DESIGNING WAVEGUIDE FILTER FOR
MICROWAVE P2P LINK

By

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FINAL PROJECT REPORT

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

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CERTIFICATION OF APPROVAL

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Approved:

_____

Wong Peng Wen
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 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.

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Annadurdy Sahetdurdyyev

ABSTRACT

The project is about designing a waveguide filter for microwave point to point link. The work will mainly be about designing a filter with high quality factor, maximum gain and minimum cost, which are primary objectives of communication system nowadays. The main problem will be choosing and analyzing the most suitable parameters that will be required for filter design. The filter will be responsible for removing all the noise from point to point radio waves transmission, resulting in almost perfectly matched signals in sending and receiving ends of the whole system.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

FYP	Final Year Project
P2P	Point to Point
HFSS	High Frequency Structure Simulator
WG	Waveguide Standard (UK)
TE	Transverse Electrical
TM	Transverse Magnetic
TEM	Transverse Electric and Magnetic
MATLAB	Matrix Laboratory

CHAPTER 1
INTRODUCTION

Waveguide filter is a filter that conveys the dissemination of microwaves in a certain direction by limiting the energy of the wave. They consist of metallic pipes with identical cross sectional area. Ideally it is assumed that the conductor and dielectric is accepted to be lossless. Even practically the loss of the filter is extremely low.

Microwave filters are type of filters that allow MW (microwaves) of certain frequency to pass while sorting out and removing other undesired frequencies in transmission lines [1]. These filters are used in high frequency applications, functioning on frequencies of 1 GHz and above, which is a very high frequency range. This frequency ranges are used for most wireless, broadcast and television transmissions, making waveguide filters very broad in applications.

Microwave filters operation is similar to electronic filters with only difference that is frequency range. Higher frequencies require allotted circuit elements to be used, like transmission lines, instead of lumped element circuits, like capacitors and inductors circuit, vastly used for low frequency applications. It makes the design of microwave filters very arduous, but it has many advantages as well. Higher frequencies allow effective coupling and useful transmission effects. At lower frequencies that is not possible.

The common design technique used nowadays is insertion-loss method, where filter designer approximates the amplitude response of filter by synthesis methods with computer aided design.

Waveguide filter are very suitable for super high frequency applications, as this types of filter have extremely low loss factor. Other notable advantage of waveguide filter is the fact that waveguides have comparably higher quality factor than many other filter types, which makes the filter much more expensive.

Waveguide band-pass filters have very small insertion loss. Even though designing these filters is very expensive, they are still more preferred over planar filters, because waveguide filter is extremely useful for frequency multiplexing in satellite network [2].
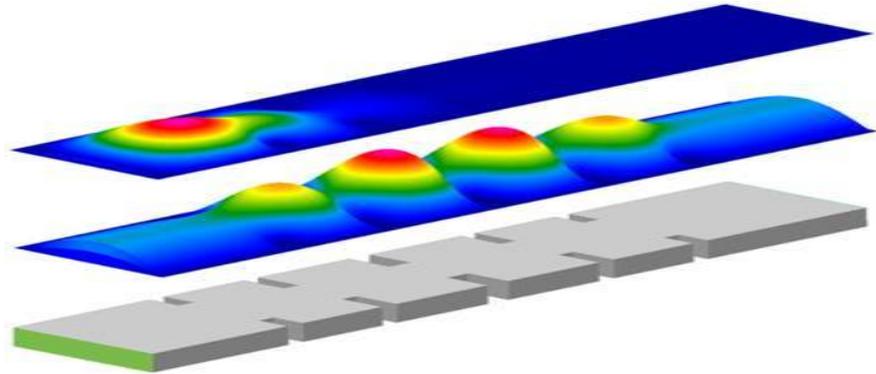
Figure 1   Waveguide (WG) Filter response in 3D

1.1   Problem Statement

In modern digital world the quality and authenticity of the signal received is very much of importance. When user receives signal it is important that the signal is very much similar to its original version, sent from transmitter. Unfortunately the perfect transmission is not attainable, but it is possible to get signal that corresponds to the original version by using waveguide filters to remove unneeded noises [1].

The typical distance for Microwave point to point transmission reaches 100 km, which is very long distance. The longer the distance, the more system is susceptible to noise. What's more Microwave point to point links must use line of sight communication between two antennas (transmitter side and receiver side). It means the antenna on transmitter side should be in line with receiver side antenna, with no vital obstacle in between [8]. But still there can be some minor obstacles that will interfere with the transmitted signal, which will add noise to the signal.

One reason that makes waveguide filters so vital but yet relatively expensive is the fact that microwave transmission transfers data in very large amounts and with very fast speed. The larger data at a time means the more processing must be implemented to analyze the authenticity of the signal. The more processing to be implemented requires the more advanced filter design.

1.2   Objectives of Study

There are several objectives that I expect to achieve upon the implementation of this project, which are:

1. Understand the steps of Waveguide filter design.
2. Design Waveguide filter prototype in HFSS software.
3. Optimize HFSS designed filter to attain acceptable result.

1.3   Scope of Study

Scope of work includes following steps:

1. Getting the specifications of waveguide filter
2. Analyzing the specifications of waveguide filter
3. Designing prototype in HFSS
4. Designing the filter based on HFSS parameters
5. Testing the filter
6. Finalizing the project

First we get the specifications of filter from our supervisor. All the further design will be based on those parameters. The specifications are about frequency range, central frequency, bandwidth, insertion loss, return loss, attenuation and impedance.

After getting the specification from SV, the analysis of the specification takes place. It is critical to understand their meaning, as the overall design success will be based on understanding of those parameters.

After understanding the parameters, I need to design a band-pass waveguide filter. The theoretical filter design is implemented in Microwave Office software, where you can build the filter from dozens of components to check how appropriate the design is to the demands. According to the specification we need to check filter's Chebyshev response.

After getting desired response, we will proceed with the designing the real filter. It will be done in a filter designing company, with the assistance of technician. Then the analysis of real filter will be implemented. I will check the real time response of real filter. The checking will be implemented using the programming software CAT. If the filter functions as expected the work will be done and I will proceed with presenting the work to my supervisor.

1.4   Relevance to Programme

Waveguide Chebyshev filter design of Microwave point to point link is relevant to the programme of my study, which is Electrical and Electronics Engineering. The project is from communication systems core branch of electrical and electronics engineering field.

What's more nowadays many industrial companies demand Universities to give more lectures on communication, as nearly all the industries in the world deal with certain communication. This project will help me to learn the design process of waveguide bandpass filter and give an idea about the principles of filter design as well as several design techniques.

CHAPTER 2
LITERATURE REVIEW

This session includes a detailed explanation of waveguide Microwave Filter Design and Application for point to point communication.

Radio waves frequencies range from 3 KHz to 300 GHz and microwave includes part of radio wave with frequency range between 300 MHz to 300 GHz. The information transmission demands simple Line of Sight between sending end and receiving ends of antennas.

A waveguide filters have single conductor consisting of pipe's boundary. They have distinct cut-off frequency, above which all the signals are allowed to pass and all the frequencies below cut-off frequency are suppressed. Cut-off frequency of waveguide structure is directly proportional to the cross sectional area of the filter [1].

2.1   Modes of Propagation

The mode of propagation of the waveguides depends on several parameters. Each waveguide can operate in a lot of patterns, each of them having different cut-off frequencies. There are two main modes of propagation of waves in waveguide structure.

2.1.1   *Longitudinal Mode*

In longitudinal mode waveguide forms a special standing wave pattern. Standing wave is type of wave that does not move, but increases and decreases at the same position [3]. This mode is related to lambdas of wave boosted by constructive interference from waves that are reflected from reflecting surfaces. Other lambdas are removed by means of destructive interference. In longitudinal mode there are several nodes that are positioned along the cavity of the waveguide.

