Design of Millimetre Wave Band Pass Filter for Radio over Fibre Application

By

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Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical and Electronic Engineering)

SEPTEMBER 2013

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CERTIFICATION OF APPROVAL

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Approved by,

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Dr Wong Peng Wen

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2013

CERTIFICATION OF ORIGINALITY

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

ABEL BELETE TADELE

ABSTRACT

Millimetre waves of the EM spectrum are characterised by their high frequency which enables them to support wider bandwidth thus high data rate. Band pass filters are important part of RF front end in radio transceivers. In this project, design of a band pass filter at 60GHz is performed. Waveguide filter type is chosen due to its ability to support filtering at high frequency with minimal loss and higher quality factor compared to other filter categories. The filter is a rectangular waveguide with circular inductive posts dispersed throughout its length making resonant cavities in between. The transmission mode is the dominant mode, TE_{10}. MATLAB is used to find out the order of a butter-worth filter which can satisfy certain given requirements which turns out to be a 6th order. HFSS (High Frequency Structural Simulation) is used to model, simulate, optimize and tune the filter design. The designed filter has a bandwidth of 3GHz (58.5 to 61.5GHz), return loss between 15 to 20dB and insertion losses 54dB (at 57GHz) and 42dB (at 63GHz). From loss vs Frequency plots, it's shown that the designed filter possesses high selectivity.

ACKNOWLEDGEMENT

First of all, I would like to thank **GOD** for giving me ability and strength to do this project.

My deepest and most sincere appreciation goes to my supervisor, Dr Wong Peng Wen, who has been guiding me at every step of the project and make sure that I follow the right track. Thus, I am very grateful for giving me the opportunity to work with him.

I would like to express my gratitude to the staffs of Electrical and Electronic Engineering Department at Univerisiti Teknologi PETRONAS especially graduate assistants in communication department for their support in my project.

At last, I thank my family for their continual support and making me who I am today.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Millimetre wave is the highest band of micro waves under radio frequency in the electromagnetic spectrum. It comprises frequency range from 30GHz to 300GHz (wave length range from 1mm to 10mm). Radio waves in this band are characterized by their capacity to allow wider bandwidth which leads to a higher data transmission rate reaching 10GBits/s and more thereby providing similar bandwidth and rate with optical fibre at that frequency [1]. Besides, millimetre wave equipment has the major advantage of being small [2]. Millimetre waves have variety of applications such as large amount data transmission, image scanner device and telecommunications [1].

Nowadays, there is broadband communication demand is increasing which calls for wireless communications with increased capacity. Millimetre wave provides can be a solution to this problem since it can provide wider band width and bitrate. However, application of millimetre wave is restricted to only short distance range (<1km) due to high attenuation [3]. Overcoming this limitation is a challenge to make millimetre waves practical.

Some ways to overcome this shortcoming are through design of equipment such as a receiver with good sensitivity, high transmit power and an antenna with high gain [2]. A band pass filter design is part of the solutions since filters are used in communication system to filter out wanted signal.

1.2 Objective and scope of study

The objective of this project is to design a millimetre band pass filter at 60GHz. RF front end, an important part of an RF receiver, lies between the antennae and intermediate frequency range stage. A band pass filter serves as part of this RF front end circuitry and it is used to filter out unwanted frequencies from the mixer output (local oscillator and received RF signal mixer) to give the desired intermediate frequency. This shows that RF filters constitutes an essential component in making a radio transceiver [4]. Therefore, designing a band pass filter that has a good performance is of a great use [5].

As mentioned in the background, millimetre wave is currently a great interest of study due to the presence of wider band pass at these frequencies. Among millimetre waves, 60GHz technology is of current interest due to the fact that the 60GHz band has one of the widest unlicensed bandwidth making it suitable for developing wireless communication technologies [6].

In this project, part of a radio communication system, band pass filter, is to be designed for radio communication at a specified frequency, 60GHz. Therefore, the project is relevant as well as achievable in the given time.

1.3 Problem Statement

Millimetre wave’s practical applications have been restricted to short range communication due to high attenuation for long transmission. Among this frequency band, the 60 GHz which is the interest in this project exhibits a property of high attenuation due to atmospheric oxygen [7]. This property makes the use of 60GHz particularly for radio over fibre application makes a huge challenge. Though the range can be increased by using a high boost antennae and modified circuits, the design techniques are still in the beginning stages [8]. There is a limitation in materials that can be used to build circuits at this high frequency [2].

CHAPTER 2

LITREATURE REVIEW

A number of studies have been done on designing a band pass filter at 60GHz using different filter designing techniques. These techniques differ from one another in matters such as structure, material used and working mechanism which leads to performance differences between them. Microstrip, a type of electrical transmission line which uses a conducting layer on top of a dielectric substrate with the substrate connected to a ground plane, is most commonly used for making circuits for microwave and millimetre wave region [9]. A microstrip square loop dual mode band pass filter was proposed [10]. However, transmission equipment that uses microstrip technologies has a limitation when the operating frequency increases. High level of attenuation appears at higher frequencies, limiting the use of striplines till 40GHz [9].

