433 MHz Stepped-Impedance Low-Pass Filter

Juan Ali Ruiz Guzman

EE444

13 May 2026

Objective

The objective of this project was to design, simulate, fabricate, and measure a 5th order Butterworth stepped-impedance low pass filter operating at a cutoff frequency of 433 MHz. The filter was designed and optimized using ADS before being physically implemented using copper tape on a cardboard substrate. The completed filter was then measured using a Vector Network Analyzer (VNA) and compared against the simulated results.

Materials

The following materials and software were used during the project:

- ADS (Advanced Design System) for simulation and optimization
- Cardboard substrate
- Copper tape
- Two SMA connectors
- Vector Network Analyzer (VNA)
- Soldering equipment

Table 1: The project specifications required

Parameter	Value
Filter Type	5th Order Butterworth
Cutoff Frequency	433 MHz
System Impedance	50 Ω
Maximum Impedance	120 Ω
Minimum Impedance	20 Ω
Desired Return Loss	> 10 dB

Design Procedure

The filter was designed using the stepped-impedance microstrip technique. In this method, narrow transmission line sections act as inductive elements while wide transmission line sections act as capacitive elements.

The design process began by calculating the transmission line dimensions needed to achieve the required characteristic impedances of 120 Ω and 20 Ω. The calculated dimensions were implemented in ADS and simulated using a microstrip substrate model representing cardboard material.

Table 2: The substrate parameters used in ADS

Parameter	Value
Relative Permittivity (ϵ_r)	2.5
Loss Tangent $(tan\delta)$	0.02
Substrate Height	1.5 mm
Conductor Thickness	35 μm

The transmission line lengths were then tuned iteratively in ADS to shift the cutoff frequency toward the desired value of 433 MHz while maintaining acceptable return loss characteristics.

The final filter layout consisted of alternating high-impedance and low-impedance transmission line sections arranged symmetrically.

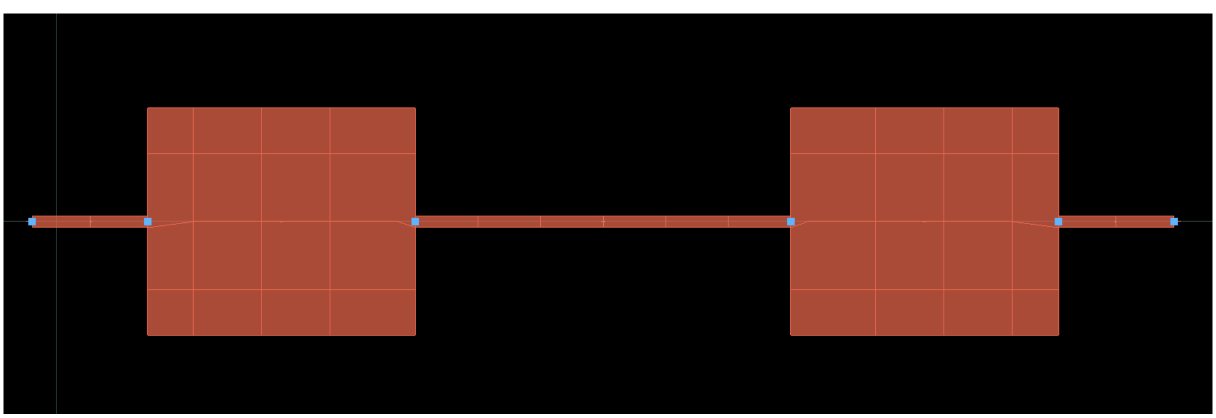

Figure 1. ADS layout of the 433 MHz stepped-impedance Butterworth low pass filter.

