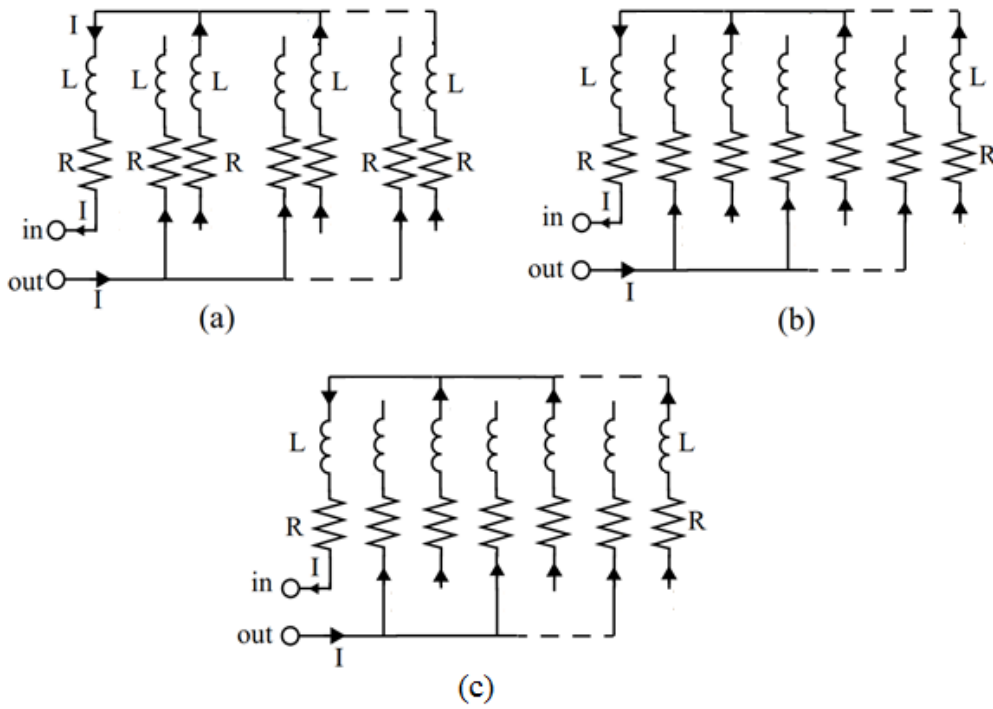


Figure 3.10: Interdigitated comb fingers represented with inductances and resistances for (a) (i) maximum (ii) minimum capacitance positions for the tunable capacitor and (b) for fixed capacitor.

So for the all the resistors are connecting in parallel so it will used the equation 3.25.

$$R_s = \left(\frac{1}{R_{m1}} + \frac{1}{R_{m2}} + \frac{1}{R_{m3}} \right) \quad (3.25)$$

Which is R_s is sheet resistance for the metal.

$$R = \frac{R_s l_f}{w_f} \quad (3.26)$$

3.4.3.2 Equivalent inductance of interdigitated beams:-

In each finger there is self-inductance that used the equation 3.27 and the mutual inductance between the rotor beams and stator beams will change depending on whether the capacitance is at its minimum or maximum configuration but here in this project will consider maximum configuration [7]. As shown in Fig. 2.6 (a), the

current passing through the inductances is in the same direction except for the left most stator beam. The mutual inductance will have its maximum value when the rotor beams are in the position creating the maximum capacitance, however for the minimum when the rotor beams are in the middle of the gap between stator beams as shown in Fig. 2.6 (b).

$$L = 2l \left(\ln \left(\left(\frac{2l}{d} \right) \left(1 + \sqrt{1 + \left(\frac{d}{2l} \right)^2} \right) \right) - \sqrt{1 + \left(\frac{d}{2l} \right)^2} + \frac{\mu}{4} + \left(\frac{d}{2l} \right) \right) \quad (3.27)$$

However, if the resistor is same, mutual inductance we calculate using equation (3.28).

