DESIGN & SIMULATION OF MEMS VARIABLE CAPACITOR FOR OPTIMUM ANTENNA TRANSMISSION

By

Noor Azreen Binti Mohd Faizol

A project dissertation submitted to the
Electrical & Electronic Engineering Programme
(Universiti Teknologi PETRONAS)
in partial fulfilment of the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr Mohd Haris Bin Md Khir)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2011

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.

(NOOR AZREEN BINTI MOHD FAIZOL)

ABSTRACT

The purpose of this project is to design and simulate the impedance matching network or known as tuner which include MEMS variable capacitor that results in wider range of frequency. The wireless communications and MEMS are widely used in many applications such as Bluetooth, Global Positioning System (GPS) and internet modem for its benefits. Nowadays, wireless communication system and MEMS are developed every day. As the development of both industries grows, some integrity signal issues such as reflection and impedance mismatch which caused important signal loss become crucial. Signal loss is the phenomenon happen when the transmitted signal is not fully received by the receiver during the transmission session due to impedance mismatched. Therefore, to reduce any signal loss due to impedance mismatch between transmitting and receiving antenna and with the connected systems, an impedance matching network or known as tuner is required. Since the demand for faster and smaller communication systems are increasing, MEMS technology is the best choice in designing this tuner since MEMS is small in size, light weight and enhanced performance and reliability. So, the MEMS tuner is designed in this project where the device has capability to tune and match the input impedance of the source with the load impedance of the antenna.

Basically this project is divided into two parts which is communication systems and MEMS. For communication part, the impedance matching analysis and parameter determination is done using MATLAB and ADS. The analysis shows the range of capacitance value to reduce the signal loss by almost 50% is 5 *p*F to 10 *p*F. For MEMS part, the MEMS structure design and simulation is done in the MATLAB with reference capacitance value from the communication part which is 5 *p*F to 10 *p*F. From the MATLAB simulation result, the device is shown to be driven by 110 V and 71.4 μN of electrostatic force to move the parallel plate to achieve 3 pF to 8 pF of capacitance value. This range of capacitance lies within the expected range of capacitance. So, the MEMS variable capacitor can be tuner that reduces the signal loss by 50% with the 3 pF to 8 pF range of capacitance.

ACKNOWLEDGEMENT

First of all, I would like to express my sincere gratitude to my beloved supervisor Dr Mohd Haris Bin Md Khir for his germinal ideas, invaluable guidance, continuous encouragement and constant support in making this research possible. He has always impressed me with his outstanding professional conduct and his knowledge in Microelectronic. I appreciate his consistent support from the first day I know him during my second visit industrial internship to these concluding moments. I am truly grateful for his progressive vision about my final year project, his tolerance of my naive mistakes, and his commitment to my future career. I cannot complete this project without his support. He did a great job as a supervisor for me.

Secondly, I would like to express very special thanks to Adz Jamros, a master student of UTP under supervision of Dr Mohd Haris Md Khir for his suggestions and co-operation throughout the study. I also sincerely thanks for the time spent proofreading and correcting my many mistakes in communications and microwave devices and components field.

Thirdly, I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals.

Finally, I would like to thank all people that help us directly or indirectly, give continuous moral support physically and mentally and come out with brilliant ideas throughout this project until the end. I do really appreciate it since their comments, suggestions and supports were crucial for the successful completion of this study.

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CHAPTER 1

INTRODUCTION

In this introductory chapter, five main sections are discussed which is background of study, problem statement, objectives, scope of study and feasibility of study. In background study section, wireless communication and MEMS are discussed in detail. Besides that, the problem that leads to the idea of this project is discussed in problem statement section and the objectives of this project are discussed in objective section. To achieve this project, scope and feasibility of the study are needed and both of it are discussed in scope of the study section and feasibility section which are in the end of this chapter.

1.1 BACKGROUND OF STUDY

In this section, two main components that are very important in this project are discussed in details which are wireless communication and MEMS. All basic theory about wireless communication and MEMS such as definition, applications and benefits are stated and discussed.

1.1.1 Wireless Communication

1.1.1.1 Definition

Wireless communication is defined as the transfer of information without the use of electrical conductors or wires between two or more devices and among devices over short or long distance. It is currently a very important and fast-growing area in the communications industry since it gives services that are impossible or impractical to implement with the use of wire.

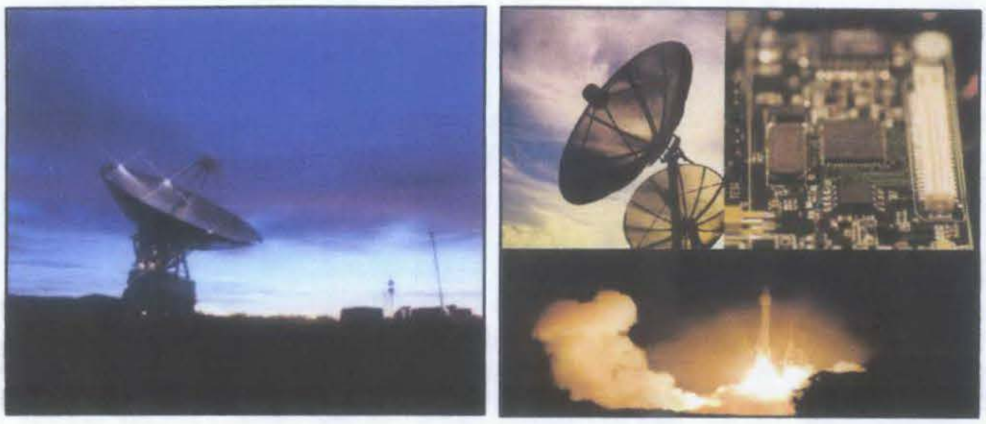


Figure 1: The wireless communication satellite. [1]

Few years ago, communication system is still in the early stage of development where people still depends on letters and telegram as medium of communication. But since the wired communication is established and fully utilized, it has become one of the major communication medium as wired communication provide benefits such as immediate transfer of information. This is important especially during emergency. People becoming too dependent on wired communications.

Nevertheless, wired communication system has limitation. Some places cannot be occupied with wired communication due to geographical and technology issues. For example, Peninsular Malaysia and Sabah Sarawak cannot be occupied by wired communication system few years ago because they are separated by the sea. Moreover, at that time, the submarine technology is not developed. So, this shows that the wired communications have limitation due to geographical and technology issues.

Due to the limitation, wireless communications is designed and introduced. Wireless communications become important in the daily life since it is introduced to users. Besides, many public and private sector and even educational institution use wireless. As the wireless communication industry grows, the manufacturing industry also grows because many applications that use the wireless communication are designed by engineers.

1.1.1.2 Applications

There are many wireless communication applications available in the market for users. These applications make life easier than few years ago when the communication systems still in the early stage of development. Example of wireless communication applications are as followed:

- Wi-Fi or Wireless.

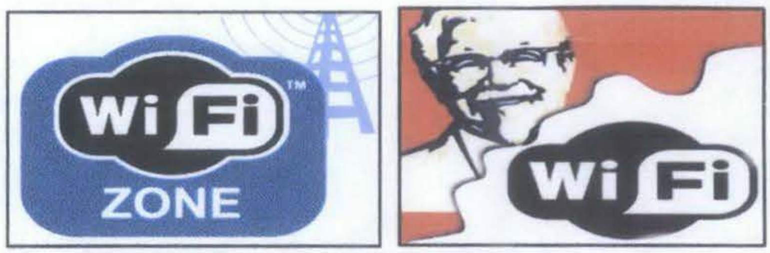


Figure 2: Examples of Wi-Fi Logo. [3] [4]

- Satellite Broadcasting.

Figure 3: Example of Satellite Broadcasting. [5]

- Phones and Modem.

Figure 4: Examples of Phones and Modems. [6] [7]

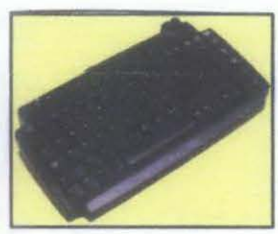
- Radio Communications.

Figure 5: Examples of Radio Broadcasting. [8]

- Gadgets.
  - Global Positioning System (GPS).
  - Bluetooth.
  - Wireless Keyboard.
  - Wireless Printer.
  - Wireless Mouse.
  - Wireless Headphones.

(a) GPS. [9]

(b) Bluetooth. [10]



(c) Keyboard. [11]

(d) Printer. [12]

(e) Mouse. [13]

(f) Headphones. [14]

Figure 6: Examples of wireless gadgets available in the market

1.1.1.3 Benefits

Wireless communication provides benefits to people. These are three benefits that make wireless communication is very important, not only for users but also for the service provider. The benefits are as follows:

1. Increased reliability and efficiency.

   Cable faults are often the primary cause of system downtime. Wires and connectors can easily break through misuse and normal use. Wireless networking can help to reduce the downtime of the network and the costs of replacing cables. Besides, it will leads to faster information transfer to users day by day.

2. Greater mobility.

   Mobility enables users to physically move while using an appliance, such as a handheld PC or data collector. Mobile applications requiring wireless networking include those that depend on real-time access to data usually stored in centralized databases. A wireless network supports mobile applications by providing access to real-time data. Not all mobile applications, though, require wireless networking.

3. Reduced cost.

   Wireless communication is much cheaper to install and maintain compared to transmission lines which include cables. Different types of cable have different ways to install and maintain. So, by using wireless, the installations and maintenance cost can be reduced.

1.1.2 Micro-Electro-Mechanical System

1.1.2.1 Definition

Micro-Electro-Mechanical System or MEMS are the small devices which combine electrical and mechanical system and fabricated on single chips by microelectronic manufacturing company all around the world. [15] The name of micro comes from the size of the feature which fabricated in the micro-meter (μm) range. The operating principle of MEMS is based on the frequency varying devices involving the resonant structures and microelectronics.

1.1.2.2 Applications

There are many MEMS-based applications available in the market for users. These applications make life easier than few years ago when MEMS-based microsystems still in the early stage of development. Nowadays, MEMS is still under development for higher achievement with the usage of advanced technology available. Examples of the MEMS-based applications are as followed:

- Automotive System.

  Accelerometers chip is used in modern cars for a large number of purposes including to trigger airbag for collision. [16][17]

- Consumer Products.

  Accelerometers are installed in consumer electronics such as

  - Game controllers (Nintendo Wii). [16]

Figure 7: Nintendo Wii. [21]

- Personal media player or hand phone (Apple iPhone, Nokia, HTC). [16]


Figure 8: HTC, Apple iPhone and Nokia. [22] [23]

- Digital camera (Canon Digital IXUS). [16]


Figure 9: Canon Digital IXUS. [24]

- Automated manufacturing.

  Mirror chips are use in display and projection screen TVs. [16]


Figure 10: Projection screen TV's. [25]

- Instrumentation.

  Inkjet nozzles printers use piezoelectric or thermal bubble ejection to deposit ink on the paper. [16][18]

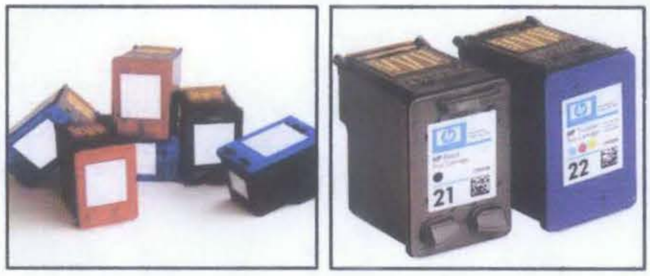


Figure 11: Inkjet nozzle printer. [26]

- Health Care.

  Bio-MEMS pressure sensors are used for medical and health applications. [19]

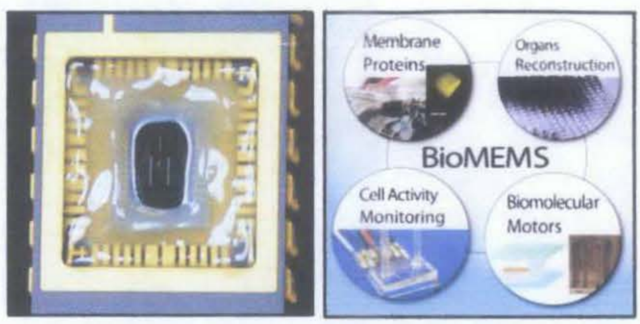


Figure 12: Example of Bio-MEMS.

- Communications.

  MEMS microphones in portable devices (hand phones and laptops). [16] [6] [20]

Figure 13: Example of laptops and hand phones.

1.1.2.3 Benefits

People used MEMS-based applications without they notice it due to the development of the MEMS technology. Besides, they keep on using it for its benefits. Below are the benefits of MEMS [15]:

- Small size.
- Light weight.
- Enhanced performance & reliability.
    - High resolution devices.
    - Array of devices.
    - Low insertion loss.
    - High isolation.
    - Extremely high linearity.
    - Greater tuning range.
- Low fabrication cost.

1.2 PROBLEM STATEMENT

Nowadays, the faster and smaller communications systems for the transmission of high-speed information, voice, video and data are developed every day. As the operation speed of the communication system industry grows, some integrity signal issues in wireless communication such as reflection which caused important signal losses become crucial [2].

Signal loss is the phenomenon happen when the transmitted signal is not fully received by receiver during the transmission session. Signal loss of the transmission using antenna is unavoidable. Usually signal loss in transmission line is due to impedance mismatch.

To overcome the signal loss problem due to impedance between transmitting and receiving antenna and with the connected system, an impedance matching network or known as tuner is required. Since the demand for faster and smaller communication systems are increasing, MEMS technology is the best choice in designing this tuner since MEMS is small in size, light weight and enhanced performance and reliability.

So, the MEMS tuner is designed in this project where the device has capability to tune and match the input impedance of the source with the load impedance of the antenna.

1.3 OBJECTIVES OF THE STUDY

The objectives of this project are as follows:

- To understand the basic principle of impedance matching in wireless communication.
- To design a tuner that includes MEMS variable capacitor to reduce the signal degradation or attenuation.
- To characterize the MEMS tuner performance using MATLAB

1.4 SCOPES OF THE STUDY

1.4.1 Understanding the Impedance Matching Principles.

The overall concept, parameters and technology of impedance matching needs to be understood deeply before proceeding to design and simulation stage of the device.

1.4.2 Design MEMS Variable Capacitor that acts as a Tuner.

Using the MEMS technology, the MEMS variable capacitor that acts as a tuner will be designed within the acceptable parameters to meet the specified requirement which is the 5 *pF* to 10 *pF* range of capacitance value.

1.4.3 MEMS Variable Capacitor Characterization using MATLAB

The MEMS variable capacitor's performance will be evaluated and characterized using MATLAB.

1.5 FEASIBILITY OF THE STUDY

For this study, the knowledge of Microelectronic, Communications and Microwave Device and Components are needed. The knowledge will be applied in the hardware and software design of this study. Besides, with the help of Dr Haris who is the supervisor and expert in Microelectronic world especially MEMS, this study can be completed within the time limit.

CHAPTER 2

LITERATURE REVIEW

This chapter briefly explain about impedance matching, reflection, smith chart, MEMS, electromechanical transducers and MEMS tunable capacitor. The important, design and types of impedance matching are discussed in impedance matching section. Then, the chapter will followed by reflection, smith chart and MEMS. Besides that, electrostatic actuator and capacitance are discussed in electromechanical transducers. In the end of this chapter, the types of the MEMS tunable capacitor are discussed which include MEMS area-tuning capacitor, MEMS gap-tuning capacitor and MEMS dielectric-tuning capacitor.

2.1 IMPEDANCE

Impedance is the combination effect of capacitance, inductance and resistance of the flow of power through wires at a given frequency. It regulates or impedes the flow of current between electrical devices that are connected by wires or electronic circuits.

2.1.1 Impedance Matching

In the transmission line, impedance matching is needed. Impedance matching is the condition where the load impedance and the source impedance in a transmission line are equal. [27]

$$Z_{load} = Z_{source} \qquad (2.1.1.1)$$

2.1.1.1 Importance of Impedance Matching

Impedance matching or tuning in the wireless communications is important for the following reasons:

- Maximum power is delivered when the load is matched to the line and the power loss and reflection from the load is minimized.
- Impedance matching sensitive receiver components such as antenna improves the signal-to-noise-ratio of the system.
- Impedance matching in a power distribution network will reduce amplitude and phase errors.

