A Project Report

On

Design and Fabrication of Butterworth 3rd Order Lowpass Filter

BY

Arnav Tripathi	**2022AAPS0501H**
Asapu Datta Harshith	**2022A3PS0639H**
Soham Erande	**2022AAPS1376H**
Srishti Yadav	**2022AAPS0505H**

Under the supervision of

Harish V. Dixit and Neha Parmar

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(ECE F312)

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE PILANI (RAJASTHAN)

HYDERABAD CAMPUS

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Birla Institute of Technology and Science-Pilani,

Hyderabad Campus

Certificate

This is to certify that the project report entitled "**Design and Fabrication of Butterworth 3rd Order Lowpass Filter**" submitted by Mr Arnav Tripathi (ID No. 2022AAPS0501H), Mr Asapu Datta Harshith (ID No. 2022A3PS0639H), Mr Soham Erande (ID No. 2022AAPS1376H), Ms Srishti Yadav (ID No. 2022AAPS0505H) in partial fulfilment of the requirements of the course Electromagnetic Fields and Microwave Engineering Laboratory (ECE F312), embodies the work done by them under my supervision and guidance.

Date: 15-04-2025

(Harish V. Dixit and Neha Parmar)

BITS- Pilani, Hyderabad Campus

ABSTRACT

In this project, a third-order Butterworth low-pass filter with a cutoff frequency of 4 GHz is designed, simulated, and fabricated on a FR-4 substrate using microstrip technology. Standard Butterworth synthesis was used in the filter's design to produce a smooth roll-off and a maximally flat passband. Transmission line theory was used to convert lumped element values into microstrip line sections while taking substrate characteristics and real-world limitations into account. Cadence AWR was used to build and optimize the filter schematic, and PCB milling techniques were used to fabricate the final configuration. The design approach was validated by experimental measurements using a Vector Network Analyzer, which showed that the manufactured filter closely matched the simulated response with a measured -3.2 dB insertion loss at the cutoff frequency.

Minor discrepancies between theoretical and measured results were attributed to fabrication tolerances and connector losses. This work demonstrates the feasibility and effectiveness of microstrip-based Butterworth filters for RF applications and provides a practical foundation for future research in high-frequency circuit design.

CONTENTS

1. Theoretical Calculation for the Filter

We have to construct a Butterworth 3rd Order Lowpass Filter. We know that for a normal Butterworth Lowpass filter:

$$|H(j\omega)|^2 = \frac{1}{1 + \left(\frac{\omega}{\omega_c}\right)^{2N}}$$

Let $j\omega = s$, $\omega_c = 4$, $n = 3$

$$|H(s)|^2 = \frac{1}{1 + \left(\frac{s}{4j}\right)^{6}}$$

The poles will occur when $\left(\frac{s}{4j}\right)^6 = -1$.

Solving with $\omega_c = 1$ for convenience,

$(s+p_1)(s+p_2)(s+p_3)$ will be the denominator, where

$p_i = \exp\left(j\left(\frac{2i+n-1}{2n}\pi\right)\right)$ for i = 1, 2, 3.

$\therefore p_1 = \exp\left(j\left(\frac{2+3-1}{6}\pi\right)\right) = -\frac{1}{\sqrt{2}} - \frac{j}{\sqrt{2}}$

$p_2 = \exp\left(j\left(\frac{4+3-1}{6}\pi\right)\right) = -\frac{1}{\sqrt{2}} + \frac{j}{\sqrt{2}}$

$p_3 = \exp\left(j\left(\frac{6+3-1}{6}\pi\right)\right) = -1$

Putting these values in

$$H(s) = \frac{k}{(s+p_1)(s+p_2)(s+p_3)}$$

We get,

$$H(s) = \frac{k}{\left(s + \frac{1}{\sqrt{2}} + \frac{j}{\sqrt{2}}\right)\left(s + \frac{1}{\sqrt{2}} - \frac{j}{\sqrt{2}}\right)(s+1)}$$

$$H(s) = \frac{k}{\left(s^2 + \sqrt{2}s + 1\right)(s + 1)}$$

$$H(s) = \frac{k}{\left(s^3 + \sqrt{2}s^2 + s + 1\right)}$$

But this is for ωc = 1, for ωc = 4, we will replace s by $\frac{s}{\omega_c}$

$$H(s) = \frac{k}{\left(\left(\frac{s}{\omega_c}\right)^3 + \sqrt{2}\left(\frac{s}{\omega_c}\right)^2 + \frac{s}{\omega_c} + 1\right)}$$

Putting in the value, we get

$$H(s) = \frac{(4 * 10^3)^3}{\left(s^3 + \sqrt{2}(4 * 10^3)s^2 + (4 * 10^3)^2 s + (4 * 10^3)^3\right)}$$

$$H(s) = \frac{64 * 10^{27}}{(s^3 + 5.656 * 10^3 s^2 + 16 * 10^8 s + 64 * 10^{27})}$$

Based on these calculations, standardised g1 = 1 (for Inductor 1), g2 = 2 (for Capacitor 1), g3 = 1 (for Inductor 2).

