RF CAD Lab Based Project

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PROJECT TITLE

Designing a Stepped Impedance Low Pass Filter with maximally flat response and having a cutoff frequency of 2.5 GHz with an attenuation of greater than -20 dB at 4 GHz

Acknowledgement

I, Rudraprasad Debnath, a student of Indian Institute of Technology Tirupati, M.tech 1st year, have completed this project titled **Designing a Stepped Impedance Low Pass Filter with maximally flat response and having a cutoff frequency of 2.5 GHz with an attenuation of greater than -20 dB at 4 GHz** under the supervision of Professor M. V. Kartikeyan. I would like to convey my heartfelt gratitude to Kartikeyan Sir for his tremendous support and assistance in the completion of my project. I am thankful to him for his immense efforts to teach us new things and growing strong concepts on the subject. It was a great learning experience as well. The project work would not have been completed without his cooperation and inputs.

Regards,
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Introduction

Filters are devices that can eliminate a preferred frequency band from a signal for a specific operation in electrical and electronic circuits. The preferred band maybe a finite, semi-infinite or infinite range of bands. Filters are of four types - **Band Pass**, that passes a specific finite range of bands and eliminates all the other frequencies lying outside it. **Band Stop**, that eliminates a specific finite range of bands and passes all the other frequencies lying outside it. **High Pass**, that passes all the frequency components greater than a given cutoff frequency and **Low Pass**, that stops all the frequency components greater than a given cutoff frequency.

In this project, I have designed a stepped impedance microwave filter that is of low pass type and has a cutoff frequency of 2.5 GHz. This filter also has a maximally flat response and more than -20 dB attenuation at 4 GHz frequency. Filter impedance is 50 ohm and highest and lowest practical impedance is 120 ohm and 20 ohm respectively. In case of microwave filters, usually alternative patches of high and low impedance are used. This structure is termed as stepped-impedance. The high impedance regions are equivalent to inductors and low impedance regions are equivalent to capacitors. This method of design is preferred as this takes less space than a similar low-pass filter designed using stubs.

The software used for this project is the Ansys HFSS Students Edition. The whole circuit is designed on a patch of **Fr4 Epoxy** that is of **1.6 mm** width and all the conductors are of **0.035 mm** width. 6^{th} order (N=6) filter is implemented where 6 lumped elements are needed in a lumped model - **3 inductors** and **3 capacitors**. That circuit is designed using the stepped-impedance method. After that, the whole thing is simulated and $\mathbf{S_{11}}$ and $\mathbf{S_{21}}$ parameters are plotted. As the cutoff frequency is 2.5 GHz, no signal should pass through it after 2.5 GHz and should come back reflected through port 1, i.e., S_{11} should be nearly 0 dB after 2.5 GHz. Similarly, S_{21} should decrease accordingly after 2.5 GHz. Thus, the two plots are obtained in the same plot the result is seen to be similar to the desired result.

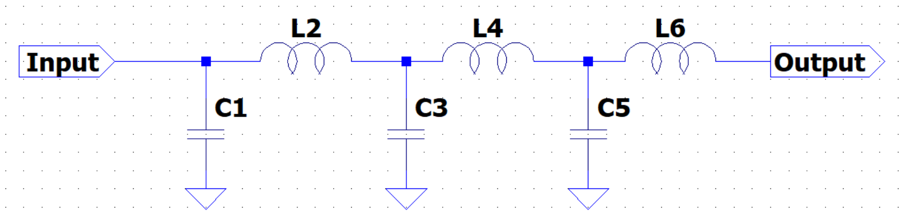


Figure 1: Lumped element element of the microwave filter

Theory

Approximate Equivalent Circuit for Short Transmission Line Section

The first step to be taken for this project is to find the approximate equivalent circuit for short length transmission lines. The line may have a very high or a very Low impedance. The approximate circuit for a short length transmission line is shown in the Figure 2.