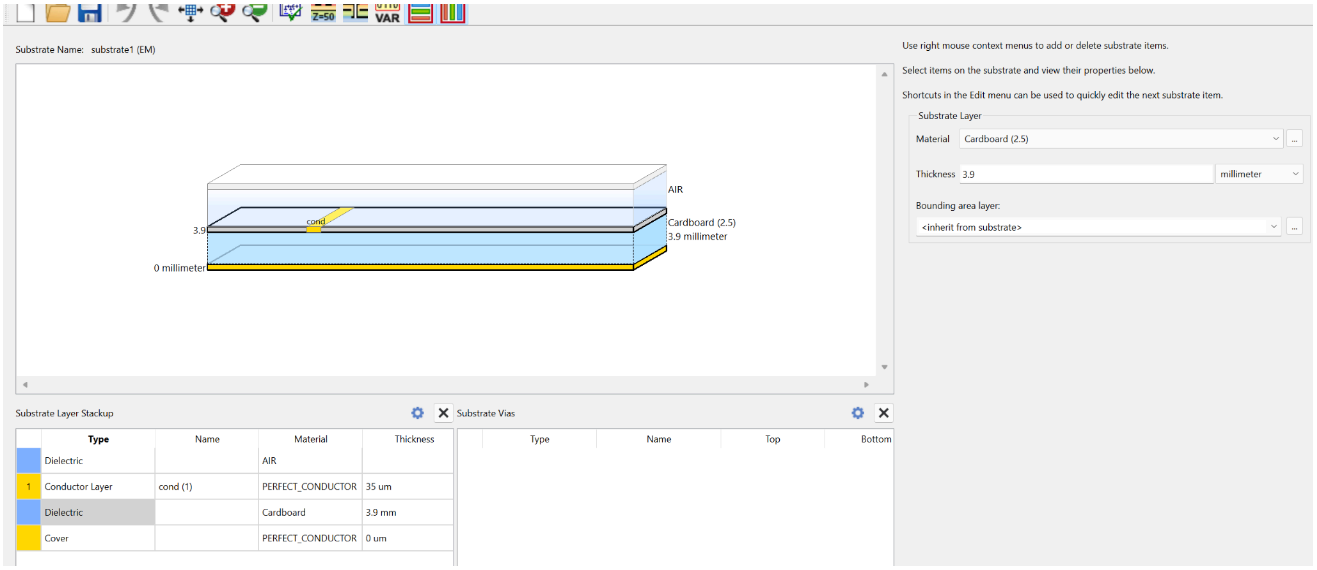

Figure 2. ADS substrate configuration used during simulation showing the cardboard substrate parameters.

Simulation Results

After optimization, the ADS simulation produced a filter response very close to the desired Butterworth low pass response.

The simulated S21 response showed:

- 3 dB cutoff frequency ≈ 432.8 MHz
- Attenuation at 865.9 MHz ≈ 22.36 dB

The simulated S11 response showed:

- Return loss near cutoff ≈ 10.17 dB

The final simulated responses are shown below.