$$M = \sqrt{L_1 L_2} H \quad (3.28)$$

And in this project all the self-inductances are the same so:

$$M=L \quad (3.29)$$

3.4.4 Determination of the other Parameters of the CMOS-MEMS Tunable Filter

a) The Quality Factor

The Quality factor of the CMOS-MEMS tunable capacitor can be calculated using equation 3.18, i.e. $Q = \frac{f_r}{\Delta f}$ where f_r is the resonant frequency of the tunable CMOS-MEMS capacitor and Δf is the bandwidth.

b) The Spring Constant of the beams

To find the spring constant of the four beams of the tunable CMOS-MEMS capacitor, we first calculate the moment of inertia, I calculated using 3.30 of the resonator. Each beam has rectangular cross-section and I is given by

$$I = \frac{w^3 t}{12} \quad (3.30)$$

Where w is the width of the beam and t its thickness.

(iii) The resonant frequency

The resonant frequency of the device is then calculated from:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k_x}{m}} \quad (3.31)$$

Where k_x is the spring constant for the four beams, m the mass of CMOS-MEMS device including beams and fingers and f_r is the resonant frequency. To calculate the mass m we use

$$m = \rho l w t \quad (3.32)$$

Where

ρ the density of the material, l is the length of the movable part, w is the width of the movable part and t is the thickness of the movable parts. Table 3.4 shows the values to calculate the mass of the fingers.

Table 3.2: Parameters to calculate the mass of fingers

Part	Density	Length (μm)	Width(μm)	Thickness(μm)
The Al layer	2700	762	10	2.1
The SiO ₂	2300	762	10	2.9
The Si	2330	762	10	40

Table 3.4 shows the central part parameters to calculate the mass:-

Table 3.3: Parameters to calculate the mass of central part

Part	Density	Length (μm)	Width(μm)	Thickness(μm)
The Al layer	2700	1060	100	2.1
The SiO ₂	2300	1060	100	2.9
The Si	2330	1060	100	40

Table 3.5 shows the spring parameters to calculate the mass:-

Table 3.4: Parameters to calculate the mass of spring

Part	Density	Length (μm)	Width(μm)	Thickness(μm)
The Al layer	2700	500	20	2.1
The SiO ₂	2300	500	20	2.9
The Si	2330	500	20	40

In addition, the quality factor can be calculated by draw the relation between amplitude and frequency by the 3dB loss the bandwidth can be determined, so the quality factor and in this part can used the equation 3.33

$$A = \frac{F_{\max}}{k \sqrt{(1 - (\frac{\omega}{\omega_c})^2)^2 + (2\zeta \frac{\omega}{\omega_c})^2}} \quad (3.33)$$

Where ω the frequency, the F_{\max} is the force, A amplitude and ζ is damping ratio.

3.4.1 Heater design

Heater used to tune the capacitor for the range and the parameters for designing this heater is:

$$\Delta l = -l\Delta T\alpha \quad (3.34)$$

$$\Delta T = T_f - T_o \quad (3.35)$$

Where α is the coefficient of thermal expansion, l length of the beam and ΔT is the final temperature.

$$R_{th} = \frac{\rho_{th} l}{A} = \frac{1}{k} \frac{l}{A} \quad (3.36)$$

$$A = wt \quad (3.33)$$

$$\Delta T = P \times R_{th} \quad (3.37)$$

Where the R_{th} is the thermal resistor and p the power need for heat.

3.4.2 Simulation MEMS tunable capacitor

The Coventirware used to design the simulation and design the tunable capacitor which is design and simulation software that has all of the properties of MEMS. Coventorware is an integrated suite of designing and simulation software that has the accuracy, capacity, and speed to address real-world MEMS designs. Here used to design the tunable capacitor. Figure the show what the software analysis.