Value of inductors:

$L_1 \ = \frac{g_1 \, Z_o}{\omega_c} = \ \frac{50*1}{2\pi*4*10^9} \approx \ 1.99nH$

$C_1 \ = \frac{g_2}{Z_o \omega_c} = \ \frac{2}{50*2\pi*4*10^9} \approx \ 1.5915 \, pF$

$L_2 = \ L_1 = 1.99 \, nH$

For MLIN,

$$L \ = \frac{Z_o L_{eff}}{v_p}$$

$v_p = \frac{c}{\sqrt{\varepsilon_{eff}}} = \ \frac{3*10^8}{\sqrt{4.4}} = \ 1.825 * 10^8 \text{ m}/s$

Solving for L_{eff},

$L_{eff} = \frac{L v_p}{Z_o} = \ \frac{1.99*10^9*1.825*10^8}{50} = 7.25mm$

Width: Assuming $\frac{W}{h} > 2$

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left(\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right)}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \left(\frac{1}{\sqrt{1 + \frac{12h}{W}}}\right)$$

Given that, substrate height h = 1.6 mm. Substituting in the equation:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \underbrace{\boxed{\left(\frac{1}{\sqrt{1 + \frac{19.2}{W}}}\right)}}_{\downarrow}$$

Can be ignored as denominator >> numerator

Given that: $Z_o = 50\ \Omega$

Assuming $\varepsilon_{eff} = 2.7$

$$50 = \frac{120\pi}{\sqrt{2.7}\left(\frac{W}{1.6} + 1.393 + 0.667\ln\left(\frac{W}{1.6} + 1.444\right)\right)}$$

Solving for W, we get W ≈ 3mm.

For the capacitor, $X_{stub} = -Z_o\cot(\beta l)$

$X_c = \frac{1}{\omega_c}$ (high frequency, small length)

$\therefore \frac{1}{\omega_c} = Z_o\cot(\beta l)$

$\beta l = \cot^{-1}\left(\frac{1}{\omega_c Z_o}\right) = \cot^{-1}(0.5) \approx 1.107\ rad$

(As C = 1.59 pF, $\omega_c = 8\pi \times 10^9,\ Z_o = 50\ \Omega$)

$$\beta = \frac{2\pi}{\lambda_g}$$

$$\lambda_g = \frac{c}{f \times \sqrt{\varepsilon_{eff}}} = \frac{3 \times 10\text{^}3}{4 \times 10\text{^}9 \times \sqrt{2.7}} = 45.7\ mm$$

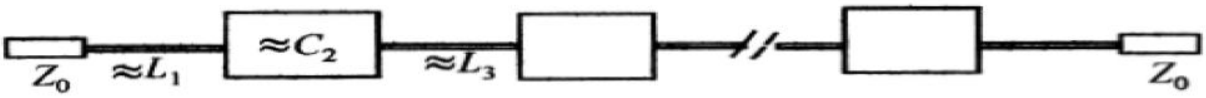
$$l = \frac{\beta l \times \lambda_g}{2\pi} = \frac{1.107 \times 45.7}{2\pi} = 8.054\ mm$$

The inductor and capacitor's width calculations are the same, so W ≈ 3mm.

2.Design and Simulation of the Filter

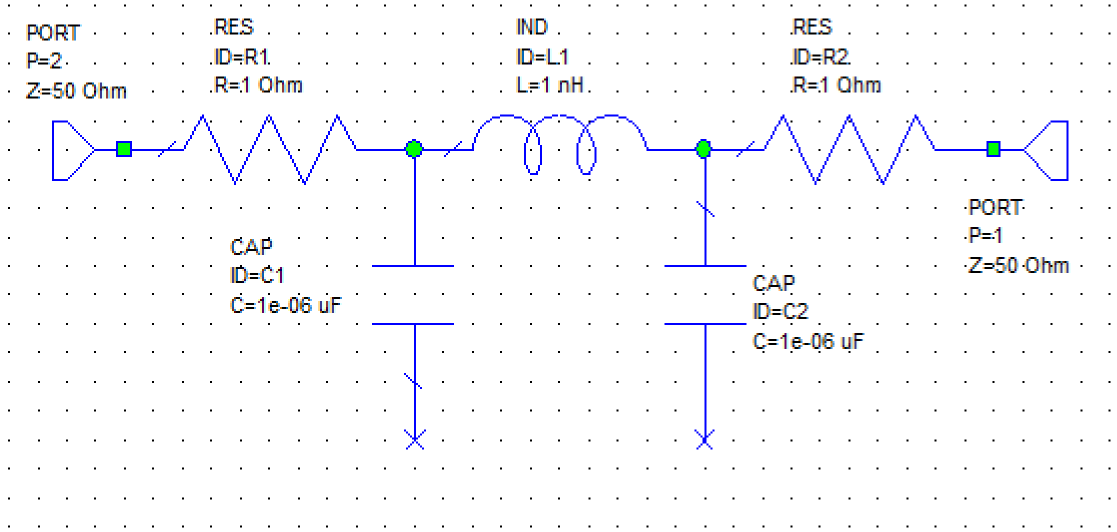
2.1 **Designing the Filter**

A low-pass Butterworth filter can be constructed using a ladder of inductors and capacitors between the source and the load. The number of elements affects the order of the filter we design. (No. of elements = Order)