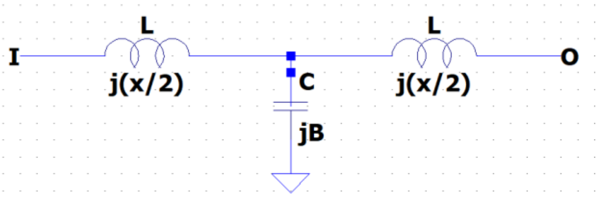


Figure 2: T equivalent circuit for a TL with $\beta l << \pi/2$

From ABCD parameter matrix of the T-section model of transmission line is given as

$$[T] = \begin{bmatrix} \cos\beta l & jZ_0 \sin\beta l \\ jY_0 \sin\beta l & \cos\beta l \end{bmatrix}$$

From the relation between the **Z** and **ABCD** parameters of the matrix, we derive,

$$Z_{11} = Z_{22} = \frac{A}{C} = -jZ_0 \cot\beta l$$

Similarly,

$$Z_{12} = Z_{21} = \frac{1}{C} = \frac{1}{jY_0 \sin\beta l} = -jY_0 \csc\beta l$$

Now, the series elements of the T-equivalent circuit are,

$$Z_{11} - Z_{12} = -jZ_0 \frac{(\cos\beta l - 1)}{\sin\beta l} = jZ_0 \tan\frac{\beta l}{2}$$

And, shunt element of the same circuit will be Z_{12}

Now, comparing with the Figure 2, we get

$$\frac{X}{2} = Z_0 \tan\frac{\beta l}{2}$$

Assuming that the transmission line is of short length and large characteristic impedance ($\beta l < \frac{\pi}{4}, Z_0 \gg 1$),

$$X \approx Z_0\beta l \qquad [For\ \beta l < \frac{\pi}{4}, \tan\beta l \approx \beta l\ \ and\ \ \sin\beta l \approx \beta l]$$

The shunt element of the circuit in Figure 2 has a capacitor as a shunt element,

$$B \approx \frac{1}{Z_0} sin\beta l = Y_0 sin\beta l$$

Assuming a very high impedance ($Z_0 \gg 1$),

$$X \approx Z_0\beta l$$
$$B \approx 0$$

Similarly, for a short length transmission line with a low characteristic impedence,

$$X \approx 0$$
$$B \approx Y_0\beta l$$

Thus, it is seen that the capacitors indicate the low impedance lines and the inductors indicate the high impedance lines in the practical microwave filter. In the practical design, we can replace the inductors and capacitors by alternating patches of high-impedance ($Z_0 = Z_h$) and low-impedance ($Z_0 = Z_l$) sections. The values of Z_h and Z_l must be kept as high as possible, so they are chosen to be the highest and lowest possible impedance to be fabricated practically. In this project, the value of Z_h is taken as 120 Ω and Z_l as 20 Ω. The lengths of the lines can be approximately calculated from the previously derived equations for X and B. To get the best response, these lengths must be calculated at $\omega = \omega_c$.

The electrical lengths of the Inductor and Capacitor sections can be calculated by the following two equations –

$$\beta l = \frac{LZ_0}{Z_h} \text{ for inductors}$$

$$\beta l = \frac{CZ_l}{Z_0} \text{ for capacitors}$$

Specifications of the desired filter to be fabricated after the completion of the project,

1. Filter type: Low Pass
2. Response: Maximally-flat
3. Cutoff Frequency: 2.5 GHz
4. Insertion loss at 4 GHz: -20 dB
5. Filter impedance: 50 Ω
6. Highest practical line impedance: 120 Ω
7. Lowest practical line impedance: 20 Ω