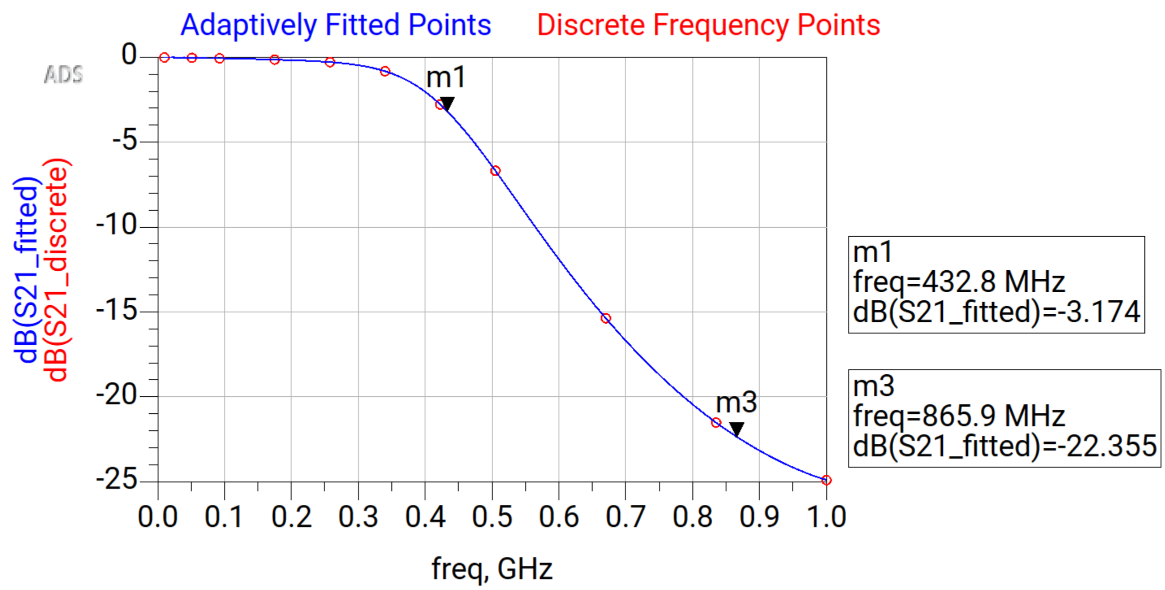

Figure 3. Simulated S21 response of the stepped-impedance low pass filter showing a cutoff frequency near 433 MHz.

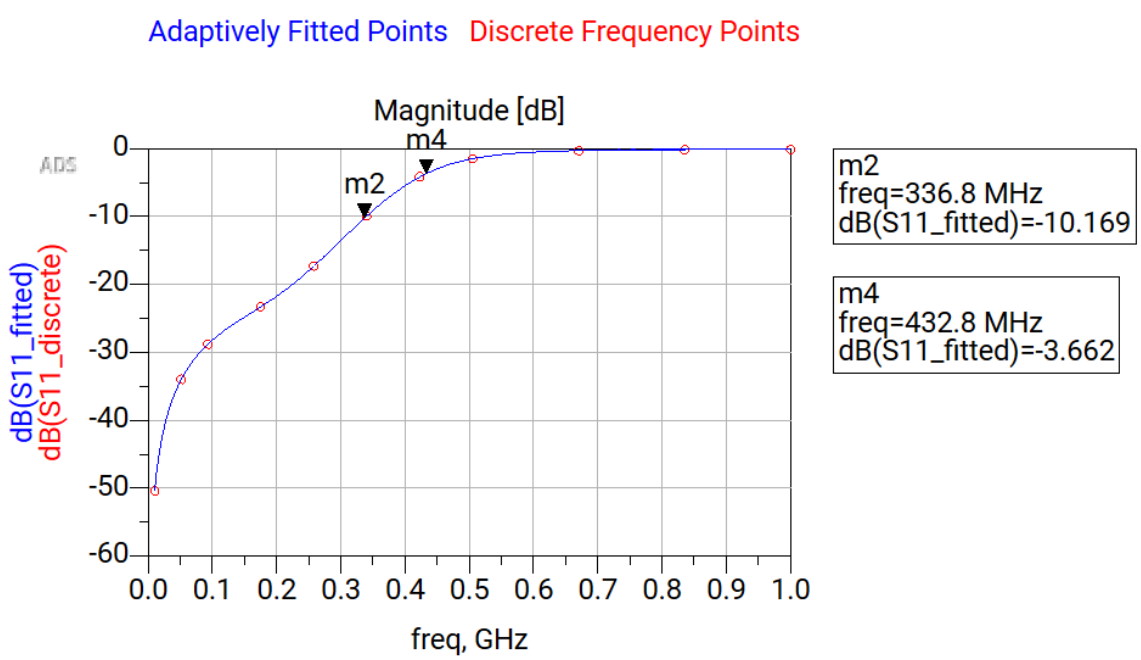

Figure 4. Simulated S11 response of the stepped-impedance low pass filter showing the return loss characteristics near the cutoff frequency.

