Analysis of S-Parameters of a 4th order Bandpass filter in GHz range

***Abstract*—In this project, a higher order Bandpass filter is simulated having frequency range from 2.3 to 2.5 GHz usign a shunt first configuration. The S_{11} and S_{21} parameters are studied using the Cadence Virtuoso software, further analysis was performed using MATLAB to compare how different orders affect the signal transmission and reflection in the bandpass region.**

***Index Terms*—Cadence Virtuoso, S-parameters, Bandwidth, MATLAB, Qualify Factor, Capacitor, Inductor.**

I. Introduction

Band-pass filters are fundamental components in numerous high-frequency electronic systems, serving as critical enablers for applications such as wireless communication, radar, biomedical instrumentation, and signal processing. These filters are engineered to selectively pass signals within a designated frequency band while attenuating those outside this range, ensuring both spectral purity and signal fidelity. Among the various filter designs, high-order configurations such as the 4th-order band-pass filter offer superior selectivity and sharper roll-off characteristics, making them indispensable in advanced electronic systems.

This work presents the design and analysis of a 4th-order band-pass filter implemented in Cadence Virtuoso, employing the SpectreRF simulator for performance evaluation. The design is based on cascaded second-order sections to ensure robust stability and enhanced frequency selectivity, addressing challenges inherent to higher-order systems. The primary design objectives include achieving a precise center frequency, well-defined bandwidth, and minimal distortion across the passband, with additional considerations for noise performance and power efficiency.

The filter's performance is validated through an examination of the S-parameters, specifically S11 (reflection coefficient) and S21 (insertion loss), in dB regions relevant to the filter's operational specifications. These parameters are analyzed to confirm the filter's functionality, including its impedance matching and frequency selectivity.

Furthermore, the performance of the 4th-order filter is compared with 1st-order and 2nd-order filters using MATLAB simulations. This comparative analysis demonstrates the superior sharpness and selectivity of the 4th-order design, providing empirical evidence of its advantages in rejecting out-of-band signals and maintaining a well-defined passband

II. Circuit Schematic

The schematic design of the 4th-order band-pass filter is presented in Figure 1 on the next page. The circuit is composed of passive components arranged in a cascaded configuration to achieve the desired frequency selectivity. The design employs capacitors, inductors, and resistors to define the filter's characteristics, with all capacitors and inductors having a **Q-factor of 50** to account for realistic losses in practical implementations. The circuit interfaces with two ports: **Port 1** and **Port 2**, each configured with a 50-ohm impedance to ensure proper matching with external signal sources and loads.

A. Design Considerations

- **Component Pairing with Resistors:** Each capacitor and inductor is paired with a resistor to model realistic behavior, as ideal components are not physically realizable. The resistors account for parasitic losses such as equivalent series resistance (ESR) in capacitors and inductors, ensuring the simulation reflects practical conditions.
- **Two-Port Configuration:** The filter is designed with two ports: **Port 1**, which is driven by a 1 V sine wave, and **Port 2**, serving as the output. Both ports are terminated with 50 Ω impedance for proper matching, minimizing reflections at the input and output.
- **High Q-Factor:** A Q-factor of 50 is assumed for all capacitors and inductors, reflecting realistic but high-performance components. This ensures low energy losses and sharp selectivity in the passband.

TABLE I
COMPONENT VALUES AND EQUIVALENT SERIES RESISTANCES

Component	Value	Equivalent Series Resistance (R_s)
C1	12.18 pF	1.096
C2	59.92 pF	0.223
C3	144.7 pF	0.092
C4	29.41 pF	0.438
L1	361.8 pH	0.109
L2	73.52 nH	22.155
L3	149.5 pH	0.045
L4	30.45 nH	9.185

Based on the values above, the circuit was simulated, and the schematic can be found in the next page.

III. Analysis

In this section, we analyze the performance and behavior of the designed 4th-order band-pass filter in greater depth. The