Very good example of this mode is laser light. The simplest laser wave is formed by two opposite mirrors around the gain portion which is also called Fabry-Perot cavity [5]. The mode order is determined by lambda and mirror distance from each other. Usually the L is much greater than lambda, which means mode numbers also large. Below you may see the longitudinal mode for several waves:
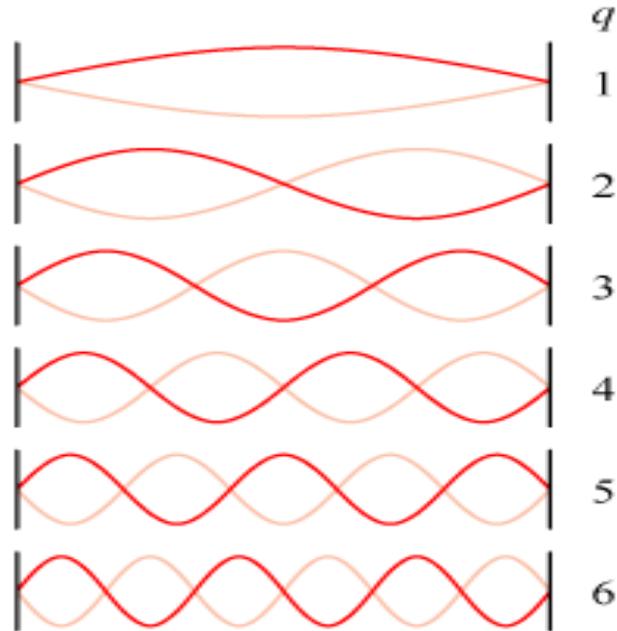
Figure 2   Longitudinal Propagation for different number of q

2.1.2 *Transverse Mode*

In transverse mode nodes are positioned perpendicular to the cavity, so when the H (electromagnetic field) pattern of the mode is measured, it is measured in plane that is perpendicular to the direction of wave propagation [3]. This is another common mode that occurs in microwave waveguides.

The main reason for occurrence of this mode is there are boundary conditions established by waveguide structure. Transverse characteristics of wave are limited within the walls of waveguide. The supported modes of a guide can be found by solving Maxwell. You may see the modes' description below [6]:

a. **TE Mode**: transverse electric mode –no electric field towards the direction of propagation.

b. **TM Mode**: transverse magnetic mode – no magnetic field towards the direction of propagation.

c. **TEM Mode**: Transverse Electro-Magnetic mode –no both Electric and Magnetic fields towards the direction of propagation.

d. **Hybrid Mode**: – has both Electric and Magnetic Fields towards the direction of propagation.

The appropriate guide is chosen from parameters we require, such as quality factor or size. When signal is generated, it is generated in several frequencies, some of which are not needed. Main signal mixes with some other signals it meets during transmission, thus some error.

2.2 Cut-off Frequency

Cutoff frequency of a waveguide is the minimum frequency for which the wave will propagate in the structure. It is important to consider cutoff frequency that can be found by considering the cutoff wavelength of the waveguide structure. After approximating the effective cutoff wavelength the cutoff frequency can be calculated by using characteristics equation of EM waves. To find frequency we set longitudinal waves to be zero in EM wave equation. It will result in any frequency below cutoff to be attenuated, or in another words the strength of signal will decrease. Below is the equation for the cutoff frequency [7] of rectangular waveguide:

$$\omega_c = c \sqrt{\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2}$$

For circular cross-sectional waveguide structure equation varies. This structure is used in transverse magnetic mode. The advantage of the structure is that there is no angular dependence, and the radial dependence is very low. Below you may observe cut-off frequency for different type of filters:
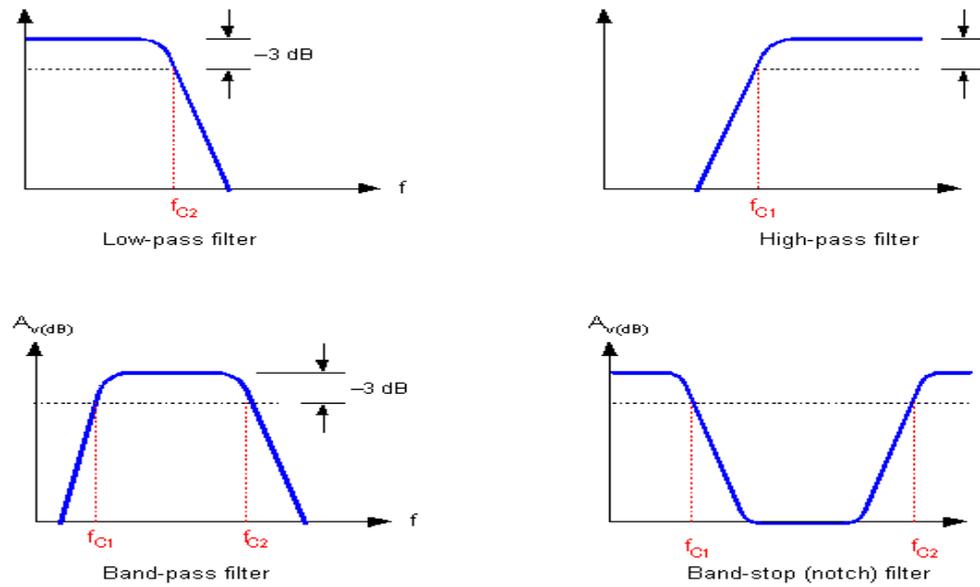
Figure 3   Cut-off frequencies of different filters

2.3   Quality Factor

Quality factor is a parameter with no dimensions. It is used to describe how under-damped the element (oscillator or resonator). It gives information about the fc (central frequency) and bandwidth of resonator. The larger the Q factor is lesser energy is lost, thus oscillations last longer.

The good example will be a pendulum hang in ceiling and oscillating in air has greater quality factor that the pendulum that oscillates inside the oil. High Q factor oscillators have low damping, so they oscillate longer.

$$Q(\omega) = \omega \; \frac{Maximum \;\; Energy \;\; Stored}{Power \;\; Loss} \qquad [3]$$

Waveguide filters have very high quality factor. High quality factor results in better power handling, so power loss is reduced. The effect of quality factor on response of the filter can be seen below:

8
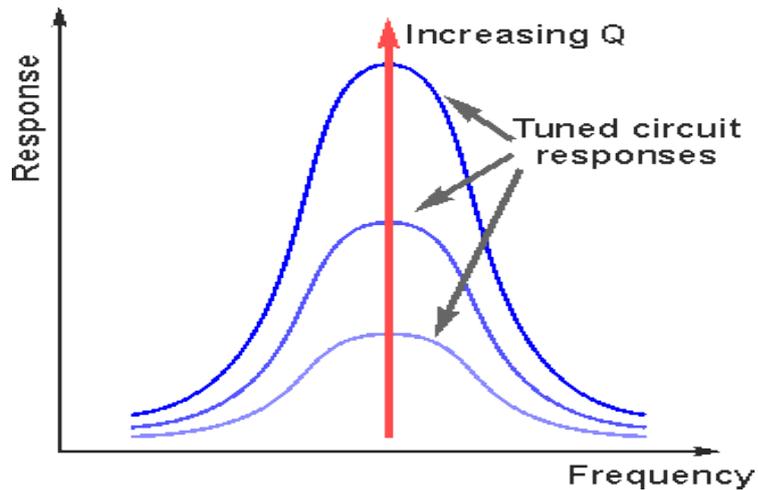
Figure 4   Effect of quality factor on response of filter

2.4   Transmission Lines

As we already seen waveguides have special structure consisting of hollow metallic tube. The function of tube is to provide distributed L (inductance), and function of hollow space is for distributed C (capacitance).

The most effective application of waveguides is very high frequency signal transmission. At these frequencies the wavelength of signal is closer to the dimensions of waveguide structure. At lower frequencies waveguides are useless for electrical transmission.

The transmission of EM waves through waveguide transmission lines is very different than transmission of two conductor lines. Waveguides act more like guiding agents of EM energy. When EM wave propagates through hollow guide, only one field will be transverse to the propagation of the EM wave, either electrical or magnetic. The un-propagated field will loop in longitudinal mode but still in direction of transmission.

The mode of transmission depends on field that is transverse to the direction of propagation. If the field is electrical, the mode is transverse Electric, if magnetic then transverse Magnetic.
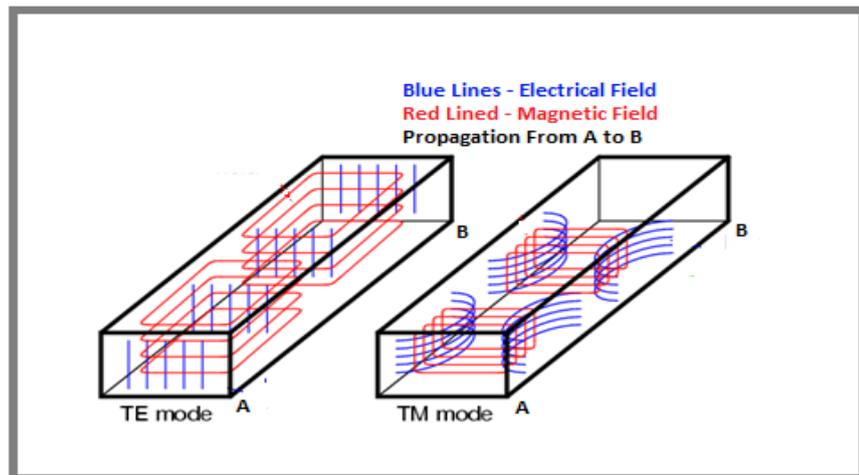
Figure 5   Transverse Electric vs. Transverse Magnetic propagation

The transmission and receiving of waveguide signals is implemented by coupling devices like antenna, which are implanted into waveguides. Waveguides increase the efficiency of transferred power from wave to output cable. New structures include movable plates and screws attached to top of waveguide in order to tune and attain desired response.

