**DESIGN OF
COMBLINE FILTER
FOR MICROWAVE P2P LINK**

By

ERKIN AHUNDOV

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Department of Electrical & Electronic Engineering
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Approved:

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Dr. Wong Peng Wen
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

September 2012

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.

Erkin Ahundov

ABSTRACT

Microwave filters are an essential part of communication systems operating in the specified frequencies range. The main challenges faced by the designers today are reduction of power loss and size of the filters. This paper is intended to develop a cavity combline bandpass filter for microwave P2P link in order to introduce it to the Malaysian market. The report attempts to find a suitable solution to the present demand in the market by offering a new design used in the field. The methodology to be used in the process of the project includes calculation of the filter parameters, designing the filter in Ansys HFSS software, simulation, designing layout of the transmission lines, fabrication, testing, and tuning. The paper also highlights the history of the microwave engineering development, and reviews the previous studies and projects of different groups to use as an example and reference in the current case. The project is the Final Year Project of a Bachelor of Engineering (Hons) Electrical & Electronics Engineering student at Universiti Teknologi PETRONAS.

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LIST OF ABBREVIATIONS

P2P	Peer-to-Peer
RF	Radio Frequencies
TE	Transverse Electric (Mode of wave propagation)
TM	Transverse Magnetic (Mode of wave propagation)
TEM	Transverse Electromagnetic (Mode of wave propagation)
HFSS	High Frequency Structural Simulator
S-matrix	Scattering Matrix (used to describe two-port networks)

CHAPTER 1
PROJECT BACKGROUND

1.1 Introduction to Microwave Filters

Today, microwave filters are used in a great variety of different fields, especially, communication systems. The microwave filters, as the name suggests, operate on the signals in the range of frequencies from 300 MHz to 300 GHz. With the spread of the modern communication technologies over the last century, the demand and use of different types of RF and microwave filters have dramatically increased.

Filters represent two-port networks that are designed to control the frequency response of communication systems by allowing through the wanted signal frequencies and rejecting the unwanted signal components. [1] In general, four types of filters are used: lowpass, highpass, bandpass, and bandstop. The nearly ideal sample frequency responses of the filters mentioned above are illustrated in Figure 1.

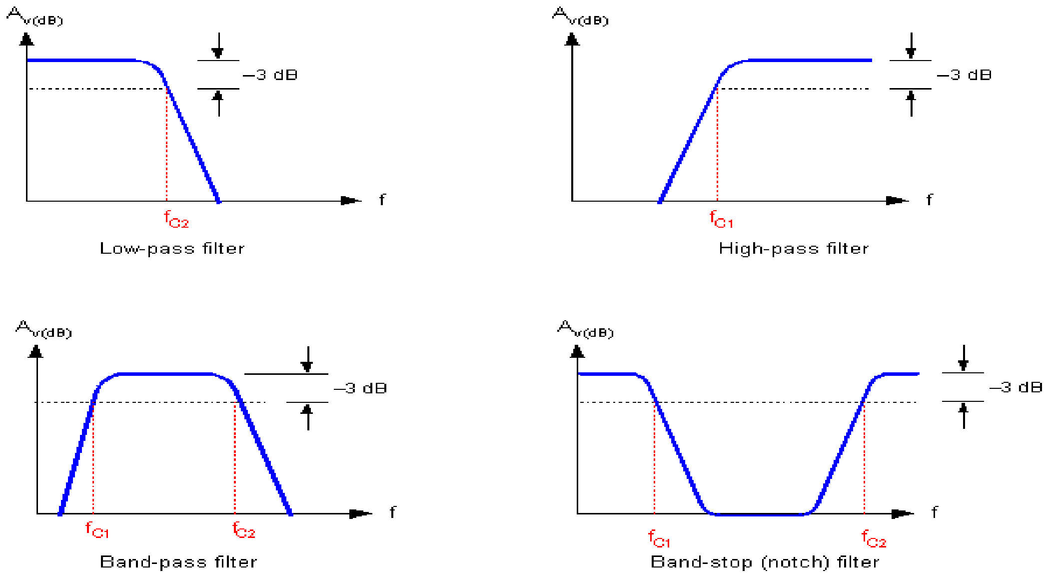


Figure 1 *Types of Filters and their sample frequency responses*

The frequencies denoted as f_c on the graphs are called cut-off frequencies which are the boundary frequencies of the filters at which the system's response will decrease dramatically, thus, stopping the unwanted signal frequencies.

There are different types of filters depending on their frequency response characteristics, such as, Butterworth, Chebyshev, Elliptic, and Bessel. Each of these types has its own applications depending on the desired frequency response.

Due to the scope of the current project, a closer look would be taken on the Chebyshev type filters only. The main characteristic of Chebyshev filters is that in their frequency response the differences from the ideal filter characteristics are minimized in the cost of the ripples in the passband. As shown on Figure 2, the frequency response of the Chebyshev lowpass filter after the cut-off frequency is much steeper than the one of the Butterworth filter, which is a great advantage in most of filter applications. The gain in the undesired frequency range should be minimized in order to prevent interference with other systems' signals. However, the presence of ripples in the passband is the trade-off of using Chebyshev filters. [2]

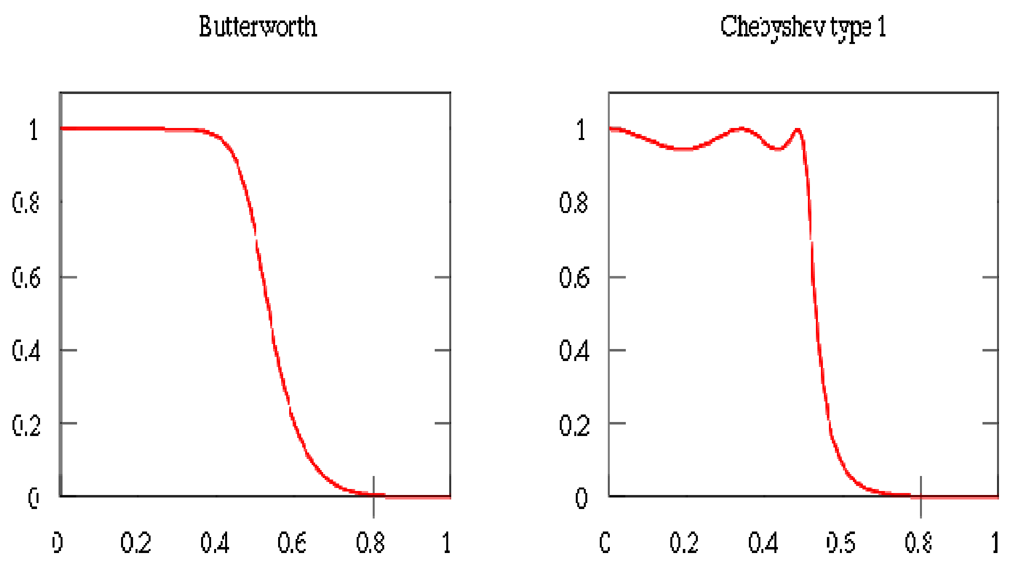


Figure 2 *Sample Responses of Chebyshev and Butterworth Lowpass Filters*

1.2 Problem Statement

Today, the communications is a very important field and it is very hard to imagine our current environment with no electromagnetic waves in the atmosphere. Moreover, the communication systems are still being developed and advanced bringing new inventions and technologies every day.

In Malaysia, like in the rest of the world, the communication is a vastly developing industry requiring more and more communication equipment. While the demand grows, there is only a small number of companies that manufacture the communication equipment. If we take a look at the production of microwave filters in Malaysia, then we will find out that there are none.

Usually, the communication companies have to purchase the microwave filters that have been produced and imported from other countries. Therefore, the aim of this project is to develop a new design of the microwave combline bandpass filter that would be demanded in local market and would cost less than analogous imported products.

Then, if a closer look is taken at that transmission lines microwave filters, the studies show that there are various types of filters produced that differ in the transmission lines used and their layout (topology). The bandpass filters that are mostly used today are interdigital filters because their frequency response is very symmetrical and is a better choice for wide bandwidths. But when it comes to the narrow bandwidths, the interdigital filters are quite large in size, which is a disadvantage. Thus, the aim of the project is to design a combline microwave filter that would be significantly smaller in size at the cost of less symmetric frequency response. [13]

1.3 Objectives of the Project

The objectives that are aimed to be achieved upon the completion of this project are as follows:

1. To study, understand the theory of the microwave filters, and develop the skills in designing them.
2. To develop a high performance combline bandpass microwave filter that can be implemented in the Malaysian market for a significantly lower price than its imported analogies.
3. To test and then implement the filter in a real P2P link application.

1.4 The Scope of Study

While working on this project I have been focusing mainly on the research and theoretical background on the subject. Literature review and study includes the general theory of microwave engineering, types of microwave transmission lines filters, comparison of their advantages and disadvantages, design steps and techniques of the combline filters, fabrication, testing and tuning of the filter prototype.

CHAPTER 2
LITERATURE REVIEW

There have been a lot of research and studies done on the microwave signals and filters theory, design, and applications. The demand in the market and these extensive studies led to the industry's rapid development throughout the twentieth century.

2.1 Two-Port Networks and ABCD parameters

Two-port network is a mathematical model that is used to represent portions of larger electric circuits as a whole block with parameters that would characterize its response to a given input. A general representation of two-port network is shown in Figure 3 below, where V_1 and I_1 are input voltage and current, respectively, and V_2 and I_2 are the output voltage and current, respectively. [3]

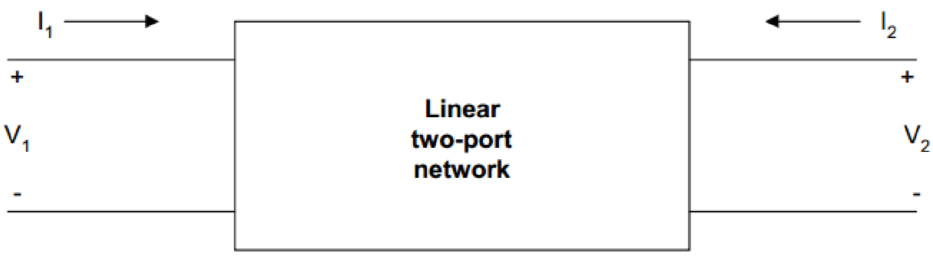


Figure 3 *General Two-Port Network*

A two-port network can be easily characterized by the ABCD parameters, which are found in the following way [3]

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (2.1.1)$$

where $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = [T]$ is called the Transfer Matrix.