By knowing the important of impedance matching in a transmission lines, a conclusion can be made where the impedance of the antenna is also important because it determines how well the signal will be transferred between antenna and the rest of the system.

This main parameter need to be well-tuned for a certain frequency in the band centre to improve functionality but still some problems remain as performance drops off at the band edges. Changing on antenna's geometry does not solve the problems. So, one way to solve it is by using tunable impedance matching networks or tuners, rather than a fixed impedance matching network [28].

Zadeh *et. al.* (2003) [28] proposed a fuzzy logic that models the uncertainty of human thought and it offers a mathematical formalism which attempts to emulate the scheme of human deduction. Fuzzy logic formalizes the treatment of vague knowledge and approximates reasoning through inference rules, establishing the bases to generate practical solutions to problems where traditional methods, which require precise mathematical models, could not be suitable.

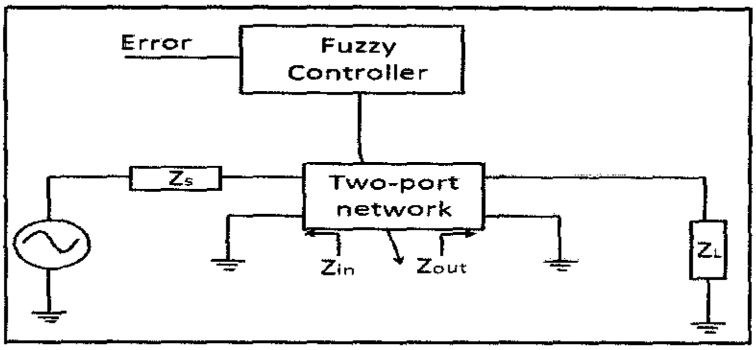


Figure 14: Impedance Matching System by Using Fuzzy Controller. [28]

Yichuang Sun *et. al.* (1998) [29] proposed an evolutionary tuning method for automatic impedance matching in radio communication systems based on genetic algorithm.

Hemminger (2005) [30] proposed an algorithm based on neural network which aimed to perform real-time impedance matching over a wide range of frequencies during transmitter operation in driving point impedance of an antenna.

Figure below shows the overall control system block diagram of the design proposed by Hemmiger. NNC is a network that outputs the antenna characteristics of a capacitive system from impedance mismatch, and NNL performs the same function for inductive systems. The tuner is a single network that adjusts the stub lengths.

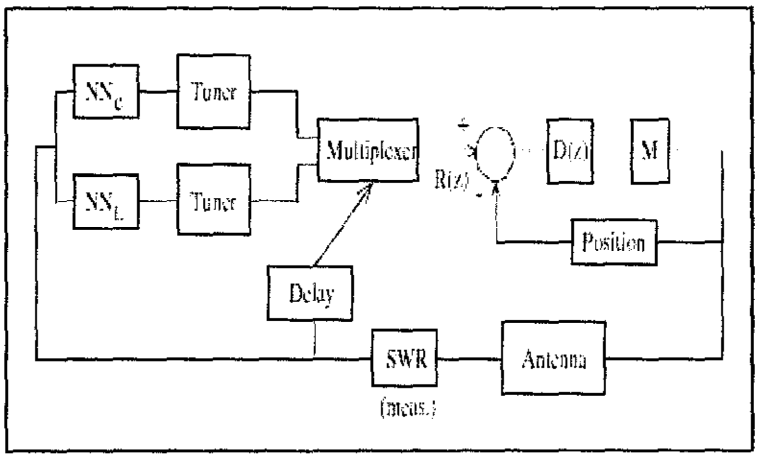


Figure 15: Overall Control System Block Diagram. [30]

Genetic algorithms and neural networks which are used by Yichuang Sun and Hemminger provide good performance in impedance matching but require a huge resources consumption which could impractical to be implemented on integrated for applications in wireless portable communications.

Munshi *et. al.* [31] described a scheme for adaptive impedance matching using a model reference adaptive controller, designed and implemented using adaptive delta-sigma with a Least Mean Square (LMS) approach.

Sjoblom *et. al.* [32] proposed an adaptive impedance tuning unit based on switched shunt capacitor banks but the steps to detect signal, compare signal strength and operate switches through all states are not described.

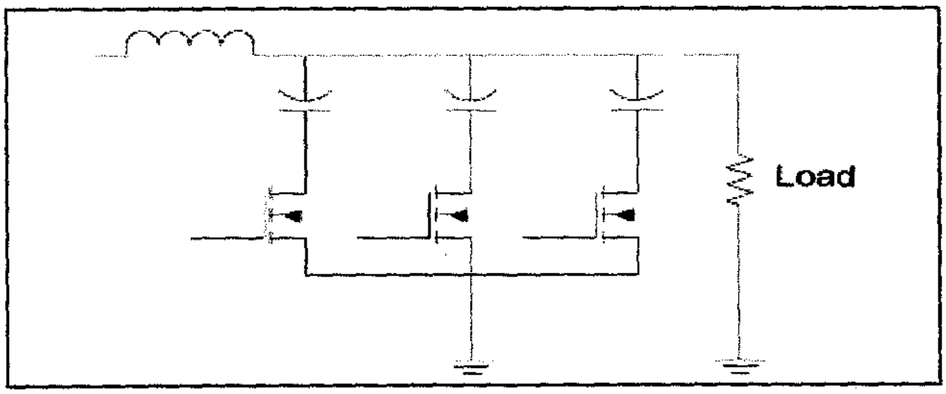


Figure 16: Impedance Tuning Unit Based on Switched Shunt Capacitors. [32]

2.1.1.2 Design of Impedance Matching Network

There are many choices for impedance matching networks are available based on the design and performance. Factors that important in the selection of a particular impedance matching network include the following:

- Complexity
  - A simpler matching network is cheaper, more reliable and less loss than a more complex design.

- Bandwidth
  - Any type of matching network can ideally give a perfect match which is zero reflection at a single frequency. In many applications, it is desirable to match a load over a band of frequencies

- Implementation
  - One type of the matching network maybe preferable compared to another based on type of transmission line or waveguide being used.

- Adjustability
  - In some application, the tunable impedance matching network is preferable and required to match variable load impedance.

2.1.1.3 Types of Impedance Matching Network

The practical matching networks are L network, Pi network and T network. The primary devices usually used in impedance matching network are capacitors and inductors. The basic and most used is L matching network. It is because of its simplicity. The L matching network is easy to build because it has only two components to be controlled for adjusting the real and imaginary part of the impedance.

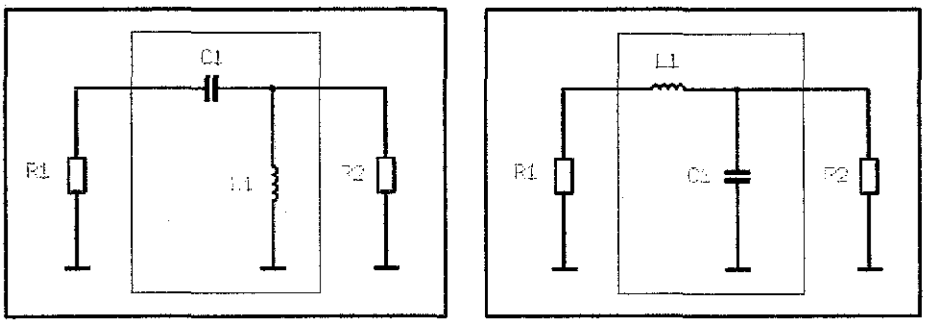


Figure 17: High-Pass and Low-Pass L-type Network.

T and Pi network require more complex for matching network design as they need to control three components which make it more expensive. For T network, it provides larger transformation than the L network. But, the Pi network gives the better results where it provides independent variation of phase shift and transformation ratio through the circuit.

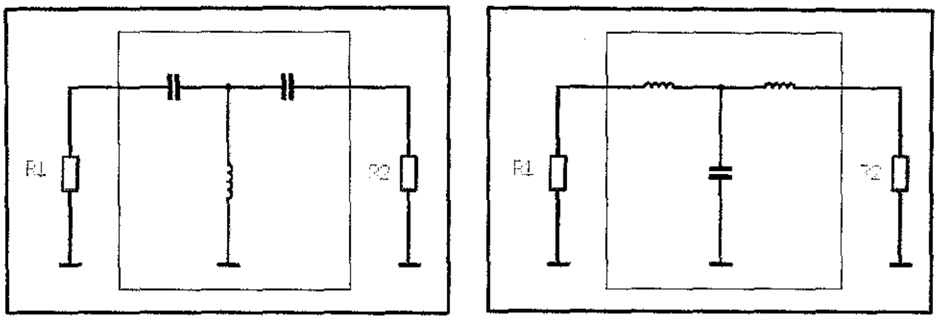


Figure 18: High-Pass and Low-Pass T-type Network.

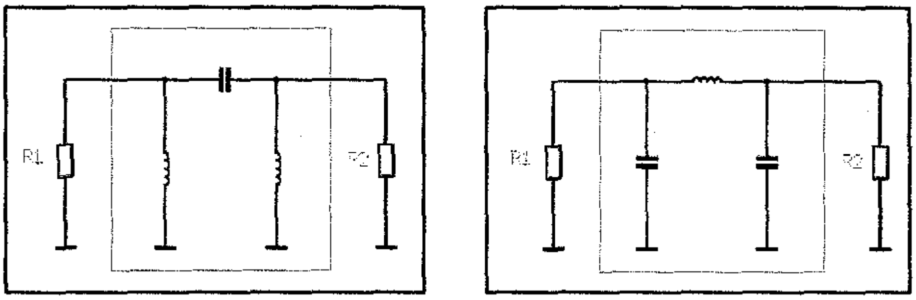


Figure 19: High-Pass and Low-Pass Pi-type Network.

Therefore, the low-pass Pi impedance matching network has been found to be the most suitable impedance matching network because it has capability to handle wide range of impedance with simple configuration.

2.2 REFLECTION

If the impedance matching is not achieved, one phenomenon will occur which is reflection. Reflection is due to impedance mismatch between the load and source impedance [33]. It occurs as the transmitted signal is not fully absorbed by the receiver.

The excess signal will be reflected back to the transmitter in either source to load or load to source directions due to differences in impedance along the transmission lines and will continues until the entire signal is absorbed. At the high data rates, impedance mismatch can produce errors in the signal [34].

Signal losses due to impedance mismatch are usually characterized through the reflection coefficient, which include load impedance and source impedance respectively. The reflection coefficient is defined as the ratio between the reflected voltage wave and incident voltage wave. It can be used to measure the integrity of the signal.

$$\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{2.2.1}$$

The higher the reflection coefficient calculated, the lower the integrity of the transmitted signal. This means, high possibility of signal loss when reflection coefficient is high. The reflection coefficient is calculated by using the formula below where Z_L and Z_o are the load impedance and source impedance.

2.3 SMITH CHART

Smith chart is the chart that contains many coordinate grids used to calculate electrical characteristics for electronic circuits. It is a tool that can be used to calculate the value and type of the components needed to construct an effective impedance matching network.

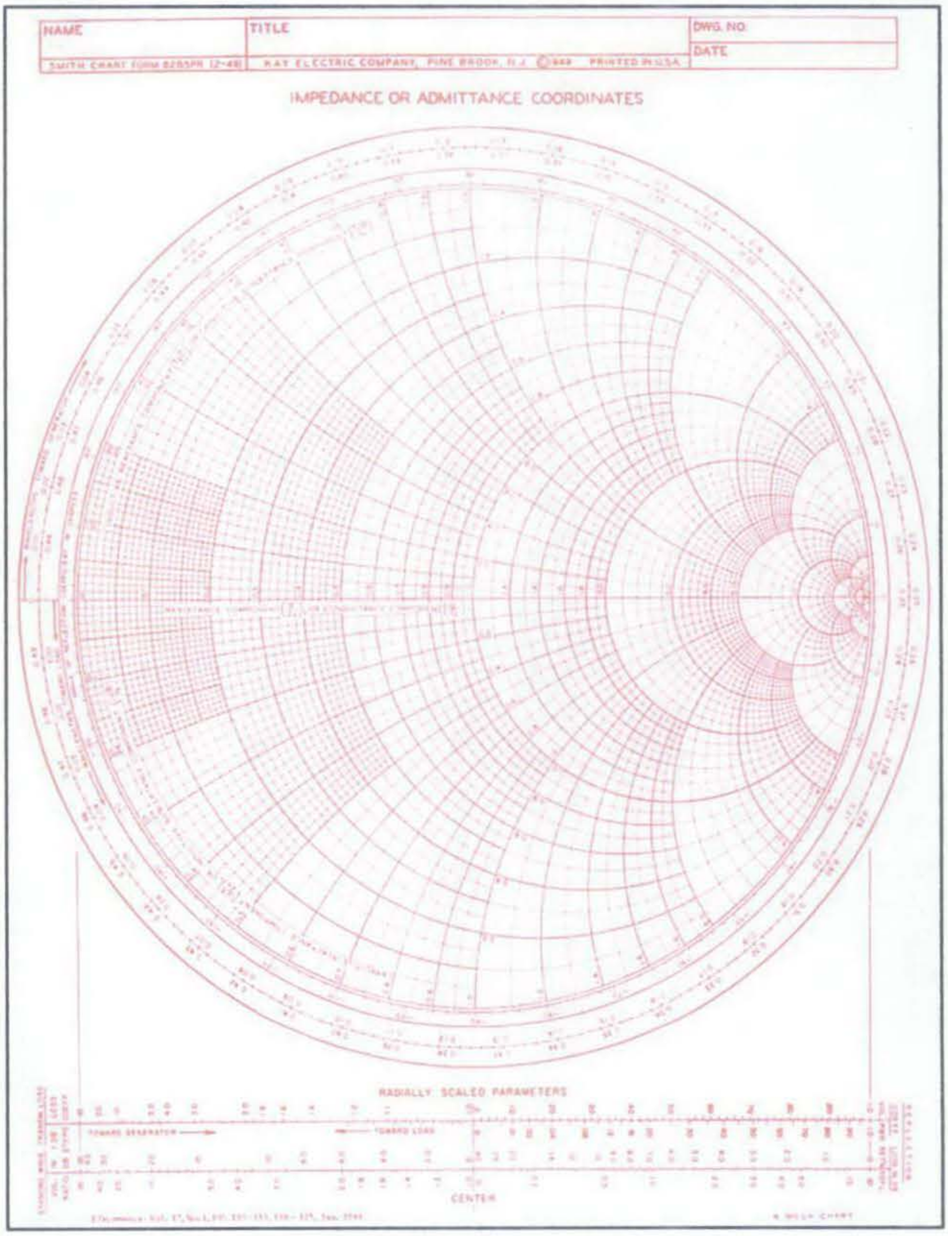


Figure 20: Impedance Smith Chart. [36]

The Smith chart is also built by considering impedance which is resistor and reactance. It can be used to analyse these parameters in both the series and parallel. Adding elements in a series is straightforward. New elements can be added and their effects determined by simply moving along the circle to their respective values. The figures below demonstrate how the various shunt and series L and C components change the circuit reflectance on the Smith Chart.