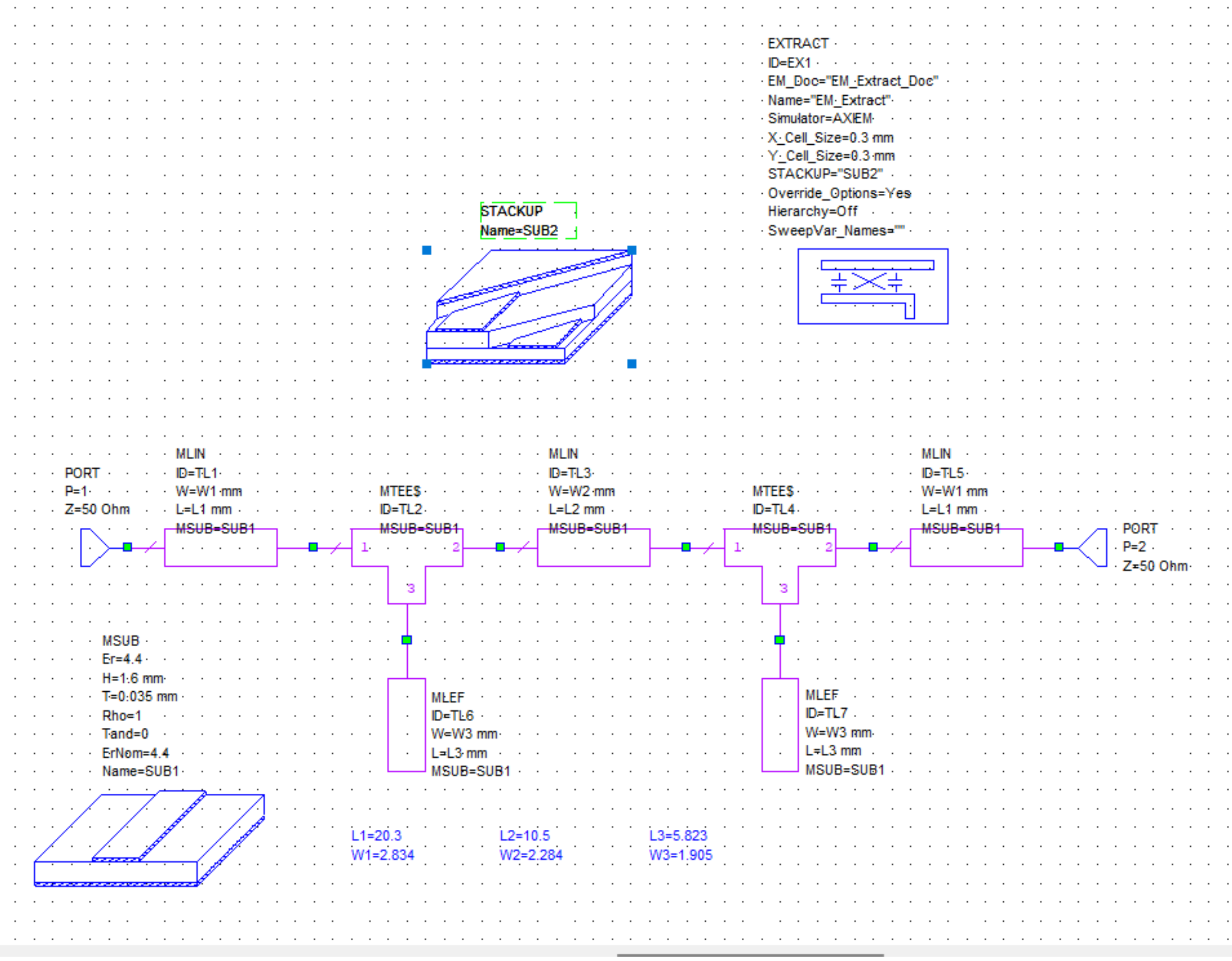


Above is a generalised model for a Butterworth LPF. For order n = 3, we have 2 capacitors with an inductor in between(as shown below,ignore values)

Using Cadence AWR, the schematic can be made as follows:



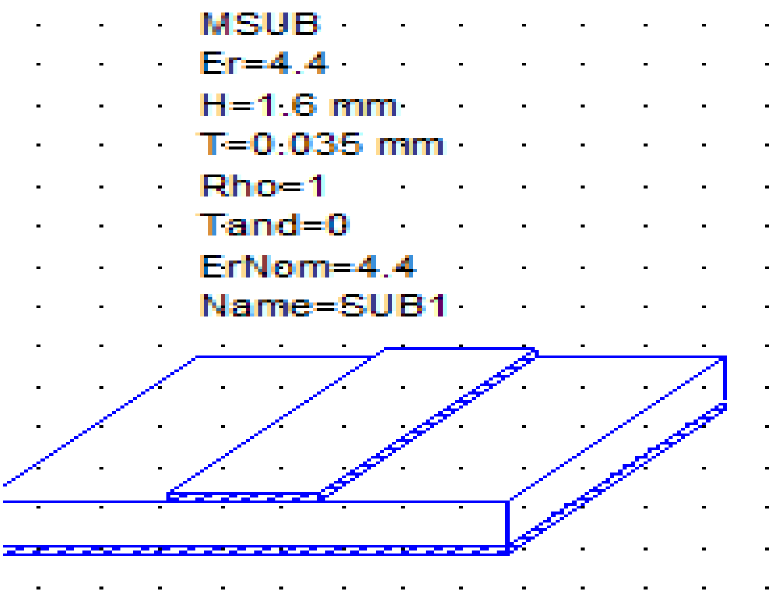
Microstrip line schematic in AWR:-



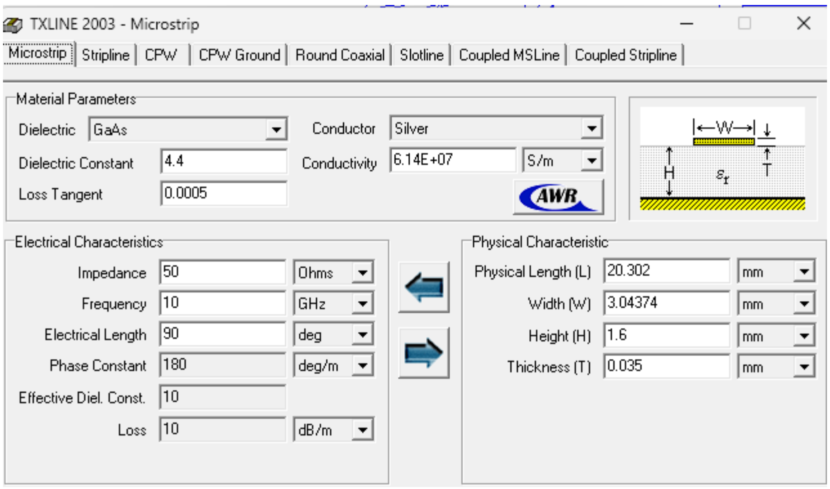
We'd like to note that none of the MLEFs are grounded; they are left in an open-circuit configuration.

- TL1,TL5 signify resistances,TL3 signifies inductor.TL6, and TL7 signify the capacitors.
- The lengths of W1, W2, W3, L1,L2, and L3 are determined after tuning them for optimal results, ie. Getting **|S(2,1)(dB)|** as close to -3dB at 4GHz frequency.
- The ports are at Z_o = 50Ω.

Details of the substrate:-



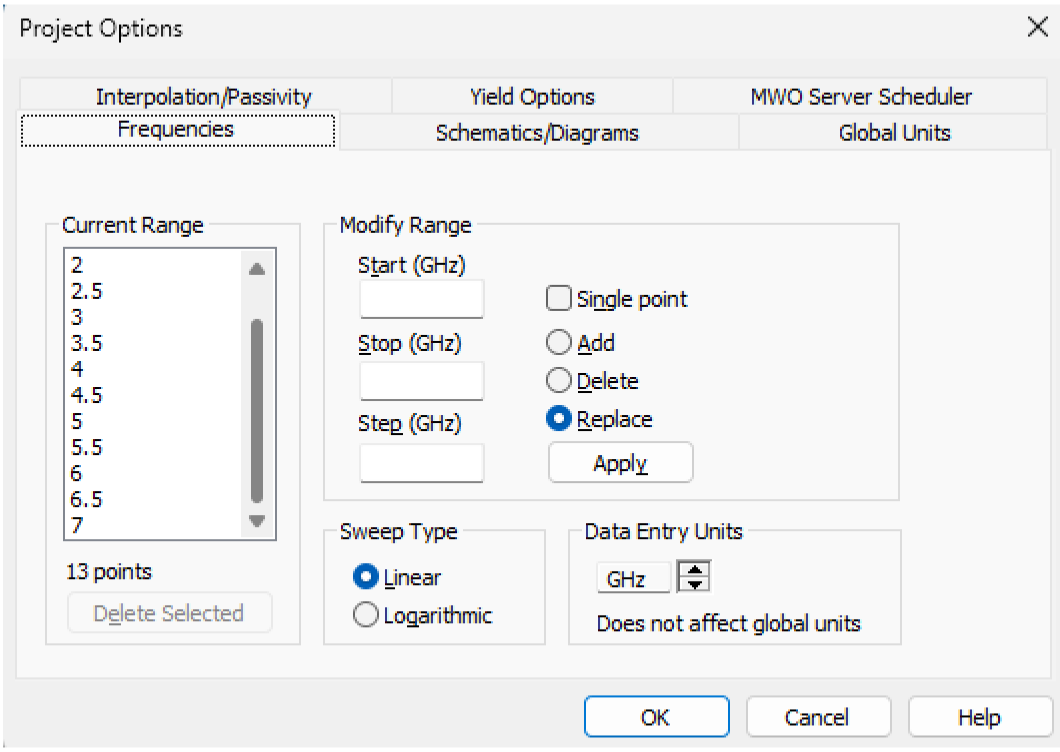
TXLine values:-



We input the values of Impedance, Frequency, and Electrical Length to get the calculated values of physical characteristics like length(L) and width(W).