The use of ABCD matrix to define the characteristics of a two-port network is the most commonly used technique. The network parameters are found using the following formulas [3]

$$A = \left.\frac{V_1}{V_2}\right|_{I_2=0} \qquad B = \left.\frac{V_1}{I_2}\right|_{V_2=0}$$

$$C = \left.\frac{I_1}{V_2}\right|_{I_2=0} \qquad D = \left.\frac{I_1}{I_2}\right|_{V_2=0}$$

If a two-port network is terminated with load impedance, Z_L, as shown on Figure 4, the input impedance is calculated as follows:

$$Z_{in} = \frac{V_1}{I_1}$$

Using the relationship between the input and output of a two-port network described in equation (2.1.1) we have the following [3]

$$\frac{V_1}{I_1} = \frac{AV_2 + BI_2}{CV_2 + DI_2}$$

$$= \frac{AV_2 / I_2 + B}{CV_2 I_2 + D}$$

$$Z_{in} = \frac{AZ_L + B}{CZ_L + D}$$

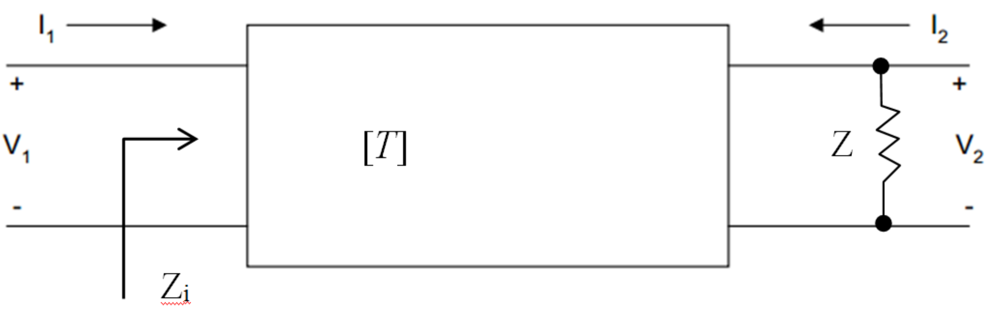


Figure 4 *Two-port network terminated with load impedance*

Furthermore, the transfer matrices for series arm and shunt arm are shown on Figures 5 and 6, respectively.

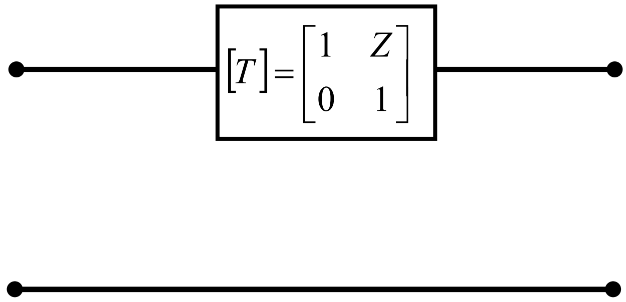


Figure 5 *Series Arm with impedance Z*

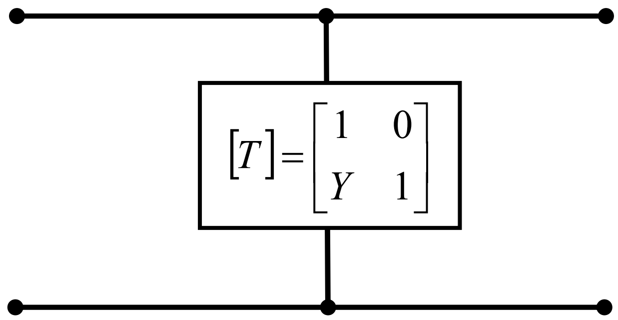


Figure 6 *Shunt Arm with admittance Y*

2.2 Two-Port Networks and the scattering matrix

Another set of parameters is also widely used in characterizing and analyzing two-port networks, called the scattering matrix or also S parameters. Figure 7 shows a typical two-port network illustrating all the voltage and current parameters at the input and output.

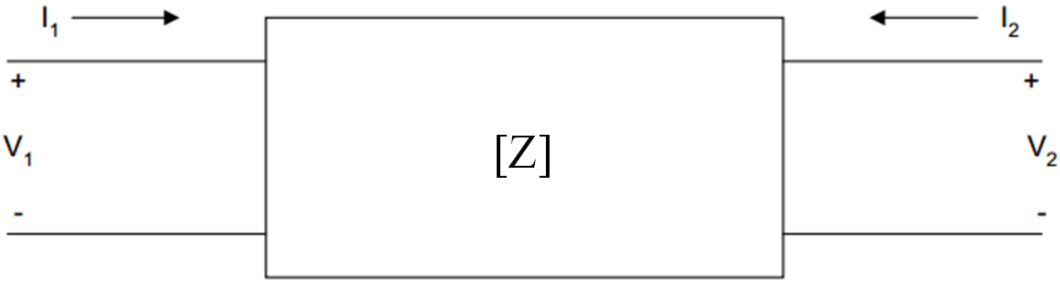


Figure 7 *Two-Port Network with [Z] impedance parameters*

Thus, we can represent the voltage in terms of the current and impedance matrices [3]

$$[V]=[Z][I]$$

where

$$[V]=\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad [I]=\begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$[Z]=\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

Now let

$$[a]=\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}=[V]+[I] \qquad \text{and} \qquad [b]=\begin{bmatrix} b_1 \\ b_2 \end{bmatrix}=[V]-[I]$$

Then also let

$$[S]=\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \text{ and } \quad [b]=[S][a]$$

or $$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix}=\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

where [S] is the scattering matrix of the two-port network.

And the impedance matrix can be rewritten in the following form:

$$Z=\frac{1+[S]}{1-[S]}$$

The S-parameters are given by [3]:

$$S_{11}=\left.\frac{b_1}{a_1}\right|a_2=0 \qquad S_{12}=\left.\frac{b_1}{a_2}\right|a_1=0$$

$$S_{21}=\left.\frac{b_2}{a_1}\right|a_2=0 \qquad S_{22}=\left.\frac{b_2}{a_2}\right|a_1=0$$

The following condition is true for the lossless networks:

$$|S_{11}(j\omega)|^2+|S_{12}(j\omega)|^2=1$$

For reciprocal and symmetrical networks:

$S_{12}=S_{21}$ and $S_{11}=S_{22}$.

Another two important parameters used for describing two-port networks are measured in decibels and are given as follows [1]:

Insertion Loss: $L_A=-20\log_{10}|S_{12}(j\omega)|\,\mathrm{dB}$

Return Loss: $L_R=-20\log_{10}|S_{11}(j\omega)|\,\mathrm{dB}$

2.3 Transverse Electromagnetic Mode of Wave Propagation

There are different types of electromagnetic wave propagation used in transmission lines, such as transverse electric (TE), transverse magnetic (TM), and transverse electromagnetic (TEM).

Transverse electromagnetic, in particular, is the mode of wave propagation when the electric and magnetic field lines are both perpendicular to the direction of wave travel through the media. TEM mode can only exist when there are two or more conductors, and when the cross-sectional dimensions of the transmission lines are relatively smaller than the signal wavelength. [4]

Figure 8 shows an example of TEM mode of propagation through a parallel plate waveguide. As seen on the figure, the magnetic field lines are circular around the conductors, whilst electric field lines are between these conductors, and both of them are in the planes perpendicular to the direction of wave travel.

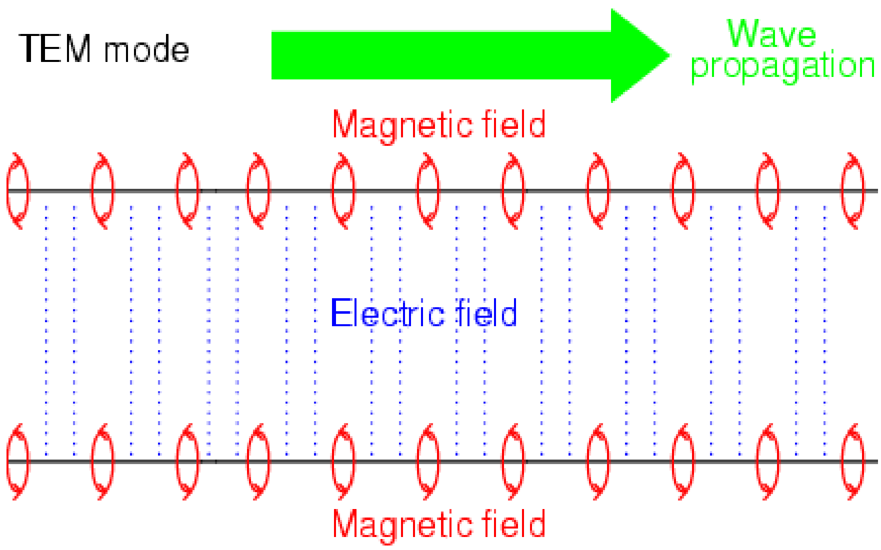


Figure 8 *TEM wave propagation in a parallel plate waveguide* [4]

TEM mode of propagation is very useful, because the cutoff frequency in it is equal to zero, i.e. $f_c=0$. Other advantages of this wave propagation mode are that there is no dispersion, or in other words, the various frequencies present in a signal would travel at the same speed.