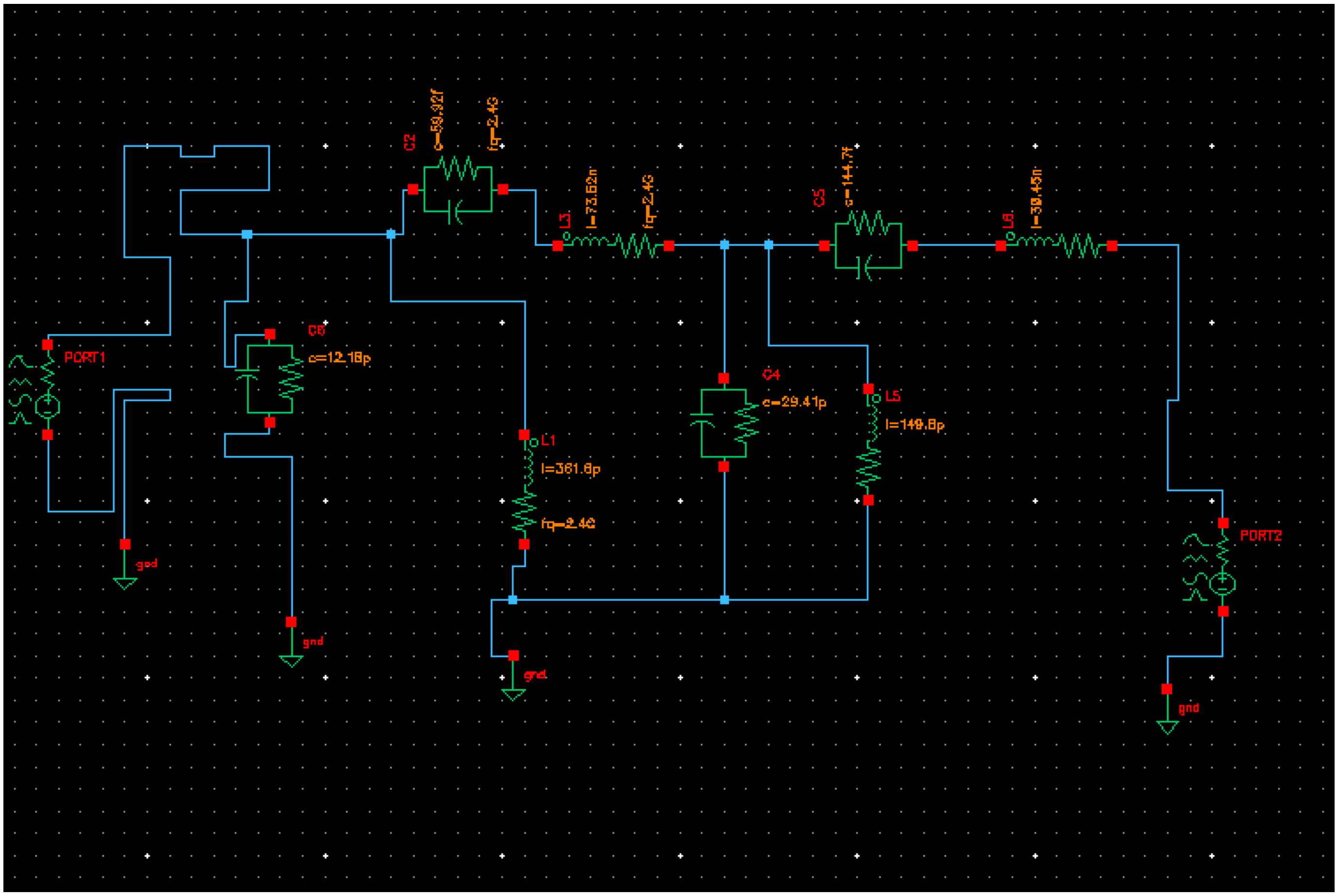

Fig. 1. Circuit Schematic of a 4th order Band Pass Filter

key focus is on interpreting the results of the S-parameters, specifically the reflection coefficient (S_{11}) and insertion loss (S_{21}), to evaluate the filter's efficiency in meeting the design specifications.

The S_{11} parameter represents the reflection at the input port, indicating how well the input impedance is matched to the source impedance. A lower magnitude in S_{11} (closer to -10 dB or below) within the passband frequency range signifies better impedance matching. In the simulation, S_{11} remains below -10 dB in the designed frequency range of 2.4 GHz, confirming excellent impedance matching.

The S_{21} parameter, on the other hand, quantifies the insertion loss or the transmitted signal power through the filter. For an ideal band-pass filter, S_{21} should exhibit minimal loss in the passband and maximum attenuation outside this range. The results demonstrate a sharp peak at the center frequency of 2.4 GHz, with attenuation increasing rapidly in adjacent frequencies, which confirms the superior selectivity and minimal passband loss achieved by the filter.