A modeling tool used by leading MEMS and CMOS fabs

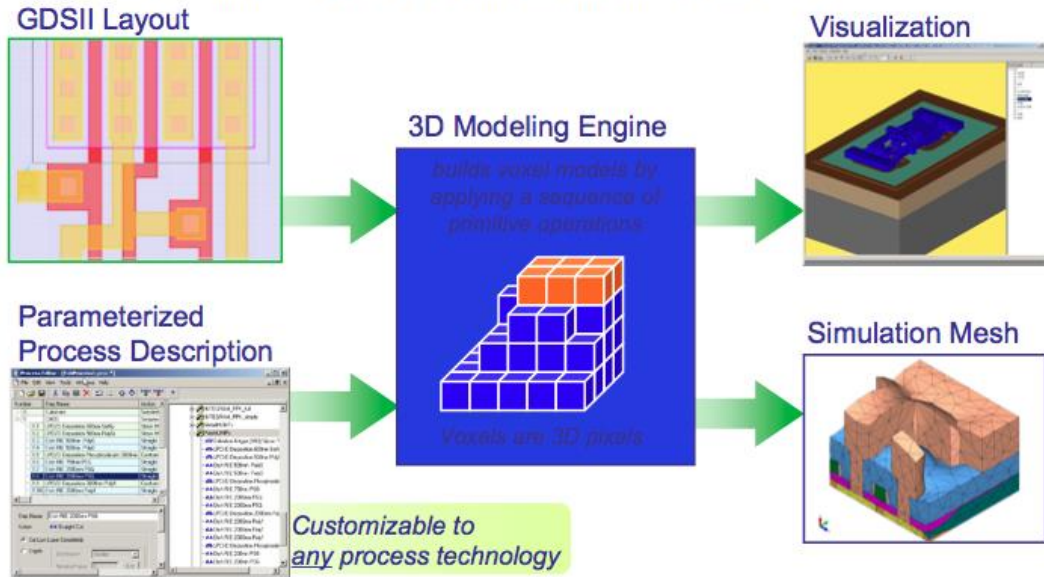


Figure 3.11: functions of coventorware software

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Design and simulation of the RF Band-pass filter

4.1.1 Design of the low pass prototype

Starting with the low pass prototype with its parameters calculated in methodology, we have to get the order of the filter by using equation 3.1 after calculating the selectivity of the filter using equation 3.2 which gives a selectivity of 2 and the order of the filter is 4 and means there are at least four transfer function to be used.

Second, the S_{11} is determined to be 0.01 using equation 3.3 and S_{12} to be 0.99 by using equation 3.4. Now, using the S_{12} value in equation 3.5 we get the ripple of the filter to be $\varepsilon = 0.1005$. Next, the values of the low pass filter elements are calculate. In addition, we use equation 3.6 to obtain the capacitance C_{Lr} where we need to first calculate the parameter η by using equation 3.7. Table 4.1 shows the values of capacitance in the low pass prototype:

Table 4.1:Low pass filter capacitor

Capacitor	Values
C_{L1}	0.9333
C_{L2}	2.2531
C_{L3}	2.2531
C_{L4}	0.9333

The low pass prototype depends on inverter of characteristic admittance which is found using equation 3.7 and table 4.2 shows the values it $K_{r, r+1}$.

Table 4.2: Inverter characteristic admittance

Inverter characteristic admittance	Values
K _{1,2}	1.3204
K _{2,3}	1.5770
K _{3,4}	1.3204

4.1.2 comb-line band pass filter

First, the geometric mid band frequency is calculated to be $\omega_0 = 9.42 \times 10^9$ rad/s and $\Delta\omega = 6.28 \times 10^8$ rad/s by choosing the electrical length of the transmission lines to be $\theta_0 = 50^\circ = 0.8727$ radians to transfer the low pass prototype to comb-line band pass filter that will used in this project. The bandwidth scaling factor α is found by using equation 3.9 to be 10.821 and the propagation constant of the line β equals 8.907×10^{-11} . Choosing $Y_{rr} = 1$ where Y_{rr} is the admittance of the r^{th} resonator we get the value of capacitor for the comb-line filter by using equation 3.11 to be $C = \beta = 8.907 \times 10^{-11}$. Finally, by using equations 3.13, 3.14, 3.15, 3.16 and 3.17 we find the values of admittance of the comb-line filter after finding values of n as shown in table 4.3 using equation 3.12 the admittance values are in table 4.4.