On chip band pass resonators made by CMOS (Complementary Metal Oxide Semiconductors) process are another set in filter technology. A coplanar wave guide resonator which is made from a metal conductor at the top with multiple dielectric substrate layers was developed using this process [4]. Another on chip band pass filter design using CMOS technology with enhanced planar ring resonators was proposed [5]. Achieving a band pass filter having minimal insertion loss when integrated with the RF system and a high frequency selectivity capacity is the main concern of designs [11]. Though the CMOS devices are workable solutions, they suffer from shortcomings on their selectivity coupled with high insertion loss making them less choosable design method at 60GHz [11].

Band pass filters which uses resonator made from a dielectric material, dielectric resonator, has a high quality factor but exhibits deteriorates for frequencies greater than 40Ghz [12].

On the other hand, wave guide filters consisting cavity resonators are characterized by high quality factor due to their low insertion loss [13]. The theory behind wave guides and an example design method is given in [14]. Wave guides are a type of transmission lines made from metal cavities. The main difference with other transmission lines and a wave guide is transmission modes. Transmission lines such as coaxial cables support Transverse Electro Magnetic (TEM) mode where both the electric and magnetic field are perpendicular to axis of propagation where as in wave guides, either Transverse Electric (TE) or transverse Magnetic (TM) modes are supported due to boundary conditions in the Maxwell equation.

A type of wave guide band pass filter composed of resonance cavities inside a wave guide coupled by row of posts (standing rods) was explained in [14]. These posts serve us shunt inductance and result in discontinuity. Based on the current surfacing on the inductive posts, a design and study of wave guide band pass filters was performed with design examples.[15]. Based on the frequency dependence characteristics of the wave guide components, a more general design way was introduced in [16]. A similar method of replacing the inductive posts with inverters couplings sections of wave guide is explained in [14].