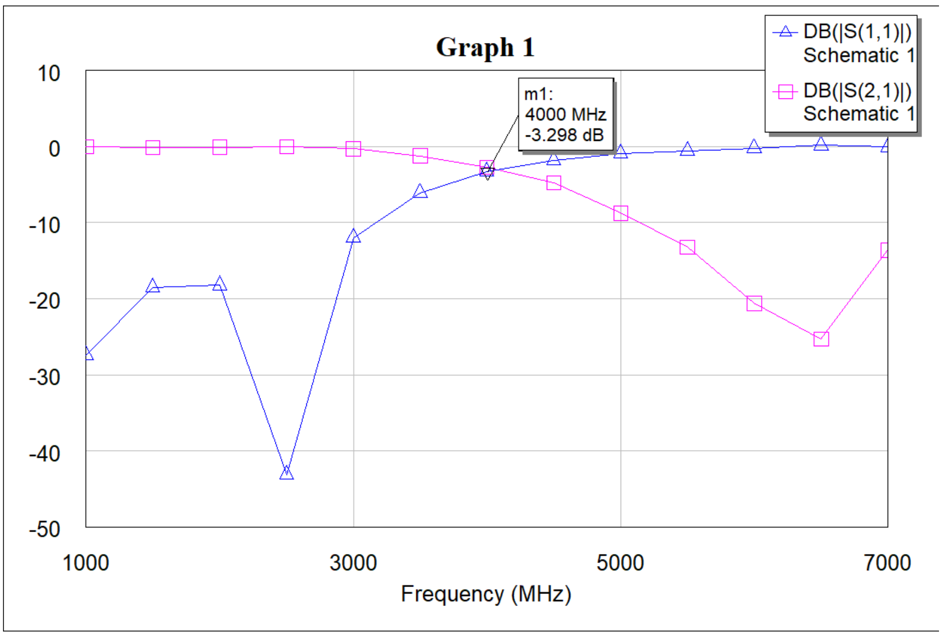
2.2 Simulating the Filter

Sweep parameters:-



Since our cutoff frequency is 4GHz, we sweep from 2GHz to 7GHz.

Simulation Result:-



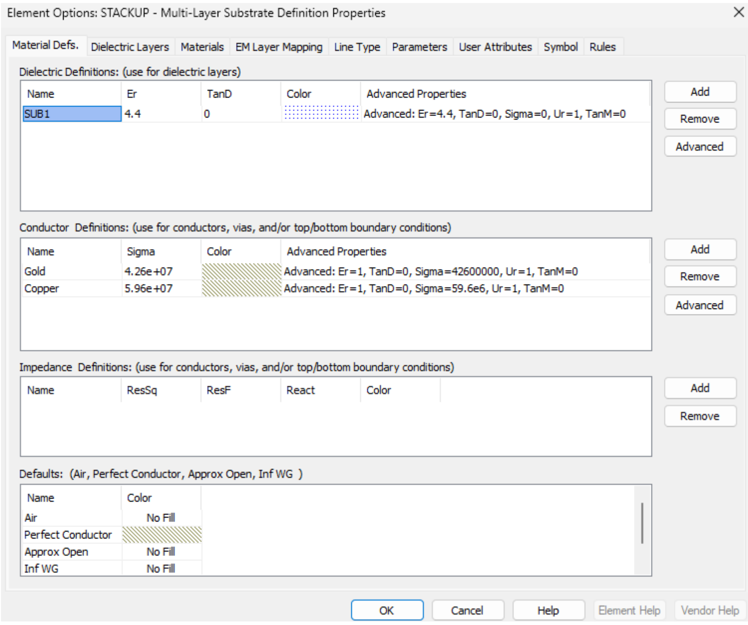
|S(1,1)(dB)| signifies the magnitude of reflection received at port 1.

While, |S(2,1)(dB)| indicated the power received at port 2, coming from port 1. It is seen that the |S(2,1)(dB)| follows typical Butterworth filter characteristics.