Table 4.3: (Name of table?????)

	Values
n ₁	3.469
n ₂	5.3905
n ₃	5.3905
n ₄	3.469

Table 4.4: Admittance

Admittance	Values (S)
$Y_{01} = Y_{45}$	0.4485
$Y_{12} = Y_{34}$	0.0841
Y_{23}	0.0647
$Y_0 = Y_5$	0.5515
$Y_1 = Y_4$	0.5505
$Y_2 = Y_3$	0.8512

After denormalization, the capacitance value is found to be 1.78 pF. After scaling to 50 ohms, the impedances of the elements are as given in table 4.5.

Table 4.5: Impedance values

Impedance	Values (Ω)
$Z_{01} = Z_{45}$	111.483
$Z_{12} = Z_{34}$	594.53
Z_{23}	772.780
$Z_0 = Z_5$	90.662
$Z_1 = Z_4$	90.827
$Z_2 = Z_3$	58.7406

4.1.3 Determination of the other Parameters of the comb line band-pass Tunable Filter

- b) The Quality Factor

From equation 3.18 which determines the qualitative behavior of simple damped oscillators, the quality factor is found to be 17.8.

4.1.4 Simulation of the comb-line band-pass filter

We use the values of impedances and capacitances obtained from the mathematical modeling to design the circuit as shown on figure 4.1

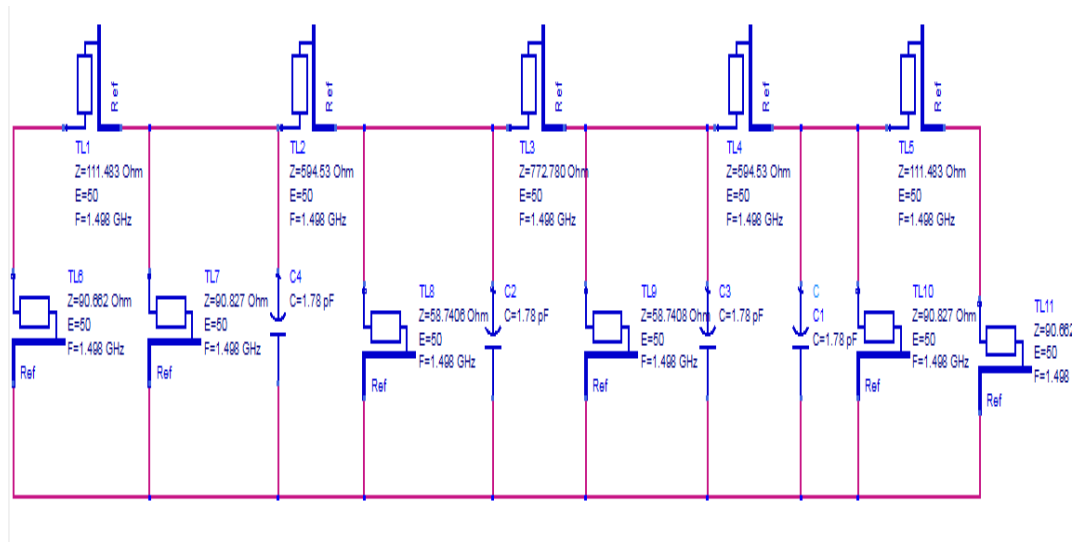


Figure 4.1: Combline Band pass filter

The output response of this circuit is shown in figure 4.2 and indicates the insertion loss, i.e., the difference in power between the input power and the output power and shows the reflected power from the circuit. Figure 4.3 shows the matching impedance for the circuit in the smith chart, i.e., the input resistor that matches with the output resistor.