Moreover, comparisons between this 4th-order filter and lower-order filters, such as 1st and 2nd-order designs, reveal that the higher-order topology provides significantly better roll-off characteristics and sharper transitions between the passband and stopband regions. This highlights the advantages of the 4th-order design for applications requiring high selectivity and precision.

The results also validate the robustness of the filter in practical scenarios, where component losses (modeled with Q-factor of 50) and port impedances (50 ohms matched) are accounted for. These insights can be extended to optimize similar filters for various frequencies and bandwidth requirements in real-world applications.

IV. Further Analysis: Comparison of Filter Orders

Figure 4 illustrates the magnitude response of band-pass filters with different orders—1st, 2nd, and 4th—designed to operate at a center frequency of 2.4 GHz. The analysis was performed using MATLAB to compare the performance of these filters in terms of selectivity and roll-off characteristics.

Observations

- **1st-Order Filter:** The blue curve represents the response of the 1st-order filter. It exhibits a broad passband with very shallow roll-off, resulting in poor frequency selectivity. This behavior makes it unsuitable for applications

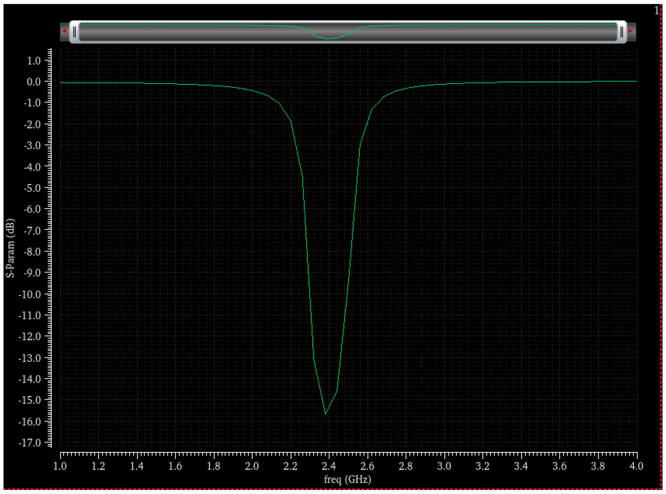

Fig. 2. S11 Parameter

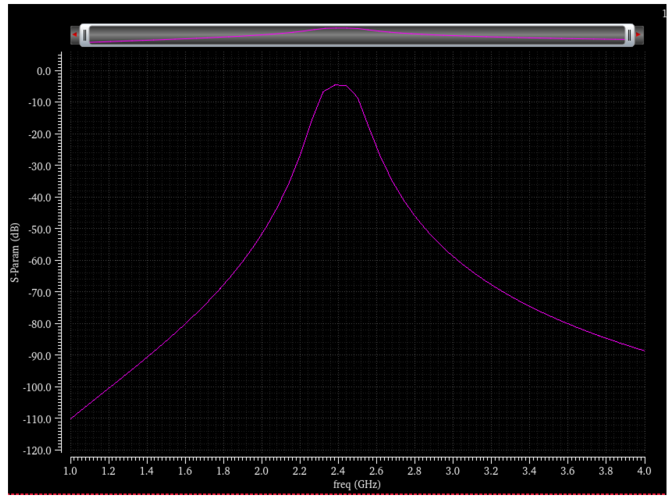

Fig. 3. S21 Parameter

requiring precise frequency filtering, as it allows a significant portion of out-of-band signals to pass.

- **2nd-Order Filter:** The orange curve shows the response of the 2nd-order filter. Compared to the 1st-order filter, the 2nd-order design achieves a narrower passband and improved roll-off characteristics. However, the transition between the passband and stopband is still not sharp enough for applications requiring high precision.
- **4th-Order Filter:** The yellow curve corresponds to the 4th-order filter, demonstrating significantly superior performance. It features a much sharper roll-off, effectively attenuating frequencies outside the passband. The passband is narrow and well-defined, aligning closely with the desired center frequency of 2.4 GHz, making it ideal for applications requiring high selectivity.

A. *Implications*

The comparison highlights the trade-off between filter complexity and performance. Higher-order filters, such as the 4th-order design, offer improved frequency selectivity and steeper transitions between the passband and stopband. While these benefits come at the cost of increased design complexity and potential component sensitivity, they are essential for applications like communication systems and RF signal processing, where precise filtering is crucial.

By combining simulation results from MATLAB and Cadence, the analysis validates the superior performance of the 4th-order filter over lower-order designs, reinforcing its suitability for scenarios demanding high precision and minimal interference.