CHAPTER 3

METHODOLOGY

3.1 **Project Flow**

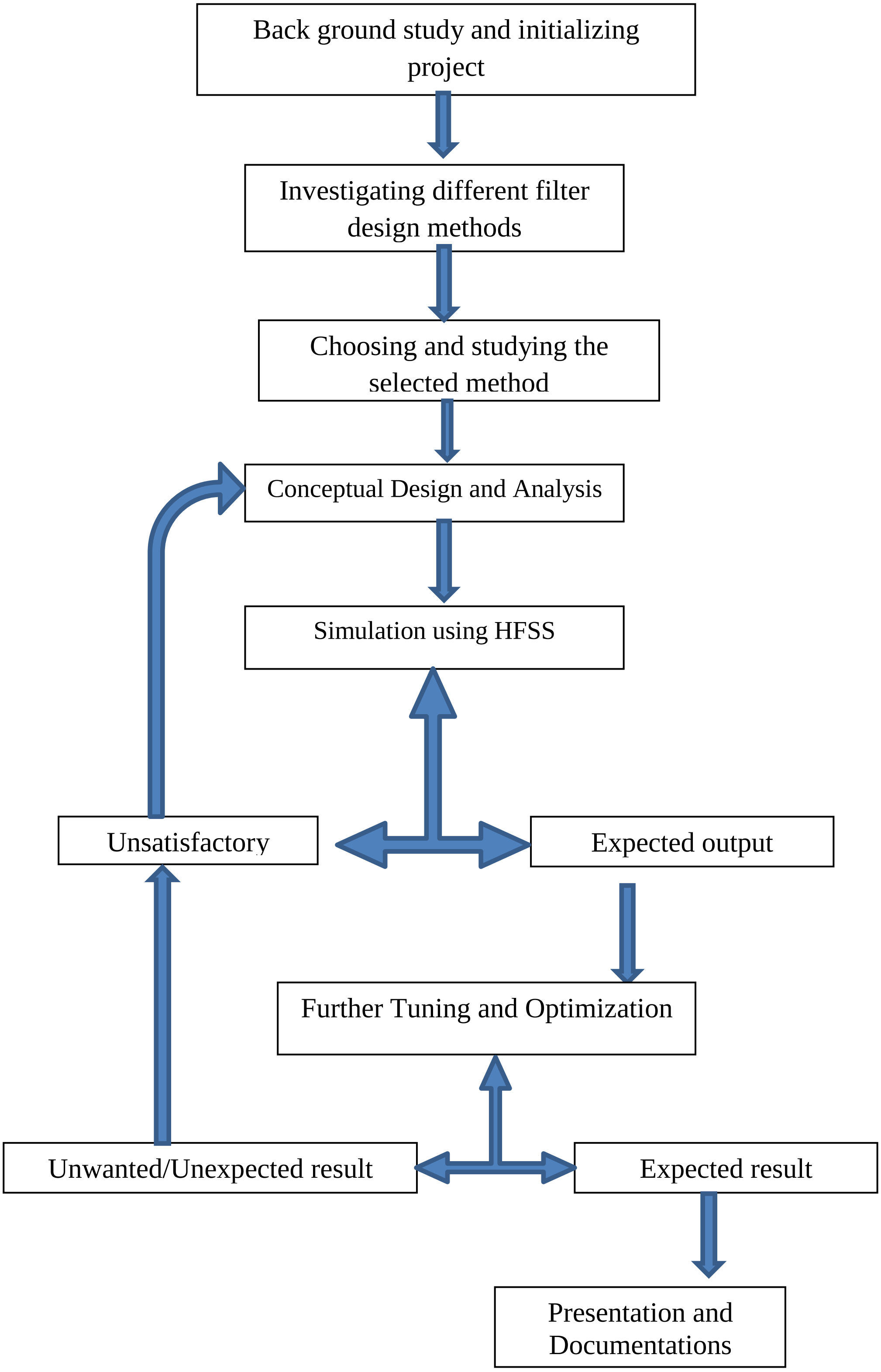


Figure 1 – Project Flow

3.2 Key Milestones

Key milestones in the project are the following

- Calculation and determining design parameters
- Modelling using
- Tuning and optimization
- Frequency Vs Loss Plots
- Final Adjustments and Verification
- Final reports and documentation

3.3 Tools used

- Matlab
- ANSYS HFSS (High Frequency Simulation Software)

CHAPTER 4

THEORY AND CALCULATIONS

4.1 Wave Guide Band Pass Filters

Following the methodology, the next step in designing the filter is to perform analysis and calculation based on the chosen type. The design approach and explanations followed in this paper is based on [14].

Wave guides are a length of hollow metallic conductor in which electromagnetic waves transmitted through. In comparison with other transmission mediums, wave guides does not support TEM (Transverse electric Magnetic) mode of transmission due to boundary conditions. Solving the Maxwell equations for waveguides yields infinite mode of transmissions with different cut-off frequencies and are either TE (Transverse electric) or TM (Transverse Magnetic) modes. The aforementioned transmission modes indicate alignment of electric and magnetic fields with respect to axis of propagation. In TE mode of transmission, electric field component along the axis of propagation is zero. On the other hand, in TM modes, magnetic field component along the axis of propagation is zero. In designing a bandpass filter using wave guides, a single transmission mode is chosen whose cut-off frequency is lower than the operating frequencies. Mostly, the dominant mode, which is the transmission mode with the lowest cut-off frequency, is chosen for transmission in order to avoid mode overlapping.

Passing to wave guide band pass filters, a rectangular wave guide filter with circular posts dispersed through the length of the guide is used. TE_{10}, the dominant mode in rectangular wave guides, is the mode of transmission chosen. The circular posts inside the wave guide serves as inductive discontinuities which excites TE mode of transmission. The circular posts can be assumed as shunt inductor immersed in a section of wave guide as shown below.

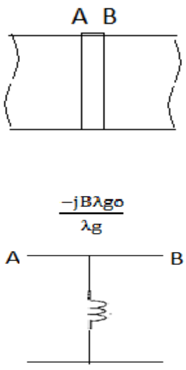


Figure 2 –Shunt inductive discontinuity in a wave guide with reference planes A & B

Wave guide sections between the posts are half wave resonators which select a specific resonant frequency whereas attenuating other frequencies. The inductive iris is then modified by symmetrically embedding it in a section of a wave guide as shown below.

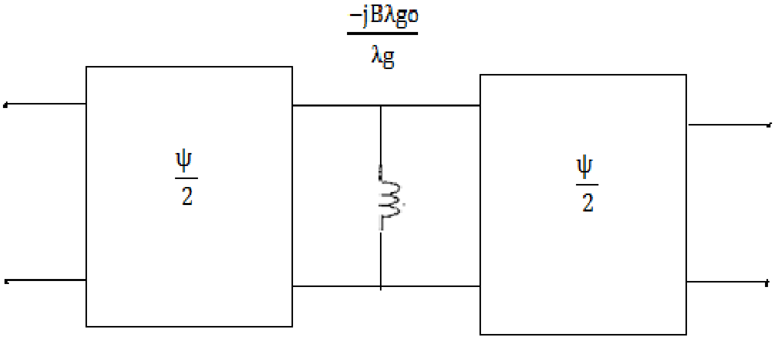


Figure 3 – Shunt inductive iris embedded in a section of wave guide

Here, ψ represents small wave guide which defines the reference planes of the inductive post, λ_{go} the guide wave length when the length of the wave guide is half a wave length long, i.e. when $l = \lambda go/2$, **B** is susceptance of the inductive post and λ_g is the guide wave length.

By expressing ψ and inductive post in their respective transfer matrices and combining them, we get a transfer matrix which can be approximated to an impedance inverter with the following frequency dependent transfer matrix,

$$[T] = \begin{bmatrix} 0 & \frac{-j\lambda go}{K\lambda g} \\ \frac{-jK\lambda g}{\lambda g0} & 0 \end{bmatrix}$$

This representation of inductive irises embedded in a wave guide with inductive impedance inverters is proven to be good approximation. Having established this point, an inductive post band pass filter can is equivalent to unit elements which are sections of wave guides separated by impedance inverters.

Now, we can start calculating various parameters involving a post wave guide band pass filter.