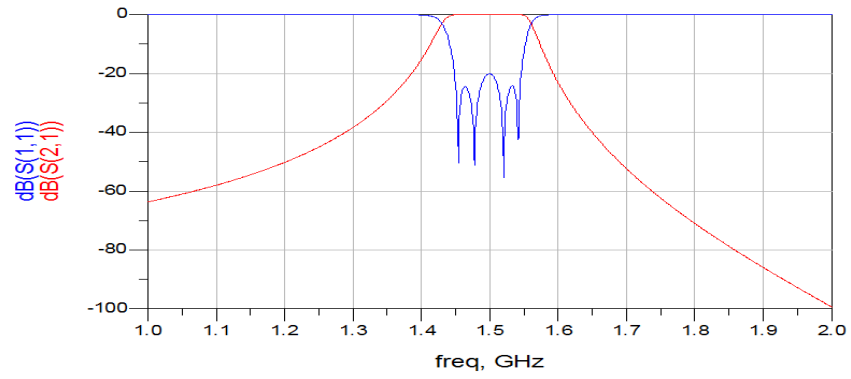


Figure 4.2: Band pass Response

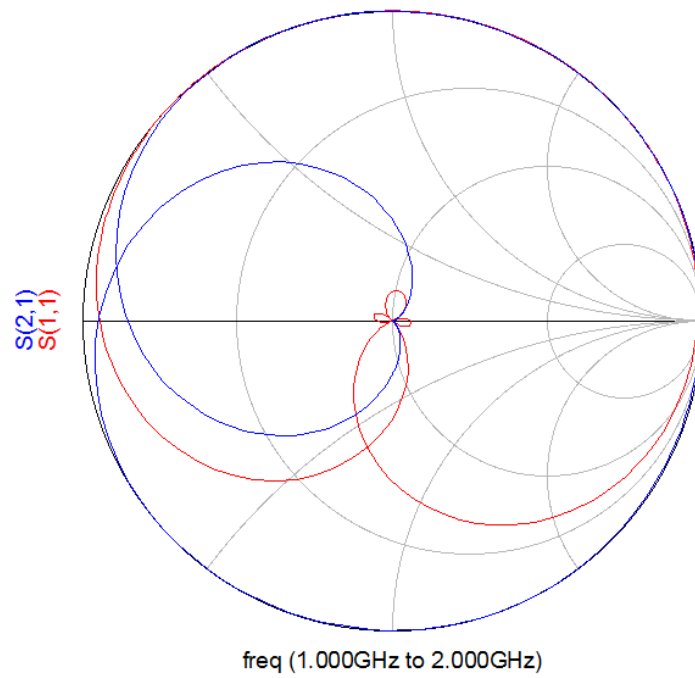


Figure 4.3: Smith chart of impedance matching

4.2 Tunable Capacitor

4.2.1 Design of the tunable Capacitor

Two capacitors connecting in parallel are used for designing the tunable capacitor: one has fixed value and one has tunable value. Using the design, the parameters given in table 4.7 are obtained using equations 3.19, 3.24 and 3.24.

Table 4.6: capacitance range

	Frequency (GHz)	Capacitance (pF)
Maximum capacitor	1.55	1.84
Minimum capacitor	1.45	1.72

Table 4.7: the parameters of the design

Design	Capacitor (pF)	Distance (μm)
Fixed	1	1
Maximum	0.84	1
Minimum	0.72	1.39

4.2.1 Equivalent resistance of the interdigitated beams

The resistivity of Aluminum is $2.82 \times 10^{-8} \Omega \cdot \text{m}$ in each finger and there are three layers of metal. For each finger for one layer the resistance using equation (3.26) is equal 3.1826Ω and for the three layers the total resistance is 0.9426Ω . The resistance for the fixed part which is 35 fingers is connected in parallel and the two fixed parts are connected in parallel which is gives a value 0.05386Ω . The resistors for the movable part is connect in parallel for the 70 fingers which yields a total resistance of 74.2627Ω . The total resistance for the capacitor (tunable or fixed) is then total resistance for the fixed part connect in series with the tunable part which has value of 74.31656Ω .