Another type of transmission lines that is suitable for TEM mode of propagation is coaxial cable. As seen on the Figure 9, the electric field lines are radial, whereas the magnetic field lines are circular, and both of them are in the cross sectional plane of the cable, which is transverse to the direction of wave travel along the coaxial transmission line.

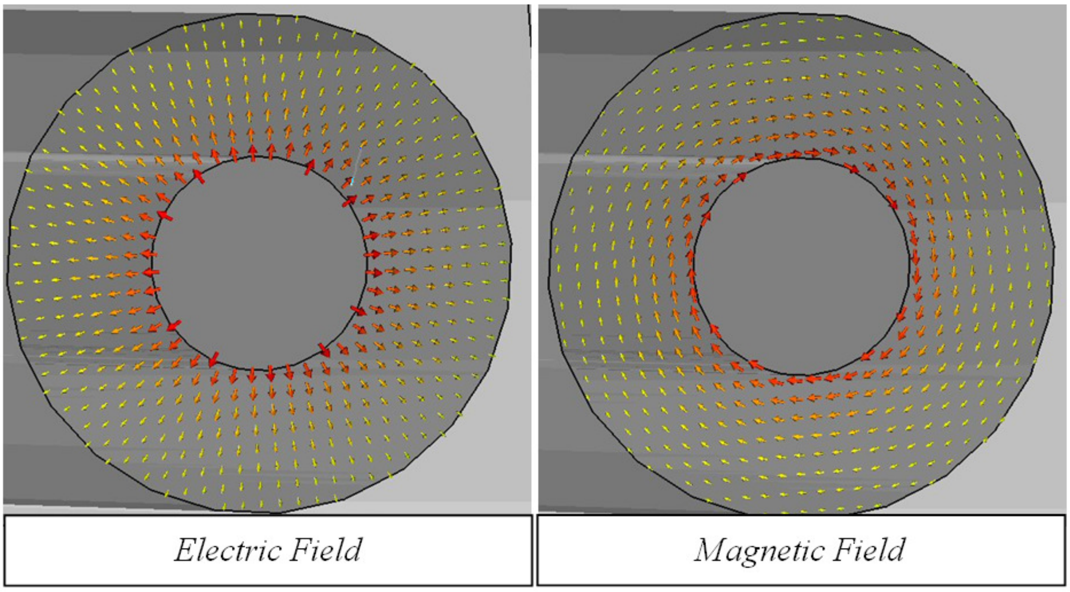


Figure 9 *TEM wave propagation in a coaxial transmission line* [4]

2.4 Coaxial Transmission Lines

Coaxial transmission lines consist of a wire conductor surrounded by a cylindrical conducting shield. The two conductors (inner and outer) are divided by a tubular dielectric insulator between them, as shown in Figure 10. In microwave communications, coaxial transmission lines mainly support the TEM mode of wave propagation which is a great advantage of using them. [5]

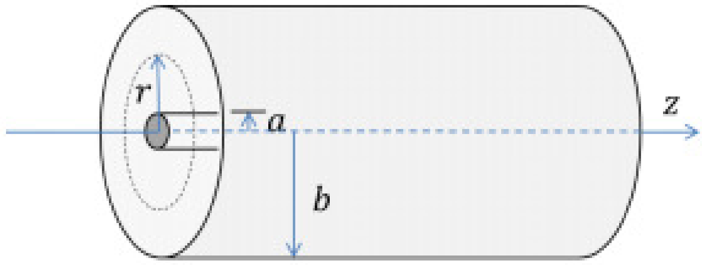


Figure 10 *Coaxial Transmission Line*

If we direct the z-axis along the transmission line, i.e. along the wave propagation, then according to TEM mode's conditions: $E_z = 0$ and $B_z = 0$.

The characteristic impedance of a lossless coaxial transmission line is calculated the following way: [2]

$$Z_0 = \sqrt{\frac{L}{C}} \tag{2.4.1}$$

The phase velocity of the TEM wave propagation inside transmission line is:

$$v_p = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu_0 \varepsilon}} \tag{2.4.2}$$

And the propagation constant is found by:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{2.4.3}$$

where L = inductance per unit length,
R = resistance per unit length,
C = capacitance per unit length,
G = conductance per unit length,
μ_0 = permeability of a vacuum,
ε = material permittivity.

The characteristic impedance can be furthermore elaborated by combining the equations (2.4.1) and (2.4.2):

$$Z_0 = \frac{60\Omega}{\sqrt{\varepsilon_r}} \ln \frac{b}{a}$$ [5]

where ε_r is the relative permittivity of dielectric material, a and b are the radii of the inner and outer conductors, respectively.

Both, electric and magnetic, fields are changed with the relation to the radius from the center of the inner conductor (vary with $1/r$) and are given by the following formulas:

$$E_r = \frac{V}{r \ln(b/a)} \qquad H_\phi = \frac{I}{2\pi r} = \frac{V}{2\pi r Z_0}$$

2.5 Microwave Combline Bandpass Filters

Microwave Combline filters are used in many communications applications for a very wide range of frequencies. Their main advantage is that they are compact in size and light in weight. Also, the combline filters are very stable to the changes in temperature and are very suitable for extreme operating conditions. [6]

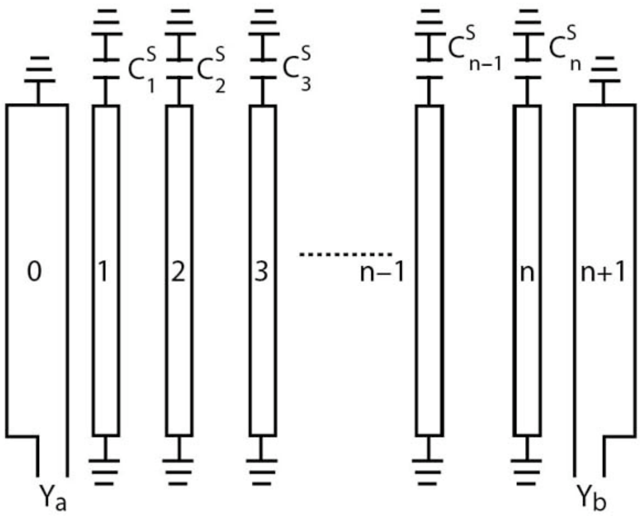


Figure 11 *Combline Filter* [7]

It is seen on Figure 11, that a combline filter consists of several transmission lines that are all short-circuited at one end. The other ends of the lines are connected to ground through lumped capacitors.

The combline filter operates in the following way. First, if we imagine that the lumped capacitors were taken out; the resonance frequency of the lines would be equal to the quarter wave. But at the same time, the couplings are supposed to resonate at the same frequency, resulting in all-stop filter. Now, if we introduce the capacitors, the lines would start resonating together along with capacitors at frequency which is lower than the quarter wave frequency. [6] [7] [8]

Compared to interdigital filters the combline filters are much smaller in size due to decreased length of transmission lines, as well as decreased spacing between the lines.

In order to better understand and predict the performance of combline filters, a simplified equivalent circuit is developed, illustrated on Figure 12.

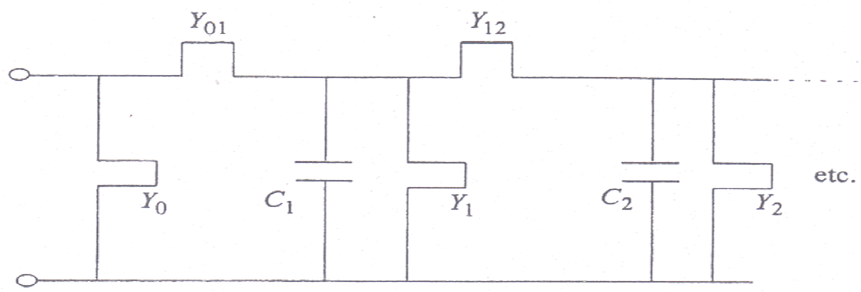


Figure 12 *Combline Filter Equivalent Circuit*

Also, some formulas have been derived in order to calculate the filter's physical parameters, listed below [6]:

$$Y_{rr} = C\omega_0 \tan(\theta_0) = \frac{C}{\beta} \tag{2.5.1}$$

$$n_r = \left[\frac{\alpha C_{Lr} \tan(\theta_0)}{Y_{rr}}\right]^{1/2} \quad (r=1,\ldots, N) \tag{2.5.2}$$

$$Y_{r,r+1} = \frac{K_{r,r+1} \tan(\theta_0)}{n_r n_{r+1}} \quad (r=1,\ldots, N\text{-}1) \tag{2.5.3}$$

$$Y_r = Y_{rr} - Y_{r-1,r} - Y_{r,r+1} \quad (r=2,\ldots, N\text{-}1) \tag{2.5.4}$$

$$Y_1 = Y_N = Y_{11} - Y_{12} + \frac{1}{n_1^2} - \frac{1}{n_1 \cos(\theta_{0)}} \quad (r=1 \text{ and } N) \tag{2.5.5}$$

$$Y_0 = Y_{N+1} = 1 - \frac{1}{n_1 \cos(\theta_0)} \tag{2.5.6}$$

$$Y_{01} = Y_{N,N+1} = \frac{1}{n_1 \cos(\theta_0)} \tag{2.5.7}$$

where Y_r are admittances of the resonators,

Y_{rr} are the coupling admittances between neighboring resonators,

θ_0 is the electrical length at the center frequency.