4.2 Calculation

The specifications of the band pass filter to be designed is as follows,

- Pass band frequencies f_1 and f_2: 58.5GHz to 61.5GHz
- Pass band return loss: 20dB
- Stop band insertion loss:
  - 40dB at 57GHz
  - 30dB at 63GHz
- WG25, dominant mode TE_{10} cut off frequency, f_c : 39.875GHz

First we find the guide wavelengths at f_1 and using f_2 the formula

$$\lambda_g = \frac{\lambda_0}{[1-(\omega_c/\omega)^2]^{1/2}}$$

Where λ_0 free space wave length, λ_0 = C/f

Using this formula, we get λ_{g1} = 7.0086 mm

λ_{g2} = 6.40704 mm

then λ_{go} is computed, λ_{go} = 6.70806 mm

Next step is finding $\alpha \ and \ \varepsilon$

From the formula $\alpha = [\frac{\lambda_{g1}}{\lambda_{go}}\sin\left(\frac{\pi\lambda_{go}}{\lambda_{g1}}\right)]^{-1}$ we get α = 7.126218

To find the ripple factorε, insertion loss in the pass band is calculated first from return loss,

$\mathrm{IL} = 20dB = 10\log(\frac{1}{S_{11}})^2$, which will give us $|S_{11}|^2 = 0.01$.then from the relation

$$|S_{11}|^2 + |S_{12}|^2 = 1, we\ get\ |S_{12}|^2 = 0.99$$

Then from the approximation $|S_{11}|^2 = \frac{1}{1+\varepsilon^2}$ in the pass band, it can be calculated $\varepsilon^2 = 0.01$

The next step is finding the order of the filter, N. The optimum equiripple (Chebyshiev type) band pass filter response, taking into account the frequency dependencies of the inverters is given by the formula,

$$|S_{12}|^2 = \frac{1}{1 + \varepsilon^2 {T_N}^2 \left[\alpha \left({}^{\lambda_g}\!/_{\lambda_{g0}} \right) Sin(\pi\, {}^{\lambda_{g0}}\!/_{\lambda_g}) \right]}$$

Where T_N is chebyshiev polynomial. For N = 6. $T_6(x) = 32x^6 - 48^4 + 18x^2 - 1$ will give the following frequency response (generated using Matlab), which meets initial specifications of the filter.

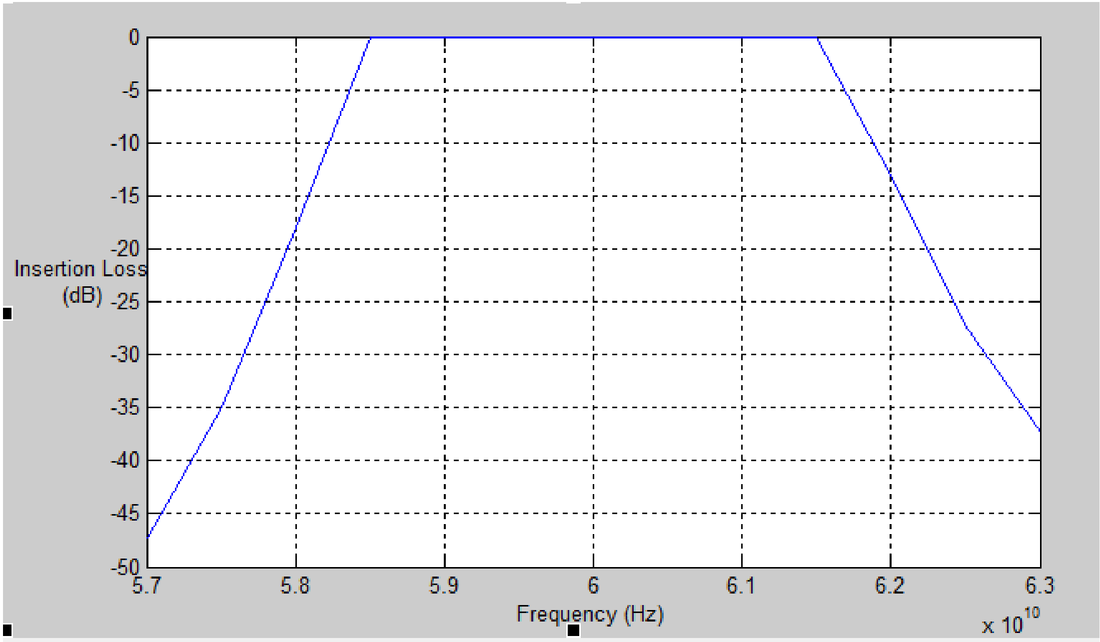


Figure 4 – Transfer function of a 60GHz wave guide band pass filter

Therefore, N = 6. Then, we will pass to calculating the circuit and physical parameters of the filter.