2.5   Waveguide Filter Design

The general design steps of waveguide bandpass filter begins with assumption of corner frequencies for high-pass and low-pass. Those frequencies are totally based on the design specifications.

After that level of ripple is determined from analysis of return loss [1]:

$$\varepsilon = \frac{1}{\sqrt{10^{L_R/10} - 1}}$$

The waveguide dimensions can be selected from standard dimensions given. Now λg1, λg2 and λg0 can be found by formulas below [1]:

$$\lambda_{g\,1,2} = \frac{\lambda_{0\,1,2}}{\sqrt{1-\left[\frac{\omega_c}{\omega}\right]^2}}$$

$$\lambda_{g0} = \frac{\lambda_{g1}+\lambda_{g2}}{2} + \left[\frac{\lambda_{g1}\cos\left(\frac{\pi\lambda_{g2}}{2\lambda_{g1}}\right)+\lambda_{g2}\cos\left(\frac{\pi\lambda_{g1}}{2\lambda_{g2}}\right)}{\lambda_{g1}\sin\left(\frac{\pi\lambda_{g2}}{2\lambda_{g1}}\right)+\lambda_{g2}\sin\left(\frac{\pi\lambda_{g1}}{2\lambda_{g2}}\right)}\right]$$

Bandwidth parameter of the filter, alpha, is calculated by [1]:

$$\alpha = \left[\frac{\lambda_{g1}}{\lambda_{g0}}\sin\left(\frac{\pi\lambda_{g0}}{\lambda_{g1}}\right)\right]^{-1}$$

Characteristic impedance is calculated from [1]:

$$Z_r = \frac{2\alpha}{\eta}\sin\left(\frac{(2r-1)\pi}{2_N}\right)$$
$$-\frac{1}{4\pi\alpha}\left\{\frac{\eta^2+\sin^2(r\pi/N)}{\sin\left((2r+1)\pi/2_N\right)}+\frac{\eta^2+\sin^2[(r-1)\pi/N]}{\sin[(2r-3)\pi/2_N]}\right\}$$

The degree of filter is determined by return loss analysis [1]:

$$N \geq \frac{L_A+L_R+6}{20\log_{10}\left[\sqrt{S+(S^2-1)}\right]} \qquad\qquad S = \frac{stop\ band}{pass\ band}$$

The susceptance (B) and characteristic admittance (K) of inductive irises then determined:

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

$$K_{r,\ r+1} = \frac{\sqrt{\eta^2+\sin^2(r\pi/N)}}{\eta}$$

$$B_{r,\ r+1} = \frac{\sqrt{Z_r Z_{r+1}}}{K_{r,\ r+1}} - \frac{K_{r,\ r+1}}{\sqrt{Z_r Z_{r+1}}}$$

At last we need to find phase length and physical length between irises:

$$\psi_r = \pi - 0.5 \left[\cot^{-1}\left(\frac{B_{r-1,\ r}}{2}\right) + \cot^{-1}\left(\frac{B_{r,\ r+1}}{2}\right) \right]$$

$$l_r = \frac{\psi_r \lambda_{g0}}{2\pi}$$

Below you may observe the final filter in two dimensions:
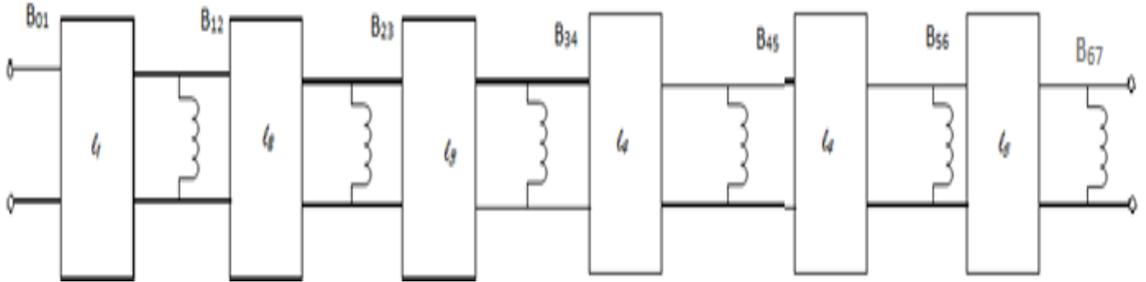
Figure 6   The final filter with shunt elements

After this, the final step is required that is iris electrical parameters conversion to physical alternative. The simplest way is using circular posts with certain diameter, shorted along the wall of structure. Number of posts depends on susceptance level required. The fixed posts make it easy to adjust the susceptance level, by adjusting the distance between posts.

To generalize the design of the filter we can say that first of all we need to approximate the edge band frequencies, to determine frequency range. Epsilon (ripple level) is determined by calculating the return loss. According to the frequency band we can determine the size of waveguide. Then we determine cutoff frequency of the structure, and lambda g one and two can be found from lambda g naught and alpha values. The formula is determined in above steps.

2.6 Waveguides in HFSS

HFSS is High Frequency Structure Simulator software used in modern communication systems to simulate the result of high frequency devices. The structure should be checked and verified through HFSS in order to approve the project. The steps need to be performed to design filter in HFSS are listed below.

1. Create New Project
2. Define Solution Type
3. Set Measurement Units
4. Draw the Object
5. Choose Object's Composition Material
6. Set Object Boundaries
7. Assign Excitation Ports
8. Set Solution Type
9. Set Frequency Sweep
10. Validate The Project
11. Simulation and Optimization

The detailed analysis of each step will be performed in next Chapter.

CHAPTER 3
METHODOLOGY

3.1 Gantt Chart

The project has a distinct border line for the implementation. The deadline of each activity for the project is determined by the University Technology PETRONAS board, and they are mentioned in course syllabus. For my project, I designed two more Gantt charts, in order to make the chart more conceivable. Below is the simplified Gantt chart for the Final Year Project I:

17 September - 07 November	07 November - 27 November	27 November - 07 December	07 December - 15 December	15 December - 21 December
Progress Report				
	ELECTREX			
		Draft Report		
			Dissertation	
			Technical Paper	
				VIVA

Table 1   Simplified Gantt Chart done in MS Excel

It is required to design Waveguide Bandpass Chebyshev Filter with transverse electric (TE) mode of propagation. The main criteria of acceptable result are return loss and insertion loss limits that need to be satisfied. Table below shows the criteria obtained from the supervisor for the final filter.

Parameters	Specifications	
Frequency Range	5150 MHz – 5250 MHz	
Center Frequency	5200 MHz	
Bandwidth	100 MHz	
Insertion Loss	1.0 dB maximum	
Return Loss	15 dB minimum	
Attenuation Maximum	-60 dB	@5080 MHz
		@5320 MHz
Impedance	50 Ohm Nominal	

Table 2   Project Specifications

3.2   Theoretical Design

Waveguide band-pass filters design includes the loading of identical length waveguides with mobile discontinuities. Below figure illustrates the theory:
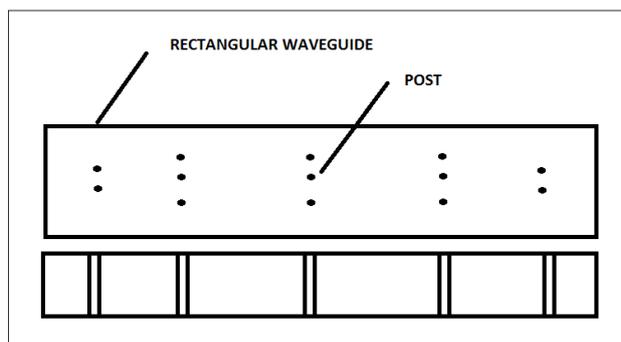

Figure 7   Waveguide structure with shunt discontinuities

The posts act like shunt inductive discontinuity, and section between two posts act like half-wave resonator [1]. This is very suitable arrangement for bandpass filter. Below you may see the equivalent circuit of shunt inductor:
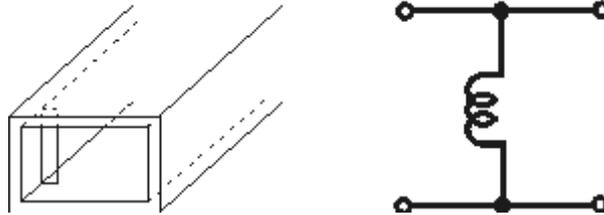

Figure 8   Inductive iris inside waveguide

3.3   Physical Realization

After all the mathematical calculations are done, the physical realization of the filter is implemented. For physical realization there are several steps that need to be performed.