CHAPTER 3
METHODOLOGY

The parameters of the bandpass combline filter that is yet to be designed are listed below:

Table 1 *The Bandpass combline filter specifications*

<table>
<tr><th>Parameter</th><th colspan="2">Specification</th></tr>
<tr><td>Frequency Range</td><td colspan="2">824 MHz – 849 MHz</td></tr>
<tr><td>Center Frequency, f_0</td><td colspan="2">836.5 MHz</td></tr>
<tr><td>Bandwidth (BW), Δf</td><td colspan="2">25 MHz</td></tr>
<tr><td>Insertion Loss (Max), L_A</td><td colspan="2">1.0 dB max (passband)</td></tr>
<tr><td>Return Loss (Min), L_R</td><td colspan="2">20 dB min (passband)</td></tr>
<tr><td rowspan="2">Attenuation</td><td rowspan="2">60 dB</td><td>@ 800 MHz</td></tr>
<tr><td>@ 869 MHz</td></tr>
<tr><td>Impedance, Z</td><td colspan="2">50 Ohm nominal</td></tr>
</table>

3.1 Process Flow Planning

After the problem has been defined and the objectives have been clearly stated, the literature review was performed in order to get the general and then specific knowledge in microwave engineering and study the previous projects that have been done in the field. The literature based research is very important for the project as it forms the basis for the successful and meaningful outcome.

The thorough study during the research allowed me to sketch a plan of work to be done to reach the objectives. Detailed planning was important to be written up defining the activities and strict timeframes within which the important milestones have to be reached. The process flowchart for the current project is illustrated in

Figure 13 below which highlights all main steps that lead to the project's successful completion.

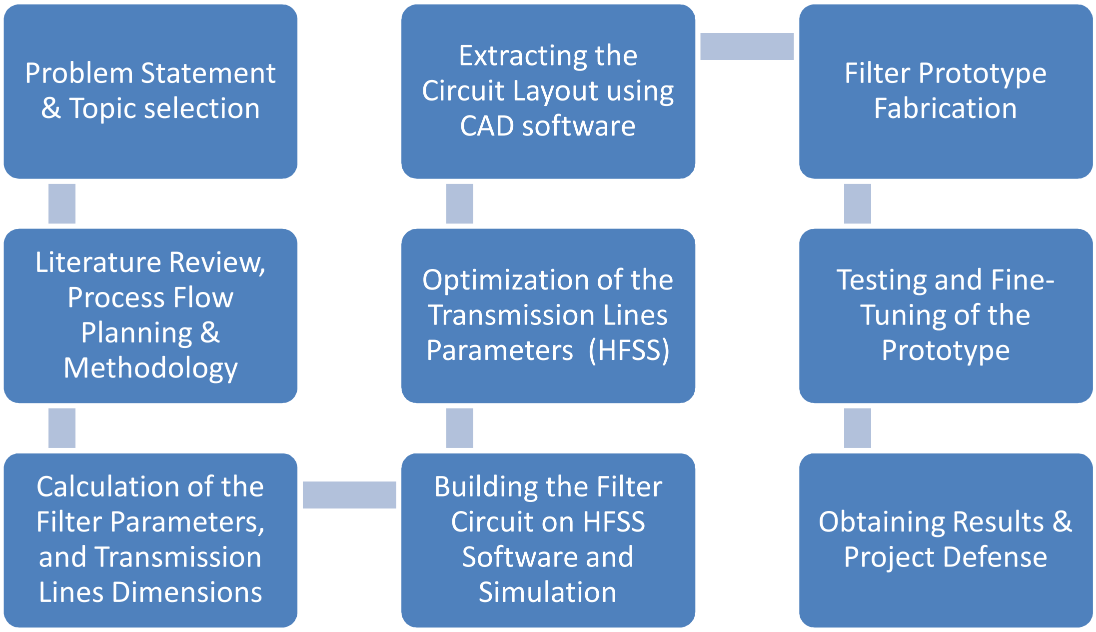


Figure 13 *The project process flowchart*

After the methodology was defined, calculation of the filter physical parameters started. It included computation of the filter's admittances, the values of the capacitors and derivation of its transfer function. Afterwards the dimensions of the transmission lines (resonators) were computed as well as the spacing between the resonators.

When the filter parameters had been acquired, the filter simulation was started using the Ansys HFSS 3D simulation software. It includes building the system in the software's interface, then simulating it and acquisition of the filter's frequency response. Based on the simulation results, optimization of the resonators' dimensions was required in order to correct the inaccuracies of the calculations.

After the filter parameters are confirmed and its simulated frequency response satisfies the objectives, the circuit from the Ansys HFSS would be extracted to the Computer-Aided Design (CAD) computer software. Afterwards, the extracted CAD design would be used for the filter fabrication that is to be done in the labs of Universiti Teknologi Petronas.

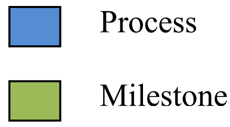
The fabricated prototype then needs to be tested using the frequency analyzer device, which will allow us to plot the frequency response of the filter. Based on the obtained results, fine tuning of the filter prototype may be required.

3.2 Tools and Software Required

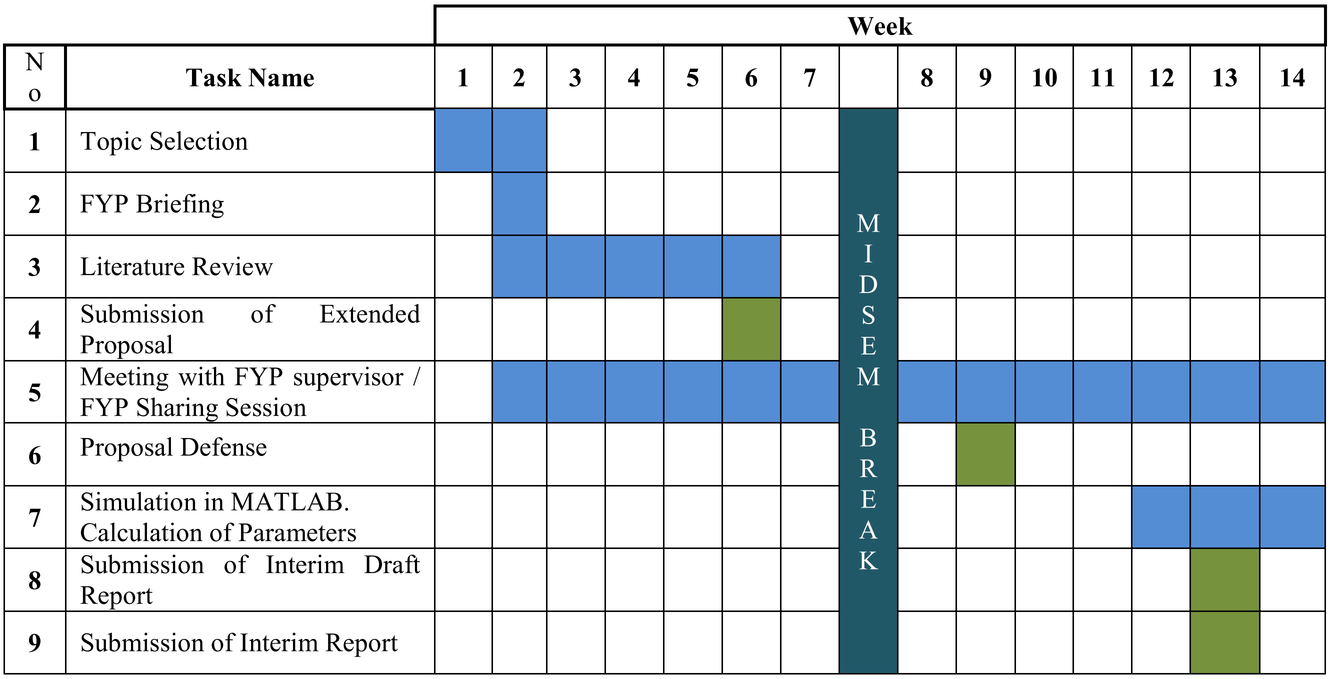
Table 2 *Tools and Software required for the Project*

Tools / Software	Function
MATLAB	• to simulate the Chebyshev Type 1 filter • to calculate the filter parameters
Ansys HFSS	• to build the 3D model of the filter and obtain simulated frequency response • to optimize the filter parameters, if required
CAD Software	• to extract the model layout for fabrication
Cavity Fabricator	• to fabricate the filter prototype
Frequency Analyzer	• to test the filter prototype and obtain its frequency response