Fabrication

The filter was fabricated using adhesive copper tape placed on a cardboard substrate. The copper tape sections were manually cut and arranged to match the optimized ADS layout dimensions. SMA connectors were soldered onto the input and output transmission lines to allow measurements using the VNA.

Care was taken to maintain symmetry and minimize discontinuities in the transmission line structure. However, because the filter was fabricated manually, small imperfections in the copper edges and connector transitions were unavoidable.

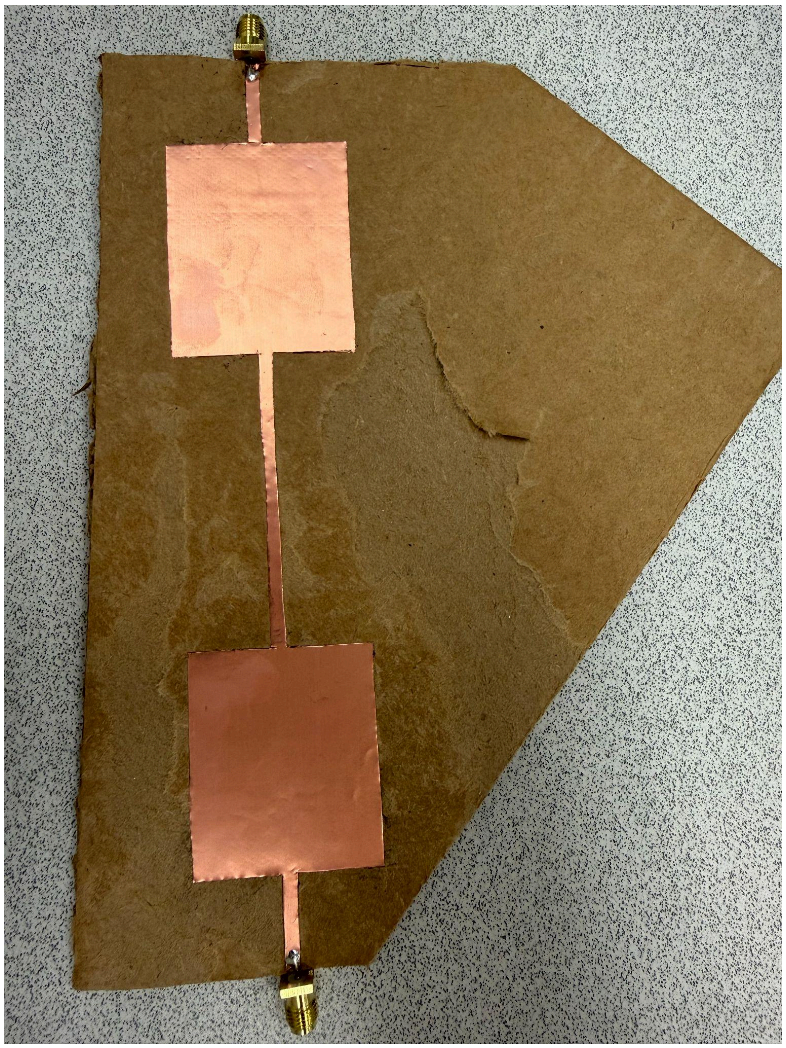

Figure 5. Fabricated stepped-impedance low pass filter implemented using copper tape on a cardboard substrate.

Measurement Results

The fabricated filter was measured using a Vector Network Analyzer over the frequency range from 300 MHz to 1 GHz.

The measured S21 response showed:

- Insertion loss at 433 MHz ≈ -3.41 dB
- Attenuation at 866 MHz ≈ -16.56 dB

The measured S11 response showed:

- Return loss at 433 MHz ≈ -16.13 dB

The measured results confirmed that the filter operated very close to the desired cutoff frequency and achieved reasonable return loss performance.

Figure 6. Measured S21 response of the fabricated low pass filter using the Vector Network Analyzer.