Implementation of the project in Ansys HFSS Students Edition

1. Determination of the number of filter sections required for the given specifications

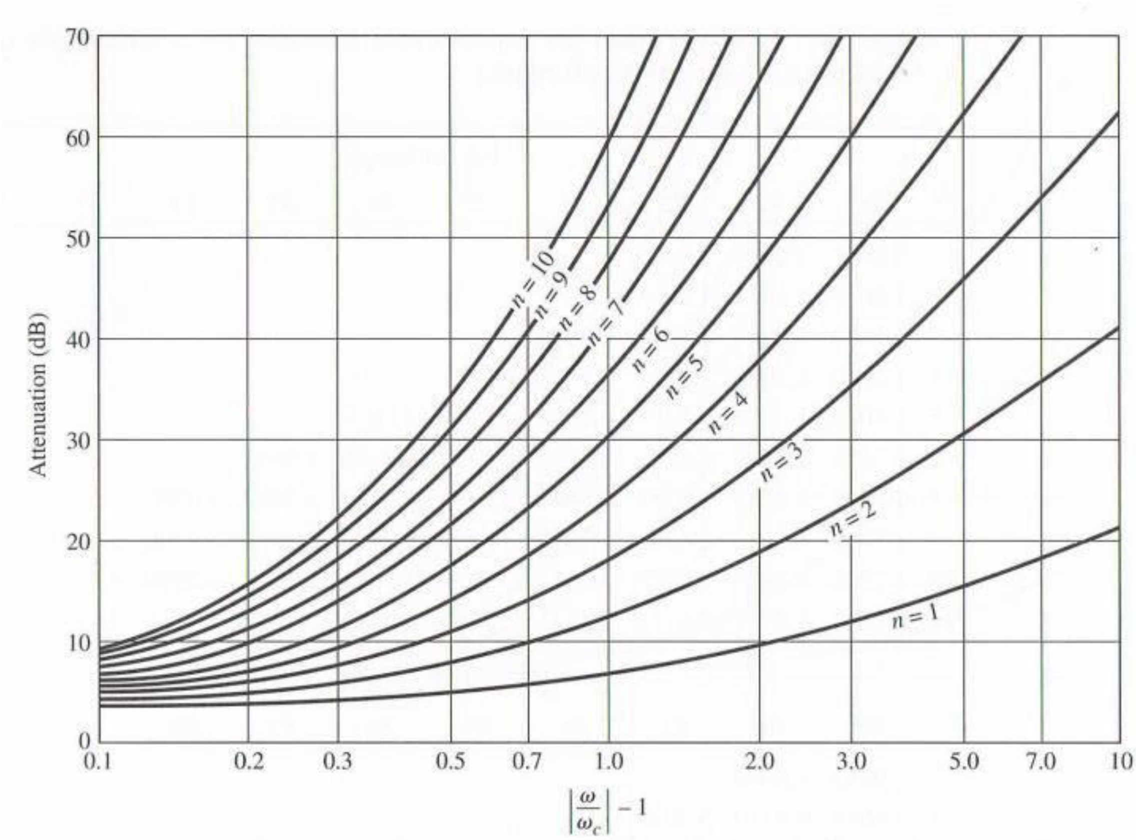


Figure 3: attenuation vs normalized frequency for maximally flat filter prototypes

To find the order of the filter and the number of sections to be used, first the following value for normalized frequency is calculated,

$$\left|\boldsymbol{\frac{\omega}{\omega_c}}\right| \boldsymbol{- 1}$$

In this given case, ω = 4 GHz and $\omega_c = 2.5$ GHz
Thus,

$$\left|\frac{\mathbf{4}}{\mathbf{2.5}}\right| - \mathbf{1} = \mathbf{1.6} - \mathbf{1} = \mathbf{0.6}$$

From the given graph, it is seen that for the value 0.6, the value N = 6 will give more than -20 dB insertion loss at 4 GHz frequency.

Hence, the order of the desired filter will be **N = 6**.

Now, we look at the following table that provides the element values for the maximally flat filter prototypes,

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7
1	**2.0000**	**1.0000**					
2	**1.4142**	**1.4142**	**1.0000**				
3	**1.0000**	**2.0000**	**1.0000**	**1.0000**			
4	**0.7654**	**1.8478**	**1.8478**	**0.7654**	**1.0000**		
5	**0.6180**	**1.6180**	**2.0000**	**1.6180**	**0.6180**	**1.0000**	
6	**0.5176**	**1.4142**	**1.9318**	**1.9318**	**1.4142**	**0.5176**	**1.0000**

From this table, we get the normalized parameter values for N = 6 order filter,

$$g_1 = 0.5176 = C_1$$
$$g_2 = 1.4142 = L_2$$
$$g_3 = 1.9318 = C_3$$
$$g_4 = 1.9318 = L_4$$
$$g_5 = 1.4142 = C_5$$
$$g_6 = 0.5176 = L_6$$