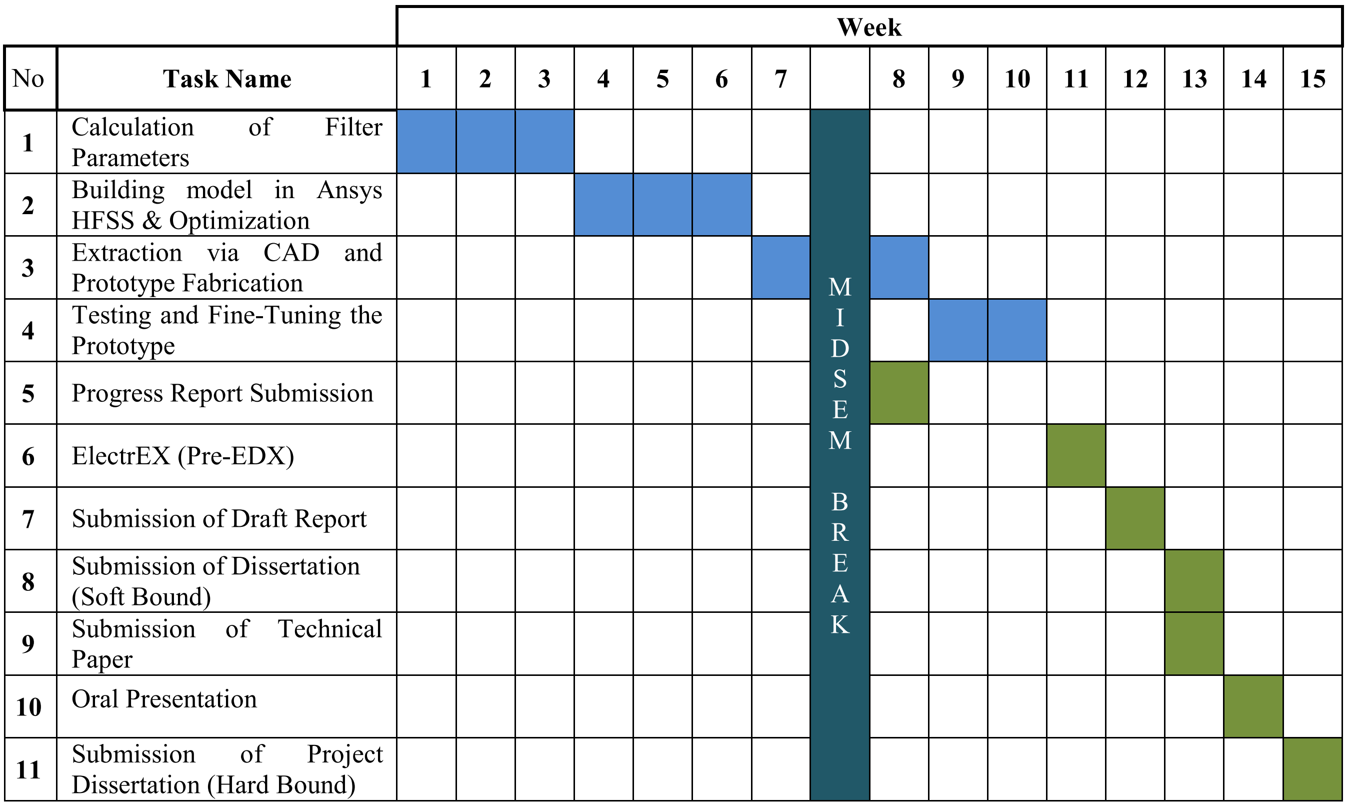
3.3 Gantt Chart and Key Milestones



Final Year Project I (May 2012)



Final Year Project II (September 2012)



CHAPTER 4
RESULTS AND DISCUSSION

4.1 MATLAB Simulation

In order to get a general idea of filter's frequency response, a filter is simulated in MATLAB. First, the order of the Chebyshev filter is calculated by the `cheb1ord` command setting the passband ripples to be within 1 dB. Then Chebyshev Type 1 lowpass filter prototype is generated using the `cheb1ap` command with the unity cutoff frequency and the order is returned by the previous MATLAB function. The lowpass prototype is then transformed into a bandpass filter that meets the requirements of this project by the aid of the `lp2bp` function. The coding that was used in MATLAB is listed in Appendix A.

After running the program the frequency response graph shown on Figure 14 was obtained from the filter simulation. The function `cheb1ord` returned the value `n` for the order of the system to be 6. Therefore, the filter designed and simulated in MATLAB is 6th order Chebyshev Type 1 **.**

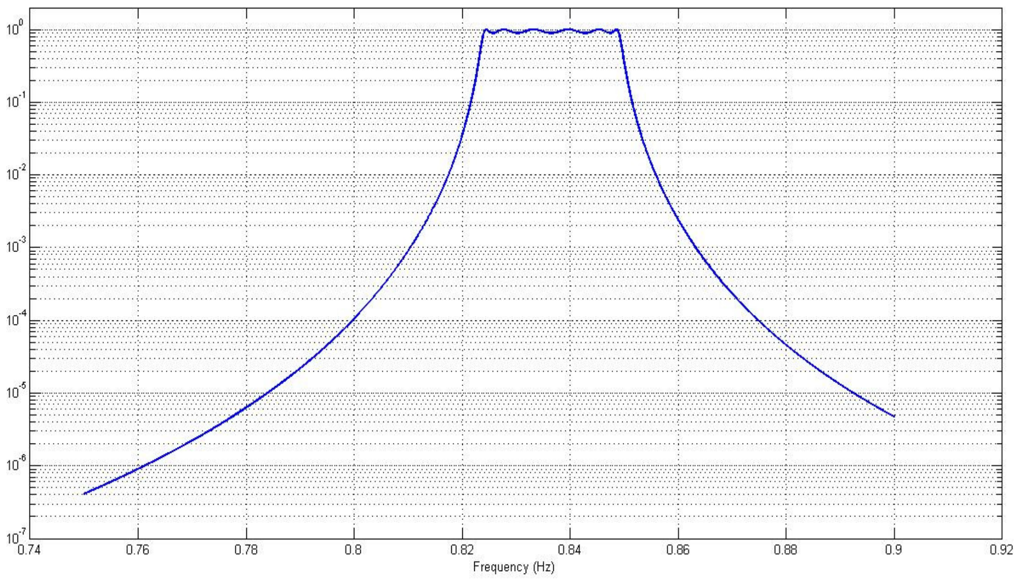


Figure 14 *The frequency response of MATLAB simulation*

4.2 Calculation of the Filter Parameters

There are several stages of mathematical analysis that lead to finding the filter's physical parameters or dimensions. First, a lowpass prototype filter is constructed based on the selectivity criteria and is then transformed into a bandpass filter with a specific center frequency and bandwidth.

4.2.1 Constructing Lowpass Prototype

The lowpass prototype filter is a lossless two-port network with the unity cut-off angular frequency consisting of lumped circuit elements and is operated at 1 Ohm nominal impedance. [9]

However, first of all, the order of the filter to be designed needs to be calculated using the following formula:

$$N \geq \frac{L_A + L_R + 6}{20\log_{10}[S + (S^2 - 1)^{1/2}]} \qquad [6]$$

where L_A = 60 dB is the stopband insertion loss; L_R = 20 dB is the passband return loss; and $S = \frac{\omega_S}{\omega_p} = 2.76$ is the ratio of the stopband to passband frequencies.

The right side of the expression above yields 5.92, thus, the order of the filter to be designed is N=6, which confirms the output of the MATLAB function. The 6th order Chebyshev lowpass prototype network is illustrated in Figure 15. It consists of shunt capacitors and impedance inverters.

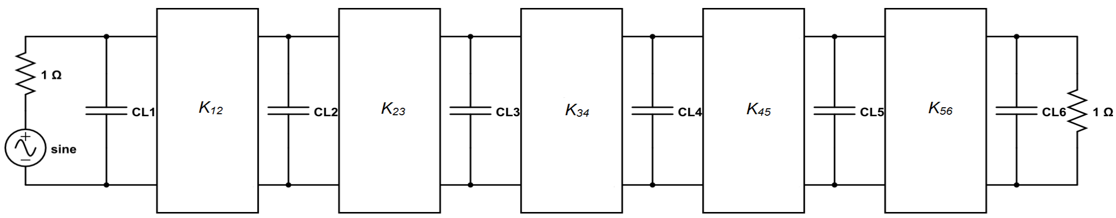


Figure 15 *The Lowpass Prototype Filter*

Next, the ripple factor is computed:

$$\varepsilon = (10^{L_R/10} - 1)^{-1/2} = 0.1005 \qquad [6]$$

To solve for the lowpass prototype filter parameters furthermore, we introduce a new parameter η, where

$$\eta = \sinh\left[\frac{1}{N}\sinh^{-1}\left(\frac{1}{\varepsilon}\right)\right] = 0.5198\,. \quad [6]$$

The shunt capacitances are then calculated using the equation

$$C_{Lr} = \frac{2}{\eta}\sin\left[\frac{(2r-1)\pi}{2N}\right] \qquad (r = 1,\ldots,N) \qquad [6]$$

which yields:

$C_{L1} = C_{L6} = 0.99584$

$C_{L2} = C_{L5} = 2.72069$

$C_{L3} = C_{L4} = 3.71653$

The characteristic admittances of inverters are found by the following formula:

$$K_{r,r+1} = \frac{[\eta^2 + \sin^2(r\pi / N)]^{1/2}}{\eta} \qquad (r = 1,\ldots,N-1) \qquad [6]$$

$K_{12} = K_{56} = 1.38754$

$K_{23} = K_{45} = 1.94314$

$K_{34} = 2.16820$

4.2.2 Determining the Q-factor

After the parameters of the lowpass prototype filter have been calculated, the unloaded quality factor of the filter Q_u can be determined from the following relation.

$$L = \frac{4.343 f_0}{\Delta f \times Q_u}\sum_{r=1}^{N} C_{Lr} \qquad [6]$$

where L is the passband insertion loss.

$\Rightarrow Q_u = 2160$

4.2.3 Transforming to Combline Bandpass Filter

Based on the parameters of the lowpass prototype we are now able to compute the parameters of the combline bandpass cavity filter. In order to make the filter more compact we choose the electrical length of the resonators at the center frequency to be θ_0=45° or $\pi/4$ radians. It means that the actual resonators will be 1/8 of the wavelength long. [6] [7] [10]

The steps taken to calculate the admittances of the transmission lines are shown in Appendix B and after scaling them to 50 Ohm, the impedances of the resonators and couplings between them are as follows:

$$Z_0 = Z_7 = 69.230\Omega$$

$$Z_1 = Z_6 = 68.641\Omega$$

$$Z_2 = Z_5 = 52.958\Omega$$

$$Z_3 = Z_4 = 52.404\Omega$$

$$Z_{01} = Z_{67} = 180.005\Omega$$

$$Z_{12} = Z_{56} = 1544.163\Omega$$

$$Z_{23} = Z_{45} = 2130.379\Omega$$

$$Z_{34} = 2231.147\Omega$$

$$C = 3.805\,pF$$

4.2.4 Physical Realisation of the Filter

The combline filter to be constructed will consist of rectangular aluminium bars that are shorted at one end and are connected to ground through a capacitor at the other. The bars are located in the middle between ground planes that act like the outer conductor of the coaxial line, while the bars being the inner ones. [11] [12]

The steps in calculating the physical dimensions of the resonators are all shown in Appendix C. The depth of the filter is b=15 *mm*, while the thickness of each resonator is t = 3 *mm*. Listed below are the widths of the resonators and the spacing between them [14]:

$w_0 = w_7 = 11.18mm$

$w_1 = w_6 = 12.10mm$

$w_2 = w_5 = 14.46mm$

$w_3 = w_4 = 14.44mm$

$S_{01} = S_{67} = 2.25mm$

$S_{12} = S_{56} = 10.95mm$

$S_{23} = S_{45} = 12.45mm$

$S_{34} = 12.6mm$

The length of the resonators is equal to one-eighth of the wavelength at the center frequency and is calculated below:

$$L = \frac{c}{f_0} \times \frac{45^o}{360^o} = 44.83mm$$

The capacitance at the end of each resonator is realised by attached conductor plates which are spaced from the ground plane by a distance *d*. From the definition of capacitance:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \qquad [5]$$

Choosing the dimensions of the plates to be 12 mm × 18 mm × 0.5 mm the spacing between the capacitor plate and the ground (the side wall of the filter) is determined to be d = 0.50 mm.