To do that, $\eta = \sinh[\frac{1}{N} sinh^{-1}(\frac{1}{\varepsilon})]$ this will give us $\eta = 0.520761$. Then impedance value are calculated as follows,

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

Where r =1,…, N we get, $Z_1 = Z_6 = 7.104416.$
$Z_2 = Z_5 = 19.145564$
$Z_3 = Z_4 = 26.24998$

Admittance of the inductive posts is calculated below,

$K_{r.r+1} = \left[\frac{\eta^2+sin^2(\frac{r\pi}{N})}{\eta}\right]^{1/2}$ Where r= 0.1,…, N. we get

$$K_{01} = K_{6,7} = 1$$

$$K_{1,2} = K_{5,6} = 1.38631$$

$$K_{2,3} = K_{4,5} = 1.940507$$

$$K_{3,4} = 2.165046$$

Based on the calculated impedance and admittance values, susceptance of the inductive irises is calculated below,

$$B_{r.r+1} = \frac{[Z_r Z_{r+1}]^{1/2}}{K_{r,r+1}} - \frac{K_{r,r+1}}{[Z_r Z_{r+1}]^{1/2}}$$

Where r=0,1…, N. and Z_0=Z_7=1 which gives us,

$$B_{0.1} = B_{6,7} = 2.290234$$

$$B_{1,2} = B_{5,6} = 8.293881$$

$$B_{2,3} = B_{4,5} = 11.552696$$

$$B_{3,4=}12.124444$$

Then, the actual guide wave length is obtained from subtracting the negative wave guide lengths of the post planes from half a wave length. That is,

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

Where r= 1,.., N. This will give us,

$$\psi_1 = \psi_6 = 2.664355$$

$$\psi_2 = \psi_5 = 2.93757$$

$$\psi_3 = \psi_4 = 2.97414$$

What follows is changing the electrical guide lengths to actual guide lengths. To do that we use the following formula,

$l_r = \frac{\psi_r}{\pi}\frac{\lambda_{go}}{2}$ where r=1,..,N and l_r is wave guide length between posts,

$$l_1 = l_6 = 2.844521mm$$

$$l_2 = l_5 = 3.136216mm$$

$$l_3 = l_4 = 3.175254mm$$

Final circuit of wave guide band pass filter is shown below,

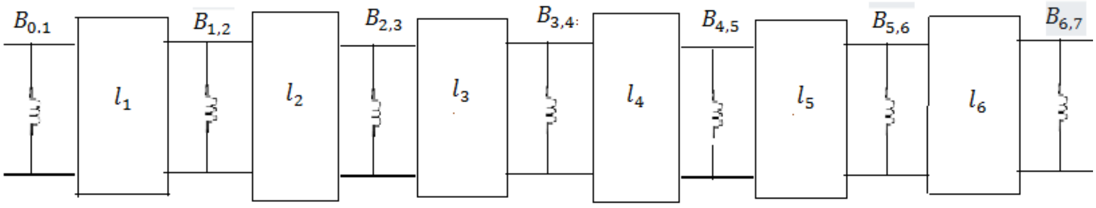


Figure 5 – Final circuit with calculated wave guide circuit values

The final stage is determining iris diameter. Guide length between posts is already calculated from the post's susceptance values. As mentioned earlier, a section of wave guide act as a cavity resonator when its length is half of the guide wavelength, i.e. when $l = \lambda go/2$. Thus, centre to centre length from one post to the next should be $l = \lambda go/2$. λ_{go} is calculated to be 6.70806 mm which gives $l = \frac{\lambda go}{2} = 3.354mm$.

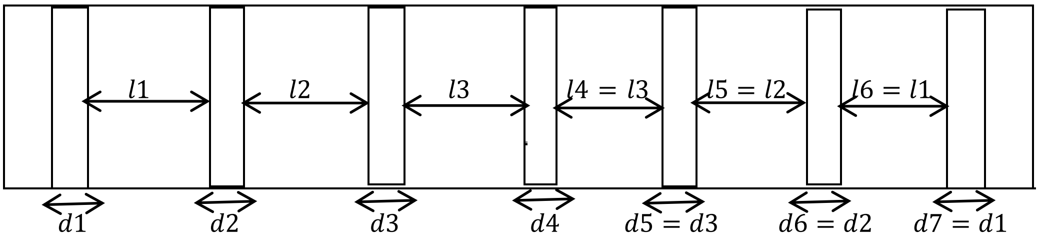


Figure 6 – Filter's parameter designations and symmetry

We start by letting d1 to be 0.6mm (also d7=d1=1.2mm) which is around post diameter values used for very high frequency applications. This gives r1=0.4mm. Resonance cavities are measured from centre of a post to centre of the next post. Thus, $r1 + l1 + r2 = 3.354mm$ which gives r2=0.11mm (d1=0.22mm). Due to symmetry, d6 is equal to d1.

Based on the same concept, $r2 + l2 + r3 = 3.354mm$ gives r3= 0.108mm which makes d3=d5=0.216. Also, $r3 + l3 + r4 = 3.354mm$ gives r4=0.071mm (d3=0.142mm).

The post diameter values, together with distance between posts, will be used as a starting parameter for simulation on the next stages. Besides, the position of posts along width of the waveguide is set to be at the centre i.e., at z=1.8796mm.

CHAPTER 5

RESULTS AND DISCUSSION

Filter model and simulation results using HFSS are stated and discussed below.