The problem in real life filter design is that discontinuities cannot be built into filter straightforward. In reality it is very hard to realize inductors and capacitors in filter, because there are plenty of approximations and compensations need to be done.

3.3.1   Richard's Transformation

There is a technique, which transforms the shunt elements into stubs that are short circuited (in case of inductors) and open circuited (in case of capacitors). The transformation is called Richard's Transformation, and this transformation is used nowadays nearly in all filter design applications.

The formulas for transformation formula of capacitors into equivalent stabs are given by:

$$jX_L = j\Omega L = jL \tan \beta l \qquad \text{Transformation of inductor}$$

$$jB_L = j\Omega C = jC \tan \beta l \qquad \text{Transformation of capacitor}$$

For waveguide bandpass filter application it is required to transform the inductances obtained in theoretical part. The inductance value is known, so we can calculate the dimensions of a post that can be used instead of inductor. Inductor will actually be changed with special short circuited stubs, which have length of $\lambda/8$:
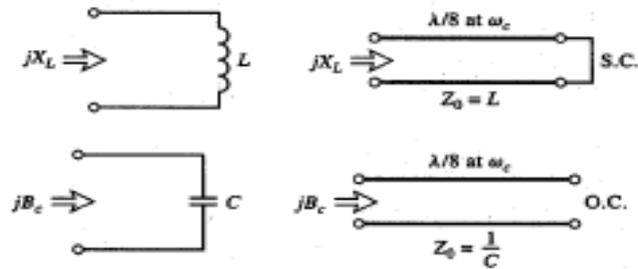

Figure 9   Richard's Transformation technique

3.3.2   *Kuroda Identities*

The main problem with Richard's transformation is the fact that the approximation is made for single straight inductors. For physical realization the inductors need to be in the form of irises separated by a certain distance (refer to figure below):
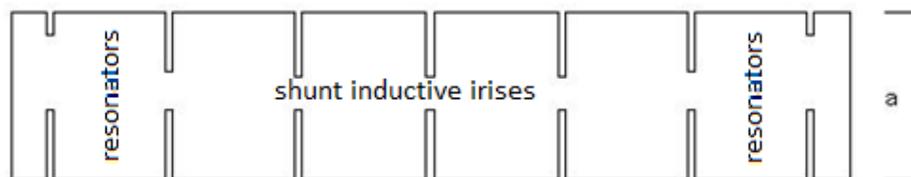
Figure 9: Desired Waveguide Iris Filter top view

Kuroda identities are perfect to transform those single inductors into more realizable inductive irises separated by some distance inside waveguide structure. The actions that can be done by using Kuroda identities are as following

Separate transformed stubs physically

Transformation of series inductance to shunt inductance

Transformation of shunt inductance to series inductance

Modification of characteristic impedances

For the above case Kuroda Identity to be used is transformation of parallel inductor input (refer to figure below) APPENDIX C:

Figure 10   Kuroda Identity Transform Parallel Inductor Input

Z1 is transformed to equivalent Z1/n2 alternative, where n is equal to:

$$n = \sqrt{1 + \frac{Z}{\omega_c L}} \qquad [15]$$
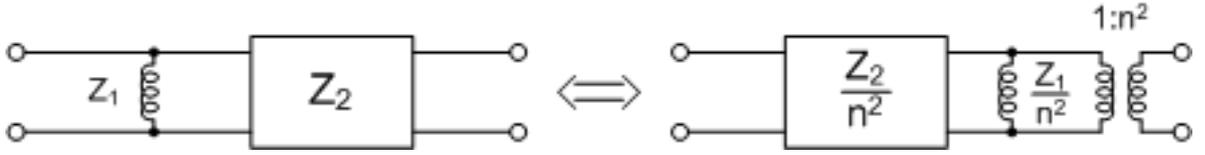
Note that inductive irises are not the same length (Figure 9), and when the filter is constructed some stubs will be longer than others.

3.4   HFSS Simulation Steps

As mentioned in previous chapter HFSS (high frequency structure simulator) is software used to observe the electromagnetic response for passive devices (filters, resonators, antennas and etc.) that deal with high frequencies (in GHz). HFSS is a three dimensional simulator-software and for that reason it is much more complicated and complex than other software.

Filters are critical elements of modern communication system, as they deal with issues of unneeded radiation and interference from outside elements. It is critical to simulate the output of the device before manufacturing, to save unneeded expenditures. HFSS is very suitable software to see the response for three dimensional structures.

First of all new project will be created. The step is required to be able to draw the structure and etc. The solution type will be defined in order to make it clear how the software will analyze the structure. Measurement units will be set to be in millimeters. Then object will be drawn based on calculated parameters of the structure.

The composition material of the filter will be aluminum guide filled with air. All the boundaries of the object except input and output ports will be perfect conductors. Input and output ports will be defined as excitation ports, where wave enters the guide and leaves it. Later the frequency sweep will be defined, which will be the desired frequency range to be analyzed. I'll set the range to be from 5 GHz to 6 GHz. Validation of the project will summarize the designing part of project in HFSS. Then the simulation of the project will be done to see the response of the filter. If the response will not be satisfactory, the optimization will be performed inside High Frequency Structure Simulator software in order to get the acceptable response of Waveguide bandpass filter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1   MATLAB Design

It is possible to generate the filter in MATLAB, to see what kind of response the structure will have. There is no specification on which exact type of filter you are designing for (Waveguide, microstrip or etc.), but it can give the passband response of the filter, which is critical to analyze before the manufacture of the filter.

There are two methods of designing the Chebyshev filter. First way is the easier way, as it approximates many parameters itself. Only passband, stopband and attenuation need to be specified. The only disadvantage of the first method is that the order is needed to be specified by the user. The function that is used in this method is called "sptool".

The second method is implemented by writing a program in MATLAB [APPENDIX A]. First the corner frequencies of the passband are defined. Then the desired ripple levels are defined for insertion loss and return loss.

The order of the filter is calculated by the MATLAB software, based on the parameters we entered. The order may be observed on the final response graph, by zooming in the desired portion of the response. Here is the part of the program written in MATLAB:

```
fs = [2*pi*5080e6 2*pi*5320e6];          % stopband corner f
fp = [2*pi*5150e6 2*pi*5250e6];          % passband corner f
A = 60;                                   % attenuation at
R = 1;                                    % ripple
```

The band of interest is the tine band in between, which is our pass band. The bandwidth we are interested in is the one that stretches from 0.5 to 0.54 (normalized) frequencies. It is 5,000 MHz to 5,320 MHz. The zoomed version of the graph, where only desired portion of graph can be seen:
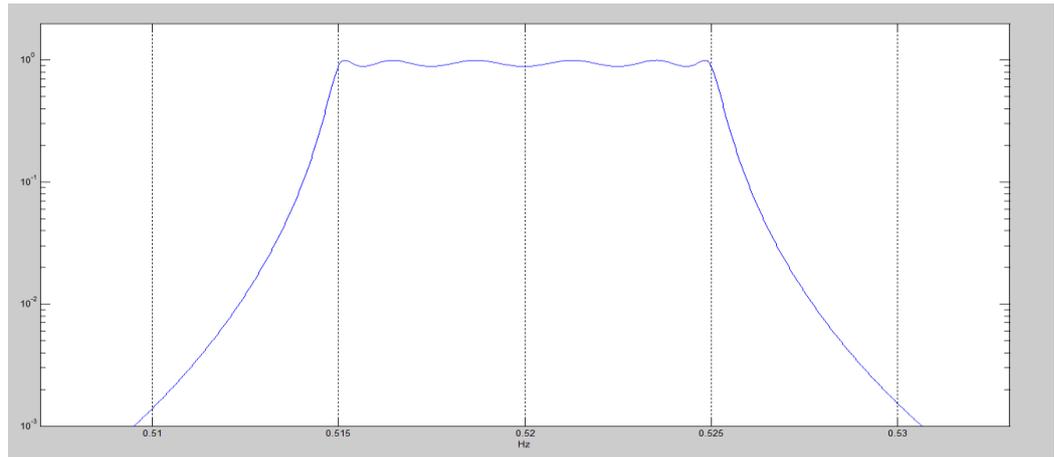
Figure 11   The response of Chebyshev bandpass filter

The ripples on the pass band can be seen clearly. The main objective is for ripples not to fall below -1 dB limit. The program successfully demonstrated the type of response to attain after implementation of the project.