4.3 Design and Simulation in Ansys HFSS

The filter design was built using the Ansys HFSS (High Frequency Structural Simulator) software. The coaxial resonators were realised by the coupled aluminium rectangular bars between parallel ground planes that act as the outer conductors. The TEM lines 0 and 7 are not resonators though they are *λ/8* long, but are the part of the impedance transformation circuit.

The filter was built in symmetry relatively to the X and Z axes, so it would be much easier to alter the spacing between the resonators using variables while keeping the symmetry of the circuit.

The resonators (lines 1 to 6) have attached thin conductor plates with an equal area at one end which act as the capacitors and are distanced from the side wall of the filter (electrical ground) to produce the desired lumped capacitance that has been calculated for the combline filter.

The filter design constructed in Ansys HFSS is shown in Figure 16 and its views from various angles are presented in Appendix D.

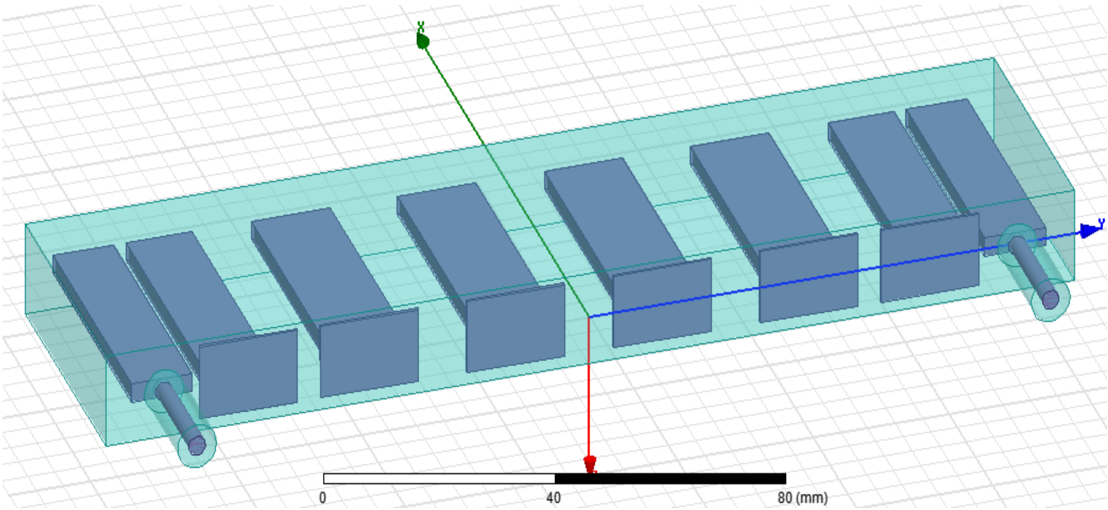


Figure 16 *Filter Design in Ansys HFSS*

The illustrated structure was analysed in Ansys HFSS and the initially obtained frequency response of the scattering parameters is plotted and shown in Figure 17. As seen from the plot, the center frequency of the filter is shifted by 90 MHz, i.e. is at 746 MHz. Moreover, the loss in the passband is very high and reaches -6 dB.

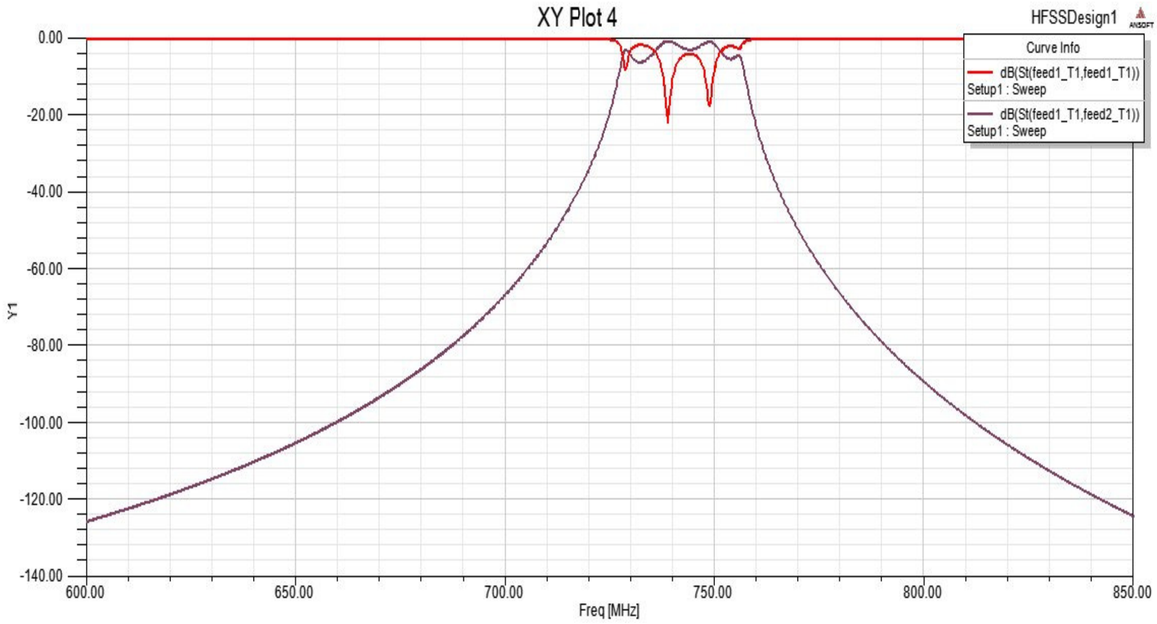


Figure 17 *Initial Frequency Response in Ansys HFSS*

The flaws mentioned above can be eliminated by optimizing the structure. The optimization in Ansys HFSS involves alteration of certain parameters until the aim is reached. Our goal is to make the passband return loss be in the range below -20 dB and the roll-off to 60 dB attenuation to be reached at 800 and 869 MHz. The variable parameters used in the optimization are the resonators' widths, spacing between the resonators, and the spacing between the capacitance plates and the ground. The frequency response of the filter after the optimization is illustrated on Figure 18.

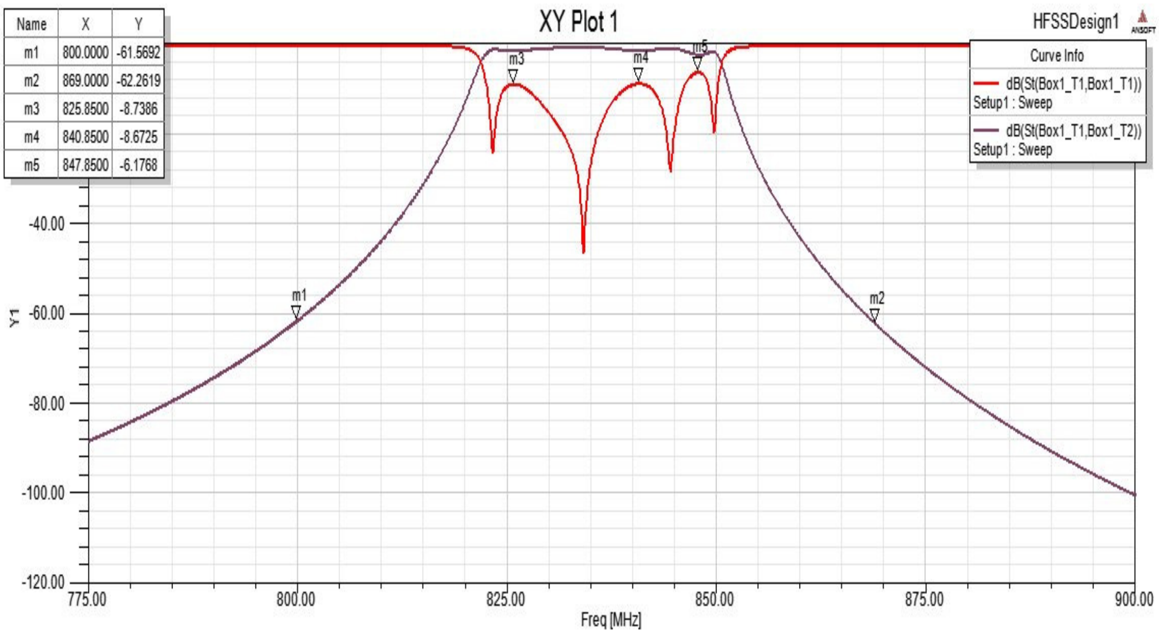


Figure 18 *Frequency Response in Ansys HFSS (after optimization)*

By altering the spacing between the capacitor plates and the ground, i.e. by varying the capacitance, the desired center frequency has been reached. Moreover, after optimizing the spacing between resonators the loss in the passband has been minimized to be within -2 dB range, and the lowest value of return loss is about -6 dB which is far less from the required -20 dB margin.

Due to the time and resources constraints that this project is faced with, the fabrication of the filter does not seem possible at the moment. However, even prior to that, a further optimization of the filter parameter is due to performed in order to obtain a better frequency response, namely to minimize the passband ripples and decrease the passband return loss below the -20 dB margin.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Since the project has started in the beginning of the previous term, I have acquired a lot of useful knowledge and skills in microwave engineering, which is one of the most important and widely used in communication systems and technologies nowadays. Communications, in turn, have undertaken a rapid development throughout the twentieth century and have become an essential part of our lives.