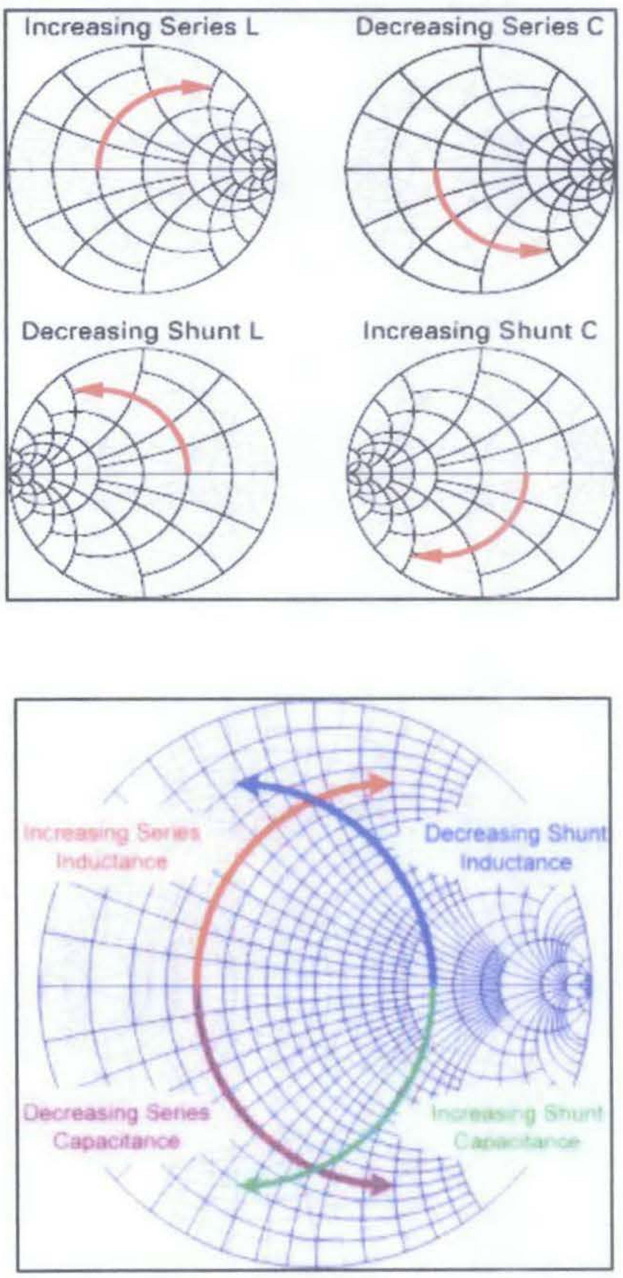


Figure 21: Circuit Reflectance Variation. [37] [38]

2.4 MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)

Micro-Electro-Mechanical Systems or MEMS are small devices fabricated by microelectronic manufacturing company all around the world. The MEMS terms refers to a collection of micro-sensors and actuators which can sense its environment and have the ability to react to changes in that environment with the use of a micro-circuit control.

They also include the conventional microelectronics packaging, integrating antenna structures for command signals into micro-electro-mechanical structures for desired sensing and actuating functions. The system also may need the micro-power supply, micro relay and micro-signal processing units. Micro-components make the system faster, more reliable, cheaper and capable of incorporating more complex functions.

MEMS techniques allow both electronic circuits and mechanical circuits to be manufactured on a single silicon chips. [39] The name of micro comes from the size of the feature which fabricated in the micro-meter (μm) range.

The operating principle of MEMS is based on the frequency varying devices involving the resonant structures and microelectronics. Production of MEMS involves micro-machining and various fabrication processes. MEMS also can be manufactured using Very Large-Scale Integration (VLSI) processing techniques.

MEMS switches, varactors and thin-film barium strontium titanate tunable capacitors have been applied to design tunable or switched matching networks [40][41] but these approaches have disadvantages on cost, tuning range which generally corresponds with the minimum and maximum available capacitance, integration or linearity problems [27].

2.5 ELECTROMECHANICAL TRANSDUCERS

In this section, electrostatic actuators which are the basic principle of one of the most common electromechanical transducers will be discussed briefly. One important step in designing the electromechanical transducers is by obtaining their electrical equivalent circuit from their analytical model. Sometimes, this may involves obtaining the mechanical equivalent circuits first and then uses the electromechanical to reach the electrical equivalent circuits..

2.5.1 Electrostatic Actuators

Electrostatic actuation is the most common or typical type of electromechanical energy conversion transducers in electromechanical systems. Furthermore, the structure of this type of transducer commonly consists of a capacitor arrangement, where one of the plates is movable by the applications of a bias voltage. This will produces displacement, a mechanical form of energy.

Electrostatic actuation is also used in MEMS widely because of its simplicity and flexibility combinations. Besides, this actuation mechanism is a surface volume phenomenon where scaling down the device dimension will enhance its effects.

In addition, electrostatic actuation also has simple fabrication process, less power consumption and small area utilization which the reason why it is the best designed for industrial applications and is preferred over the other actuation mechanisms. Electrostatic actuation is preferred over thermal actuations for variable capacitors because of higher actuation speed and greater deflection stability.

A variable MEMS variable capacitors using electrostatic actuation with digital control was discussed by Hoivik *et. al.* (2001) [42]. In this paper, a capacitance variation due to change in voltage is discussed in detail. The capacitance variation is successfully achieved because the individual capacitor plates are connected to the bond pads by different width of beams fixtures.

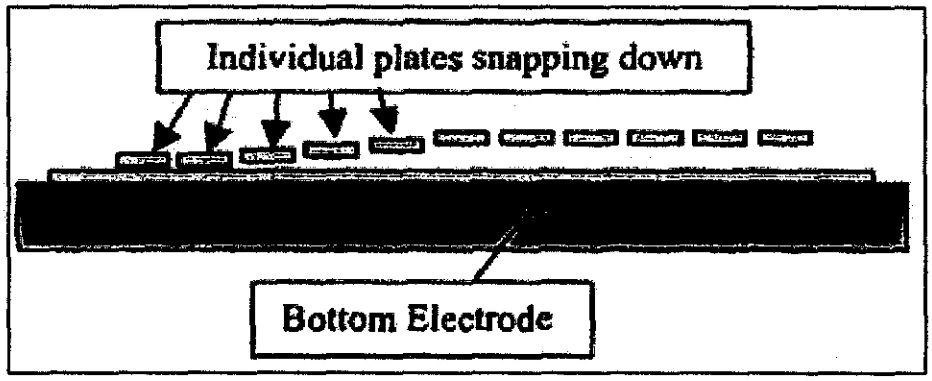


Figure 22: Schematic diagram of the capacitor plate arrangement. [42]

Figure 22 shows the schematic diagram of the capacitor plate arrangement which includes top and bottom plate. The top plate is design with the combination of 30 equal area plates. The top plate moves towards the bottom plate in the cascading manner as the voltage bias is applied to the plates. The tuning ratio recorded from the capacitor is 4:1. Besides, the measured Q recorded at 750MHz is 140.

For the electrostatic actuator, the parallel plate of a capacitor is used. With the application of different voltage bias between the plates, the electrostatic force is produced and can be obtained from Coulomb's Law. Electrostatic force concept based on parallel plate is illustrated below:

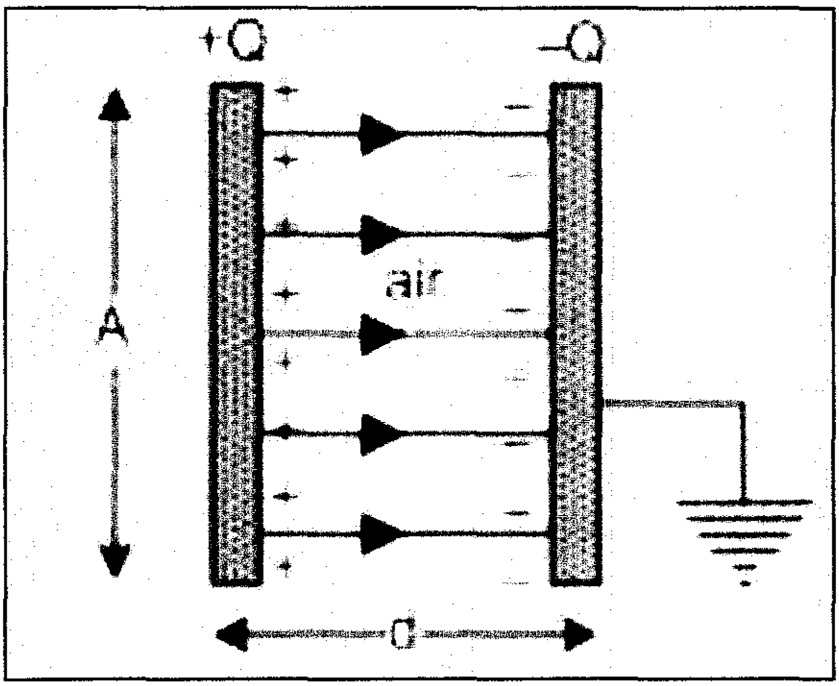


Figure 23: Electrostatic force between two parallel plates. [43]

This is the simple example for electrostatic force between two parallel plates with application of voltage bias. There are two parallel surface areas (*A*) with material dielectric (ε_r) and separated by a distance (*d*). Then, the potential voltage (*V*) across these plates creates an electrostatic force. The electrostatic force is obtained from Coulomb's Law which is [44]:

$$F = \frac{1}{2}\varepsilon_0 \varepsilon_r A \frac{V^2}{d^2} \qquad (2.5.1.1)$$

2.5.2 Capacitance

Capacitance is defined as the ratio of an impressed charge on a conductor to the corresponding change in potential or the ratio of the charge on either conductor of a capacitor to potential difference between the conductors. In this project, the capacitance between two parallel plates is considered.

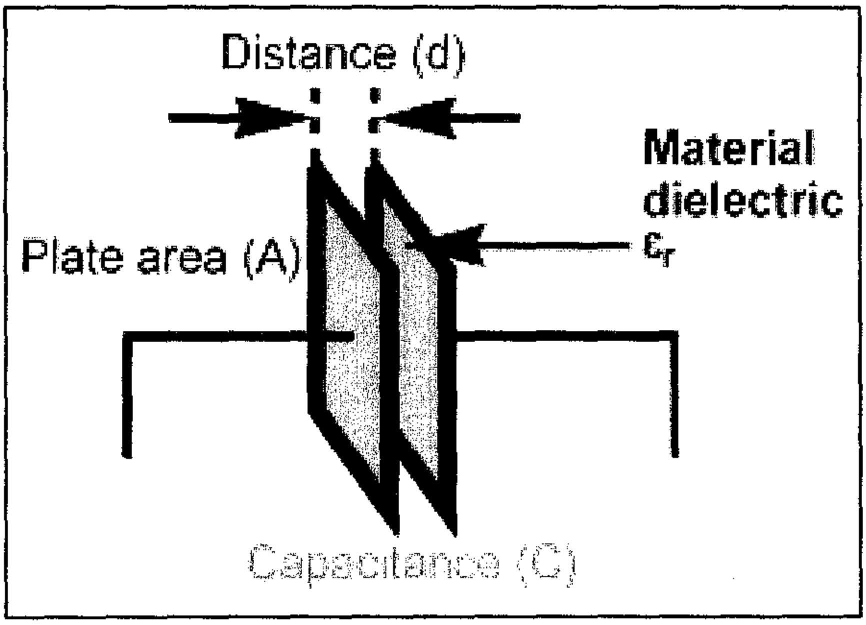


Figure 24: Capacitance between the two parallel plates. [45]

The movement of the plates either forward or backward with the application of voltage bias will result in the capacitance. Capacitance can be calculated with the few parameters such as area of the plate, gap distance between the parallel plate and dielectric material.

With A is the surface area, d is the gap between the parallel plate, ε is the dielectric material and assumption that no fringing fields, the capacitance of the parallel plate capacitor at rest is widely known to be as Equation (2.5.2.1). However, when the voltage is applied across this system, the top plate will moves forward or backward to the other plate and it will make different in gap of the plates and area such as in Equation (2.5.2.2 and 2.5.2.3) [46]. With that, the capacitance with the plates at the new position is shown in Equation (2.5.2.4).

$$C = \frac{\varepsilon A}{d}, \qquad (2.5.2.1)$$

$$d = d_0 \pm x, \qquad (2.5.2.2)$$

$$A = A_0 \pm x, \qquad (2.5.2.3)$$

$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon(A_0 \pm x)}{d_0 \pm x}. \qquad (2.5.2.4)$$

2.6 MEMS TUNABLE CAPACITORS

Capacitor is defined as the electronic component that stores electrostatic energy. The capacitance of parallel plate capacitors with surface area *A*, separated by a gap *d*, and medium dielectric constant ε can be written as Equation (2.5.2.1). From the equation, it is clear that the three parameters which are *ε*, *d*, and *A* can be varied to obtain a tunable capacitor. Therefore, MEMS tunable capacitor can be divided into three categories which is gap tuning, area tuning and dielectric tuning.

2.6.1 MEMS Gap-Tuning Capacitors

The tunable capacitor can be made with two parallel plates which one is fixed *(Stator)* and other one is movable *(Rotor)*. The movable plate will move in the vertical direction with the gap between the two parallel plates can be adjusted electrostatically by applying a voltage bias which will result in the displacement of the parallel plates and leads to the capacitance variation. The movable plate starts moving towards the fixed plate due to the electrostatic force produced by applying the voltage bias to the two parallel plates.

The maximum displacement of gap tuning between the two parallel plates is $\frac{1}{3}$ of the initial gap between them. If this condition is not followed in the design, the two parallel plates will sticks together. This condition limit the gap between the two parallel plates to $\frac{2}{3}$ of the initial gap, which restricts the theoretical limit to 50% to any electrostatically, actuated parallel plate system.

Young *et. al.* (2001) [47] [48] discussed a design of a micro-machined gap-tuning capacitor which consists of 1μm thick aluminium plate suspended in the air with four mechanical folded beam suspensions acting as springs. The electrodes used are 200 μm by 200 μm with the 2 μm by 2 μm holes spaced 10 μm apart. The initial gap is 1.5 μm and the measured Q is 62. As the results, the capacitance shows variation 2.11 *p*F to 2.46 *p*F as the voltage bias are being varied from 0 V to 5.5V. This leads to the tuning range of 16%. Figure 25 shows the top view of the micro-machined variable capacitor made on silicon substrate.

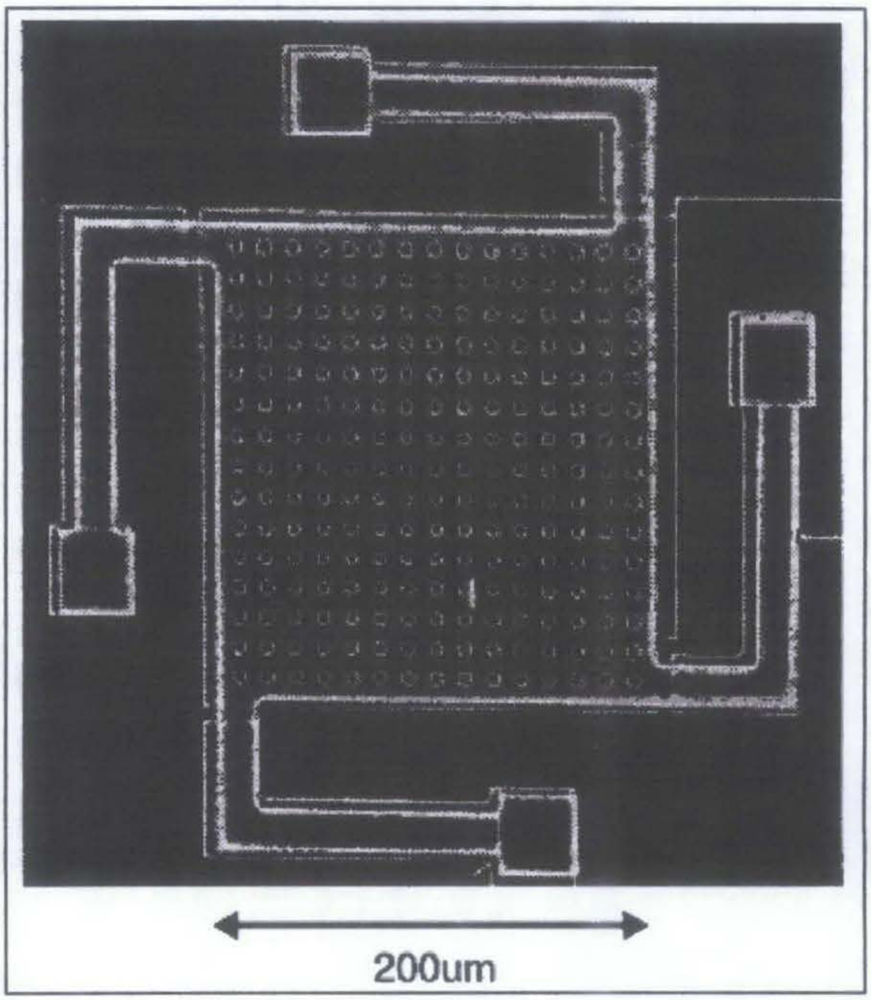


Figure 25: Top view of the variable capacitor. [47]

2.6.2 MEMS Area-Tuning Capacitors

Since there is no tuning limit for area-tuning capacitors, area-tuning is preferred over gap-tuning for MEMS tunable capacitors. One of the most simple and common methods in designing MEMS area-tuning capacitor is by using the interdigitated comb finger structure. In the interdigitated comb finger structure, only two main components should be concerned which are the supporting spring design and length of the comb finger as it is practically limits the tuning range of the MEMS tunable capacitors.

