Design of a Hairpin Bandpass Filter for X-Band Applications

Submitted by

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Project Title

Design of a Hairpin Bandpass Filter (BPF) for X-Band applications

Acknowledgement

I, **Rudraprasad Debnath**, a student of **Indian Institute of Technology Tirupati**, MTech 1st year, have completed this project titled **Design of a Hairpin Bandpass Filter for X-Band Applications** 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/pass 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 Bandpass filter for X-Band applications. Now what is the X-band? X-band is defined as the frequency spectrum from 8 GHz to 12.4 GHz. So, our main goal to design this filter is to provide a passband within the specified frequency band. X-band is highly preferrable for Naval Radars, Police speed radar and other military applications.

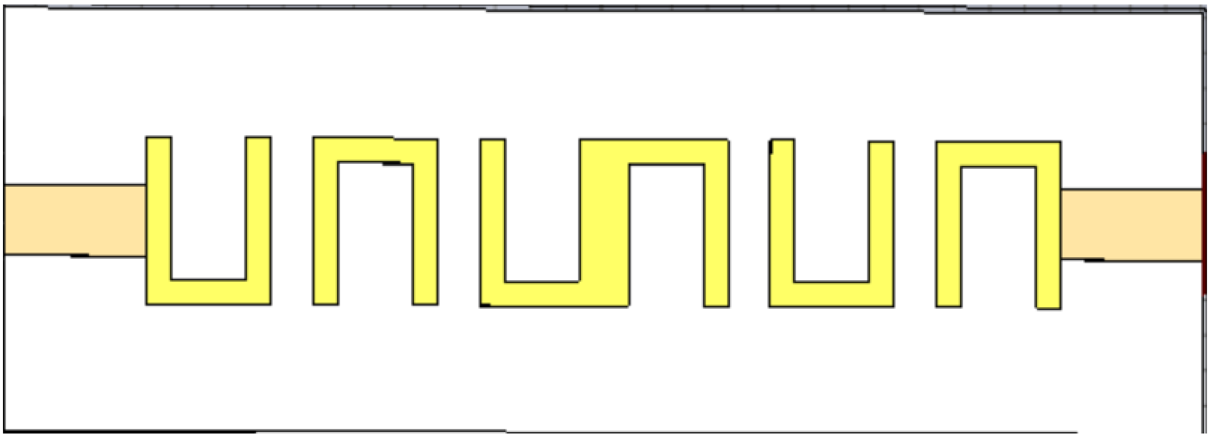
The software used for this project is the Ansys HFSS Students Edition. The whole circuit is designed on a patch of **Rogers RT 5880** that is of **1.6 mm** width and all the conductors are of **0.035 mm** width. Six resonators are placed side by side of each other to work as a filter. Distance between each is mentioned and two waveguide ports are used to feed the excitation. The Rogers RT5880 substrate is chosen as it has a permittivity value of $\epsilon_r = 2.2$ that results in less loss.

Design Procedure and Specifications

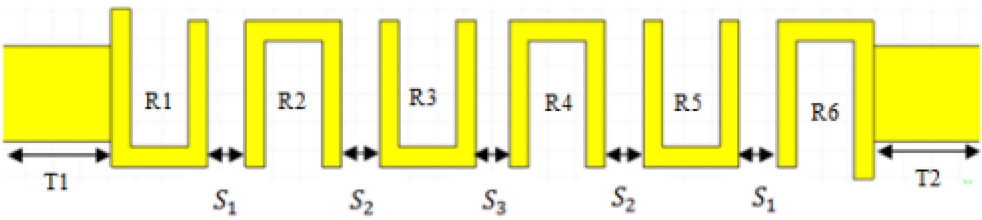
There are several methods for designing a filter. For that, the specifications must be mentioned. The specifications for the filter are shown below –

Specification	Value/Type
1. Working Frequency	10.5 – 10.6 GHz
2. No. of poles	6
3. Centre frequency	10.55 GHz
4. Response Type	Chebyshev
5. Bandwidth	100 MHz
6. Fractional Bandwidth	0.01

The substrate used for this purpose is **Rogers RT5880**. The main design of the device is shown in the below picture.



There are six "U" shaped identical resonators placed serially with two ports (50 ohm) placed at the two corners. It can be seen that the 3rd and 4th resonators are connected to each other. That is done for more accurate results. Distance between each resonator is fixed and specified later, and also the dimensions of the resonators.