By working on this project and doing an extensive research on the subject, I have gained a valuable knowledge about the microwave filters, various methods of their design and fabrication. There are a lot of design techniques based on the type of transmission lines used and their layout topology, all of them have their advantages and drawbacks, so, it is up to the designer to decide which filter characteristic is the most important in the cost of the others.

Thus, it was decided to use the coaxial transmission lines as the resonators for our combline bandpass filter because the wave propagation mode in them is always Transverse Electromagnetic (TEM) which is very useful in such high frequencies. Another advantage of coaxial transmission lines filter is that the quality factor that can be achieved using the rectangular bars is quite high, resulting in high selectivity of the filter.

Therefore, one can conclude, that it is obviously feasible to achieve the objectives predefined in the beginning of the project progress. Moreover, it seems very realistic to develop a high performance microwave filter that can be implemented in the Malaysian market for a significantly lower price than its imported analogies.

Unfortunately, due to time and other resources constraints the current project may not seem to have be successfully completed. However, important lessons have been learnt and very useful and practical skills have been developed as well as new ones are acquired.

5.2 Recommendations

As for the future projects and studies in the same field, there is still a plenty of work to be done in order to complete the predefined objectives and get a better idea and full picture of the filter fabrication, testing and implementation. An essential part of the project is ought to be completed, which includes fine optimization of the filter parameters, fabrication, testing, and fine-tuning.

The step to be completed at this point of time is the optimization of the structure parameters. It includes altering the widths of the resonators, spacing between them, and distance between the capacitor plates and the ground until the desired frequency response is obtained.

Even if an ideal frequency response is obtained after the optimization using the software, most probably, the frequency response of the fabricated filter would differ from it. Therefore, fine tuning of the filter should be performed by inserting and tightening the screws inside the filter box. By changing the screws' penetration, we are able vary the couplings between resonators and the lumped capacitances attached to them; thus, alter the frequency response characteristics if there are any inaccuracies.

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APPENDICES

APPENDIX A

MATLAB SIMULATION CODING

```
Wp = [2*pi*824e6 2*pi*849e6]; % define the passband corner
                                frequencies (-1 dB)

Ws = [2*pi*800e6 2*pi*869e6]; % define the stopband corner
                                frequencies (-60 dB)

Rp = 1;                       % passband ripple

Rs = 60;            % attenuation at stopband corner frequencies Ws

[n,Wp] = cheb1ord(Wp,Ws,Rp,Rs,'s');  % Chebyshev Type 1 order
                        calculator. Returns the order of the filter n

[z,p,k] = cheb1ap(n,Rp); % Designs prototype Chebyshev type 1
                               lowpass filter

[A,B,C,D] = zp2ss(z,p,k);     % Convert to state-space form

u1 = 2*824e6*pi/1000e6; % normalizing the passpand frequencies

u2 = 2*849e6*pi/1000e6;

Bw = u2-u1;                   % Bandwidth in rad/sec

Wo = sqrt(u1*u2);             % Center frequency in rad/sec

[At,Bt,Ct,Dt] = lp2bp(A,B,C,D,Wo,Bw); % Transformation from
                                     prototype lowpass to bandpass


[b,a] = ss2tf(At,Bt,Ct,Dt);         % Convert to TF form.

w = linspace(0.75,0.9,500000)*2*pi;     % Generate frequency vector.

h = freqs(b,a,w);                  % Compute frequency response.

semilogy(w/2/pi,abs(h)), grid      % Plot log magnitude vs. freq.

xlabel('Frequency (Hz)');
```

APPENDIX B

LOWPASS TO BANDPASS FILTER TRANSFORMATION

The lowpass prototype values are as follows:

$C_{L1} = C_{L6} = 0.99584$

$C_{L2} = C_{L5} = 2.72069$

$C_{L3} = C_{L4} = 3.71653$

$K_{12} = K_{56} = 1.38754$

$K_{23} = K_{45} = 1.94314$

$K_{34} = 2.16820$

An intermediate parameter α is calculated [6]:

$$\alpha = \frac{2\omega_0 \tan(\theta_0)}{\Delta\omega\{\tan(\theta_0) + \theta_0[1 + \tan^2(\theta_0)]\}} = 26.0308$$

From the formula (2.5.1)

$$\beta = \frac{1}{\omega_0 \tan(\theta_0)} = 1.90263 \times 10^{-10}$$

Also from (2.5.1)

$$Y_{rr} = \frac{C}{\beta}$$

Choosing $Y_{rr} = 1$, we can determine the value of the lumped capacitance at the end of each resonator

$$C = \beta = 1.90263 \times 10^{-10}$$

Based on (2.5.2) another set of intermediate parameters n_r is computed that will be later used for determining the couplings between resonators

$$n_1 = n_6 = 5.0914$$

$$n_2 = n_5 = 8.4156$$

$$n_3 = n_4 = 9.8359$$

The couplings between the resonators are calculated using (2.5.7) and (2.5.3)

$$Y_{01} = Y_{67} = 0.27777$$

$$Y_{12} = Y_{56} = 0.03238$$

$$Y_{23} = Y_{45} = 0.02347$$

$$Y_{34} = 0.02241$$

The admittances of the transmission lines are then calculated using the formulas (2.5.4) to (2.5.6)

$$Y_0 = Y_7 = 0.72223$$

$$Y_1 = Y_6 = 0.72843$$

$$Y_2 = Y_5 = 0.94415$$

$$Y_3 = Y_4 = 0.95412$$

APPENDIX C
CALCULATION OF THE PHYSICAL DIMENSIONS

The static capacitances between the neighbouring coupled lines and the ground are illustrated in Figure 19 and are calculated below based on the relation

$$\frac{C}{\varepsilon} = \frac{377}{Z_0(\varepsilon_r)^{1/2}} \qquad [5]$$

$$\frac{C_0}{\varepsilon} = \frac{C_7}{\varepsilon} = 5.4456$$

$$\frac{C_1}{\varepsilon} = \frac{C_6}{\varepsilon} = 5.4923$$

$$\frac{C_2}{\varepsilon} = \frac{C_5}{\varepsilon} = 7.1188$$

$$\frac{C_3}{\varepsilon} = \frac{C_4}{\varepsilon} = 7.1941$$

$$\frac{C_{01}}{\varepsilon} = \frac{C_{67}}{\varepsilon} = 2.0944$$

$$\frac{C_{12}}{\varepsilon} = \frac{C_{56}}{\varepsilon} = 0.2441$$

$$\frac{C_{23}}{\varepsilon} = \frac{C_{45}}{\varepsilon} = 0.1770$$

$$\frac{C_{34}}{\varepsilon} = 0.1690$$

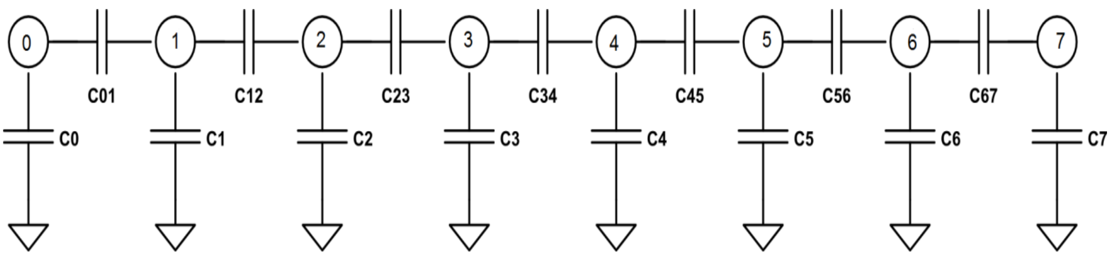

Figure 19 *Static Capacitances of the Filter*

The cross section of two rectangular bars of width *w* between parallel planes is shown in Figure 20 along with all the static capacitances that must be taken into account when designing the filter. The thickness of the lines is t and the distance between the ground planes is b. Coupling between the bars as a function of the normalized spacing is illustrated in the Figure 21 and is equal to

$$\Delta C = C'_{fo} - C'_{fe} \qquad [14]$$

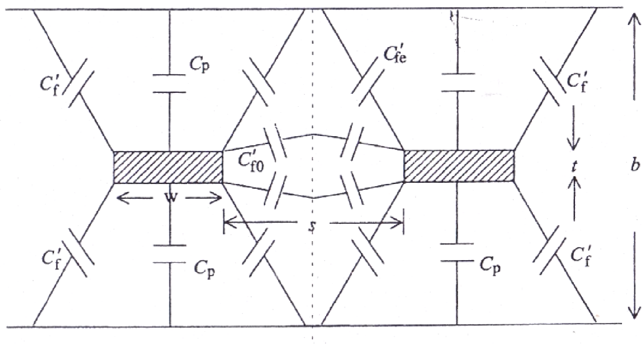

Figure 20 *Coupled Rectangular Bars between Parallel Plates* [14]

Choosing t/b = 0.2, and using the respective curve for the coupling capacitances $\Delta C/\varepsilon$ in the Figure 21 we can determine the normalised spacing between the bars

$$\frac{S_{01}}{b} = \frac{S_{67}}{b} = 0.15$$

$$\frac{S_{12}}{b} = \frac{S_{56}}{b} = 0.73$$

$$\frac{S_{23}}{b} = \frac{S_{45}}{b} = 0.83$$

$$\frac{S_{34}}{b} = 0.84$$

Then the even-mode fringing capacitances are determined from the same graph but using the C'_{fe} / ε curve for t/b = 0.2

$$C'_{fe\_01} = C'_{fe\_67} = 0.17$$

$$C'_{fe\_12} = C'_{fe\_56} = 0.56$$

$$C'_{fe\_23} = C'_{fe\_45} = 0.59$$

$$C'_{fe\_34} = 0.60$$

The normalized widths of the bars are calculated based on the following relationship

$$w_r = \frac{b-t}{4}\left(\frac{C_r}{\varepsilon} - 2C'_{fe\_r-1,r} - 2C'_{fe\_r,r+1}\right) \qquad [14]$$

which yields:

$$w_0 = w_7 = 0.9314(b-t)$$
$$w_1 = w_6 = 1.008(b-t)$$
$$w_2 = w_5 = 1.2047(b-t)$$
$$w_3 = w_4 = 1.2035(b-t)$$

The Q factor of a rectangular bar can be related to the impedance of the transmission line by the following expression. [6]

$$\frac{Q}{b(f)^{1/2}} = 2000 - 7.5Z_0 \qquad \left(0.1 < \frac{t}{b} < 0.5\right)$$

Taking Z_0 = 60.8 Ω as the average impedance we can find an approximately suitable value for the spacing between the ground planes b = 1.53.