In the interdigitated comb structure, one of the combs is static and the other one is movable with the application of voltage bias. As voltage bias is varied between the structures, the electrostatic force is produced. It actuates and moves the finger so that it can change the overlapping area between the fingers but the gap between them remains the same.

Larson *et. al.* (1991) [49] proposed a design of a micro-machined electrostatically controlled variable positioning device with metal conductors. An electrostatic produced by the micro-motor is used to slide the fingers to change the overlapping area between the capacitors at RF frequencies from 2 GHz to 45 GHz. As the results, the proposed micro-machined variable capacitor shows a variation of capacitance from 0.035 *p*F to 0.1 *p*F with application of voltage bias from 80 V to 200 V. The interdigitated MIMAS capacitors in open and close position are shown in Figure 26.

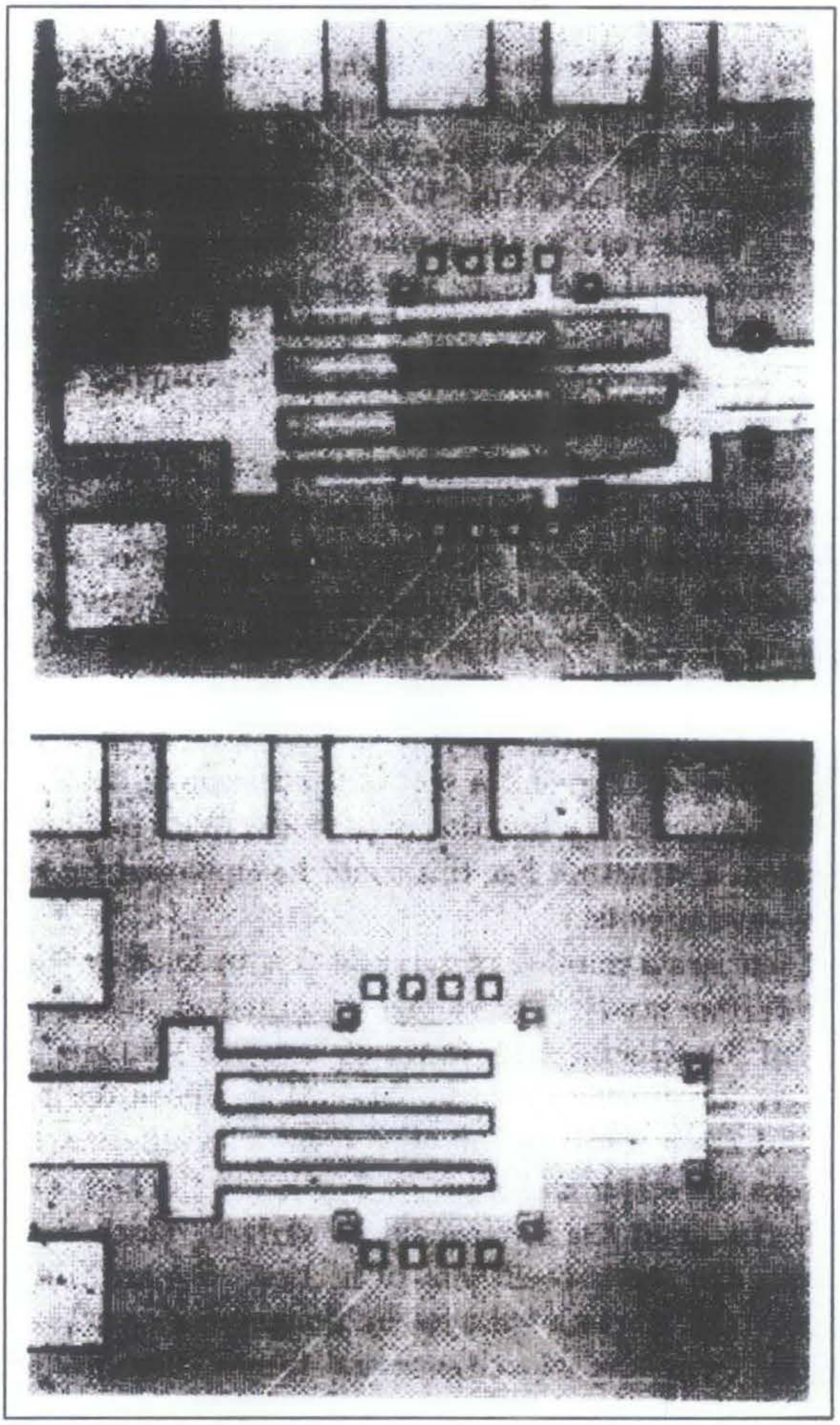


Figure 26: Interdigitated MIMAC capacitors in open and close position. [49]

2.6.3 MEMS Dielectric-Tuning Capacitors

The changing of the material properties between the two parallel plates can leads to High-Q tunable MEMS capacitors. It is clear from the Equation (2.5.2.4) that the change of medium dielectric constant can leads to the capacitance variation of the two parallel plates.

CHAPTER 3

METHODOLOGY

This chapter include project activities, Gantt chart and tool required in completing this project. The process of this project from the beginning to the end is explained in project activities section. The chapter continue with the Gantt chart for FYP I and FYP II Planning throughout two teaching semesters in UTP. In the end of the chapter, the tool required either software or hardware are discussed in detail.

3.1 PROJECT ACTIVITIES

This project is divided into two parts which are communication and MEMS. Firstly, this project starts with a literature review for wireless communication, impedance matching, MEMS and other important topics as discussed in literature review chapter *(refer to literature review chapter).* After the literature review is done, the process of this project move to the communication part. As shown in Figure 27, the first step in communication block is the impedance matching analysis and parameter determinations using MATLAB. The parameters then implemented in ADS software with the proposed low-pass impedance matching network is designed. From the ADS, the components value of the proposed low pass impedance matching is verified. If the components value did not meet the requirement of the tuner which to give 5 pF to 10 pF of capacitance value, the first step on the communication block will be done again. If the components value meets the requirement, the process continues to the MEMS block. In MEMS block, the MEMS structures which consist of parallel plate, electrostatic actuator and spring are designed *(refer to result and discussion chapter)* and its performance is simulated in MATLAB. If the expected capacitance value is not achieved, the first step of the MEMS block will be done again. Else, the process continues with the final evaluation and performance verification of the MEMS structure will be done. The final evaluation and performance verification will be discussed in the next chapter which is result and discussion chapter in detail.

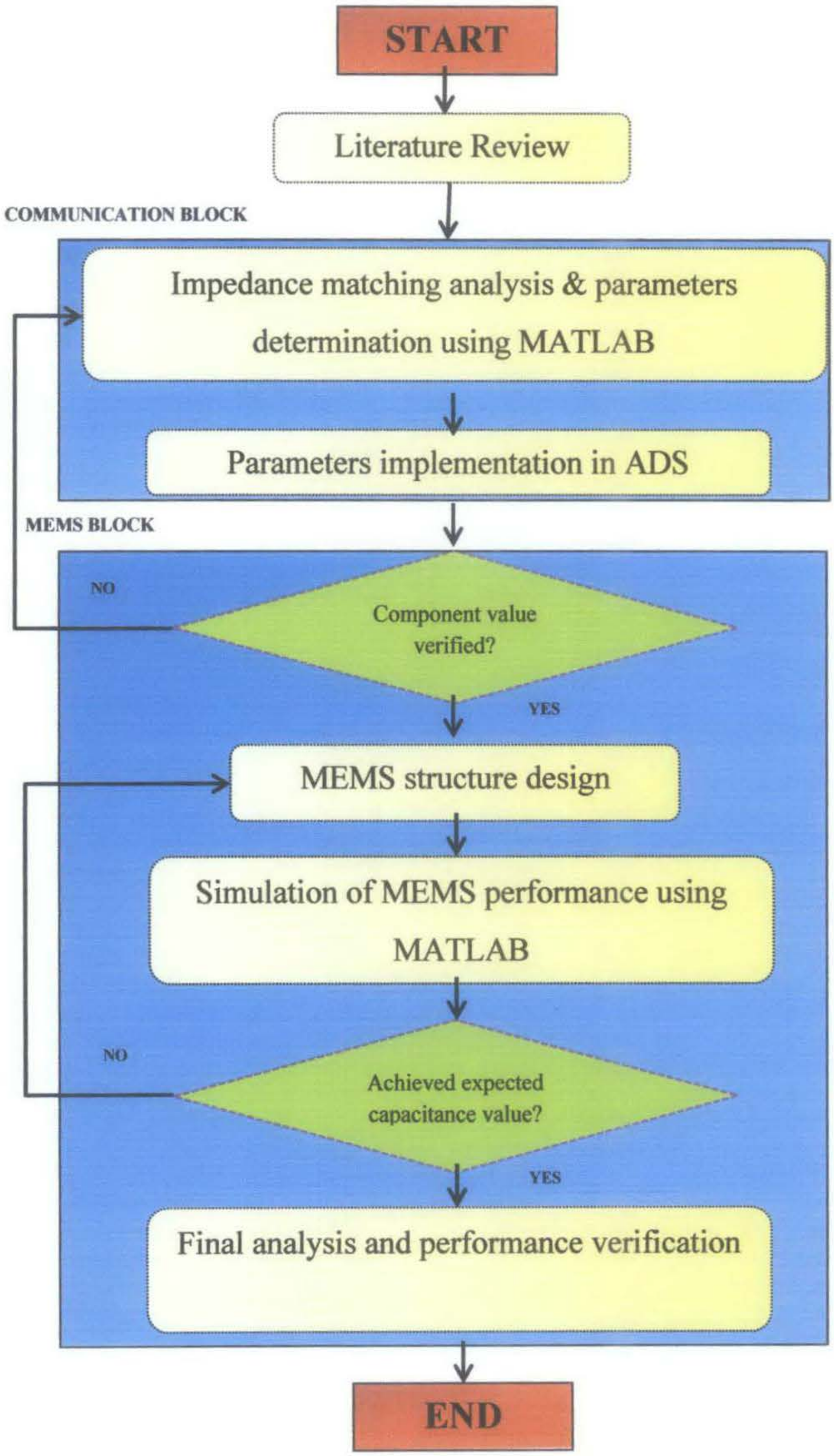


Figure 27: Project Activities.

3.2 GANTT CHART

3.2.1 FYP 1 Planning

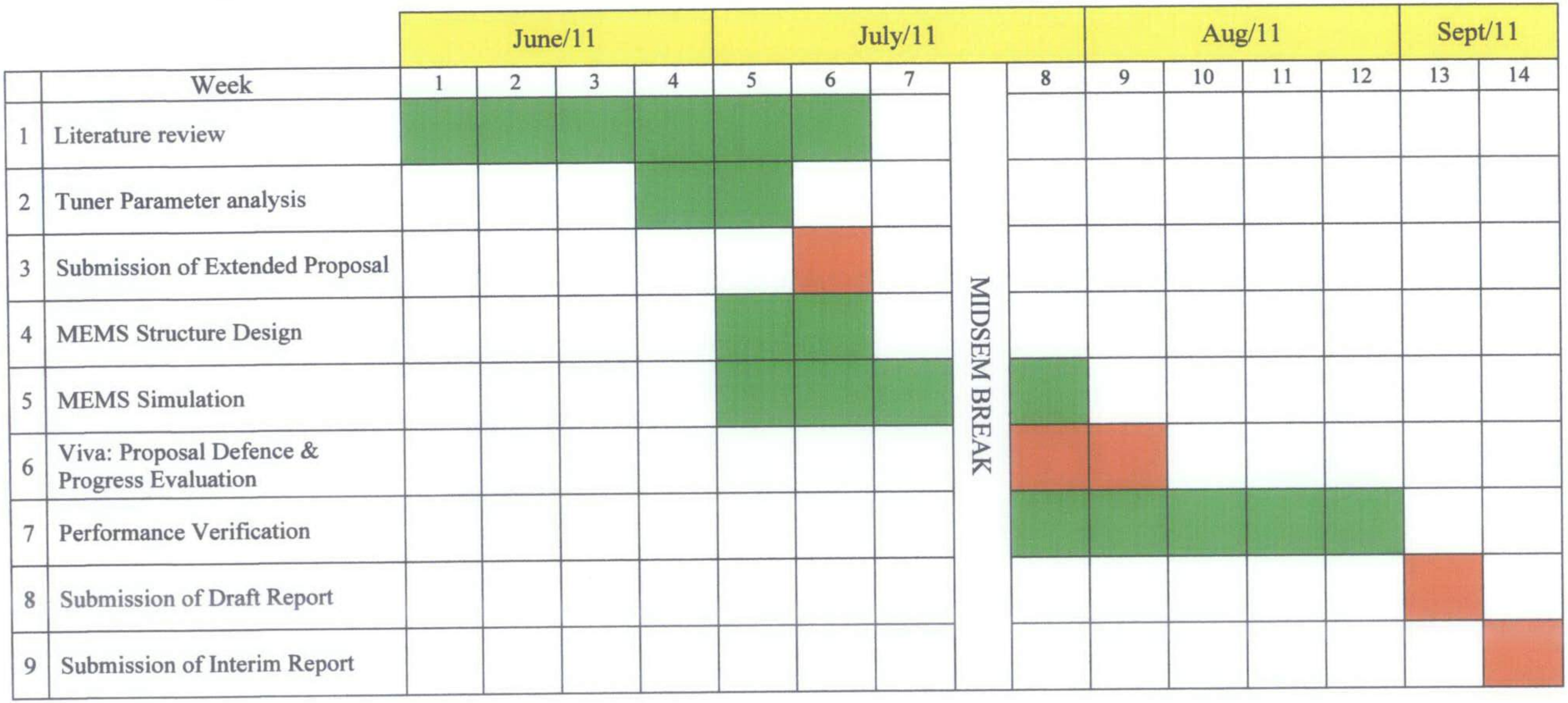


Figure 28: FYP 1 Planning.

		Sept/11				Oct/11				Nov/11				Dec/11			
	Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Continue								MIDSEM BREAK								
2	Submission of Progress Report																
3	Project Continue																
4	Pre-EDX																
5	Submission of Draft Report																
6	Submission of Dissertation Report (SoftBound)																
7	Submission of Technical Paper																
8	Oral Dissertation																
9	Submission of Project Dissertation (HardBound)																

Figure 29: FYP 2 Planning.

3.3 TOOL REQUIRED

The tools and software that will be used for this project are as follows.

1. **Agilent Advanced Design Systems (ADS)**

   ADS is an electronic design automation software system produced by Agilent EEs of EDA, a unit of Agilent technologies. It provides an integrated design environment to designers of RF electronic product. Agilent ADS supports every step of the design process including schematic capture, layout, frequency-domain and time domain circuit simulation, and electromagnetic field simulation. These functions allow users to fully characterize and optimize an RF design without changing the tools.