Microstrip Line width calculation

To calculate the width of the microstrip line, some standard formulae are used. These are-

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

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

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

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

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

In this case, $\epsilon_r = 2.2$ $Z_0 = 50\ \Omega$.

B = $(377\pi / (2 \times 50 \times \sqrt{2.2}) = 7.9825$

Thus, W/h = 3.08 where h = 1.6mm
:. W = 3.08 x 1.6mm = 4.9mm
A point to be noted is that a hairpin BPF uses a line of half wavelength,

$$L = \frac{\frac{\pi}{180}}{K0\sqrt{\epsilon e}}\theta 0 \quad \text{and} \quad K_0 = \frac{2\pi}{\lambda}$$

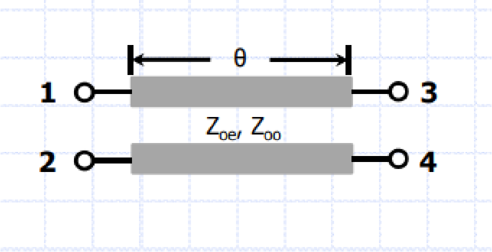
From the above calculations we find that,

$K_0 = 198.96\ m^{-1}$
L = 11.5 mm

Hairpin Bandpass Filter Theory

Basic Theory: Hairpin BPF is one of the most commonly used bandpass filters. Theory of the device resembles the theory of parallel-coupled resonators as that is what the device is made of. The resonators are of almost half-wavelength long and they are folded in ‘U’ shapes to make a compact structure that takes less space. To get a perfect resonance, the length of a microstrip line resonator must be a multiple of $\lambda/2$.

From the figure shown in the diagram of a parallelly-coupled line, first the Z-matrix is to be calculated. Z_{oe} = even mode characteristic impedance, Z_{oo} = odd mode characteristic impedance



$$Z_{11}=Z_{22}=Z_{33}=Z_{44} = \frac{-j}{2}(Z_{oe}+Z_{oo})\cot\theta$$
$$Z_{12}=Z_{21}=Z_{34}=Z_{43} = \frac{-j}{2}(Z_{oe}-Z_{oo})\cot\theta$$
$$Z_{13}=Z_{31}=Z_{24}=Z_{42} = \frac{-j}{2}(Z_{oe}+Z_{oo})\csc\theta$$
$$Z_{14}=Z_{41}=Z_{23}=Z_{32} = \frac{-j}{2}(Z_{oe}-Z_{oo})\csc\theta$$

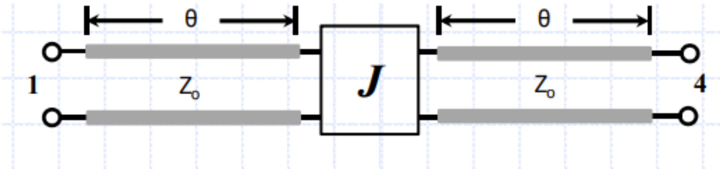
Thus, the impedance matrix

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} \frac{-j}{2}(Z_{oe}+Z_{oo})\cot\theta & \frac{-j}{2}(Z_{oe}-Z_{oo})\cot\theta \\ \frac{-j}{2}(Z_{oe}+Z_{oo})\csc\theta & \frac{-j}{2}(Z_{oe}-Z_{oo})\csc\theta \end{bmatrix}$$

And from the impedance matrix, we can calculate the ABCD matrix

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \frac{Z_{11}}{Z_{41}} & \frac{|Z|}{Z_{41}} \\ \frac{1}{Z_{41}} & \frac{Z_{44}}{Z_{41}} \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \frac{Z_{oe}+Z_{oo}}{Z_{oe}-Z_{oo}}\cos\theta & j\frac{(Z_{oe}-Z_{oo})^2 csc^2\theta-(Z_{oe}+Z_{oo})^2 cot^2\theta}{2(Z_{oe}-Z_{oo})\csc\theta} \\ 2\frac{j}{Z_{oc}-Z_{sc}}\sin\theta & \frac{Z_{oe}+Z_{oo}}{Z_{oe}-Z_{oo}}\cos\theta \end{bmatrix}$$