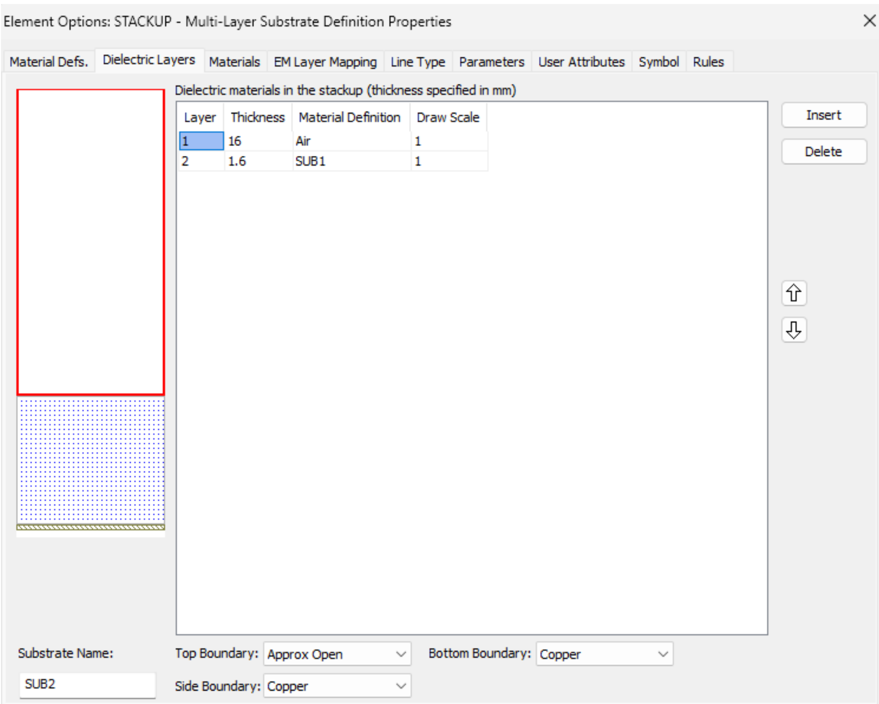
In an ideal scenario,|S(2,1)(dB)| should be equal to -3dB at 4GHz frequency.

Element Options:-

Material Definitions



Dielectric Layers



Materials

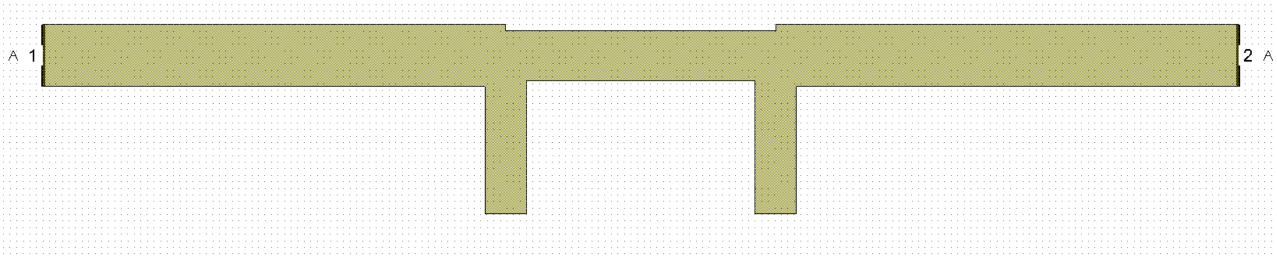
Element Options: STACKUP - Multi-Layer Substrate Definition Properties

Material Defs. | Dielectric Layers | Materials | EM Layer Mapping | Line Type | Parameters | User Attributes | Symbol | Rules

Material properties for conductors, vias, etc... (thickness specified in mm)

Name	Thickness	Material Definition	Etch Angle	Roughness	Solve Inside
Perfect Conductor	0.035	Perfect Conductor	0	0	☐
Cu	0.035	Copper	0	0	☐