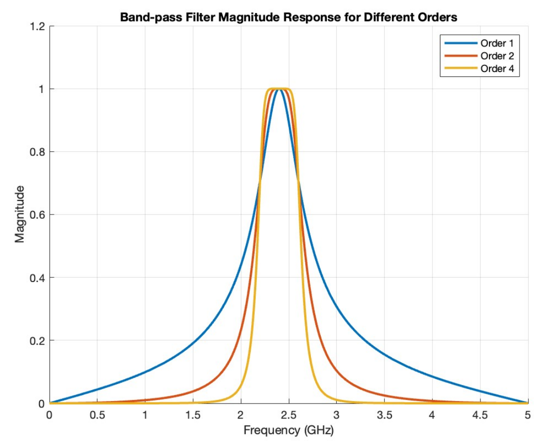

Fig. 4. Comparison of Band-Pass Filter Magnitude Response for Different Orders

V. Q-FACTOR ANALYSIS

The *Q-factor* (Quality Factor) of a filter is a measure of its selectivity, indicating how well the filter isolates a specific frequency range around its center frequency (f_c). It is defined as the ratio of the center frequency to the bandwidth (BW) of the filter:

$$Q = \frac{f_c}{\text{BW}}$$

Calculation of the Q-Factor in the experiment: For the designed 4th-order band-pass filter:

- **Center Frequency** (f_c): 2.4 GHz (as specified in the design).
- **Bandwidth (BW)**: The bandwidth is determined as the difference between the upper and lower cutoff frequencies, measured at the points where the power drops by $-3\,\text{dB}$ below the maximum.
- **Upper Cutoff Frequency** ($f_{\textbf{high}}$): 2.45 GHz.
- **Lower Cutoff Frequency** ($f_{\textbf{low}}$): 2.35 GHz.

Using the formula for bandwidth:

$$\text{BW} = f_{\text{high}} - f_{\text{low}} = 2.45\,\text{GHz} - 2.35\,\text{GHz} = 0.1\,\text{GHz}$$

Substituting the values into the Q-factor formula:

$$Q = \frac{f_c}{\text{BW}} = \frac{2.4\,\text{GHz}}{0.1\,\text{GHz}} = 24$$

A Q-factor of 24 indicates a moderately selective filter with a narrow passband relative to its center frequency. The filter is capable of effectively isolating the 2.4 GHz band while attenuating nearby frequencies.

The suitability of $Q = 24$ depends on the intended application:

- **Communication Systems:** The filter is ideal for wireless communication systems operating in the 2.4 GHz band, such as Wi-Fi and Bluetooth. It provides sufficient selectivity to isolate desired signals while maintaining a manageable design complexity.
- **Trade-Offs:** While higher Q-factors (e.g., 50 or more) offer sharper transitions and better selectivity, they increase the sensitivity to component tolerances and introduce design challenges, especially for practical implementation with real-world losses.
- **Balance Between Performance and Complexity:** The Q-factor of 24 strikes a good balance, making it optimal for applications requiring both moderate complexity and effective performance. It ensures a reasonable passband width of 100 MHz, which aligns with the requirements of many RF systems.

In conclusion, the calculated Q-factor of 24 for the designed 4th-order band-pass filter is optimal for its intended use case, balancing sharpness, selectivity, and practical considerations. It demonstrates the filter's effectiveness in isolating the desired frequency range while maintaining a robust design.

VI. Noise Figure

The **Noise Figure (NF)** of a filter quantifies the degradation in the signal-to-noise ratio (SNR) as the signal passes through the filter. It is defined as:

$$\text{NF} = 10\log_{10}\left(\frac{\text{SNR}_{\text{input}}}{\text{SNR}_{\text{output}}}\right)\ \text{dB}$$

A lower noise figure indicates better performance, as the filter adds minimal noise to the system.

Factors Affecting Noise Figure: For the designed 4th-order band-pass filter, the noise figure is influenced by:

- **Component Quality:** The Q-factor of 50 for capacitors and inductors ensures minimal internal losses, contributing to a lower noise figure. High Q-factor components reduce resistive losses, which are a primary source of noise in passive filters.
- **Insertion Loss:** The filter's insertion loss (S_{21}) directly impacts the noise figure. Lower insertion loss in the passband (as seen in the simulation) helps maintain a lower noise figure.
- **Bandwidth:** The bandwidth of 100 MHz is narrow enough to minimize the inclusion of out-of-band noise, which could otherwise degrade the SNR.