For the lines shown in the above figure,

[ABCD] = [ABCDleft][J][ABCDright]

$$= \begin{bmatrix} \cos\theta & jZ0\sin\theta \\ j\frac{1}{Z0}\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 0 & -j\frac{1}{J} \\ -jJ & 0 \end{bmatrix} \begin{bmatrix} \cos\theta & jZ0\sin\theta \\ j\frac{1}{Z0}\sin\theta & \cos\theta \end{bmatrix}$$

$$= \begin{bmatrix} \left(jZ_0 + \frac{1}{jZ_0}\right) sin\theta cos\theta & j(JZ_0{}^2 sin^2\theta - \frac{cos^2\theta}{J}) \\ j(\frac{1}{jZ_0{}^2} sin^2\theta - Jcos^2\theta) & \left(jZ_0 + \frac{1}{jZ_0}\right) sin\theta cos\theta \end{bmatrix}$$

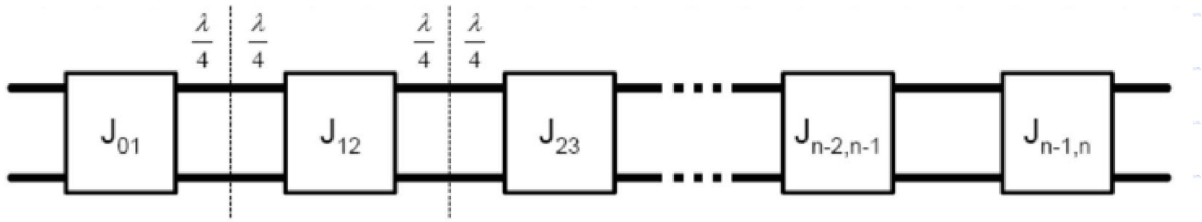
Comparing the A and C terms, when $\theta \approx \frac{\pi}{2}$

$$\frac{Z_{oe} + Z_{oo}}{Z_{oe} - Z_{oo}} = \left(jZ_0 + \frac{1}{jZ_0}\right)$$

And

$$\frac{Z_{oc} - Z_{sc}}{2} = jZ_0{}^2$$

$$\boxed{\begin{aligned} &\Rightarrow Z_{oe} = Z_0(1 + JZ_0 + J^2 Z_0{}^2) \\ &\Rightarrow Z_{oo} = Z_0(1 - JZ_0 + J^2 Z_0{}^2) \end{aligned}}$$



For the design shown in the above figure,

$$\frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi FBW}{g_n g_{n+1}}}$$

Where, FBW = Specified fractional bandwidth of the filter

g_n = normalized parameter values obtained from the Chebyshev response chart

For a Hairpin BPF, there are some separate parameters those need to be defined.

K_n is the coupling coefficient between the resonators that can be defined as,

$$K_n = \frac{FBW}{\sqrt{g_k g_{k+1}}}$$

The design of the filter is conducted by using low pass filter parameters based on Chebyshev table with ripple of 0.01 dB as the design parameter to get coupling coefficient. It is used to determine the distance between hairpin resonator. Based on Chebyshev table, the six-order filter have the following parameters.

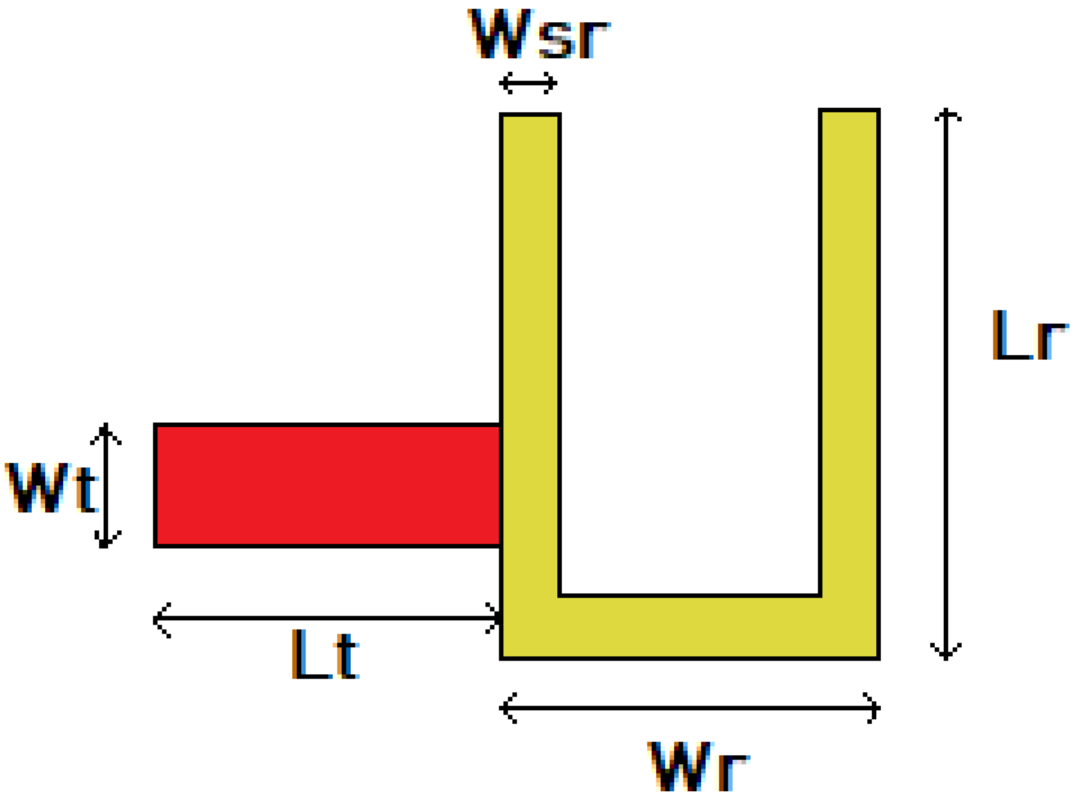
g1 = 0.7814
g2 = 1.3600
g3 = 1.6897
g4 = 1.5350
g5 = 1.4970
g6 = 0.7098
g7 = 0.9085