The electrical lengths of the patches are calculated from the equations

$$\beta l = \frac{LZ_0}{Z_h} \textbf{ for inductors}$$

$$\beta l = \frac{CZ_l}{Z_0} \textbf{ for capacitors}$$

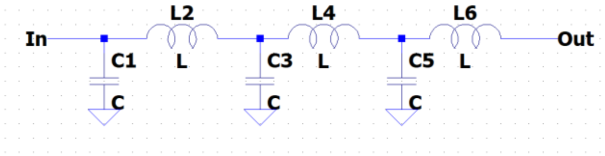


Figure 4: Lumped element diagram for the porposed filter

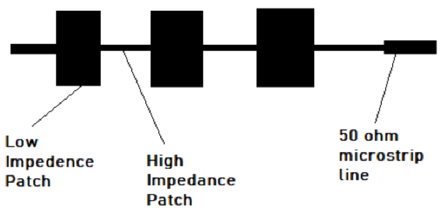


Figure 5: Microstrip layout of the

Proposed filter

2. Calculation of the dimensions of the filter

The next step is to calculate the lengths and widths of the proposed low-pass filter. To do that, the following formulae are used,

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12h / W}}$$

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}} \ln\left(\dfrac{8h}{W} + \dfrac{W}{4h}\right) & for\ W/h \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[W/h + 1.393 + 0.667\ln\left(W/h + 1.444\right)\right]} & for\ W/h \ge 1 \end{cases}$$

$$\frac{W}{h} = \begin{cases} \dfrac{8e^A}{e^{2A} - 2} & for\ W/h < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left(\ln(B - 1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right)\right] & for\ W/h > 2 \end{cases}$$

$$where \quad A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

Where,
ε_e = Effective dielectric constant of the substrate.
ε_r = Dielectric constant of the given substrate Fr4 epoxy (4.4 in this case).
h = Substrate thickness = 1.6 mm in this case.
W = conductor width.

The following table depicts the several dimensions of the sections of the microwave filter,

Section	$Z_i = Z_h$ or Z_l	βl_i (deg)	W_i (mm)	l_i (mm)
1 (C1)	20Ω	11.86	11.1	2.05
2 (L2)	120Ω	33.76	0.408	6.56
3 (C3)	20Ω	44.27	11.1	7.64
4 (L4)	120Ω	46.11	0.408	8.96
5 (C5)	20Ω	32.41	11.1	5.59
6 (L6)	120Ω	12.36	0.408	2.4

3. Designing the microwave filter microstrip line model in Ansys HFSS Software

After completing all the required calculations for the lengths and widths of the several patches required to design the proposed filter, the Ansys HFSS Software is opened. At first the Fr4 epoxy substrate is chosen form the materials list with relative dielectric constant = 4.4. A ground plane is also chosen under the substrate. Substrate thickness is chosen as 1.6 mm.

The orientation of the designed Filter is shown in the figure beside. After creating the ground plane, the high and low impedance patch regions are designed alternatively. They are united together to create the top patch. After designing all the regions with respective length and width, two 50 Ω microstrip lines are added at the two ends those will work as ports. An overall top-view of the complete microwave filter model is shown in figure 7 below.

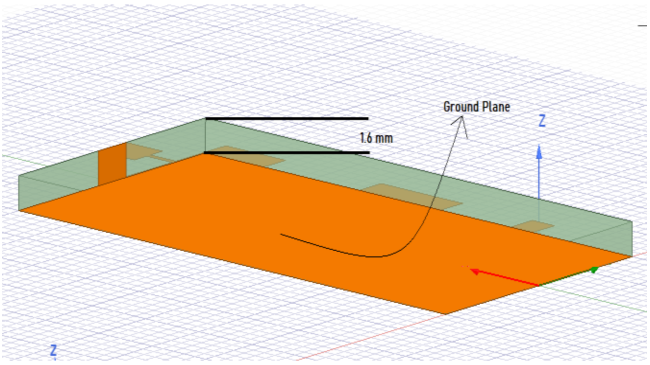


Figure 6: The ground plane

The length of the substrate is 20 mm and width is 10 mm. Substrate thickness is 1.6 mm. Ground plane and conductor thickness is 0.035 mm.