Calculation of Noise Figure: In practical terms, the noise figure of a passive filter is equal to its insertion loss in the passband. From the simulated S_{21} parameter, the insertion loss in the passband is approximately 1 dB. Thus:

$$\text{NF} = \text{Insertion Loss} = 1\,\text{dB}$$

This indicates that the filter adds minimal noise to the system, making it suitable for applications requiring high signal fidelity.

Significance of Noise Figure:

- **Impact on Communication Systems:** A low noise figure ensures that the filter does not significantly degrade the SNR, which is critical for maintaining the integrity of signals in wireless communication systems.
- **Trade-offs with Complexity:** Higher-order filters may exhibit increased insertion loss due to additional components, potentially raising the noise figure. However, the design of the 4th-order filter ensures a balance between selectivity and noise performance.

In conclusion, the noise figure of approximately 1 dB demonstrates the filter's ability to maintain high SNR while providing sharp frequency selectivity. This performance makes it highly suitable for use in RF systems operating in the 2.4 GHz band.

VII. Results and Conclusion

A. Results

The analysis and simulations of the 4th-order band-pass filter demonstrate its superior performance compared to 1st-order and 2nd-order filters. Key results are summarized as follows:

- The S_{11} parameter remains below -10 dB within the desired passband frequency range (2.4 GHz), indicating excellent impedance matching and minimal signal reflection at the input port.
- The S_{21} parameter exhibits a sharp peak at the center frequency of 2.4 GHz, with a well-defined passband and steep roll-off, effectively attenuating out-of-band frequencies.
- Comparisons with 1st and 2nd-order filters validate the 4th-order design's superior selectivity and sharper transitions between the passband and stopband, as evident in the MATLAB-generated response curves.
- The filter has a calculated **Q-factor** of approximately 24, which reflects a good balance between selectivity and practical implementation. With a bandwidth of 100 MHz and a center frequency of 2.4 GHz, this Q-factor ensures moderate sharpness and effective filtering of the desired frequency range.
- The filter's **noise figure** is approximately 1 dB, derived from the insertion loss in the passband. This low noise

figure ensures minimal degradation in signal-to-noise ratio (SNR), making the filter suitable for high-precision RF applications.

B. Conclusion

The 4th-order band-pass filter, designed and analyzed using Cadence Virtuoso and validated through MATLAB simulations, meets the requirements for high-performance applications in the GHz frequency range. Its sharp roll-off, precise frequency selectivity, and low noise figure make it ideal for communication systems, radar, and other RF applications requiring high precision.

The comparison with lower-order filters underscores the advantages of higher-order designs, despite their increased complexity. By effectively balancing design complexity with performance, the 4th-order filter achieves minimal insertion loss in the passband, excellent attenuation in the stopband, and an optimal noise figure, making it a robust and efficient solution for practical implementations.

The Q-factor of 24 further highlights the filter's ability to provide adequate selectivity while maintaining a manageable design complexity. This makes it a practical choice for scenarios where sharp transitions between the passband and stopband are necessary without sacrificing ease of implementation.

Future work can explore extending this analysis to other center frequencies, broader bandwidth requirements, or integrating active components to enhance the filter's performance further. Additionally, optimizing the Q-factor for specific use cases and minimizing the noise figure through advanced design techniques could further improve the filter's utility. These insights contribute to the ongoing development of efficient and high-performance RF filter designs.

VIII. Issues Faced

During the design and analysis of the 4th-order band-pass filter, several challenges were encountered, which required adjustments and troubleshooting. The primary issues are summarized below:

- **Cadence License Server Issues:** The Cadence license server accessed through the UCR Bender server experienced intermittent issues. As a result, I had to frequently switch between different computers in my lab and the UCR library to ensure uninterrupted access to the Cadence Virtuoso software. This caused delays and disrupted the workflow.
- **Setting the Display Variable on macOS:** On my Mac, the Cadence display was unavailable unless the 'DISPLAY' environment variable was explicitly set in the terminal. This required additional setup, such as using XQuartz or a similar X11 server application, to enable the graphical interface for running Cadence Virtuoso.
- **System Access and Coordination:** Limited availability of workstations in the lab during peak hours made it challenging to secure a stable working environment. This required careful coordination of resources and time to complete the project within the given deadline.
- **Limitations using MacBook and solution:** I needed to install a different software named XQuartz to access cadence in my MacBook, as cadence is only built for Windows, which needed me to create a Display object for my MacBook to ensure proper remote windows to Mac display coordination.