	Capacitor Input, R_S=R_L=1 Ω, f=1 rad/sec									
Order	C1	L2	C3	L4	C5	L6	C7	L8	C9	R_{Load}
2	0.4489	0.4078								0.9085
3	0.6292	0.9703	0.6292							1
4	0.7129	1.2004	1.3213	0.6476						0.9085
5	0.7563	1.3049	1.5773	1.3049	0.7563					1
6	0.7814	1.3600	1.6897	1.5350	1.4970	0.7098				0.9085
7	0.7970	1.3924	1.7481	1.6331	1.7481	1.3924	0.7970			1
8	0.8073	1.4131	1.7824	1.6833	1.8529	1.6193	1.5555	0.7334		0.9085
9	0.8145	1.4271	1.8044	1.7125	1.9058	1.7125	1.8044	1.4271	0.8145	1
	L1	C2	L3	C4	L5	C6	L7	C8	L9	R_{Load}
	Inductor Input, R_S=R_L=1 Ω, f=1 rad/sec									

Design, Simulation and Results

The Hairpin BPF was designed in the CST Microwave Studio software using the dimension values obtained from literature study from various papers. The dimensions can be tabulated in the following table –

L (total length of device)	12 mm
W (total width of the device)	33.8 mm
L_r (length of each resonator)	4.7 mm
Wsr (width of each resonator)	0.7 mm
L_{tap} (length of each feeding tap)	4 mm
W_{tap} (width of each tap)	2 mm
W_r (width of a whole resonator)	3.5 mm
Gap (gap between two resonatots)	1.2 mm



The structure for a single resonator with a feeding tap is shown in the above figure with all the details marking of dimensions. In this case, the number of the resonators is six. So, the resonators are designed on a Rogers RG 5880 substrate. The fully designed diagram of the filter is shown in the figure below.