4.2.2 Equivalent inductance of the interdigitated beams

In each finger there is self-inductance and using equation (3.27) it is found that the self-inductance is 0.8020439 nH and all the interdigitated beams have the same values. If the two inductances are equal in value the equivalent inductance and also the self-induced emf across the inductors will be zero as the two inductors cancel each other out. This is because as the two currents, i_1 and i_2 flow through each inductor in turn the total mutual flux generated between them is zero due to the two flux's produced by each inductor being both equal in magnitude but in opposite directions. Therefore the equivalent inductance value in inductor is 0 and the inductance is therefore not included in the tunable capacitor model in figure 4.4 .

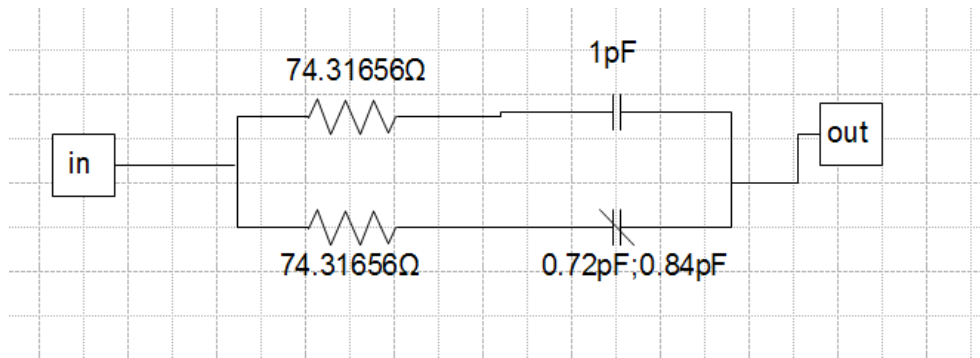


Figure 4.2: the equivalent circuit for the indigitated comb finger

4.2.2 Determination of the other Parameters of the CMOS-MEMS Tunable Filter

a) Spring constant

The spring constant for the tunable capacitor is determined by using the moment of inertia of the rectangular beam of cross section $3 \times 10^{-20} \text{ m}^2$ and find the average young modulus for the material which is 158G. Therefore the spring constant will be 455.59 N/m and this is multiplied by four for the four beams giving $k_x = 1822.39 \text{ N/m}$.

b) Resonant frequency:-

The resonant frequency of the tunable capacitor is determined by first obtaining the mass of the movable part of the device. Table 4.8 shows the component values constituting the mass. Using these values in equation 3.31, the resonant frequency is found to be 48.4KHz.

Table 4.8: mass of the movable part

Part	Mass (kg)
70 fingers	8.34×10^{-10}
Central part	1.73×10^{-8}
Beam parts	4.22×10^{-9}
Total	1.97×10^{-8}

4.2.3 Simulation of the tunable capacitor

Figure 4.3 shows the 3D design of the tunable capacitor using CoventorWare software with zoom in portions to give details of the finger configuration, heater for the tunable capacitor and the spring and beam of the capacitor.