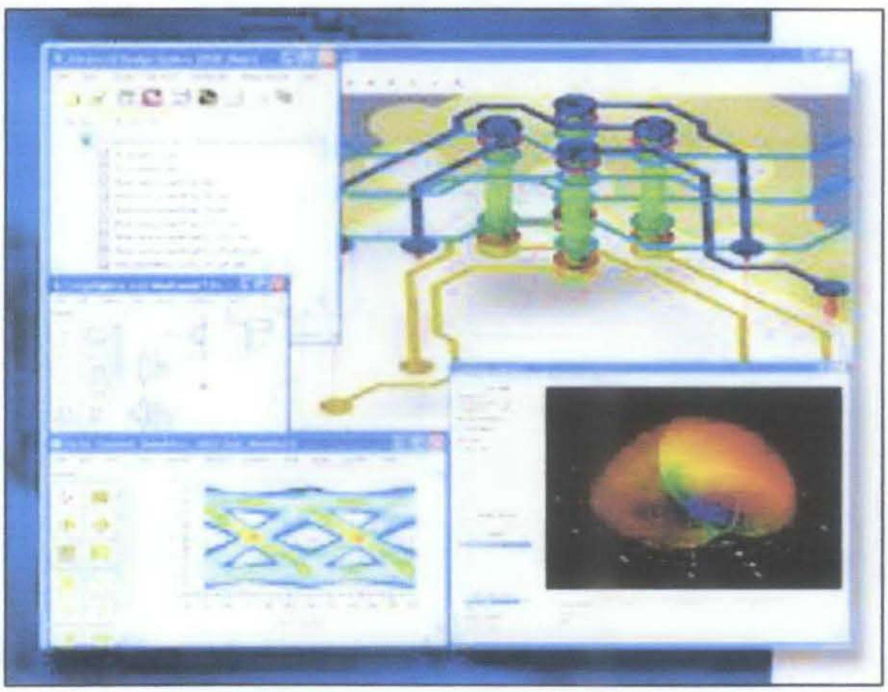


Figure 30: Snapshot of ADS software. [50]

For this study, one of the functions available in the ADS is impedance matching and smith chart plot. This makes the ADS is the most suitable software to be used in designing the circuit.

2. Matrix Laboratory (MATLAB) R2010a

Matrix Laboratory (MATLAB) is a numerical computing environment and fourth-generation programming language developed by MathWork. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfacing with programs written in other programming languages. For this study, MATLAB will help in plotting the graph

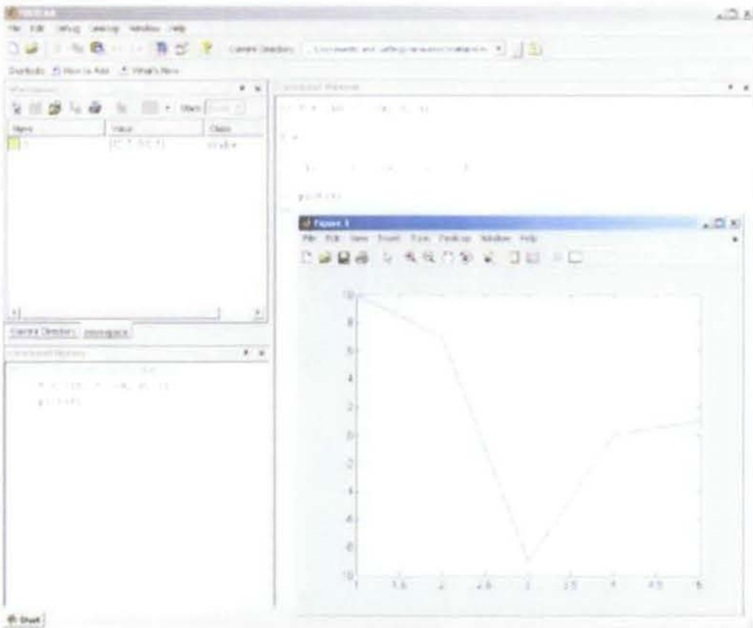


Figure 31: Snapshot of Graph Plotting. [51]

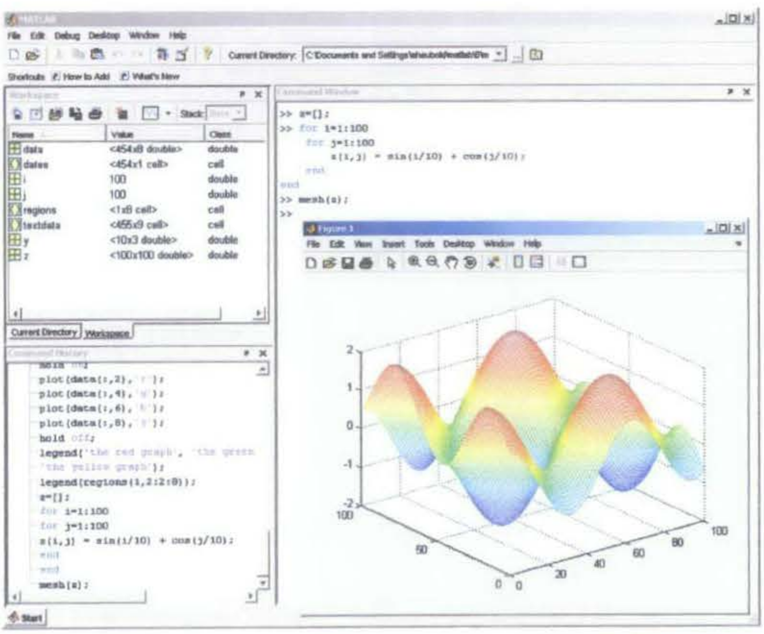


Figure 32: Snapshot of Graph Plotting using MESH. [51]

3. Computer Simulation Technology (CST STUDIO SUITE)

The electromagnetic simulation software CST STUDIO SUITE is the culmination of many years of research and development into the most efficient and accurate computational solutions to electromagnetic design. It comprises CST's tools for the design and optimization of devices operating in a wide range of frequencies. Analyses may include thermal and mechanical effects, as well as circuit simulation. All programs are accessible through a common interface with facilitates circuit and multi-physics co-simulation. [52]

CST STUDIO SUITE comprises the few modules but in this project, CST ELECTROMAGNETIC STUDIO (EMS) is used. CST EMS is an easy-to-use tool for the analysis and design of static and low frequency EM applications such as motors, sensors, actuators, transformers, and shielding effects.

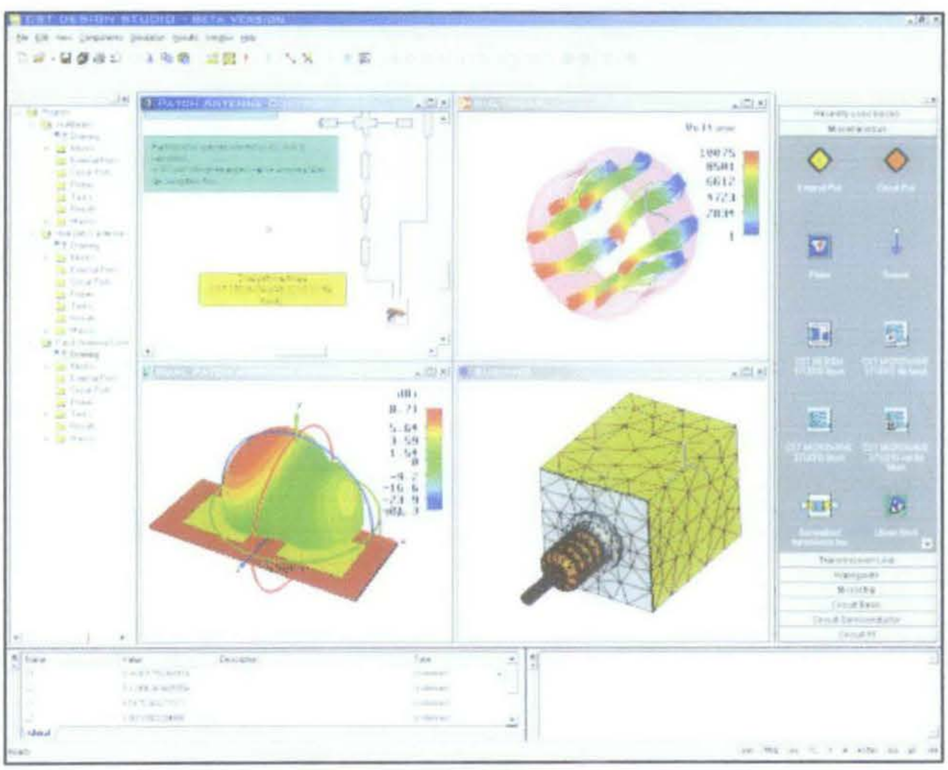


Figure 33: Snapshot of CST software. [53]

4. Antenna and MEMS variable capacitor.

Cylindrical Dielectric Resonator Antenna (CDRA) which will be used to test the MEMS variable capacitor after is has been fabricated.

Figure 34: Fabricated CDRA.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter will discuss about all the results obtained from the beginning of this project to the end. This chapter is divided into four main sections which are impedance matching, electrostatic actuator, the dimensions of full structure and MATLAB simulation result of the full structure. The impedance matching section then divided into three subsections which are RLC parameters determination, component simulation values and constant effects toward capacitance. The chapter continues with electrostatic actuator section and dimension of full structure section. The electrostatic actuator section is divided into three subsections of comb finger design, spring design and proposed electrostatic actuator while the dimension of the full structure section is divided into three subsections of the dimension of the parallel plate, electrostatic actuators and spring. At the end of this chapter, the MATLAB simulation result of the full structure is discussed which it included the graph of voltage versus electrostatic force, electrostatic force versus displacement and voltage versus displacement.

4.1 IMPEDANCE MATCHING

In this section, the RLC parameters are determined by using mathematical equations. Then, the components value simulations are done with the usage of the RLC parameters for verification. Besides, the constants effect towards capacitance also discussed in this section to get the range of the MEMS dimension before proceeding for design stage.

4.1.1 R, L, C Parameter Determination

In this project, the low-pass Pi impedance matching network is chosen due to its capability to handle wider impedance matching range. There are five steps to follow in order to design the Pi-type impedance matching network at any frequency [54]. The steps are as follows:

1. Firstly, the value of R_1, R_2 and Q_o are being determined and specified based on the CDRA antenna with frequency 2.4 GHz to 2.5 GHz.

$$R_1 = 68.2 - j0.45\ \Omega,$$
$$R_2 = 50\ \Omega,$$
$$Q_o = 0.3017. \quad (4.1.1.1)$$

2. Secondly, the designable condition of Q_o is being verified by using two mathematical conditions which are as follows:

$$Q_o \geq \frac{1}{2}\sqrt{\frac{R_1}{R_2} - 1} \quad for\ R_1 \geq R_2\ (1) \quad (4.1.1.2)$$

And

$$Q_o \geq \frac{1}{2}\sqrt{\frac{R_2}{R_1} - 1} \quad for\ R_2 \geq R_1\ (2) \quad (4.1.1.3)$$

In this project, condition (1) in Equation above is used since the R_1 is bigger than R_2. So, the value of Q_o is calculated to be **1.5**.

3. Thirdly, the value of Q_1 and Q_2 are then computed by using the equations below.

$$Q_1 = \frac{2Q_O R_1 - \sqrt{4Q_0{}^2 R_1 R_2 - (R_1 - R_2)^2}}{(R_1 - R_2)^2} \quad (4.1.1.4)$$

$$Q_2 = \frac{2Q_O R_2 - \sqrt{4Q_0{}^2 R_1 R_2 - (R_1 - R_2)^2}}{(R_2 - R_1)^2} \quad (4.1.1.5)$$

In this project, the value of Q_1 is calculated to be equal to **1.67** and the value of Q_2 is calculated to be equal to **1.33**.

4. Fourthly, the value of X_L, BC_1 and BC_2 are being determined by using the equations below.

$$X_L = \omega L = \frac{2Q_O R_1}{1+4{Q_O}^2} \quad (4.1.1.6)$$

$$BC_1 = \omega C_1 = \frac{2Q_O}{R_1} \quad (4.1.1.7)$$

$$BC_2 = \omega C_2 = \frac{1}{R_2}\sqrt{\frac{R_2}{R_1}\left(1 + 4{Q_O}^2\right) - 1} \quad (4.1.1.8)$$

In this project, the value of X_L is calculated to be **20.46**, the value of BC_1 is calculated to be **0.044** and the value of BC_2 is **0.050.**

5. Lastly, the values of L, C_1 and C_2 at any given frequency are calculated by using equations below.

$$X_L = \omega L = 2\pi f L \quad (4.1.1.9)$$

$$BC_1 = \omega C_1 = 2\pi f C_1 \quad (4.1.1.10)$$

$$BC_2 = \omega C_2 = 2\pi f C_2 \quad (4.1.1.11)$$

The low-pass Pi-type impedance matching network is expected to operate over a band of frequencies $f_{min} \leq f \leq f_{max}$ for a given R_1, R_2 and Q_o. Therefore, the range of the C_1, C_2 and L values within a band frequency of $\boldsymbol{f_{min} = 2.4\,GHz \leq f \leq f_{max} = 2.5\,GHz}$ are noted below.

$$\mathbf{1.36\,nH \leq L \leq 1.3\,nH} \quad (4.1.1.12)$$

$$\mathbf{5.92\,pF \leq C_1 \leq 5.8\,pF} \quad (4.1.1.13)$$

$$\mathbf{7.32\,pF \leq C_2 \leq 7.18\,pF} \quad (4.1.1.14)$$

4.1.2 Components Simulation Values

From the R, L, C parameter determination section, the range of each components that will be used in the design stage are successfully determined. With it, the next step of this chapter which is components simulation value using CST microwave studio and Agilent ADS can be done.

Firstly, the CDRA was design in the CST microwave studio with the targeted frequency range of 2.4 GHz to 2.5 GHz. The simulated antenna is fabricated using FR-4 substrate based on the simulation in the CST software. After the fabrication of the antenna, the antenna return loss (*S11*) response data was extracted in S1P format from CST software and will be used with Agilent ADS software. The data represents the real CDRA as it will be connected to the source of the proposed impedance matching network. The targeted frequencies range is from 2.4 GHz to 2.5 GHz.

In the Agilent ADS software, the design of the low pass Pi-Network impedance matching is created and the S1P is imported. With the calculated range of the components values, the Pi-type impedance matching network is simulated for verification in the ADS to achieve the ability of tuning the CDRA within the targeted frequencies range. From the simulation, the variable values of the tunable capacitors can be determined and verified.

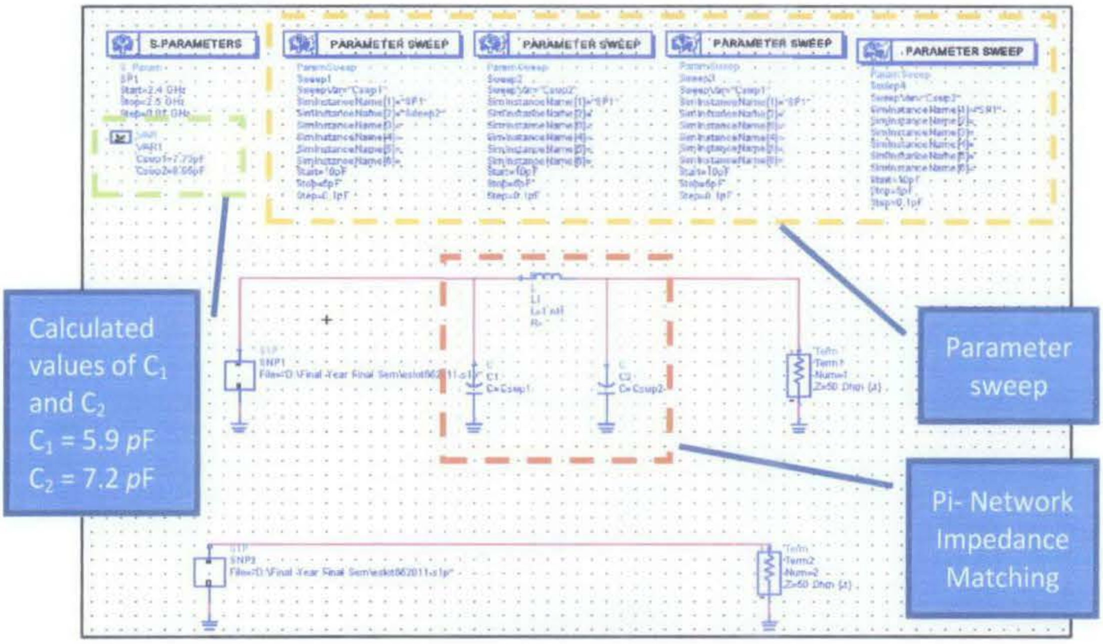


Figure 35: Agilent ADS Software Simulation Screen Capture.

Figure 35 shows the Agilent ADS simulation done with the parameter sweep function and S-parameter functions. The parameter sweep function is used since it is a function to run multiple simulations while varying the parameter. Figure 35 also shows two circuits constructed where one of them is with Pi-Network impedance matching and another one is without Pi-Network impedance matching. It is to compare the whether the proposed circuit improved the result of the original circuit.