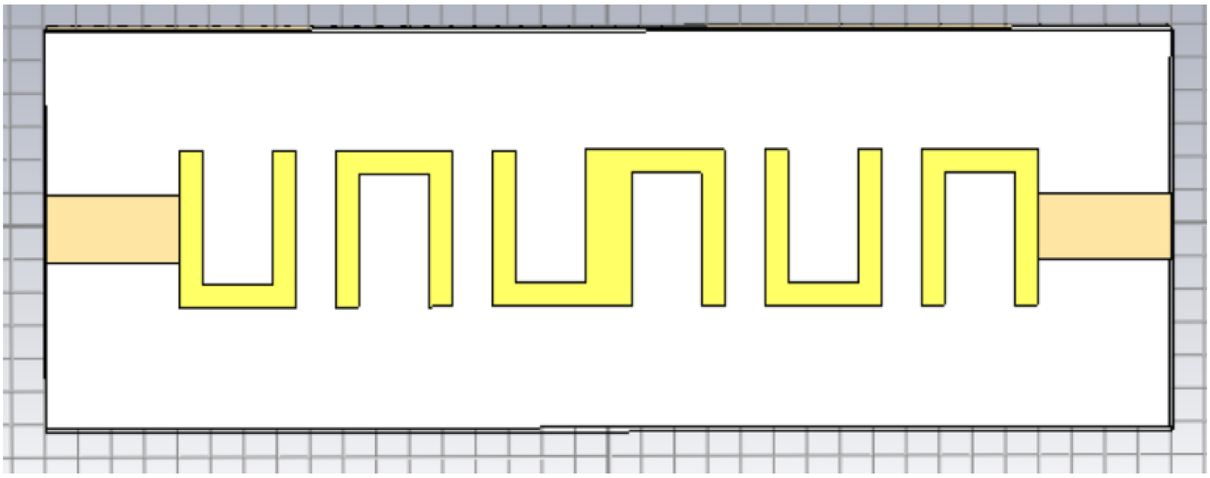
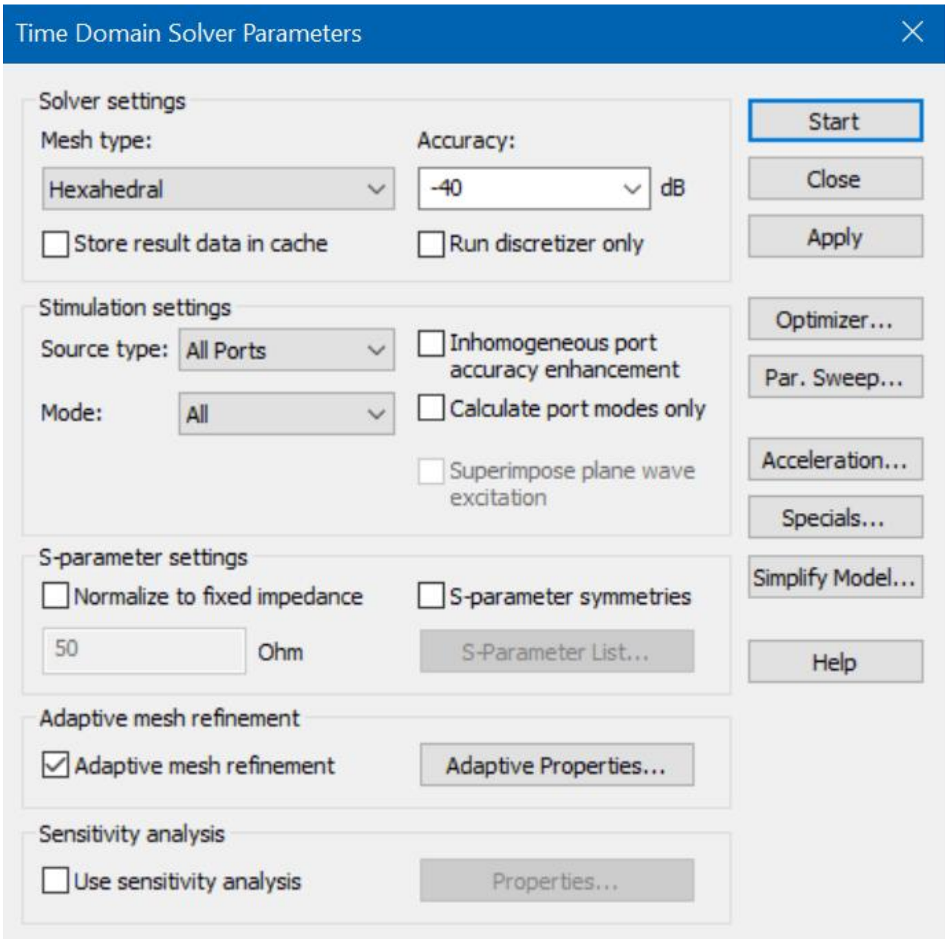


Figure: Hairpin BPF

The two resonators in the middle are clubbed together for better result. The simulation setup is done in CST Studio using a time domain solver as follows –