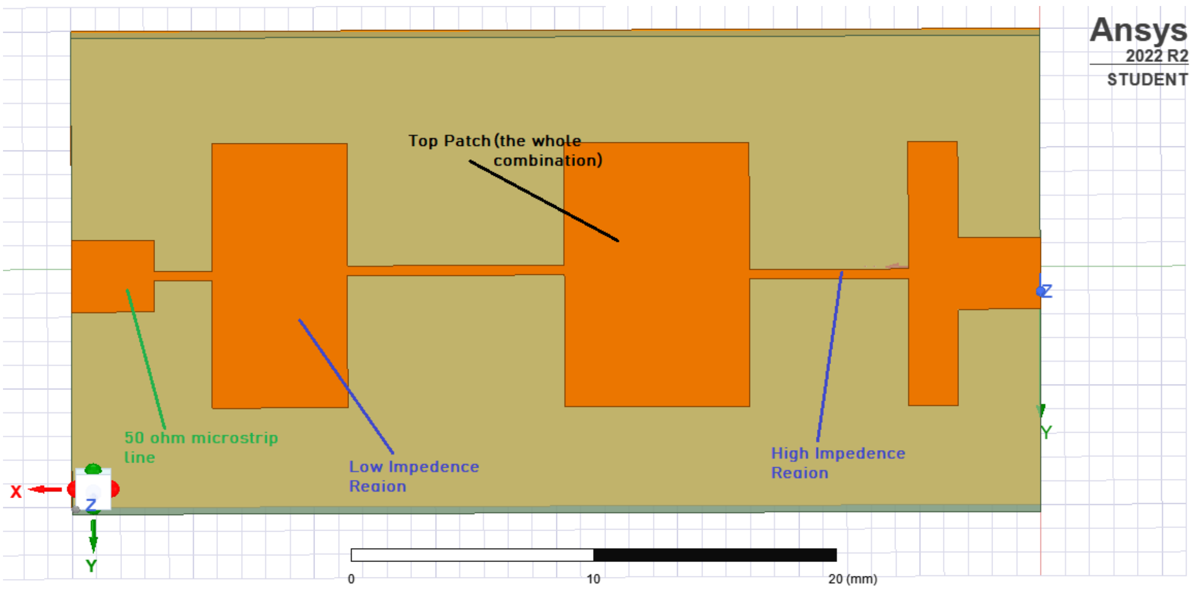


Figure 7: The designed proposed filter microstrip model

4. Simulation and creating modal solution reports

After the circuit is completed, the next step is **Simulation**. To simulate the circuit, the whole system is checked for validation. If all the tests are right, then there is no problem or mismatch in the design.

After that, a solution setup is added, and a frequency range of 5 GHz is chosen for experiment. Maximum number of passes is kept as 6.

After that, a frequency range of 2 to 7 GHz is chosen and the design Is simulated by “Analyse all” option.