EM Extract Layout:-

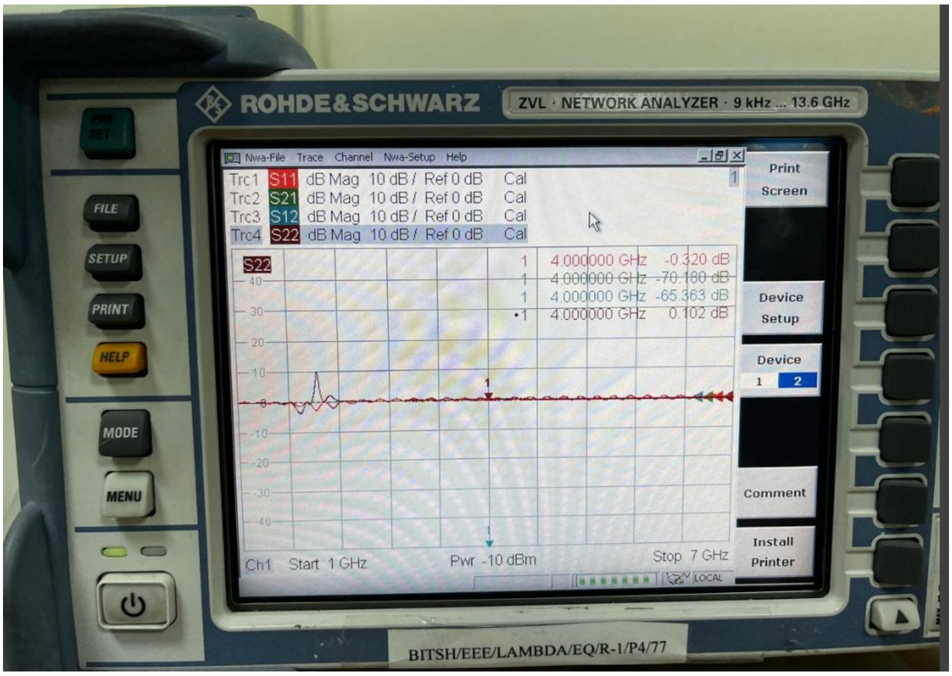


3.Fabrication of the Filter

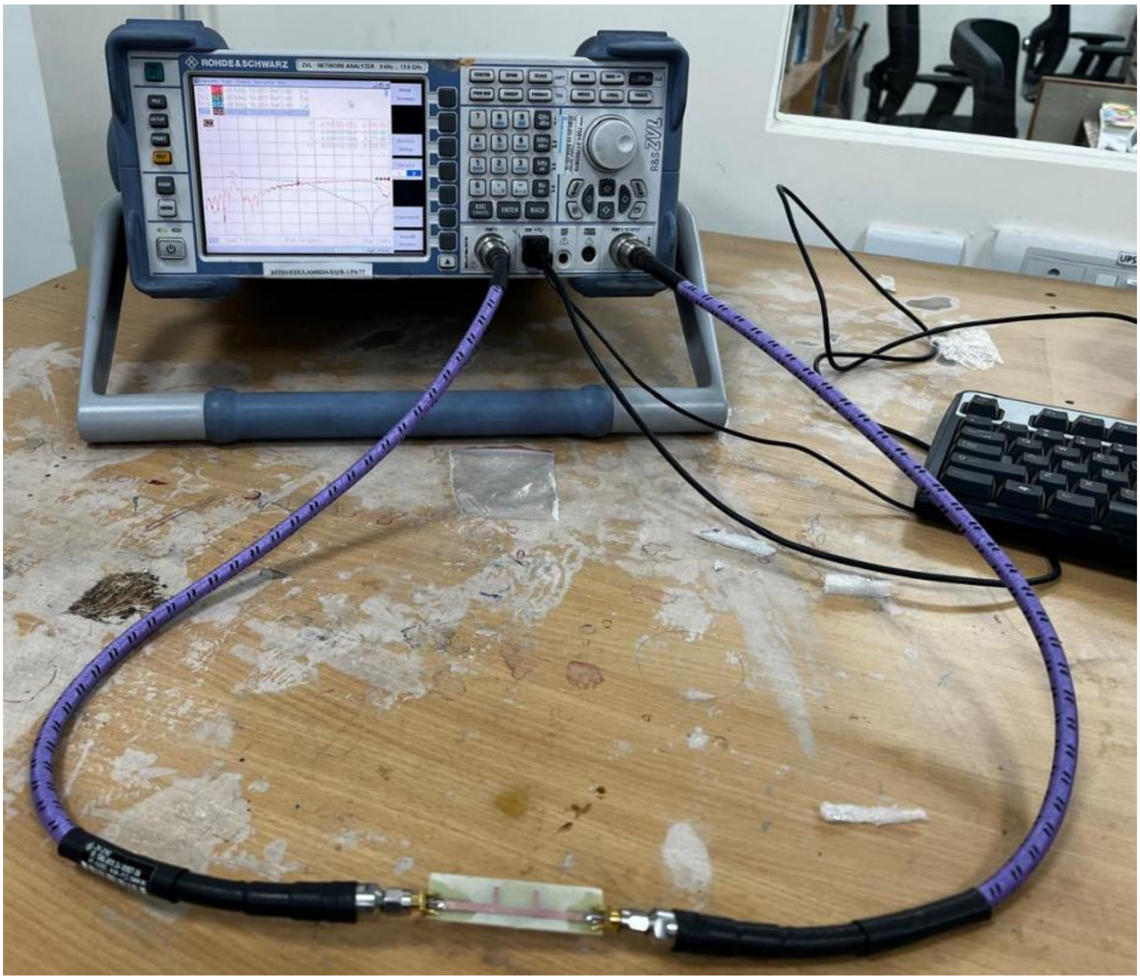
The above design was converted into a Gerber file and then fabricated in the LAMBDA lab milling machine. After the substrate was etched, the terminal ports were soldered to enable usability.