4.2   Theoretical Design

The appropriate waveguide structure that corresponds to frequency ranges from 5.15 GHZ to 5.25 GHz is WG12 that has dimensions of 48mm x 22mm. Table below gives certain parameters for the different waveguide structures [11]. I am using UK Standards for the design, so WG structures are used [APPENDIX B]. WR structures are based on US standards.

Design	F range	Cutoff	Attenuation	MATERIAL	BAND	Dimensions
WG12	3.95x 3.85	3.152	2.08 - 1.44	Brass	F,G	48 x 22

Table 3   WG12 Design Structure

By using formulas I explained before, the parameters of the filter were calculated:

$\lambda_{g1} = 73.66$ mm

$\lambda_{g2} = 71.45$ mm

The guide's characteristic length can be calculated from λg0 formula and it is:

$\lambda_{g0} = 72.56$ mm   [1]

The bandwidth parameter alpha is calculated to be:

$\alpha = 20.95$

After obtaining alpha, the order of the filter is calculated:

$N \geq 6.12$

Order of the filter is critical, and it is used to calculate some other parameters as well, like ripple factor:

$\varepsilon = 0.18$

Special parameter η need to be calculated in order for us t proceed to the next step. The η parameter is calculated to be:

$\eta = 0.35$

Characteristic impedance, admittance and susceptance normalized to 1Ω ohm are:

$Z1 = Z7 = 26.53$
$Z2 = Z6 = 74.25$
$Z3 = Z5 = 107.32$
$Z4 = 119.13$

K01 = K78 = 1

K12 = K67 = 1.5888

K23 = K56 = 2.4391

K34 = K45 = 2.9488

B01 = B78 = 4.9563

B12 = B67 = 27.8982

B23 = B56 = 36.5720

B34 = B45 = 38.3187

Then I determined the phase length ψ (in radians) and physical length (in mm) between inductive discontinuities:

$\psi 1 = \psi 7 = 2.9140$

$\psi 2 = \psi 6 = 3.0785$

$\psi 3 = \psi 5 = 3.0882$

$\psi 4 = 3.0894$

l1 = l7 = 33.6508

l2 = l6 = 35.5499

l3 = I5 = 35.6620

l4 = 35.6764

4.3 Physical Design

The parameters of inductive irises need to be transformed into inductive posts, short circuited to the waveguide structure. The Richards transformation and Kuroda identity should be performed on inductors, to obtain the structure realizable in actual filter design.

Richard's transformation of inductor to short circuited stub, was done by using following formula:

$$jX_L = j\Omega L = jL \tan \beta l$$

The result obtained gave the stub with dimensions:

The width of irises: 2 mm

The height of irises (equal to height of guide): 22.15 mm

1st Iris Length: 26.823 mm

2nd Iris Length: 36.833 mm

3rd Iris Length: 38.385 mm

4th Iris length: 38.505 mm

5th Iris Length: 38.385 mm

6th Iris Length: 36.833 mm

7th Iris Length: 26.823 mm

Above dimensions are calculated for single stub, which is not practical for physical realization. The Kuroda identity number 3 (APPENDIX C) need to be performed to make 2 stubs from single stub.

After implementing Kuroda identity the dimensions obtained are as following:

The width of irises: 2 mm

The height of irises (equal to height of guide): 22.15 mm

1st Lower Iris: 20 mm

1st Upper Iris: 6.823 mm

2nd Lower Iris: 20 mm

2nd Upper Iris: 16.833 mm

3rd Lower Iris: 20 mm

3rd Upper Iris: 18.385 mm

4th Lower Iris: 20 mm

4th Upper Iris: 18.505 mm

5th Lower Iris: 20 mm

5th Upper Iris: 18.385 mm

6th Lower Iris: 20 mm

6th Upper Iris: 16.833 mm

7th Lower Iris: 20 mm

7th Upper Iris: 6.823 mm
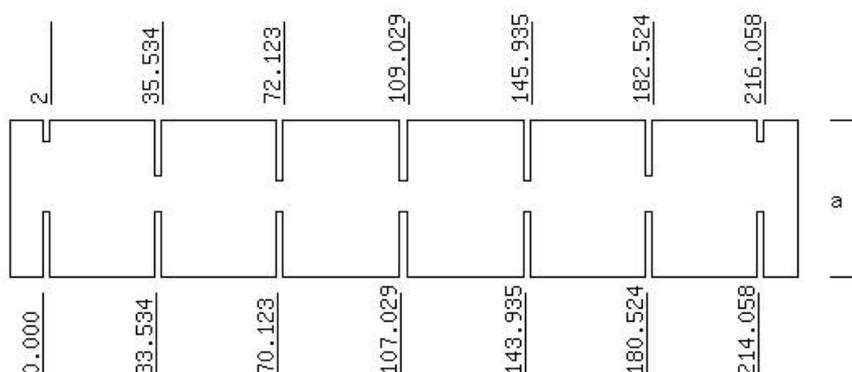
The final design looks like this:

Figure 12   Final Modified Filter

4.4   Filter Prototype in HFSS

4.4.1   Creating New Project

First of all I was required to create a new project for my Waveguide Filter. It can be done by going to ANSOFT HFSS "Project" Menu and choosing "New Project" from sub-categories.

The green line is "x" coordinate, blue line is "y" coordinate and red line is the "z" coordinate on Cartesian coordinate's plane. The lines are very useful when analysis of the filter design is done.

4.4.2   Defining Solution Type

After creating new project the "Solution Type" of the simulation step needs to be defined. The step can be performed by going to ANSOFT HFSS Menu and clicking the category "Solution Type". As the simulation will be improved continuously, we need to choose "Driven Modal" mode. This mode is good for the project which is controlled by the source. Below you may see the window where the modes can be chosen.

4.4.3   Setting Measurement Units

As we used the standard measurement units in our parameters calculation part, we need to define the units of measurement that will be displayed on ANSOFT HFSS project window. By the default the units are assumed to be in millimeters, thus we need to change them to centimeters. On ANSOFT HFSS we go to "Modeler" Menu on top, and choose the category "Set Model Units".

4.4.4   Drawing the Guide

To draw rectangular box, go to "Draw" Menu and press "Box" category. The 3D starting point of structure set through X, Y and Z boxes appearing on the bottom-right corner. Then dX, dY and dZ boxes will appear. These boxes are used to define the length of structure in X, Y and Z coordinates respectively.

The main structure of my project is rectangular box, with dimensions: dX = 47.55 mm, dY = 240 mm, dZ = 22.15 mm. After drawing main object, the discontinuities need to be implanted on the object. The discontinuities are formed by subtracting the required portion of the guide using SUBSTRACT command in HFSS. First discontinuities are drawn on the guide by defining their position and three dimensional lengths. Overall seven discontinuities were formed.

Below there is a complete diagram of the filter I designed in High Frequency Structure Simulator software.

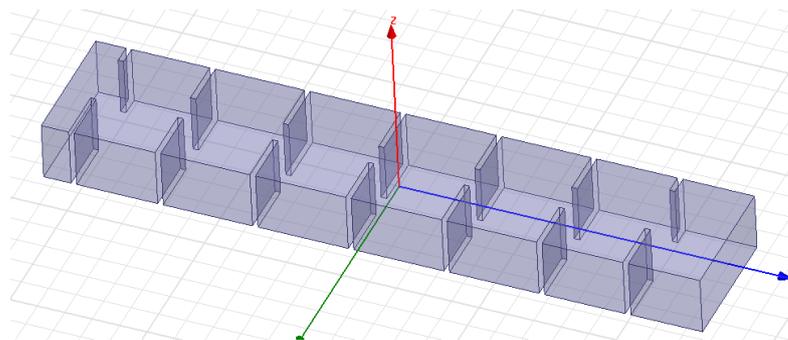Length = 240 mm;   Height = 22.15 mm;   Width = 47.55 mm

Figure 13   Filter Designed in HFSS

4.4.5 Choosing the Composition Material

After designing the filter the composition material of the filter need to be assigned. The step can be performed by going to the "Modeler" Menu and selecting "Assign Material" category. The required material is chosen from the list of available materials. For rectangular waveguide air is chosen as the default, because it is not filled with anything. Vacuum can be also chosen instead, as for simulation all the losses are assumed to be negligible.