5.1 Results

The wave guide filter is composed of seven inductive posts forming 6 cavities inside a metal cavity. The calculated results are used to make a model of the filter. For 60GHz, the waveguide standard used is WG25 which gives width and height values of the cavity to be 3.7592x1.8796mm. The model is designed in symmetrical way, that is, design parameters such as post radius and distance between posts for the first three cavities is mirrored to the rest cavities which lies after the central inductive post.

For the first simulation, All posts are placed at the middle of the cavity and has similar radius. After that, Aluminium is selected as the material for post and cavity walls with air filling the remaining gaps inside the cavity. A Perfect E boundary conditions is assigned for the Aluminium surfaces. Wave-ports (input and output) with excitation are defined. The filter model is shown below enclosed with an external box surrounding its sides except at input and output ports.

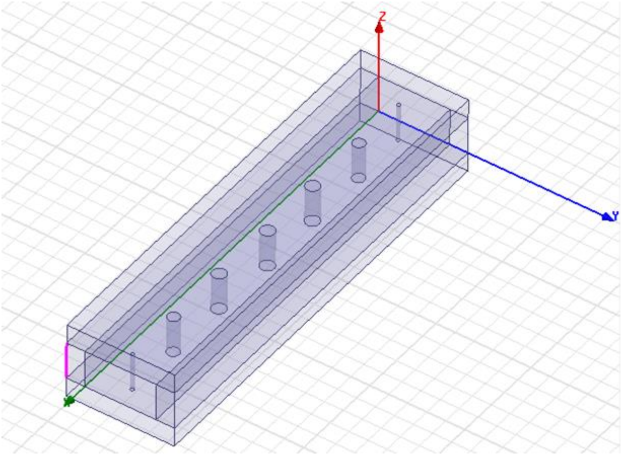


Figure 7 – 3D model of the waveguide filter

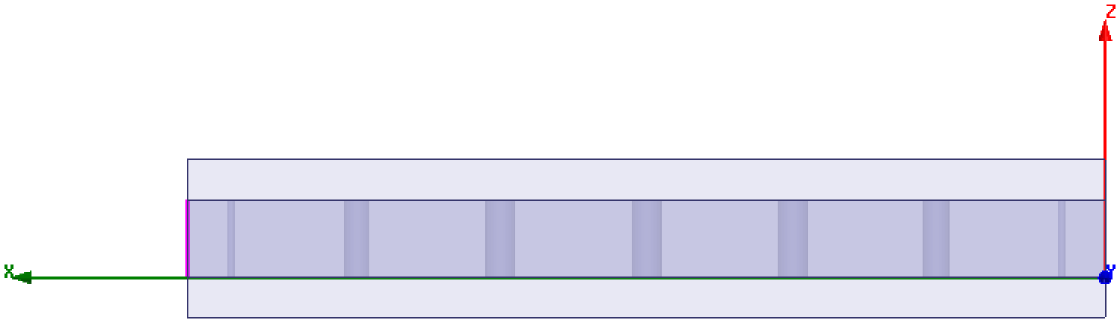


Figure 8 – Side view of the filter model

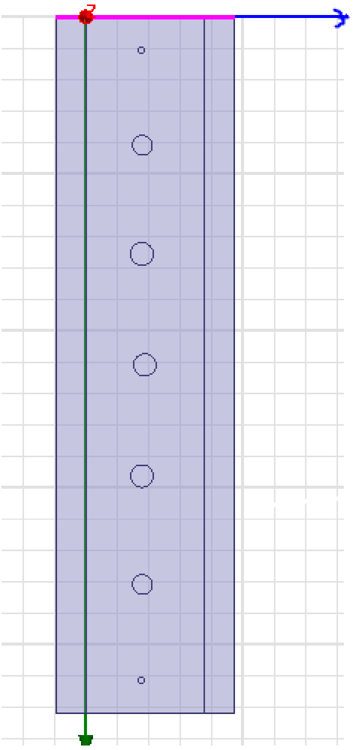


Figure 9– Top view of the filter model

To see the return and insertion loss of the filter are then generated from the model. The first result is shown below.