The final filter looked like this:

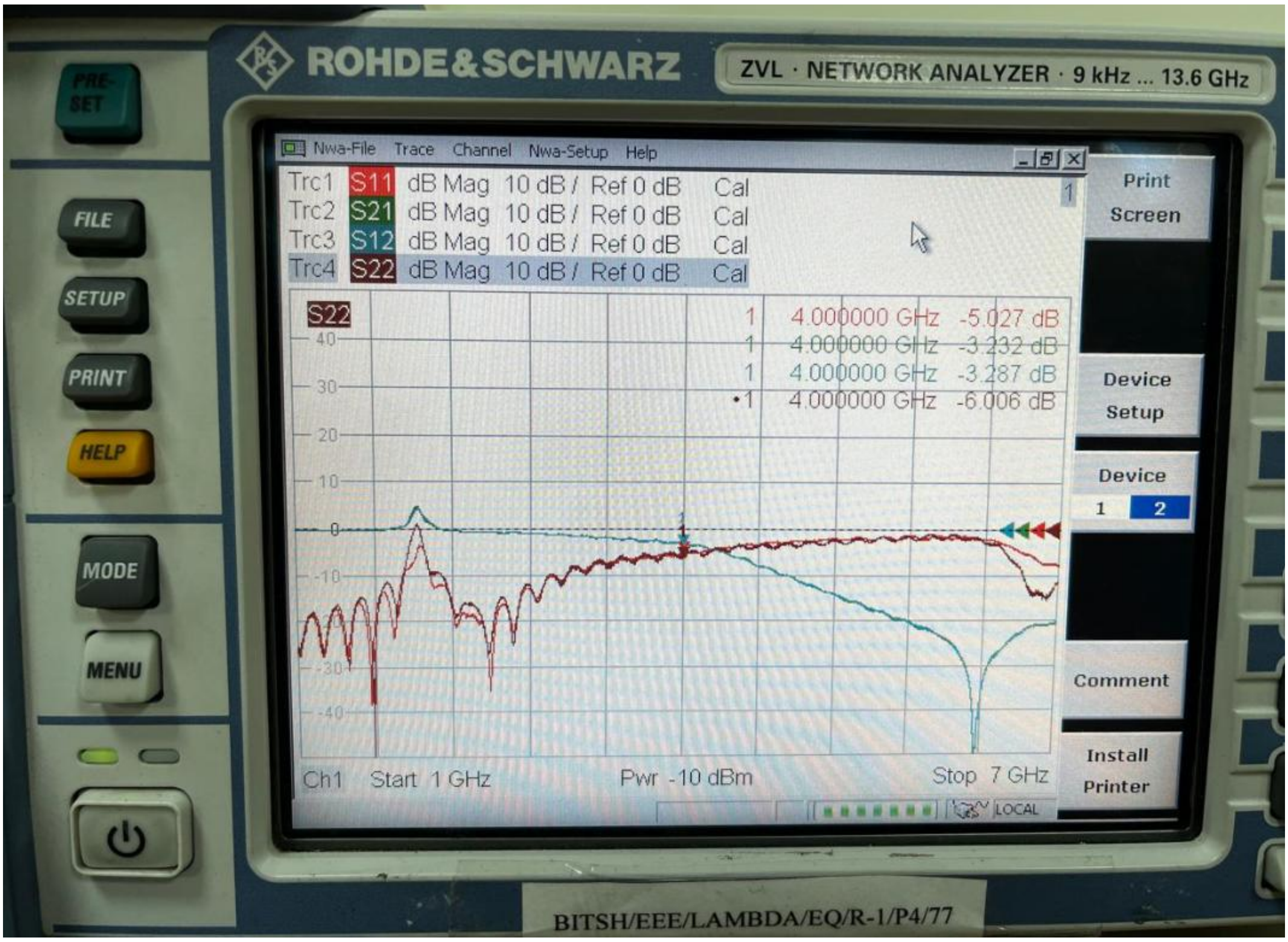
First, we removed the noise gain from the wires of the Vector Network Analyser (VNA) and brought them to zero to minimise system error as shown:



The filter was then connected to it:



The plotted S_{21} and S_{11} graphs are as shown below:



There is a small peak in the passband of the filter as seen in the result. This peak is coming because the machine was unable to perfectly tune the case where no load is applied. We should ideally see a flat line throughout, but there is a peak at the same position where the peak is occurring in the passband.

CONCLUSION

In this work, a third-order Butterworth low-pass filter with a 2 GHz cutoff was designed, simulated, and analyzed using microstrip technology on an FR-4 substrate. The design followed the standard Butterworth approach to ensure a flat passband and a smooth transition to the stopband. Lumped LC elements were translated into microstrip line sections using transmission line theory, with careful consideration of the substrate's properties and practical constraints—such as the challenges of implementing shunt stubs in microstrip form.

From the graph plotted by the VNA, we can observe that the plot resembles a 3rd order lowpass Butterworth filter. The cutoff frequency can be seen as a little less than 4GHz, which was the value assigned to our group. This minute error can be accounted to the errors in the fabrication process (routing and soldering). The gain observed at the 4GHZ frequency is -3.2 dB, which is very close to the theoretical -3dB value.

Overall, this project demonstrated that it is feasible to realize a compact and effective third-order low-pass filter for RF applications using cost-effective FR-4 material. The process offered valuable experience in the design, optimization, and simulation of microstrip filters, laying a solid foundation for future research in high-frequency communications.

References:

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