4.4.6 Setting the Guide's Boundaries

After choosing the material the boundaries of the guide should be defined. Boundaries of the guide include the behaviors of the electrical and magnetic fields in problematic regions and some interfaces related with the guide itself. This can be done by going to "Modeler" Menu and selecting "Faces" category from the list. Then the faces of the guide need to be chosen. After that the boundary set by going to "Set Boundary" menu and choosing "Perfect Conductor". The chosen faces will act like perfect conductors.

After defining the perfect conductor sides, we need to define the sides with limited conductivity. The step can be defined through "HFSS" Manu on the top and selecting "Boundaries" category. On "Boundaries" category "Assign" category and then "Finite Conductivity" category is selected. The diagram below shows the perfect conductor boundaries of the guide.
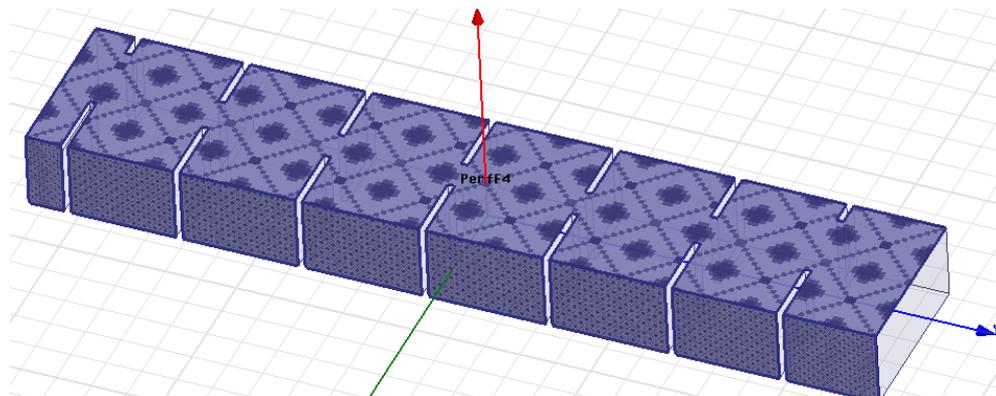

Figure 14   Perfect Conductor Boundaries of Filter

4.4.7 Assigning the Parameters of Excitation

The next step of design process is the assigning of the parameters of excitation. The step is vital for the design as it defines the origins of the forces (fields, currents, voltages and charges) on the guide surfaces. This steps includes two sub-steps, which will be the assignment of the ports and integration lines of the different modes.

4.4.8 Assigning of the Ports

Ports can be assigned through the HFSS Menu, by selecting the "Excitations" category. Under this category "Assign" sub-category is selected and the Port is selected from "Wave Port".

The port assignment is also vital, as it defines the position where the wave will enter the guide and where it will leave the guide. It means two ports are to be designed for the guide. The software automatically finds the solution to the ports dimensions by exciting them separately, one at a time.

This step is critical for defining the mode of the port. For WG12 we require four modes, as only four modes were analyzed. It means we need four lines of integration. The step can be performed by selecting the "New Line" from the Menu of Integration Lines. The ports need to be defined based on Cartesian coordinates, so "X, Y and Z" boxes appear again on the bottom. The coordinates of the points need to be defined on XYZ plane. The step should be repeated for each point. The excitation of Port 2 of my filter is shown below:
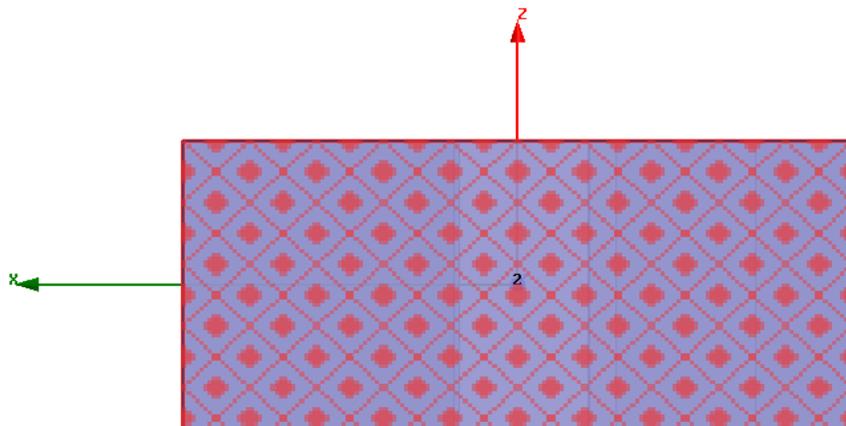

Figure 15   Excitation Port 2 of the Filter

4.4.9 Setting the Solution Type

After performing the steps where we define the parameters of the filter, we need to set the type of solution. There are two types of solution setting, which are Adaptive and Frequency Sweep.

The General Tab is selected, and certain parameters are modified, based on our preferences. On the frequency Solution, the frequency is set to the value equal to guide frequency, which is the optimal choice. The minimum 2/3 of final frequency value also is acceptable. For my filter, which is designed to analyze maximum of 5.25 GHz, the frequency is set to 6.95 GHz.

After that delta S need to be set, this is the variance of distance for the parameter from current one till the next. This step finalizes the Adaptive Solution Setup.

4.4.10 Frequency Sweep

In this step, instead of Setup Analysis, from HFSS Menu, we choose "Add Sweep" category. Sweep dialog will appear upon pressing the Add Sweep category. Again the frequency needs to be set at 6.95 GHz, for the optimal output. By performing this step we finalize the setting up of the Waveguide Bandpass Filter.

4.4.11 Project Validation

After all the steps are performed correctly, the results need to be validated by the system. It is crucial for system to understand if the steps are performed orderly. The step can be performed by selecting "Validate" category from the ANSOFT HFSS Menu on the top. The software will begin the analysis and show the results. Below there is the Validation window from my project.
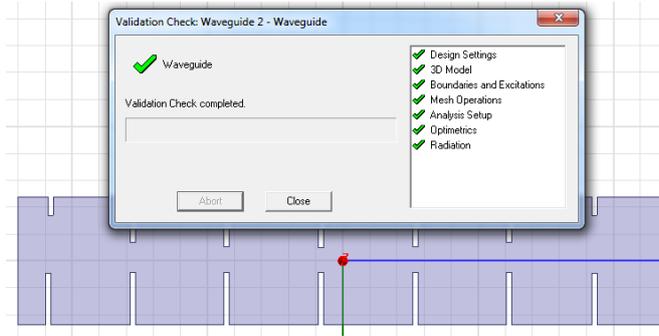
Figure 16   Validated Project "Waveguide 2"

4.4.12   *Simulation and Optimization*

The simulation in HFSS should give the ripples in passband and flat response in the Stopband. As the order of the filter is 7th the ripple number should be six, and preferably ripples should be closer to the flat bandpass response region. Below there is a simulation results for my Waveguide Bandpass Filter of 7th order.

As you may observe there are four ripples in the passband, and the Stopband has flat response. The result does not cooperate with the assumption I did. I assumed 7th order for my filter. The response was not good enough to be acceptable, so optimizations needed to be done to the filter parameters.

Optimization includes defining the variables of the filter, which will be the iris length and resonator length of the filter. The perfect response is calculated by the software by interpolation of length of irises and resonators. The complete setup of optimization can be seen from the diagram below.

Figure 17   Variable Range Setup

30

There were thirteen variables in the project. These variables are modified by HFSS software to attain the required criteria specified in Optimization Setup.

Next step is defining the parameters that need to be altered. According to project specifications it is required to have return loss (scattering parameter S11) below -15 dB and insertion loss (scattering parameter S21) in between 0 dB and -1 dB.

Scattering parameters define the power transmission from port to port. S11 means the power from Port 1 to Port 1 when Port 2 is open circuited, or in other words it is the ration of incident power to reflected power. S21 defines the power transmitted from Port 1 to Port 2, or in other words it is ration of transmitted power to received power.