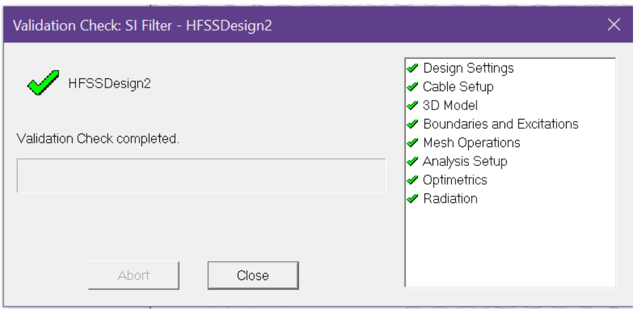


Figure 8: Validation check

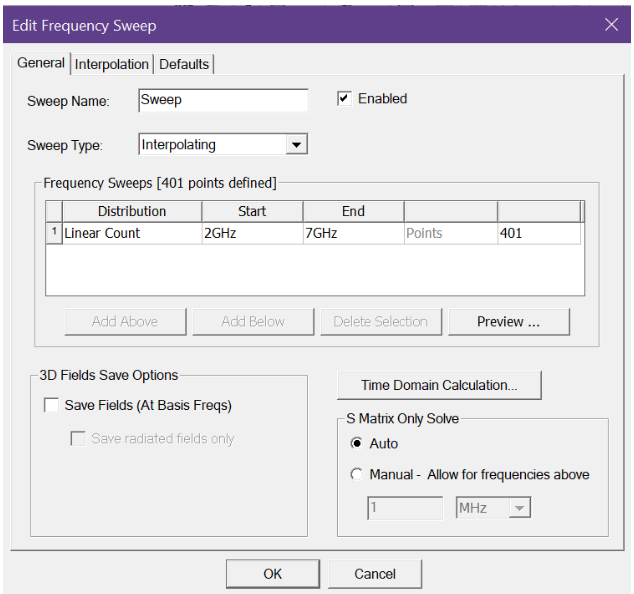


Figure 9: Selecting frequency sweep

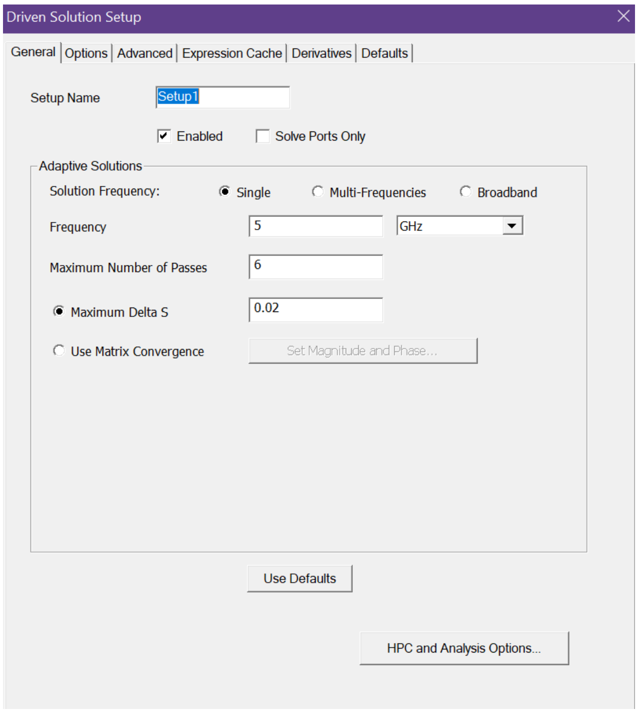


Figure 10: Modal solution setup

After the completion of simulation, the results are examined. The results are shown in the next section.

5. Creating results using rectangular plot

After the simulation is over, the results are plotted in the form of **Rectangular plot**. The S_{11} and S_{21} parameters are plotted in the single graph and their properties are examined. If the cutoff frequency is 2.5 GHz, then no signal should pass through the filter after that frequency, thus S_{21} parameter must decrease after than frequency. Similarly, the S_{11} parameter must be nearly 0 dB after 2.5 GHz. The obtained results are published below –