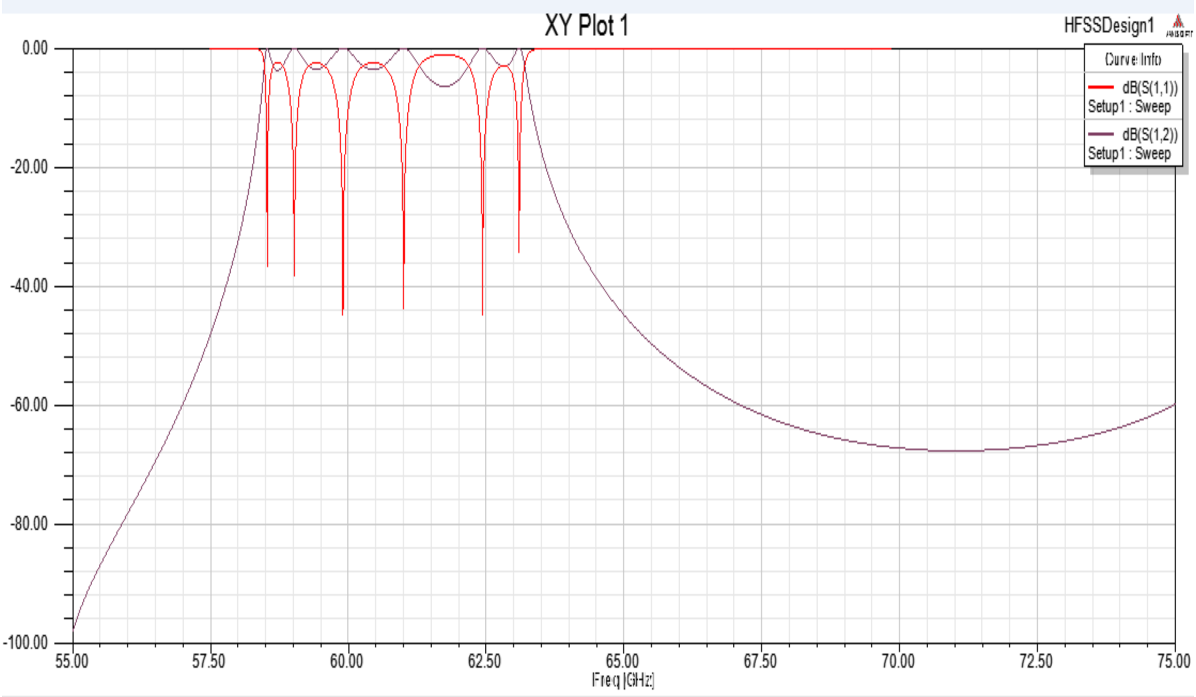


Figure 10 –Return and insertion loss before optimization

Optimization is performed on the model by entering a goal which defines the return loss and reflection loss responses at different frequencies. The following figure shows the return/insertion losses after optimization.

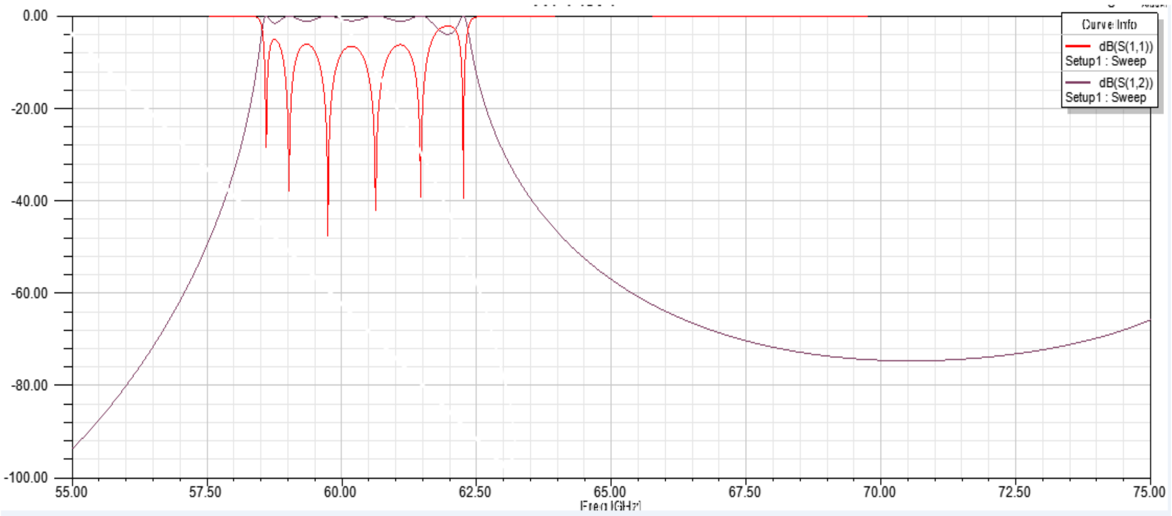
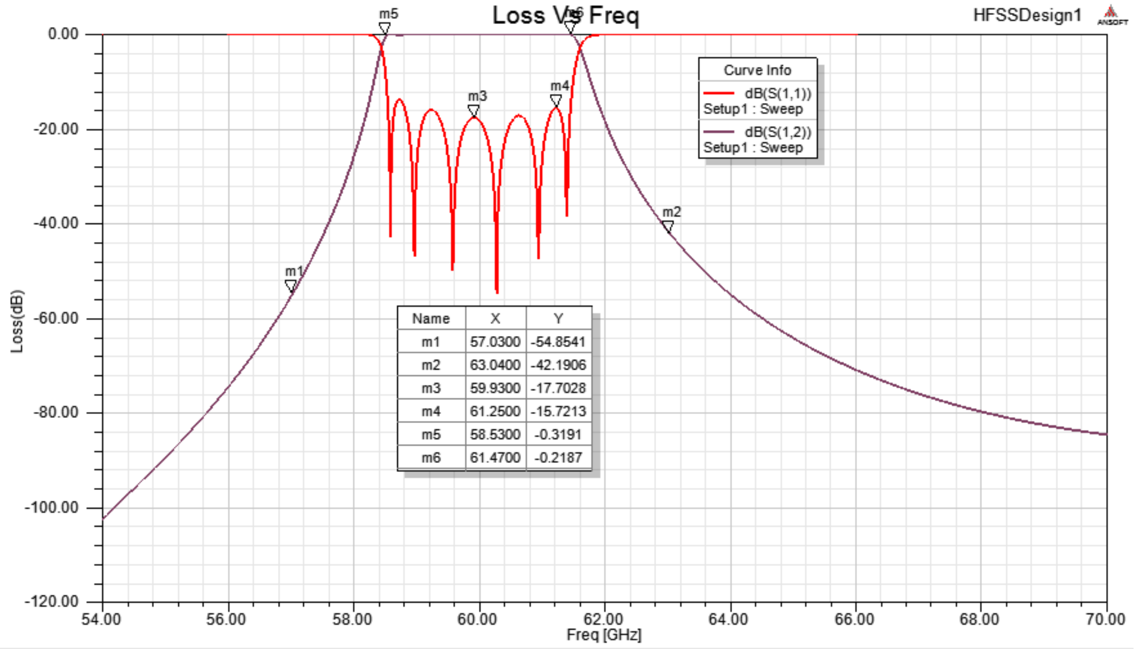