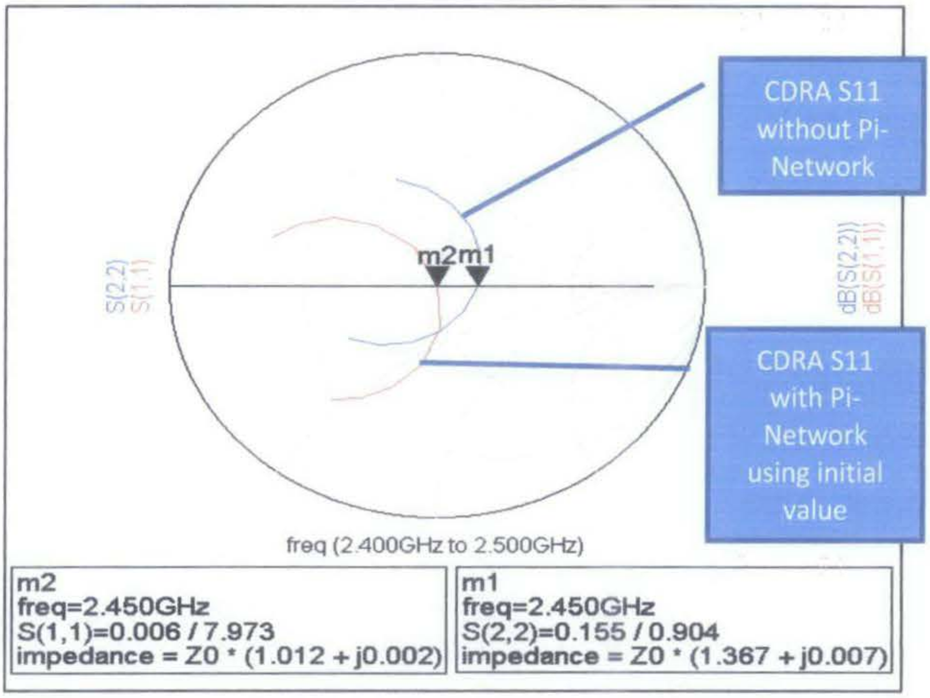


Figure 36: Result of the initial value of proposed and original result.

From Figure 36, we can see that CDRA S11 with the Pi-Network using initial value gives a good match at 2.45 GHz compared to CDRA *S11* without the Pi-Network. Good impedance matching means the reflection coefficient is lower. The lower reflection coefficient gained, the higher the integrity of the transmitted signal. This means, low possibility of signal loss when reflection coefficient is high. So, this shows the CDRA *S11* with the Pi-Network is better.

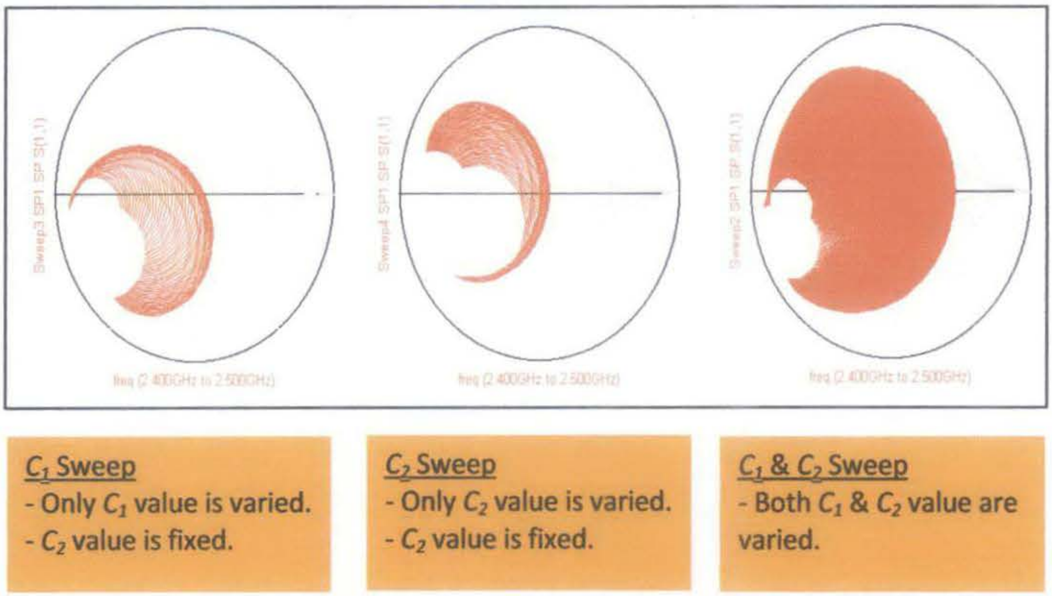


Figure 37: C_1 and C_2 sweep value on smith chart.

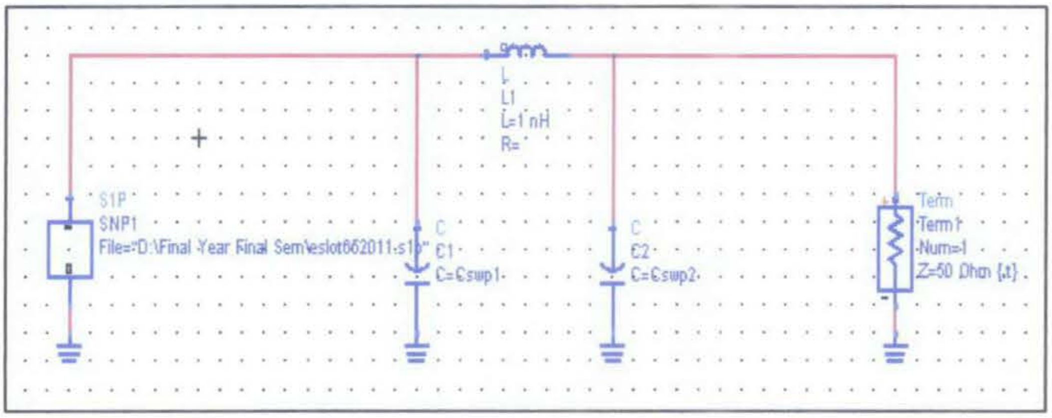
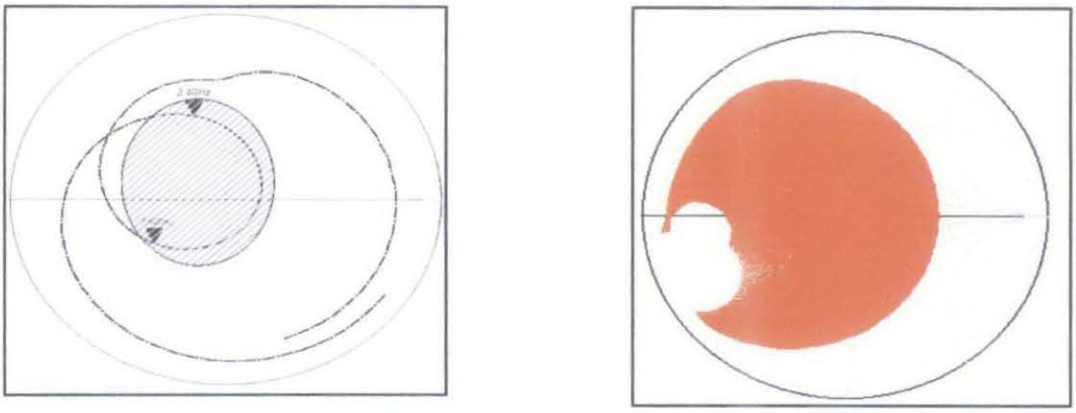


Figure 38: The proposed circuit with the Pi-Network Impedance Matching.

Figure 37 shows the parameter sweep value of both variable capacitors, C_1 and C_2 on smith chart. C_1 is the first capacitor and C_2 is the second capacitor in the proposed circuit as shown in Figure 38. In the first smith chart of Figure 38, only C_1 value is varied and C_2 value is fixed. In the second smith chart, only C_2 value is varied and C_1 value is fixed. This first two smith chart is done to view the variation of an individual capacitor within the targeted frequency range and with the parameter sweep function. The third smith chart of Figure 37 shows the result of variation of both variable capacitors, C_1 and C_2 with the parameter sweep function.



(a) Proposed Area. (b) Simulated Area.

Figure 39: Mismatch target area.

Figure 39 shows the mismatch target area of the circuit designed. The proposed area is the result of the original circuit which is without the Pi-Network impedance matching and the simulated area is the result of the proposed circuit which is with the Pi-Network using the parameter sweep function. From Figure 39, we can see clearly that the proposed area was well covered by the simulated area which is the circuit with the Pi-Network impedance matching.

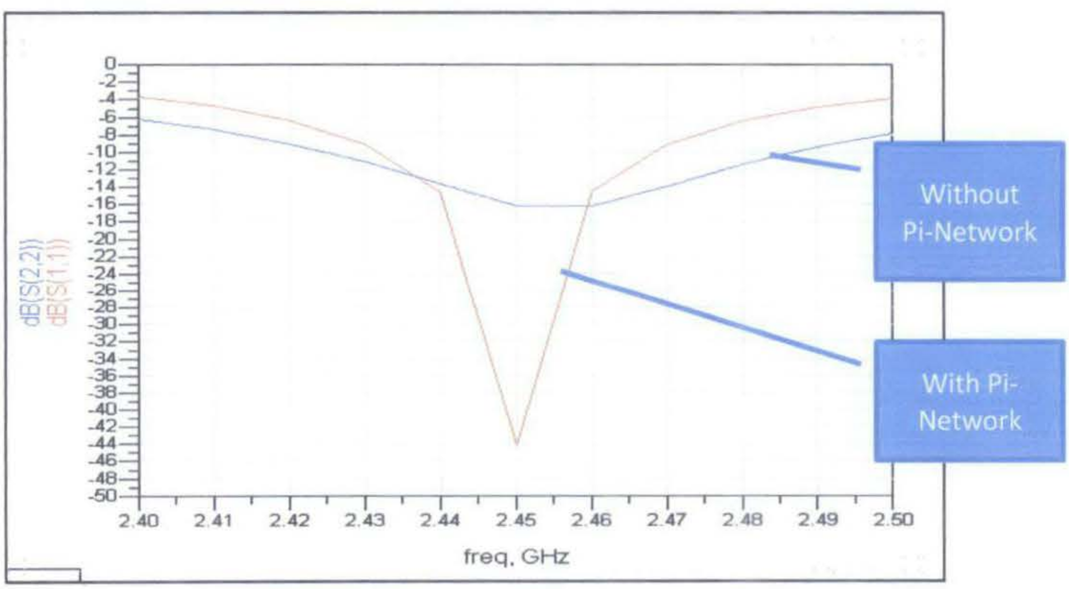


Figure 40: Graph of S11 initial point of the circuits designed at 2.45 GHz.

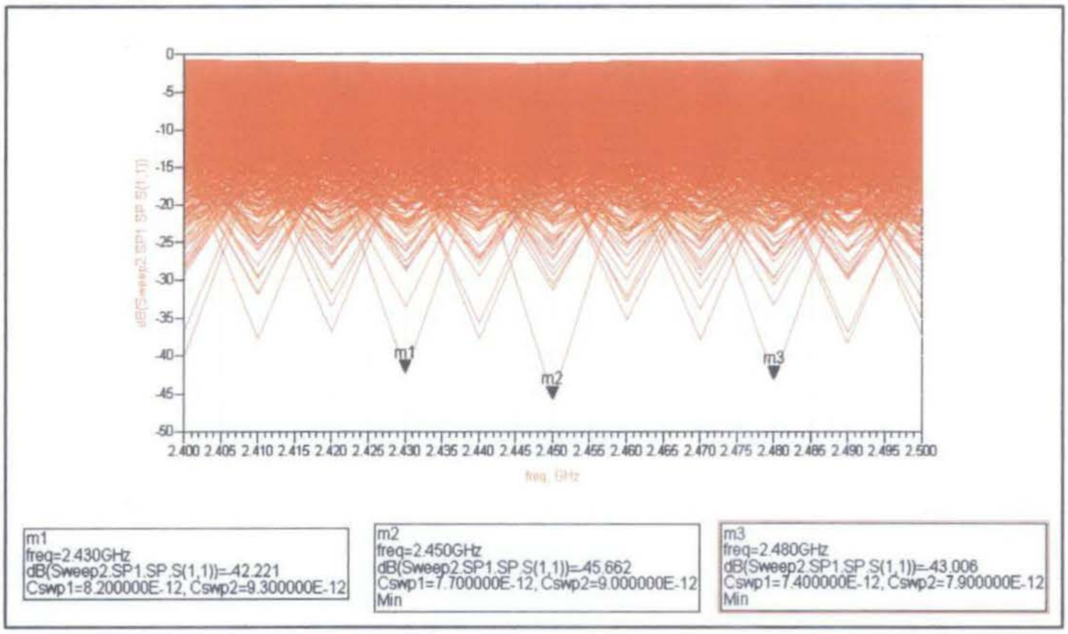


Figure 41: S11 Graph of both circuits using parameter sweep function.

Figure 40 shows the graph of antenna return loss (*S11*) initial point of both circuits designed in Agilent ADS software and Figure 41 shows the graph of the antenna return loss (*S11*) of both circuits designed using the parameter sweep functions. The result of the circuit with the Pi-Network gives the better result in term of decibels where it can reach up to 44 *dB* within the targeted frequency range 2.4 GHz to 2.5 GHz

From all the simulation results, we can conclude that the proposed circuit design is sufficient to overcome the problem of the return loss in software simulation. The design of the Pi-Network impedance matching is verified to be correct. Besides that, the simulated components value of inductor (L) and the range of variable capacitors (C_1 and C_2) are obtained. The final value of the inductor (L) and the range of variable capacitors (C_1 and C_2) that will be used for MEMS design are stated below:

$$L = 1\,nH\ (Fixed) \qquad (4.1.2.1)$$

$$C_1 = C_2 = 5\,pF - 10\,pF\ (Varied) \qquad (4.1.2.2)$$

4.2 ELECTROSTATIC ACTUATOR

To design an electrostatic actuator, there are two essential components that are required which is comb finger design and spring design which will act as amplifier to amplify the displacement of actuator. Each one of them has different structure designs and equations with certain parameters required, which will be used in the design process.

Based on the impedance matching calculation and simulation result, the electrostatic actuator is designed to be able to move the parallel plate to achieve capacitance as listed in Table 1 below.

Table 1: Expected criteria of electrostatic actuator.

Criteria	Value
Capacitance	$5\ pF - 10\ pF$

Besides that, electrostatic actuator must be able to move the parallel plate in the unit of μm or lower in order to supply voltage lower than 110 V. If the electrostatic actuator is expected to move the parallel plate higher than μm unit, the electrostatic force must be high and supplied voltage is also high because the electrostatic force is directly proportional with the supplied voltage.

4.2.1 Comb Finger Design

In this project, the comb finger structure will be used for the electrostatic actuator. Comb finger structure actuators consist of two interdigitated finger structures, where one comb is fixed *(Stator)* and the other one comb is movable *(Rotor)*. Applying a voltage difference between the comb finger structures will result in a displacement of the movable comb finger structure either in forward or backward direction from the fixed comb finger by electrostatic forces.

Figure 42 shows the illustration of the comb finger in 3D view and Figure 43 shows the illustration of the comb finger in 2D view. Both figures give us the better view of the comb finger structure.