To set the optimization for these parameters the frequency range of passband is selected and the minimum required result is specified. Below there is the demonstration of the steps explained above.
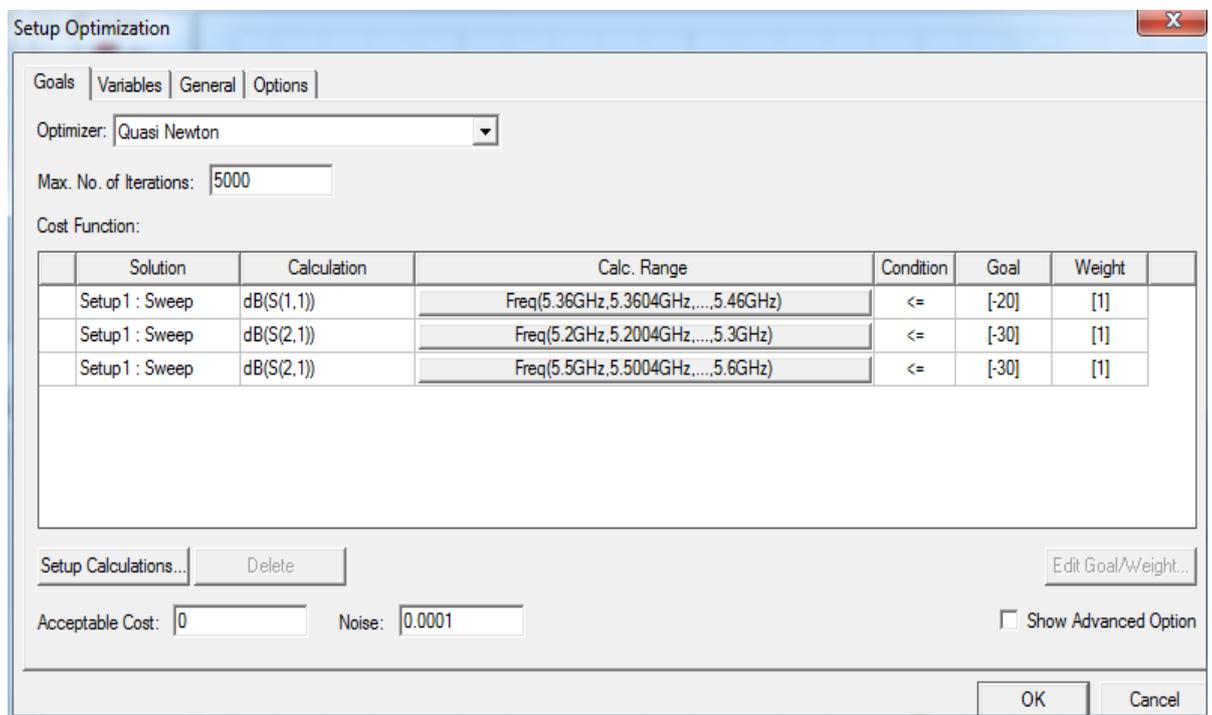

Figure 18   Defining the Minimum Acceptable Result

After setting the optimization setup, software performs iterations for each step, and finds out the best response based on the desired specifications. The acceptable parameter value is directly integrated to the design.

After performing nearly 500 iterations the acceptable response was obtained. The response had irregular ripples, but all the ripples were lesser than 15 dB range (specification for return loss). The insertion loss was very good (maximum -0.2 dB), which is extremely good result. The complete diagram of Chebyshev response of Waveguide Bandpass Filter for Microwave Point to Point Link in High Frequency Structure Simulator software can be seen below:

Name	X	Y
m1	5.3736	-16.3852
m2	5.4100	-28.8541
m3	5.4496	-14.8607
m4	5.3744	-0.1021
m5	5.4492	-0.1439

Curve Info
dB(S(1,1))
Setup1 : Sweep
dB(S(2,1))
Setup1 : Sweep
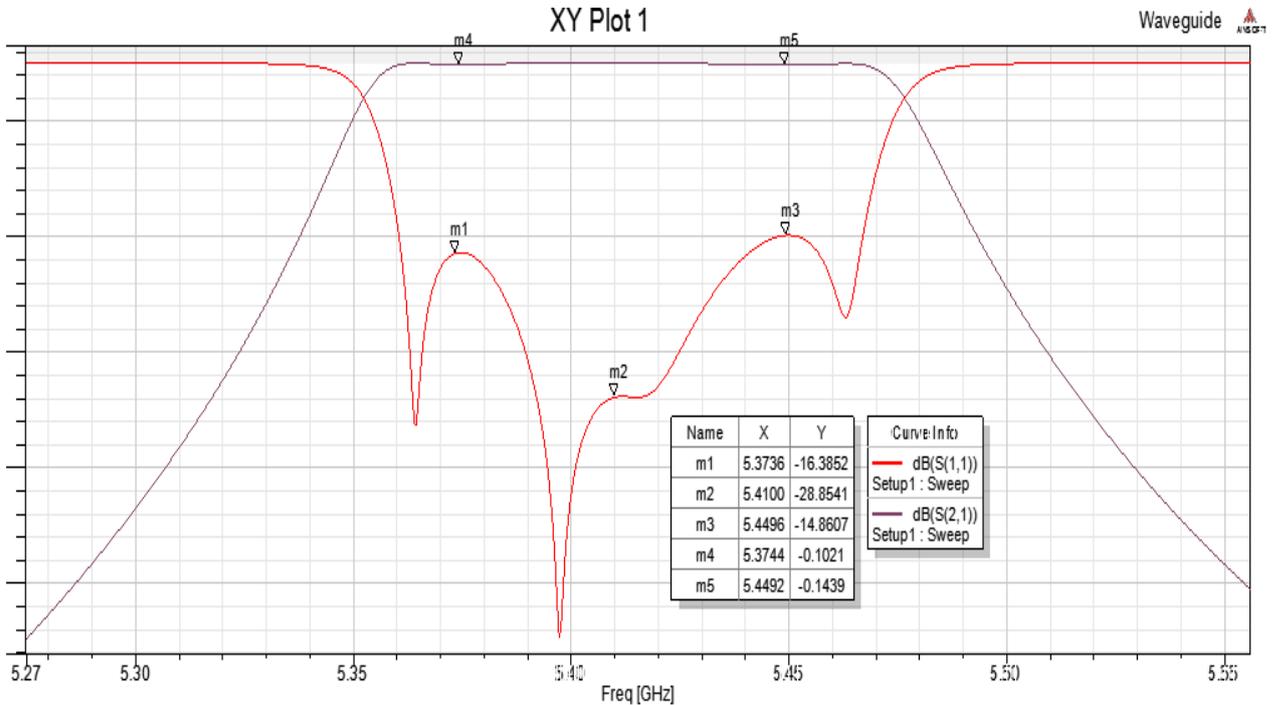
Figure 19   Plot of Scattering Parameters S11 (red) and S21 (grey)

The ripples of S11 in passband are irregular. S21 response is perfectly flat. S11 parameter is used to measure the reflection losses (or return losses) and S21 parameter is used to measure the insertion loss.

From the graph it can be deducted that the insertion loss is very low, meaning the transmission line or medium will not be vastly affected from insertion of filter into that medium. Reflection losses are all lower than 15 dB, meaning the incident Power is at least 31 times bigger than reflected Power. Generally speaking the final obtained results are very decent, and this filter can be used in real life application.

The comparison of obtained results and desired results can be seen in Table below:

SPECIFICATION NAME	DESIRED VALUE	OBTAINED VALUE
Frequency Range	5.150 GHz – 5.250 GHz	5.362 GHz – 5.468 GHz
Passband	100 MHz	106 MHz
Center Frequency	5.200 GHz	5.415 GHz
Insertion Loss	-1 dB < X < 0 dB	- 0.2 dB < X < 0 dB
Return Loss	< -15 dB	< -15 dB
Stopband Attenuation	-60 dB max	-60 dB max
Nominal Impedance	50 ohm	50 ohm

Table 4   Comparison of desired result with obtained result

The design was fully completed, with acceptable results. The fabrication of the filter can be commissioned.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

This project is a perfect aid that helped me to fulfill my objectives for the project, which were:

4. Understand the steps of Waveguide filter design.
5. Design Waveguide filter prototype in HFSS software.
6. Optimize HFSS designed filter to attain acceptable result.

Waveguide filters are special filters that direct the wave in certain direction. Usually waves are spread all around, which means the transferred signal will not have exactly the same strength at a receiving end as in sending end.

Waveguide filters have very high quality factor. It means the energy loss during transmission is relatively small compared to many other types of filters. It makes these filters more desired in nowadays communication system. The main disadvantage of the filter is relatively high cost, but the price of filter justifies the quality of the transferred information.

The quality of transferred signal is very important in communication. That is why much work is done to improve the communication quality. This is another reason to use why Waveguide filters in communication system, as it provides more quality signal transfer, with low attenuation. Lower attenuation means the strength of signal is not lost over a long distance.

Project was helpful in understanding the steps of designing Microwave Waveguide filter for point to point link. First of all the structure of waveguide must be chosen. It depends on the frequency range of pass band. For this project WG12 waveguide structure (UK standard) was used as it had the frequency range of 3.95 GHz to 5.85 GHz. Requirements of the project stated that the frequency range of designed filter should be 5.15 GHz to 5.25 GHz, which is well within the range of frequencies of Waveguide WG12.