The design is then simulated, and the following results are obtained –

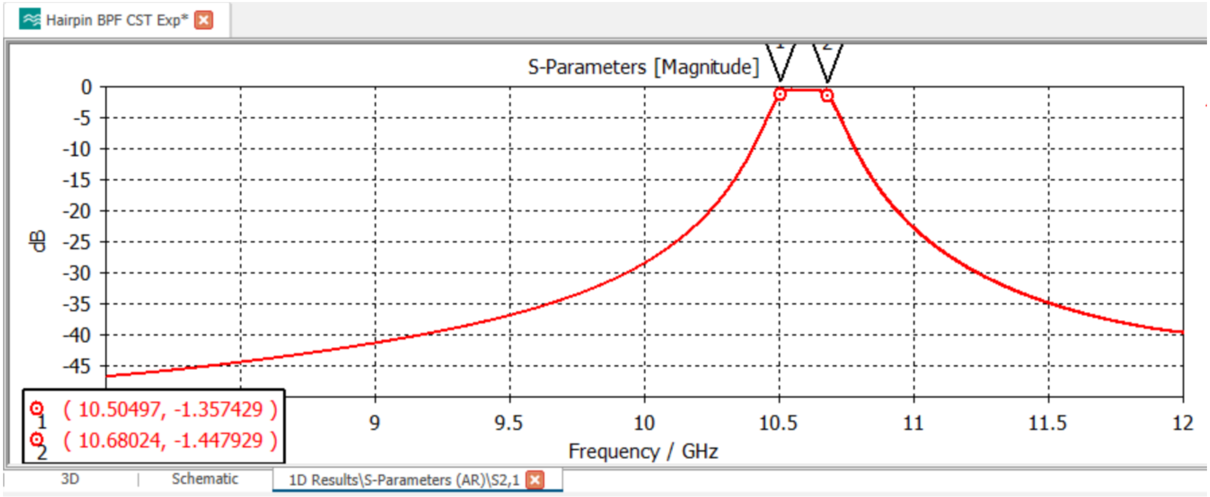


Figure: S_{21} curve for the device

The above figure shows the Simulated curve of the S_{21} parameter for the device. It shows that Centre frequency of the filter is almost 10.7 GHz, and is possesses a good smooth pass-band in the X-band frequency spectrum.

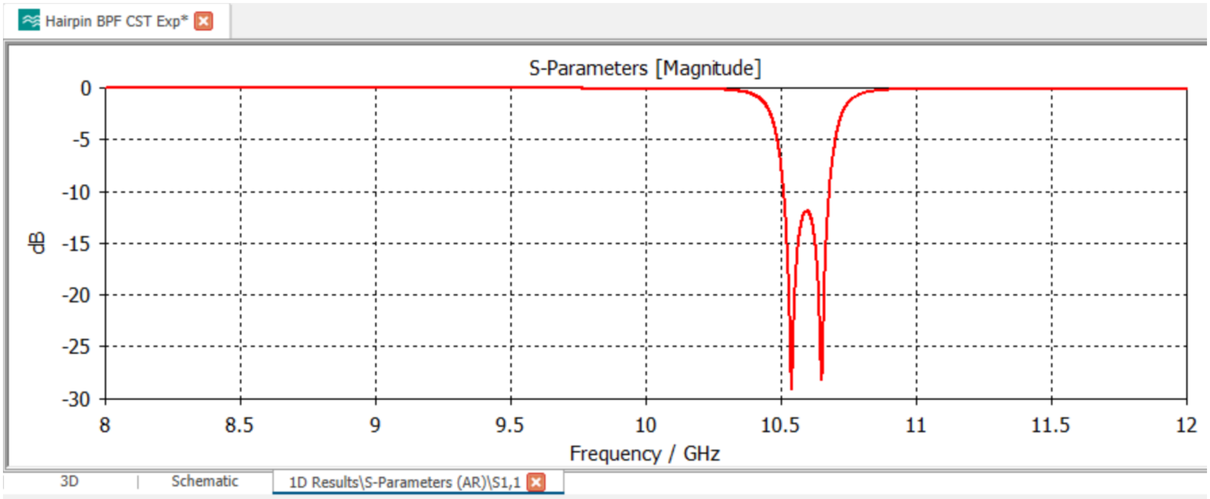


Figure: S_{11} curve for the device

References

[1] "*Design and Simulation of Microstrip Hairpin Bandpass Filter with Open Stub and Defected Ground Structure (DGS) at X-Band Frequency*", T Hariyadi , S Mulyasari and Mukhidin, Universitas Pendidikan Indonesia.

[2] *Microwave Engineering*,D.M. Pozar, 4th Edition New York: J. Wiley & Sons, Inc.

[3] "*Design and simulation of hairpin band pass filter for different substrate*", Abhay Purohit, Sandeep Toshniwal, International Journal of Engineering and

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