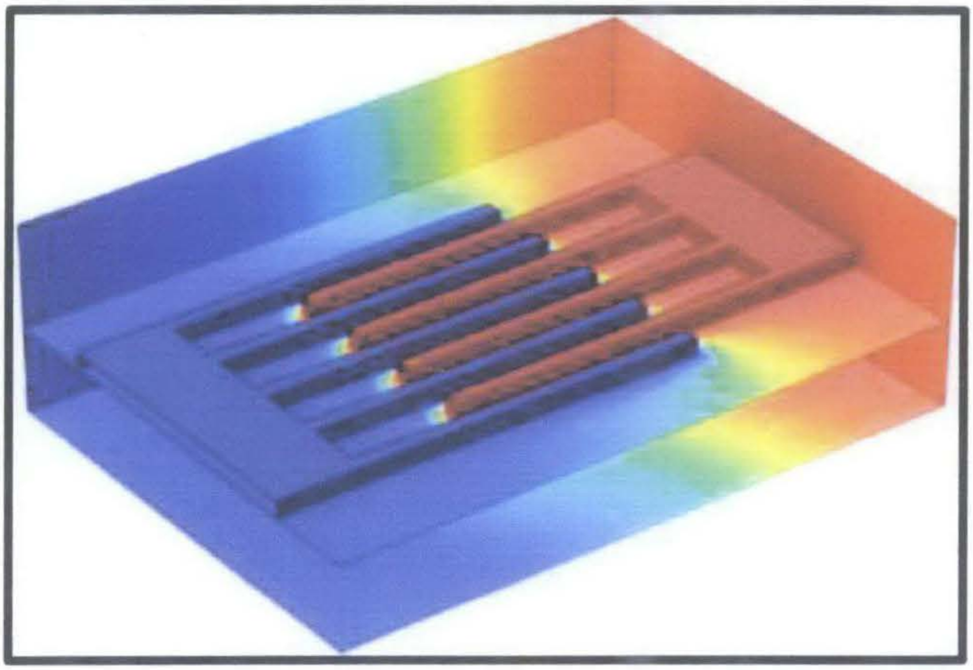


Figure 42: Comb finger structure illustration in 3D view [55].

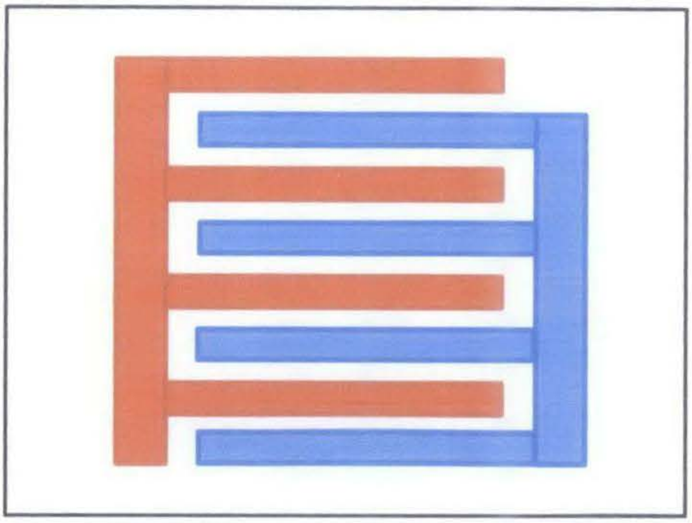


Figure 43: Comb finger structure illustration in 2D view.

One of the advantages of using the comb finger structure is its ability to resonate which allows high displacements for corresponding small input. This is the reason why comb finger structure is popular to designing resonators. Besides resonators, comb finger structure actuators also have been used as electromechanical filters, optical shutters, micro-grippers, voltmeters and the driving element in vibro-motors and micromechanical gears. [57]

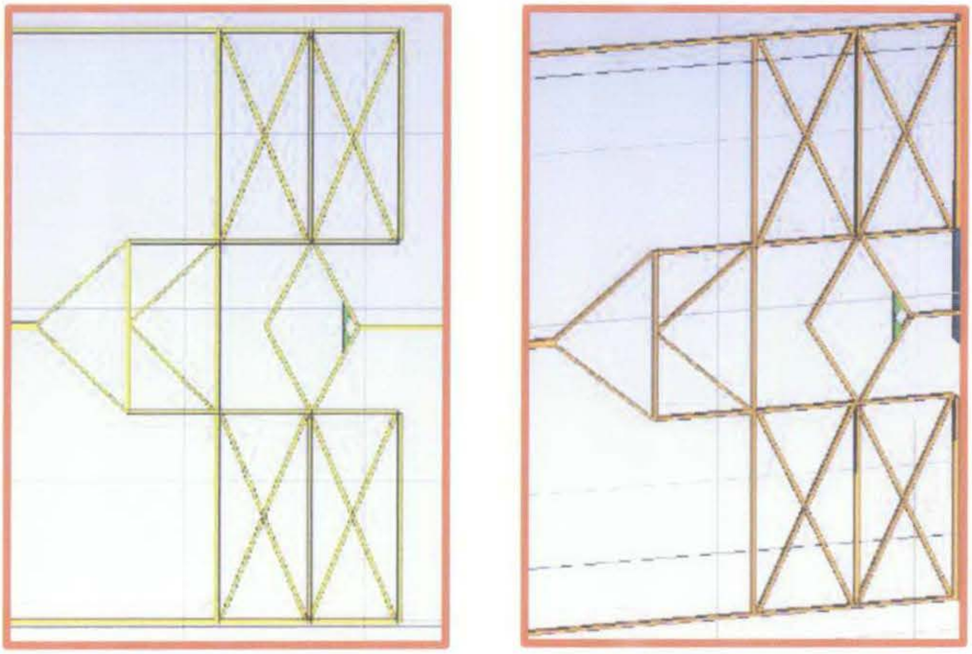
The parameters that contributed to the electrostatic force calculation are the suspension stiffness (*k*), the permittivity of the medium (ε), the number of comb fingers (*N*), the gap spacing between the fingers (*d*) and the thickness of the comb fingers (*t*). The electrostatic force displacement relation in the dielectric formula is given by the Equation 21 below.

$$F = kx = \frac{N\varepsilon_o t}{d} V^2 \qquad (4.2.1.1)$$

From Equation (4.2.1.1), we can definitely see that the electrostatic forces increase with decreasing gap spacing between the comb fingers (*d*) and an increasing number of comb fingers (*N*) [57].

4.2.2 Spring Design

The springs that will be attached to the structure are calculated to see the flexibility of the design. In this project, the spring will be attached at the fixed parallel plate, at the comb fingers as to hold the fixed plate and comb fingers and at the side of the parallel plate as amplifier to amplify the displacement by the factor of 1000 to achieve the expected displacement of the parallel plate for the expected capacitance value. Figure 44 shows the proposed spring attachment to the device.



(a) 2D view (b) 3D view

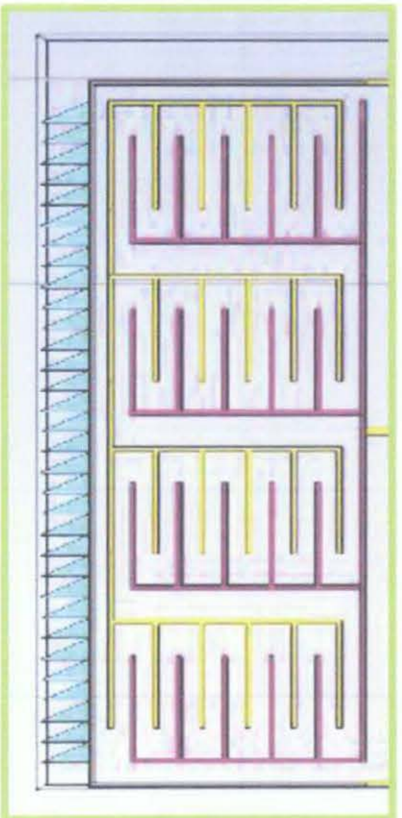
Figure 44: The proposed spring attachment to the device.

In the spring design, the most important thing is the spring constant. In order to measure spring constant, there are few parameters that should be determined and confirmed before proceed which is the flexure width (w), flexure thickness (t), and flexure length (l). Besides, the Young Modulus of 165 GPa is used to specify the flexibility of the springs. The spring constant can be determined by Equation listed below [57].

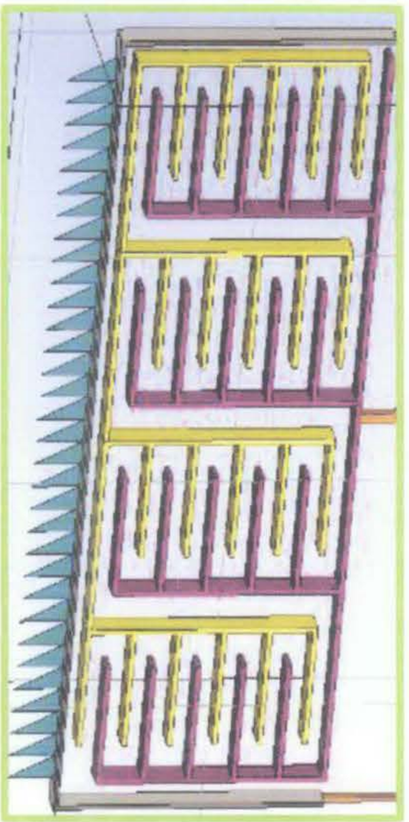
$$K = \frac{F}{x} = \frac{6EI}{l^3} = \frac{Et^3w}{2l^3} \quad (4.2.2.1)$$

4.2.3 Proposed Electrostatic Actuator Structure

After the comb finger and spring had been designed, the full electrostatic actuator device structure can be constructed in the software. Figure 45 shows the 2D view and 3D view of the electrostatic actuator. The dimension of the electrostatic actuator will be discussed in the next section.



(a) 2D view



(b) 3D view

Figure 45: The proposed electrostatic actuator.

4.3 DIMENSION OF THE MEMS VARIABLE CAPACITOR

The MEMS variable capacitor consists of parallel plate, electrostatic actuator and spring. The dimension of the parallel plate, electrostatic actuator and spring are obtained from the calculations and simulations in the impedance matching section, electrostatic actuator section and spring section found in Result & Discussion chapter. The detail dimensions are listed in the Table 2 below.

Table 2: Dimension of the MEMS variable capacitor.

	Parameter	Symbol	Value	Unit
MEMS	Number of comb finger	N	200	-
	Supplied voltage	V	110	V
	Air permittivity	ε_o	8.85×10^{-12}	F/m
	Length of the comb finger	l	100	μm
	Length of the overlap finger	l_o	70	μm
	Width of the comb finger	w	4	μm
	Thickness of the comb finger	t	20	μm
	Gap distance between the comb finger	d	6	μm
	Spring constant	k	35.64	N/M
	Silicon Young's Modulus	E	165	GPa
	Length of the spring	l	100	μm
	Width of the spring	w	4	μm
	Thickness of the spring	t	6	μm
COMMUNICATION	Length of parallel plate	l	3	mm
	Width of the parallel plate	w	1	mm
	Thickness of the parallel plate	t	2	mm
	Gap distance between the parallel plate	d	3	μm

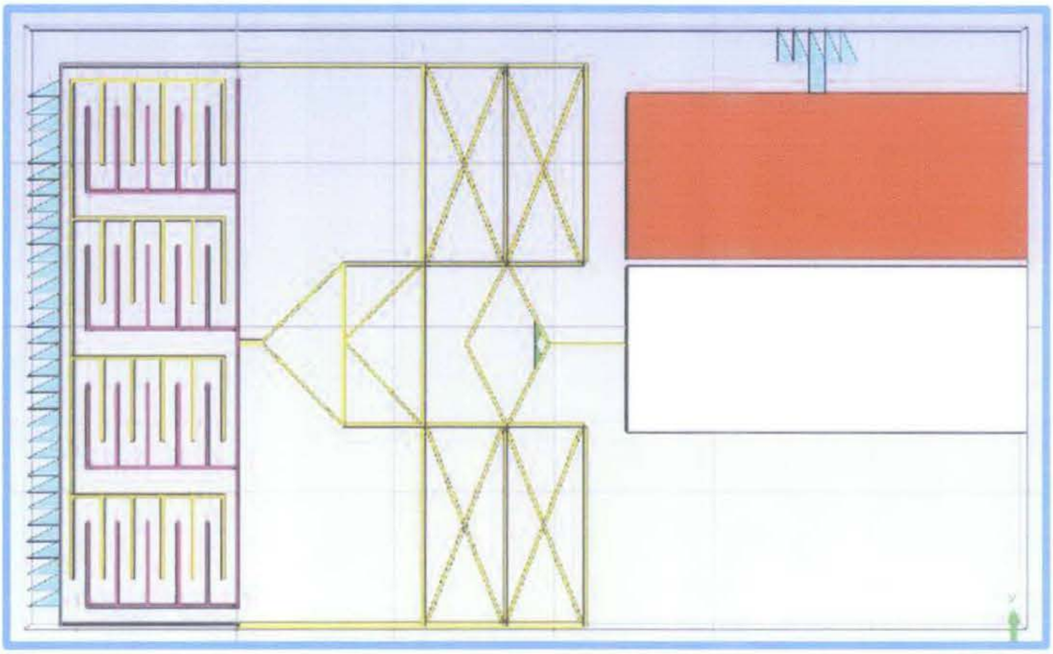


Figure 46: The 2D view of MEMS variable capacitor structure design.

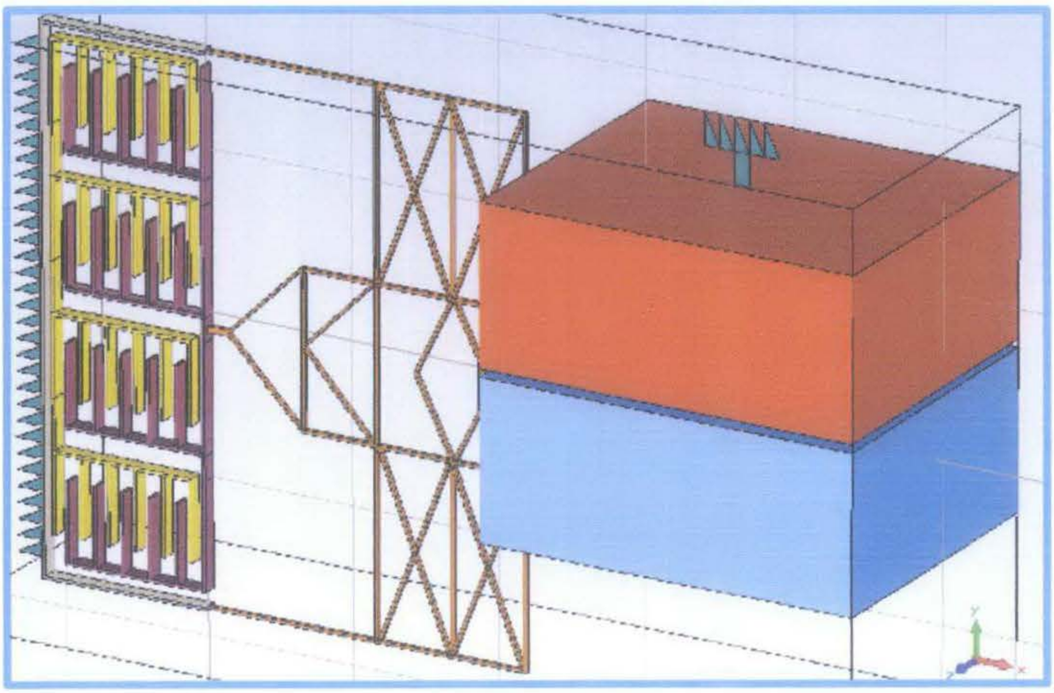


Figure 47: The 3D view of MEMS variable capacitor structure design.

4.4 MATLAB SIMULATION RESULT OF THE FULL STRUCTURE

After the dimension of the full structure had been confirmed, all parameters that are calculated using the equations in the designing stage will be listed in Table 3 below.

Table 3: Result parameters.

Parameter	**Symbol**	**Values**	**Unit**
Spring constant	k	35.64	N/m
Electrostatic force	F	71.4	μN
Supplied voltage	V	110	V
Number of comb finger	N	200	-

From this result, few simple MATLAB codes are created in M-files to plot graphs and calculate few parameters such as thickness of the parallel plate *(refer to Appendix I)*. The graphs that are plotted in the MATLAB software will be helpful in the analysing stage.

From MATLAB graph, we will discover the relationship between supplied voltage, electrostatic force produced by the electrostatic actuator and displacement of the parallel plate.