The design of filter is not an easy task, as there are dozens of steps and approximations need to be done. It was a real challenge, as it required the neatness and proper approximation. If any of approximations were selected wrongly, the filter would fail to give the desired response.

There are certain things that can be improved as well for the sake of the project. HFSS is very helpful tool in designing the three dimensional object like antennas, filters, resonators and etc. The main limitation of the software is the fact that it is not very easy to conceive. To build the object there are dozens of steps to perform, which is quite hard, especially if we are talking about the exact accuracy of parameters. There can be several ready structures, like waveguides, coaxial filter outlines and etc. that will aid the designer in the process of construction of the filter.

The modifications in HFSS software will make the design of Microwave Waveguide filters much easier, and it will significantly reduce the design time. Another advantage of the software will be the fact that many people will be eager to use the software, over other competing software, as HFSS would be more sophisticated and easy to understand.

Waveguide filters involve very broad range of frequencies so any development in this area of filter design is accepted to be a vital step in learning these structures and their benefits to communication system. Waveguide filters have huge advantage over many other types of filter in terms of power loss and quality factor and the future development of Waveguide filter design will be vital for development of communication industry.

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APPENDICES

APPENDIX A
MATLAB CODE FOR BANDPASS FILTER RESPONSE

```matlab
fs = [2*pi*5080e6 2*pi*5320e6];          % stopband corner f
fp = [2*pi*5150e6 2*pi*5250e6];          % passband corner f
A = 60;                                  % attenuation at
R = 1;                                   % ripple


[n, fp] = cheb1ord(fp, fs, R, A,'s');    % expression to determine order
[z, p, k] = cheb1ap(n, R);               % Chebyshev low-pass filter
[A,B,C,D] = zp2ss(z, p, k);              % state-space representation



f1 = 2*5150e6*pi/10000e6;                % normalizing frequencies
f2 = 2*5250e6*pi/10000e6;




BW = f2-f1;                                    % Bandwidth
fo = sqrt (u1*u2);                       % Center frequency

[At, Bt, Ct, Dt] = lp2bp(A, B, C, D, fo, BW);  % Low-pass to bandpass


[b,a] = ss2tf (At,Bt,Ct,Dt);             % Transfer function of filter
w = linspace (0.01,1,50000)*2*pi;        % Frequency vector
h = freqs (b, a, w);                     % Compute frequency response

semilogy(w/2/pi, abs(h)), grid           % Response plot
xlabel( 'Hz');                           % Labeling
```
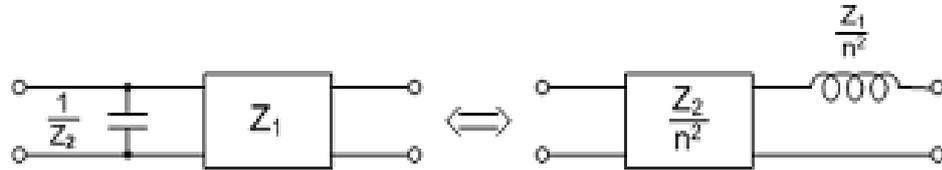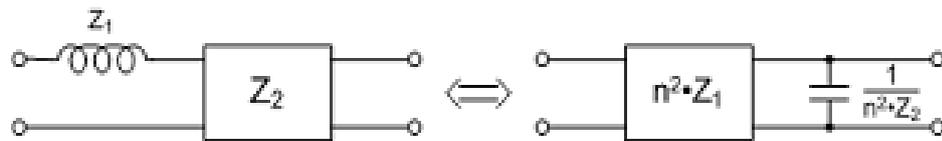
APPENDIX B
WAVEGUIDE STANDARDS AND SPECIFICATIONS

Table 5   WG Standards and Specifications

DESIGN	F RANGE	CUTOFF	ATTENUATION	MATERIAL	BAND	DIMENSIONS
WG0	0.35 - 0.53	0.281	0.054 - 0.034	Alum	B,C	533 x 267
WG1	0.41 - 0.625	0.328	0.056 - 0.038	Alum	B,C	457 x 229
WG2	0.49 - 0.75	0.393	0.069 - 0.050	Alum	C	381 x 191
WG3	0.64 - 0.96	0.513	0.128 - 0.075	Alum	C	292 x 146
WG4	0.75 - 1.12	0.605	0.137 - 0.095	Alum	C,D	248 x 124
WG5	0.96 - 1.45	0.766	0.201 - 0.136	Alum	D	196 x 98
WG6	1.12 - 1.70	0.908	0.317 - 0.212	Brass	D	165 x 83
WG6	1.12 - 1.70	0.908	0.269 - 0.178	Alum	D	165 x 83
WG8	1.70 - 2.60	1.372	0.501 - 0.330	Alum	E	109 x 55
WG9A	2.20 - 3.30	1.736	0.877 - 0.572	Brass	E,F	86 x 43
WG9A	2.20 - 3.30	1.736	0.751 - 0.492	Alum	E,F	86 x 43
WG10	2.60 - 3.95	2.078	1.102 - 0.752	Brass	E,F	72 x 34
WG10	2.60 - 3.95	2.078	0.940 - 0.641	Alum	E,F	72 x 34
WG11A	3.30 - 4.90	2.577			F,G	59 x 29
WG12	3.95 x 5.85	3.152	2.08 - 1.44	Brass	F,G	48 x 22
WG12	3.95 x 5.85	3.152	1.77 - 1.12	Alum	F,G	48 x 22
WG13	4.90 - 7.05	3.711			G,H	40 x 20
WG14	5.85 - 8.20	4.301	2.87 - 2.30	Brass	H	35 x 16
WG14	5.85 - 8.20	4.301	2.45 - 1.94	Alum	H	35 x 16
WG15	7.05 - 10.0	5.26	4.12 - 3.21	Brass	I	29 x 13
WG15	7.05 - 10.0	5.26	3.50 - 2.74	Alum	I	29 x 13

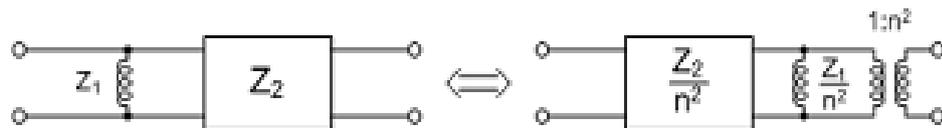# APPENDIX C

KURODA IDENTITIES
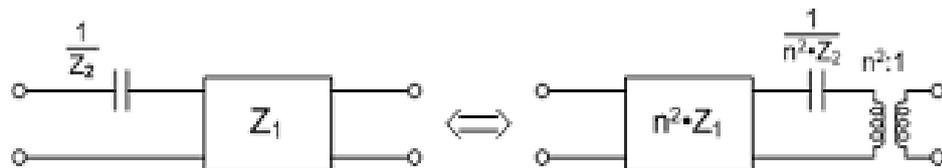

Kuroda Identity (Transform) Parallel Capacitor Input

Kuroda Identity (Transform) Series Inductor Input

Kuroda Identity (Transform) Parallel Inductor Input

Kuroda Identity (Transform) Series Capacitor Input
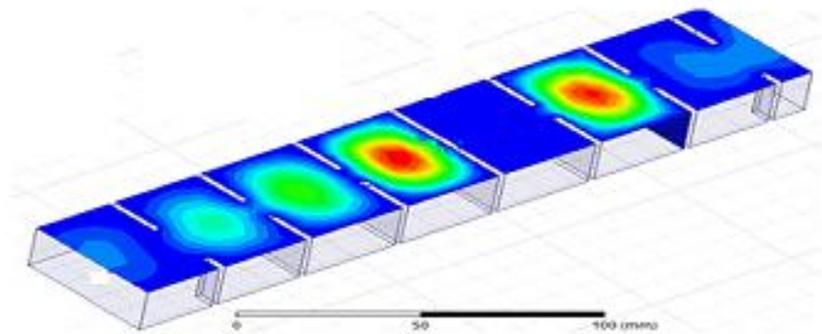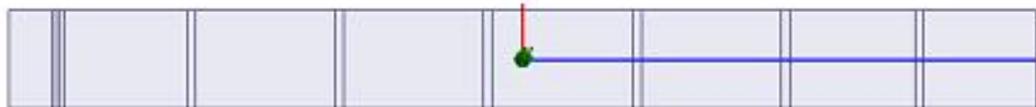
APPENDIX D

WAVEGUIDE FILTER: 3D VIEWS

Figure 1: Diagonal View

Figure 2: Side View

Figure 3: Top View