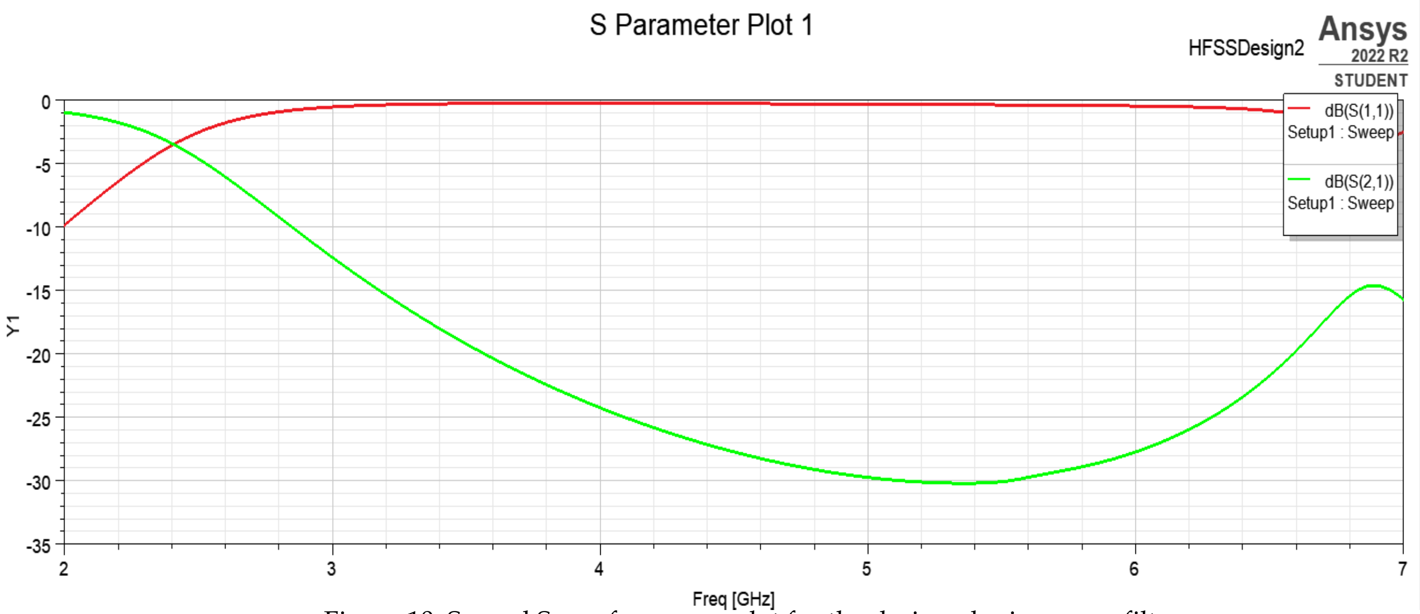
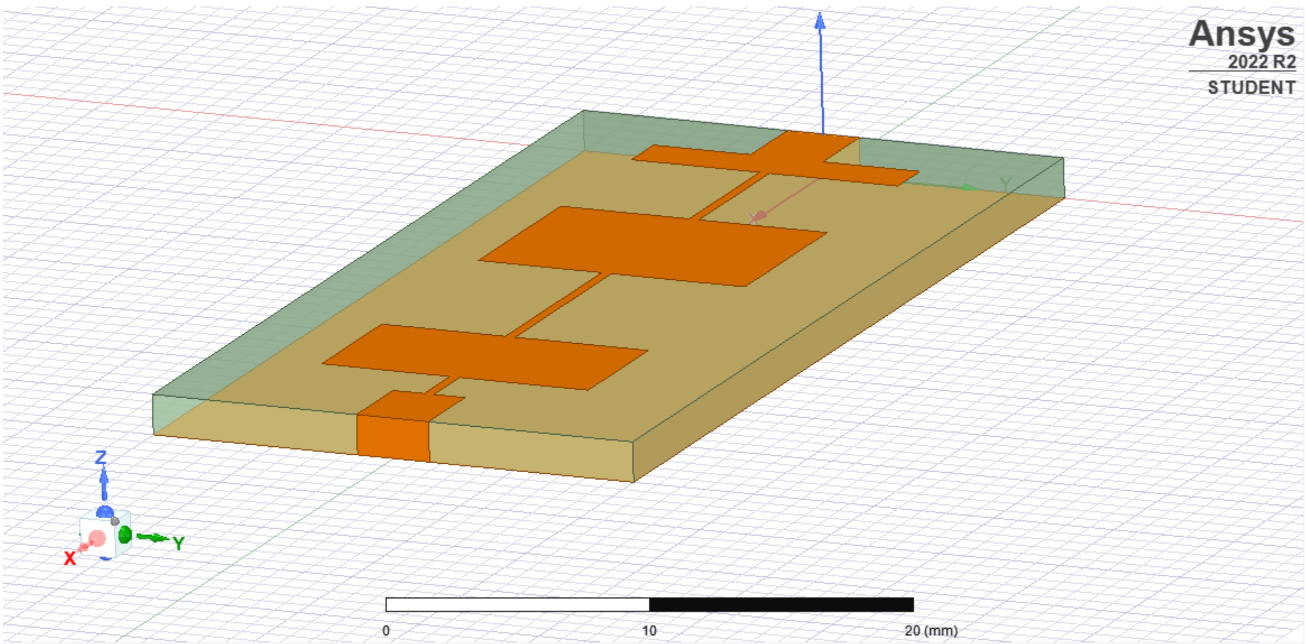


Figure 10: S_{11} and S_{21} vs frequency plot for the designed microwave filter

It is clear from the graph that the S_{21} parameter decreases after the cutoff frequency of 2.5 GHz and S_{11} is also almost 0 dB after that. And it also has a attenuation of almost -24 dB at 4 GHz that is greater than -20 dB (as proposed).



Conclusion and References

In this project, a microwave filter is designed that has a cutoff frequency of 2.5 GHz and has almost -24 dB of insertion loss at 4 GHz. While going through this project, the technique to design a maximally-flat response filter was learnt. By plotting the required parameters to examine the properties of the filter, it is seen that the obtained result fulfils the required properties mentioned in the problem statement, and the transfer characteristics is close to the characteristics of an ideal filter.

References

[1] David M. Pozar, "Microwave Engineering", John Wiley, 2000.
[2] Sheetal Mitra, D.K. Kumuda, "Stepped Impedance Microstrip Low-Pass FilterImplementation for S-Band Application", International Journal of Latest Trends in Engineering and Technology (IJLTET)