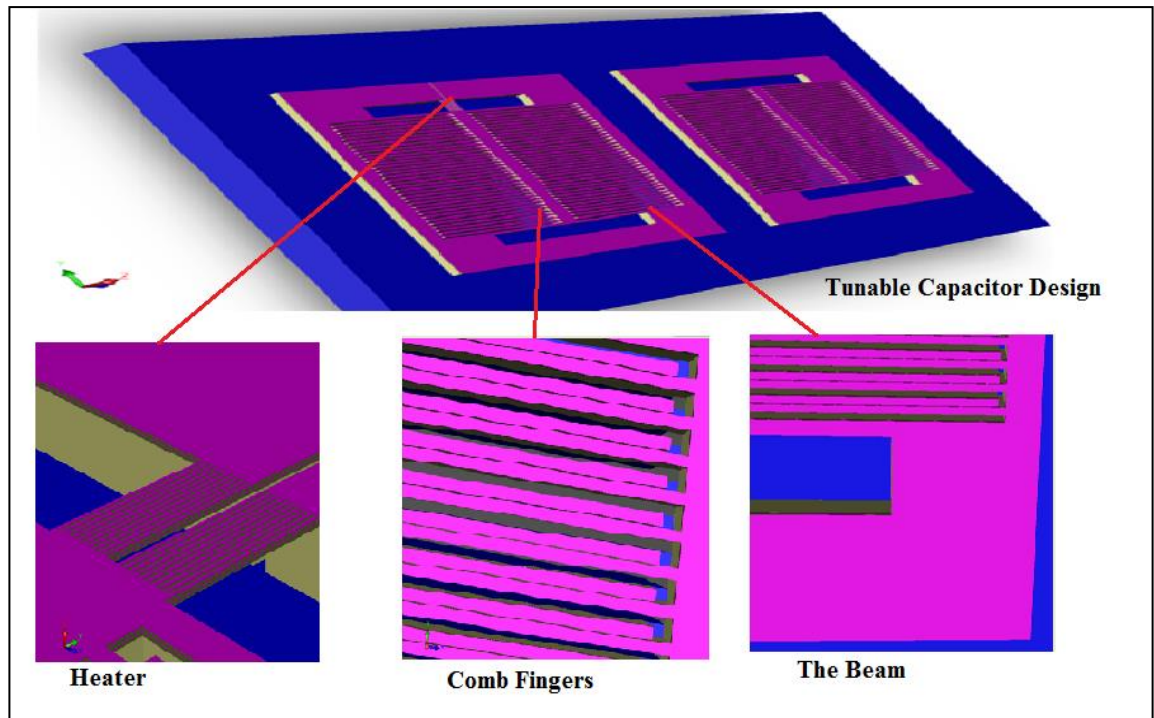


Figure 4.3: 3D coventorware tunable capacitor

4.2.4 Heater design:-

Using equations 3.34, 3.35, 3.36, and 3.37 it is found that the temperature required to tune the capacitor for $0.39\mu\text{m}$ distance is 165.5C° , the thermal resistor is $2391.96\text{K}/\text{W}$ and the power needed is 182.07mW which gives a current of 8.725mA and a voltage of 20.867V .

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

Conclusion

This project aims to design, theoretically model and simulate a tunable RF band-pass filter in the range 1.45GHz- 1.55GHz. The theoretical modeling and simulation of a comb-line filters RF band-pass Filter enabled the determination of the range of capacitance to be 1.72pF to 1.84pF. Using these values, two capacitors were designed to be connected in parallel in order to increase the capacitance; one of the capacitors has a fixed value and the other is tunable with a resonant frequency of 48.4 KHz and a quality factor of 2.0. The tunable capacitor uses electrothermal actuator to be tuned and requires 20V for this purpose.

Recommendation:

- It is required to explore new techniques to increase the tunable frequency range of frequency more than 100 MHz.
- To simulate the tunable capacitor and validate the parameters determined in the theoretical calculations such as in the electrothermal actuation for tuning, the tuning range and the quality factor of the device.
- To integrate the tunable capacitor with the comb-line band pass filter to get the tunable RF band pass filter with low insertion loss, small size and low power consumption

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APPENDICES

Table A.1:Gantt Chart FYP1

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of the project														
Preliminary research work (background of the MEMS , RF filter)														
Extended Proposal submission						★								
Design the filter and simulate														
Submission of the draft report													★	
Submission of interim Report														★

Table A.2: Gantt Chart FYP II

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mathematical Modeling	■	■	■												
Simulate capacitor switch				■	■	■	■								
Design tunable capacitor									■	■					
Submission of progress report								★							
Pre-EDX											★				
Submission of Draft Report													★		
Submission of dissertation (soft														★	
Submission of technical paper														★	
Oral presentation															★
Submission of project															★