Choosing b = 1.5 cm = 15 mm, which gives t = 3 mm, we can now calculate the actual dimensions of the combline filter

$$w_0 = w_7 = 11.18mm$$
$$w_1 = w_6 = 12.10mm$$
$$w_2 = w_5 = 14.46mm$$
$$w_3 = w_4 = 14.44mm$$

$$S_{01} = S_{67} = 2.25mm$$
$$S_{12} = S_{56} = 10.95mm$$
$$S_{23} = S_{45} = 12.45mm$$
$$S_{34} = 12.6mm$$

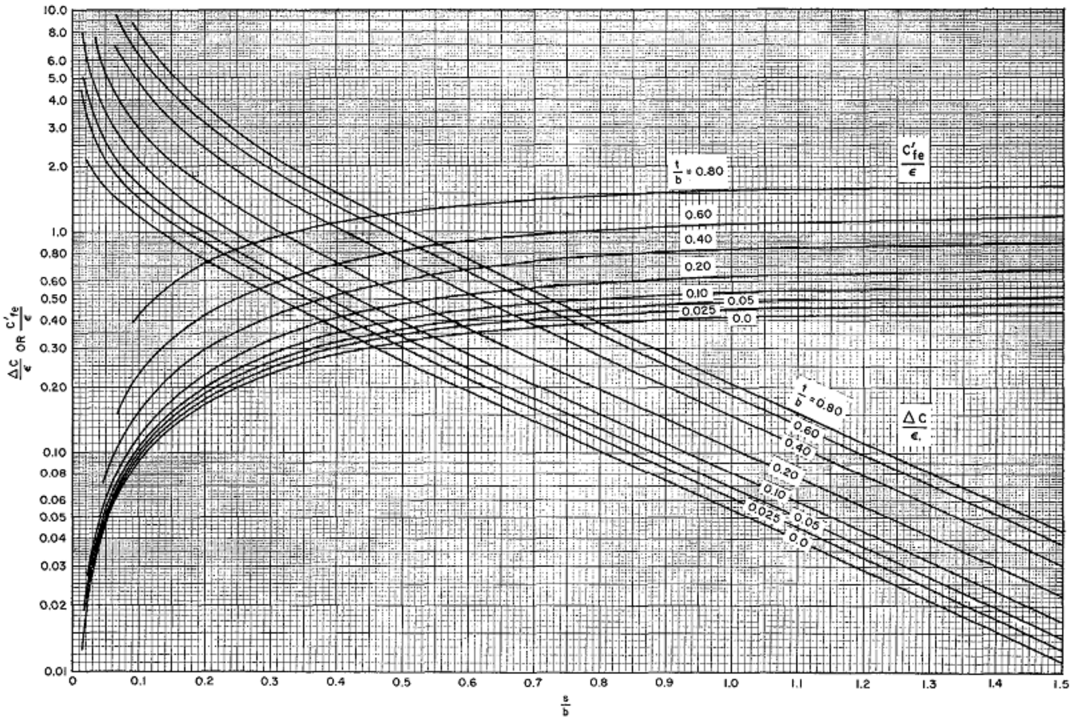

Figure 21 *Coupling capacitances of rectangular bars*

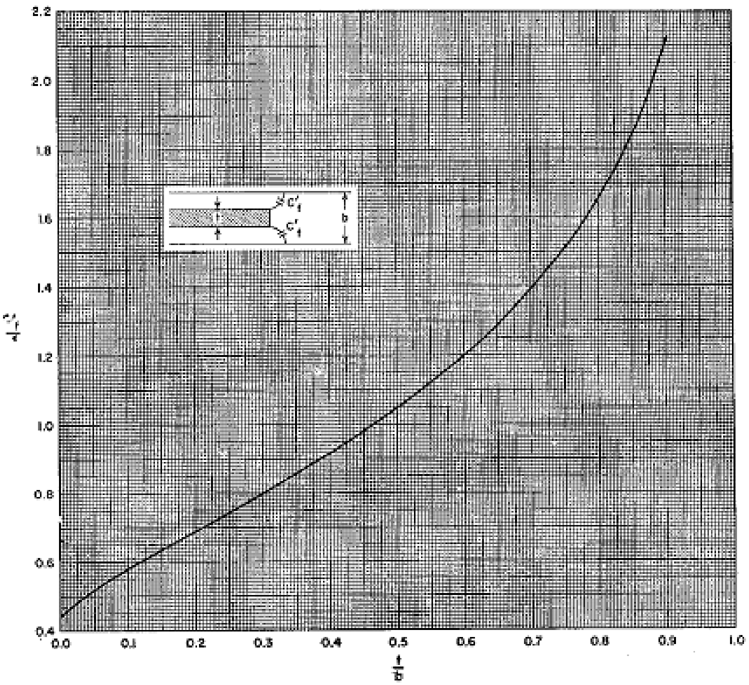

Figure 22 *Fringing capacitance of an isolated rectangular bar*

(Source: [14] Getsinger, W. J. (1962). Coupled Rectangular Bars Between Parallel Plates. *IEEE Transactions on Microwave Theory and techniques, 10(1),* 65-72).

APPENDIX D

FITER DESIGN IN HFSS

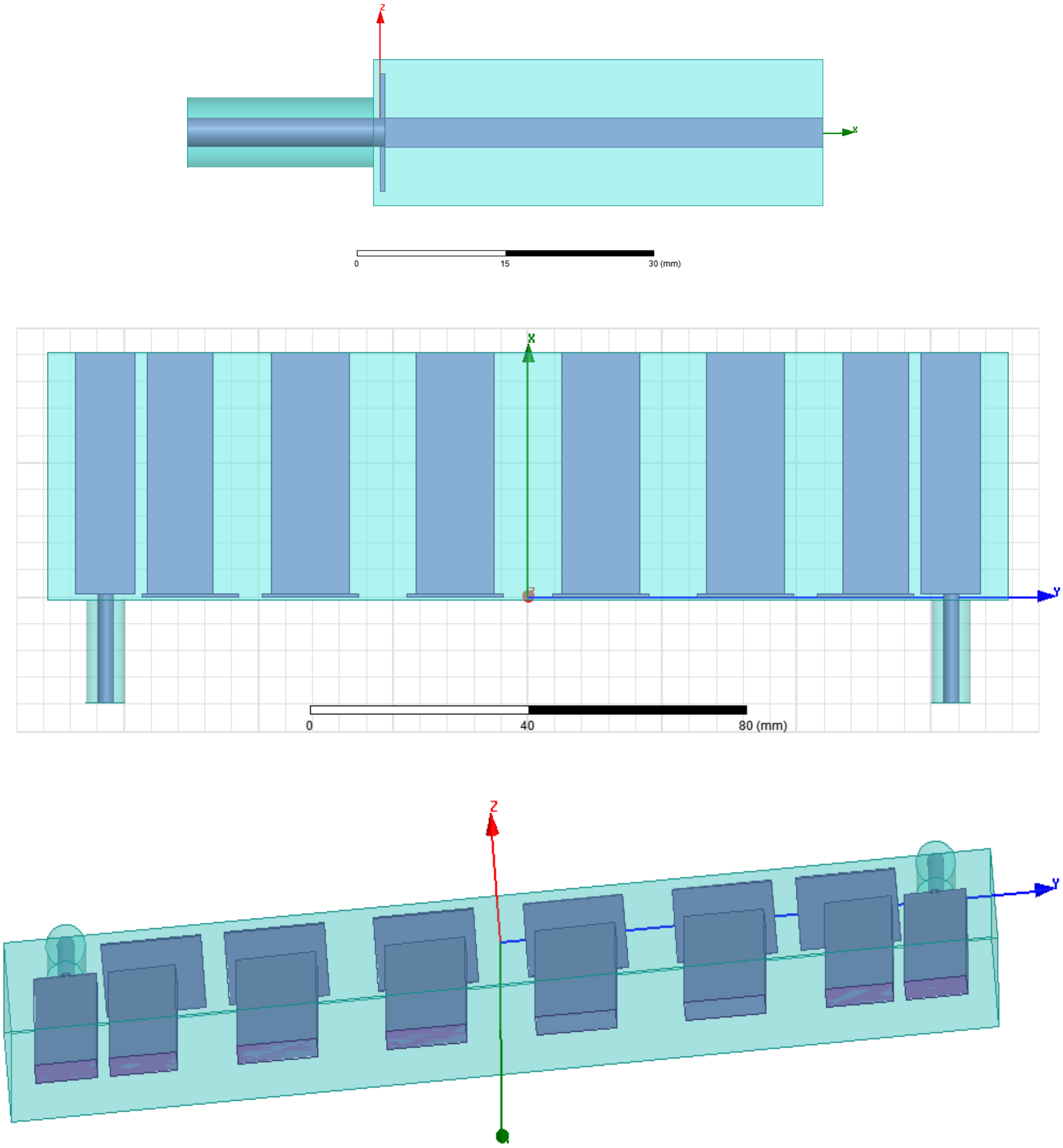

Figure 23 *Combline Filter Design in Ansys HFSS (various angles)*