4.4.1 Voltage versus Electrostatic Force

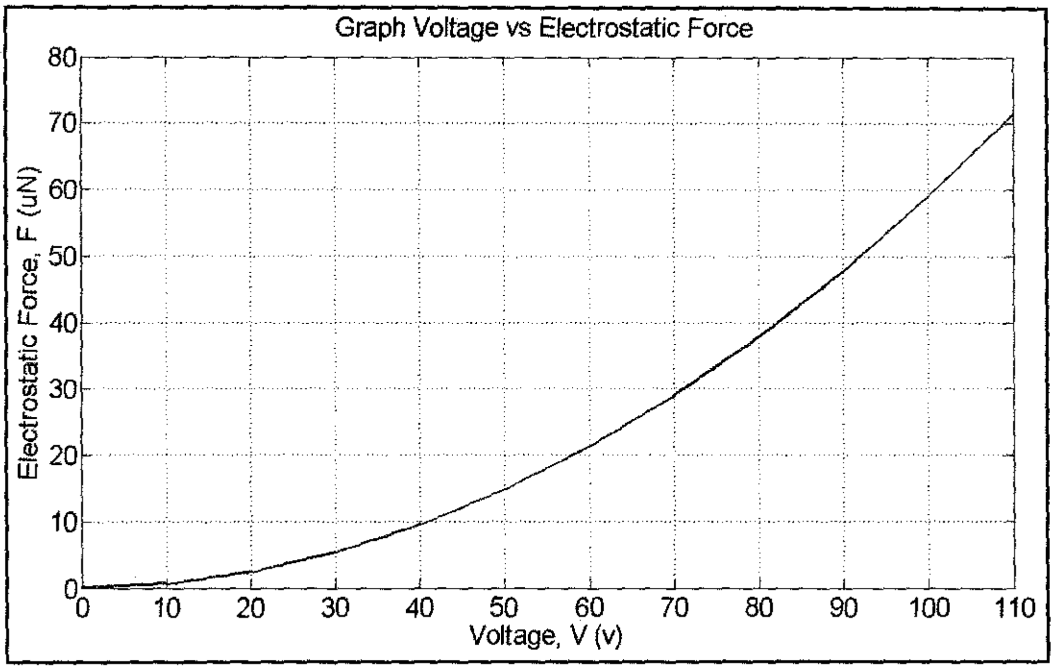


Figure 48: Graph voltage versus electrostatic force.

Figure 48 shows the graph voltage versus electrostatic force which plotted to get the relationship between the voltage and electrostatic force that produced by 200 pairs of comb finger is analysed carefully. For the range of voltage from 0 V to 110 V that is supplied to the device, the electrostatic force produced by electrostatic actuator is within the range of 0 μN to 71.4 μN. Therefore, we can say that for every 1 V supply to the electrostatic actuator, 0.65 μN of electrostatic force is produced.

So, from the graph, we can conclude that the electrostatic force increases as the supplied voltage increases. Besides, the range of the electrostatic force produced by the comb finger at the range of supplied voltage allows the flexibility of the design to suit specific fabrication technology.

4.4.2 Electrostatic Force versus Displacement

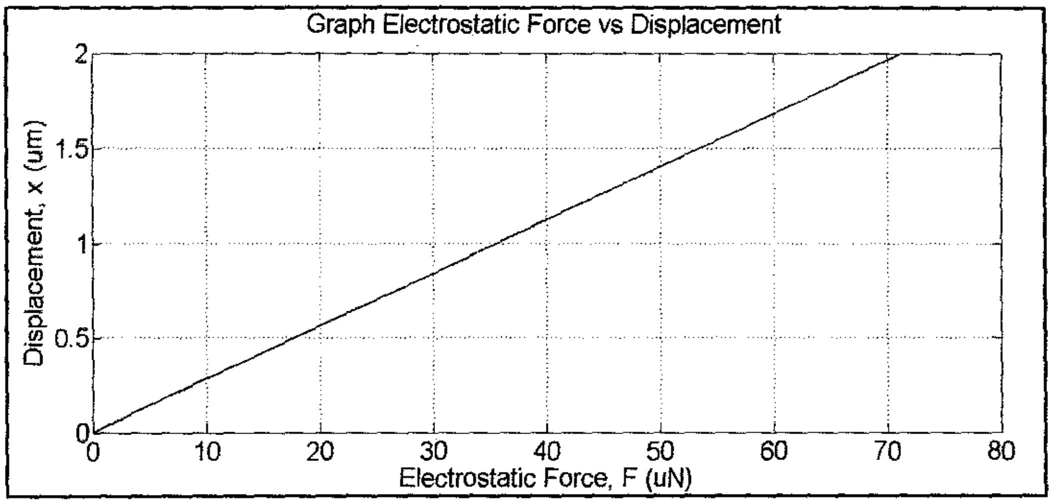


Figure 49: Graph electrostatic force versus displacement.

Figure 49 shows the graph electrostatic force versus displacement which plotted to get the relationship between the electrostatic force that produced by 200 pairs of comb finger and displacement is analysed.

For the range of electrostatic force from 0 μN to 71.4 μN that is produced by the electrostatic actuator with the range of 0 V to 110 V supplied voltage, the displacement of the comb finger is 0 μm to 2 μm. In order to have 2 μm displacements, 71.4 μN of electrostatic force should be produced.

Therefore, from the graph, we can conclude that the displacement of the parallel plate increases as the electrostatic force produced by the electrostatic actuator and the supplied voltage increases.

4.4.3 Voltage versus Displacement

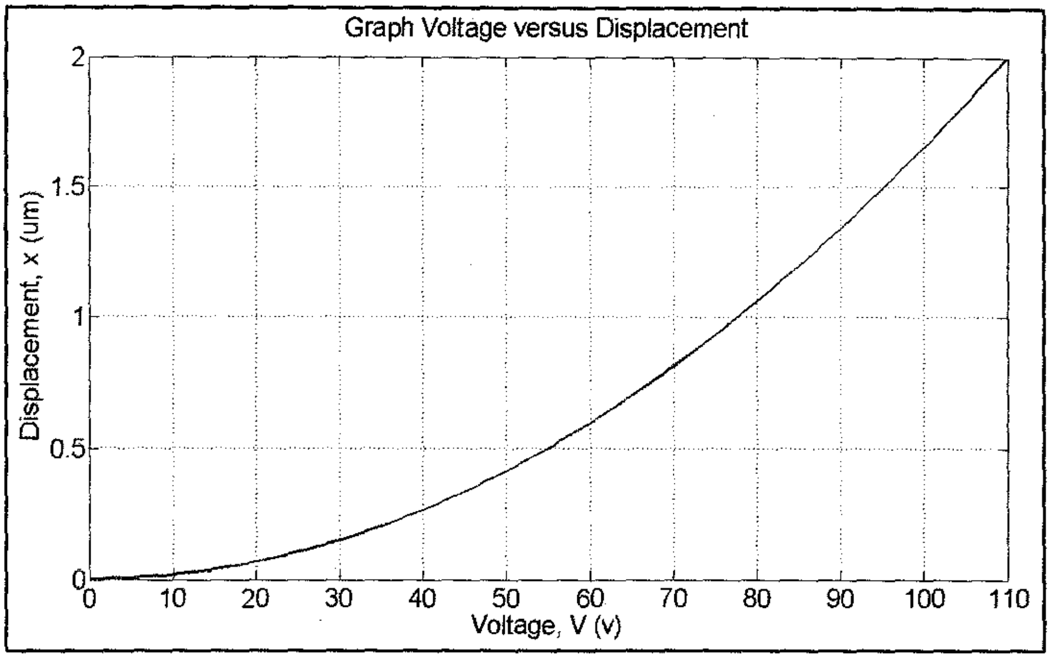


Figure 50: Graph voltage versus displacement.

Figure 50 shows the graph voltage versus displacement which plotted to get the relationship between the supplied voltage and displacement is analysed.

For the range of supplied voltage from 0 V to 110 V, the displacement of the comb finger is 0 μm to 2 μm. In order to have 2 μm displacements, 71.4 μN of electrostatic force should be produced. Therefore, we can say that for every 1 V supply to the electrostatic actuator, 0.018 nm of displacement of comb finger is gained and 0.65 μN of electrostatic force is produced.

From the graph, we can conclude that the displacement of the comb finger increases as the electrostatic force produced by the electrostatic actuator and the supplied voltage increases. Moreover, the displacement of the comb finger leads to the displacement of the parallel plate to achieve its objective of 5 pF to 10 pF of capacitance value.

4.4.4 Displacement versus Capacitance

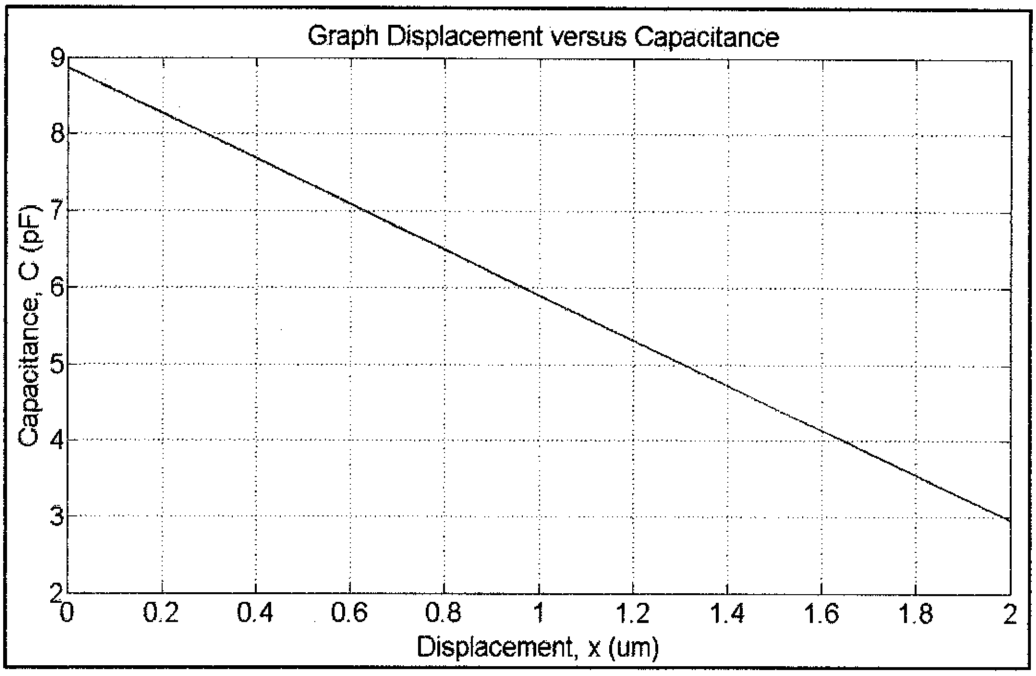


Figure 51: Graph displacement versus capacitance.

Figure 51 shows the graph displacement versus capacitance which plotted to get the relationship between the displacement of the comb finger and capacitance value. For the range of supplied voltage from 0 V to 110 V, the displacement of the comb finger is 0 μm to 2 μm. In order to have 2 μm displacements, 71.4 μN of electrostatic force should be produced. Therefore, we can say that for every 1 V supply to the electrostatic actuator, 0.018 *n*m of displacement of comb finger is gained and 0.65 μN of electrostatic force is produced. With the existence of spring which acts as the amplifier, the displacement of the comb finger is amplified by factor of 1000 to ensure it sufficient to move the parallel plate to achieve the expected capacitance value.

From the graph, we can conclude that the capacitance value decreases as the displacement of the comb finger and the supplied voltage increases. The capacitance value produced by the displacement of the parallel plate is 3 *p*F to 8*p*F which lies within the expected capacitance value of 5 *p*F to 10 *p*F.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This chapter concludes the projects and gives few recommendations for improvements in future. The conclusion summarizes the project with the performance and shows the project is successfully achieved its objectives as mentioned in introduction chapter (*refer to introduction chapter*). The recommendation provides rooms for improvement in future.

5.1 CONCLUSION

As conclusion, the MEMS variable capacitor acts as a tuner to reduce the signal loss due to impedance mismatch. The device is driven by the electrostatic force produced by the electrostatic actuator. The electrostatic actuator uses a number of comb-finger structures with the existence of supplied voltage to produce electrostatic force. This electrostatic force will move the parallel plate either forward or backward direction to get the desired capacitance value.

From the results and discussions chapter, we can conclude that MEMS variable capacitor has the capability to move the comb finger at most 2 μm with the supplied voltage of 110 V, 71.4 μN electrostatic forces produced by the electrostatic actuator and amplification factor of 1000 which will contribute to the range of 3 pF to 8 pF capacitance values. This range lies within the expected capacitance value which is 5 pF to 10 pF.

In addition, the results show that MEMS variable capacitor can improves the antenna transmission session by almost 50%. With that, the main objective of this project which to design and simulate the MEMS variable capacitor for optimum antenna transmission is achieved.

5.2 RECOMMENDATIONS

There are few recommendations can be done to improve this project since this project gives great impact to the industry. Some of the recommendations can be done immediately but some may take up to at most of a year.

Firstly, the dimension of the parallel plate can be improved. The dimension of the parallel plate can be smaller than the proposed dimension but still within the micro-meter range because the MEMS technology usually in the micro-meter range. Even though, the dimension of the parallel plate can be smaller than the proposed dimension but still it has to get the same capacitance value or higher capacitance value to make it valuable to the industry.

Besides that, the dimension of the electrostatic actuator also can be improved where the dimension can be smaller than the proposed dimension but still have to consider few parameters. The parameters are number of comb fingers, supplied voltage, gap distance between the comb fingers and spring constant. The number of comb finger can be higher but still within the range of 0 to 200 and the supplied voltage have to be within the range of 0 to 110 V to be considered as low supplied voltage. Moreover, the gap distance between the comb finger and the spring constant also can be lower.

Additional recommendation is definitely to improve on the viability of this project by researching and reviewing more on the literature review of the other methods that can be applied to the current directions of this project.

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APPENDICES

APPENDIX I: MATLAB CODE

1. MATLAB Code 1: Graph Voltage versus Electrostatic Force.

```
clc
n = 200;
e = 8.85e-12;
t = 20e-6;
V = 0:10:110;
d = 6e-6;
F = (n*e*t*(V.^2))./d;
F1 = F./1e-6;

plot(V,F1);
xlabel('Voltage, V (v)');
ylabel('Electrostatic Force, F (uN)');
title('Graph Voltage vs Electrostatic Force');
grid on
```

2. MATLAB Code 2: Graph Electrostatic Force versus Displacement.

```
clc
n = 200;
e = 8.85e-12;
t = 20e-6;
V = 0:10:110;
d = 6e-6;
F = (n*e*t*(V.^2))./d;
F1 = F./1e-6;

s = 6e-6;
E = 165e9;
w = 2e-6;
l = 100e-6;
k = (E*w*(s.^3))./(2*(l.^3));
x = F/k;
x1 = x./1e-6;

plot(F1,x1);
xlabel('Electrostatic Force, F (uN)');
ylabel('Displacement, x (um)');
title('Graph Electrostatic Force vs Displacement');
grid on
```

3. MATLAB Code 3: Graph Voltage versus Displacement and Graph Displacement versus Capacitance.

```
clc
n = 200;
e1 = 8.85e-12;
t = 20e-6;
V = 0:5:110;
d = 6e-6;
F = (n*e1*t*(V.^2))./d;

tc = 6e-6;
E = 165e9;
w = 2e-6;
l = 100e-6;

k = (E*w*(tc.^3))./(2*(l.^3));
x = F./(k)
x1 = x./1e-6;

e2 = 8.85e-12;
T = 1e-3;L = 3e-3;
L1 = L-(x.*1e3);
A = T.*L1;
d1 = 3e-6;
C = (e2.*A)./d1

figure (1)
plot(V,x1);
xlabel('Voltage, V (v)');
ylabel('Displacement, x (um)');
title('Graph Voltage versus Displacement');
grid on

figure (2)
C1 = C./1e-12;
plot(x1,C1);
xlabel('Displacement, x (um)');
ylabel('Capacitance, C (pF)');
title('Graph Displacement versus Capacitance');
grid on
```

DESIGN & SIMULATION OF MEMS VARIABLE CAPACITOR FOR OPTIMUM ANTENNA TRANSMISSION

By

Noor Azreen Binti Mohd Faizol

A project dissertation submitted to the

Electrical & Electronic Engineering Programme

(Universiti Teknologi PETRONAS)

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(Electrical & Electronic Engineering)

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