Figure 7. Measured S11 response of the fabricated low pass filter using the Vector Network Analyzer.

Comparison of Simulated and Measured Results

Table 3 compares the ADS simulated results with the measured VNA results obtained from the fabricated filter. Overall, the measured response closely followed the simulated response, particularly near the desired 433 MHz cutoff frequency. Differences in attenuation and insertion loss were primarily caused by fabrication tolerances, substrate inconsistencies, and additional losses introduced by the copper tape implementation and SMA connector transitions.

Table 3: Comparison of simulated and measured stepped-impedance low pass filter performance.

Parameter	Simulated Result	Measured Result	Difference
3 dB Cutoff Frequency	432.8 MHz	433.0 MHz	+0.2 MHz
S21 at 433 MHz	-3.17 dB	-3.41 dB	-0.24 dB
Attenuation at 866 MHz	-22.36 dB	-16.56 dB	+5.80 dB
Return Loss (S11) at 433 MHz	-10.17 dB	-16.13 dB	-5.96 dB
Filter Response Type	Butterworth LPF	Butterworth LPF	Matches
System Impedance	50 Ω	50 Ω	Matches

Discussion

The fabricated stepped-impedance low pass filter successfully demonstrated the expected Butterworth low pass behavior and operated near the target cutoff frequency of 433 MHz. The measured response showed approximately −3.41 dB insertion loss at 433 MHz and approximately −16.13 dB return loss, which satisfied the required return loss specification of greater than 10 dB.

Although the overall response closely followed the ADS simulation, several differences between the simulated and measured results were observed. The measured insertion loss was larger than expected and the roll-off response was less ideal than the simulated Butterworth response. These discrepancies were mainly caused by practical fabrication limitations and non-ideal substrate characteristics.

One major source of error was the use of cardboard as the substrate material. Unlike FR-4 or commercial RF laminates, cardboard has non-uniform dielectric properties and inconsistent thickness throughout the material. Variations in the dielectric constant directly affect the effective electrical lengths and characteristic impedances of the transmission lines, causing shifts in the frequency response.

Another significant factor was the manual fabrication process using copper tape. The copper edges were not perfectly straight or smooth, and small gaps and overlaps were present at some transitions. These imperfections introduced discontinuities and impedance mismatches that increased reflections and insertion loss.

The SMA connector soldering and transitions between the connectors and copper tape also contributed additional parasitic effects. Since the filter dimensions at 433 MHz are physically large, even small alignment errors in the narrow high-impedance sections could noticeably affect the response.

Additionally, the ADS simulation assumed ideal substrate properties and ideal conductor geometries, while the fabricated filter contained losses associated with the copper tape adhesive, surface roughness, solder joints, and the cardboard substrate itself. These losses contributed to the higher measured attenuation compared to simulation.

Despite these limitations, the measured cutoff frequency remained very close to the desired 433 MHz specification and the filter demonstrated proper low pass operation. The project successfully showed how stepped-impedance microstrip filters can be designed and implemented using low-cost materials while also highlighting the challenges associated with practical RF fabrication techniques.

Conclusion

A 5th order Butterworth stepped-impedance low pass filter operating at 433 MHz was successfully designed, simulated, fabricated, and measured. ADS simulations were used to optimize the transmission line dimensions before physical implementation using copper tape on cardboard.

The fabricated filter achieved a measured insertion loss of approximately −3.41 dB at 433 MHz and a return loss of approximately −16.13 dB. The measured results closely followed the expected Butterworth low pass response and validated the overall design process.

The project demonstrated the practical implementation of microstrip stepped-impedance filters and highlighted the effects of fabrication tolerances and substrate losses on real-world RF filter performance.

Future improvements could include fabricating the filter on FR-4 or Rogers laminate instead of cardboard, using etched copper instead of hand-cut copper tape, and improving connector transitions to reduce mismatch and insertion loss. Additional tuning of the transmission line dimensions could also improve the agreement between simulation and measurement.