Figure 11 –Return and insertion loss after optimization

To get a better response, different parameters of the filter are selected for tuning. The final result after tuning is shown below.



Name	X	Y
m1	57.0300	-54.8541
m2	63.0400	-42.1906
m3	59.9300	-17.7028
m4	61.2500	-15.7213
m5	58.5300	-0.3191
m6	61.4700	-0.2187

Figure 12 –Return and insertion loss after Tuning

The filter parameters which are used for tuning and optimization are stated below with their final result. Posts are identified by numbers counting from origin to the center post. That is, post 1 is the firs post from the origin, has a distance Y1 from Y axis and has a radius of R1. The same goes for the rest of the posts. After post 4 which is the center post, the rest are symmetrical. Post 5 has the same parameters as post 3 and the same goes for post 6 and 7 which have equivalent parameters with post 2 and post 1 respectively. S is the thickness of the enclosing box. L is the distance between input wave port and post 1. L1 is the distance between post 1 and post 2. L2 is between post 2 and post 3 whereas L3 is between post 3 and post 4. The distance between the posts is also symmetrical.

Parameter	Value(mm)
Y4	1.88714
Y3	1.7936837806732
Y2	1.81018
Y1	1.7739416604964
R4	0.362085
R3	0.361847
R2	0.316363
R1	0.100878
L3	2.81358
L2	2.79148
L1	2.627340656639
L	0.946673
s	0.96365851314099

Table 1- Tuned design parameters

5.2 Discussion

Insertion loss plots at the pass band frequency (58.5GHz to 61.5GHz) shows that insertion loss is close to zero.

The specification of the filter states a reflection loss of 40dB at 57GHz and a loss of 35dB at 63GHz in which both of them are met with even better selection as shown in the plots above. The filter has six cavities which are denoted by the return plot's six nodes at the pass band. Return loss at the pass band is between 15dB and 20dB which is in an acceptable range.

CHAPTER 6

CONCLUSION

Millimetre waves which constitute the upper band of the microwave spectrum have the ability to support wider bandwidth since they have very high frequency Due to a high degree of attenuation, making millimetre waves practical is a challenge. Among millimetre waves, the 60GHz band is of a special interest due to a high level of attenuation by atmospheric oxygen at this particular frequency. This characteristic makes 60GHz suitable for PAN (Personal Area Network). 60GHz is chosen since it has a wide unlicensed bandwidth in many countries and can support a high data transmission rate.

Band pass filters are important components in radio communication for filtering out unwanted frequency ranges. The objective of this project is to build a 60GHz wave guide band pass filter which will support the larger data transmission which can be compared to optical fibres.

After evaluating the different parameters of the model, simulation is performed using Ansoft HFSS 3D software. The return loss and insertion loss plots shows that the designed bandpass filter perform as required with 3GHZ band pass and high quality factor.

A wave guide band bass filter cantered at 60 GHz with a band width of 3GHz (58.5 to 61.5GHz) possesses return loss between 15 to 20dB and insertion losses 54dB (at 57GHz) and 42dB (at 63GHz). The Filter possess higher selectivity factor.

Due to unavailability of testing equipment in UTP for filters operating at millimetre wave range, a prototype was not fabricated and tested.

Finally, the project has introduced me to modelling and different simulation stages of a wave guide filter. Besides, I learned patience during the challenging final tuning stages. Thus, the whole project was a big learning experience.

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Appendix: Gant Chart

No	Detail tasks	Week 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	HFSS Tutorial	🟥	🟥												
2	First Simulation		🟥	🟥											
3	Optimization and Tuning			🟥	🟥	🟥									
4	Verification of design by SV						●								
5	Final Adjustments							🟥	🟥						
6	Verifying Design									🟥	🟥				
7	Poster Presentation											●			
8	Reports and Finalizing project												🟥	🟥	🟥