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Performance Analysis and Optimization of a Microstrip Parallel Coupled Line Bandpass Filter for C-Band Satellite Receiver Applications

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Abstract

The design and optimization of a microstrip parallel coupled line bandpass filter (BPF) for C-band satellite receiver applications are the main focus of this work. Various filter orders (third order to seventh order) were analyzed and compared based on key performance parameters, including insertion loss, return loss, bandwidth, and shape factor. The optimized fifth order filter was selected as the most suitable due to its low insertion loss of -0.625 dB, deep return loss of -31.443 dB, and adequate bandwidth of 565 MHz, ensuring efficient signal transmission with minimal reflection. The calculated shape factor of 1.7 indicates a sharp roll-off, enabling effective rejection of out-of-band interference while maintaining a well-defined passband. The proposed design achieves a balance between performance, complexity, and real-world applicability, making it a reliable and efficient solution for C-band satellite communication systems.

A. Introduction

Filters play a crucial role in RF and microwave applications by allowing specific frequency ranges to pass while attenuating others. Depending on the specifications, implementation can involve lumped elements or transmission lines such as microstrip, coaxial, and waveguides. A common application of bandpass filters is in satellite receivers, where pre-selection of signals is performed, and out-of-band signals are suppressed [1]. Metallic waveguide-based filters are preferred for their high performance but come with drawbacks like being heavy, bulky, and difficult to manufacture [2]. To overcome these limitations, microstrip bandpass filters provide an appealing alternative due to their lightweight, compact planar design and ease of fabrication, which contributes to better system efficiency and reduced costs [3].

A bandpass filter with a center frequency of 3.9 GHz is designed and modeled on an FR4 substrate in [4]. The filter features a 1.25 GHz bandwidth, -3 dB insertion loss, and -17.3 dB return loss. A bandpass filter presented in [5] features a single section with multiple coupled lines and two stubs. Placing the stubs at the ends of the coupled strips creates two transmission zeros, while adjusting the stub width enables band tuning. Although group delay is typically a concern in distributed element models for microwave filters, the design in [5] demonstrates a flat group delay. In [6], quasi-reflectionless BPF characteristics are achieved by absorbing reflected power using resistive components. In [7], a compact BPF is fabricated on a 99.9% Al_2O_3 substrate with dimensions of 9 mm × 6 mm × 0.25 mm. The filter operates at a center frequency of 28 GHz, offering a fractional bandwidth (FBW) of over 14%, an insertion loss below 1.5 dB, and two transmission zeros near the passband edges.

In [8], an absorptive microstrip bandpass filter is introduced, featuring a bandpass section made of a quarter-wavelength coupled line and four stubs, each consisting of a lumped resistor in series with a short-circuited quarter-wavelength transmission line. In [9], a vertical transition structure is integrated into a parallel-coupled filter designed for the 5G upper band at a center frequency of 28 GHz, achieving a minimum insertion loss of 1.5 dB. Additionally, [10] presents a microstrip parallel coupled line bandpass filter based on a seventh-order Chebyshev response, operating at a center frequency of 4.1 GHz with an insertion loss of 4.92 dB, suitable for C-band TV satellite downlinks. A parallel coupled line bandpass filter was designed with a center frequency of 28 GHz and a fractional bandwidth of 0.1, corresponding to a bandwidth of 2.8 GHz in [11]. The filter follows a Chebyshev response with a 0.5 dB passband ripple. Various substrate materials were considered, and simulations were conducted for each to determine the optimal choice for the filter design. In [12], the microstrip parallel coupled line bandpass filter was constructed with feed lines connected to two ports and parallel-coupled lines positioned between them. The spacing between these elements was minimized to reduce potential errors.

In the proposed work, a microstrip parallel coupled line bandpass filter for C-band satellite receiver applications was designed using Chebyshev approximation with 0.5 dB passband ripple. The performance of the filter was analyzed by evaluating five different filter orders. To achieve an optimal filter response, the optimization process was conducted using Advanced Design System (ADS) software.

B. Research Methodology

This section outlines the methodology employed in this research including, theoretical synthesis of the bandpass filter, key parameters in filter performance, design and simulation of parallel coupled line bandpass filters.

Theoretical Synthesis of the Bandpass Filter

A good bandpass filter minimizes signal loss within its passband while maintaining a narrow bandwidth and maximizing out-of-band attenuation. A Chebyshev approximation with a 0.5 dB passband ripple is chosen because it provides a steeper initial drop in the stopband compared to other filters. According to [13], the center frequency and the fractional bandwidth of the bandpass filter can be obtained by using equations 1 and 2.

$$\omega_0 = \sqrt{\omega_1 \omega_2} \quad [1]$$

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \quad [2]$$

where ω_1 and ω_2 are upper and lower cutoff frequencies of the bandpass filter. In a parallel coupled line bandpass filter, the strips are arranged closely in parallel to achieve the desired coupling and provide the required bandwidth, offering advantages over other filter configurations. For the N^{th} order filter, there are N+1 coupled line sections. Layout for an N+1 section coupled line bandpass filter is shown in figure 1.

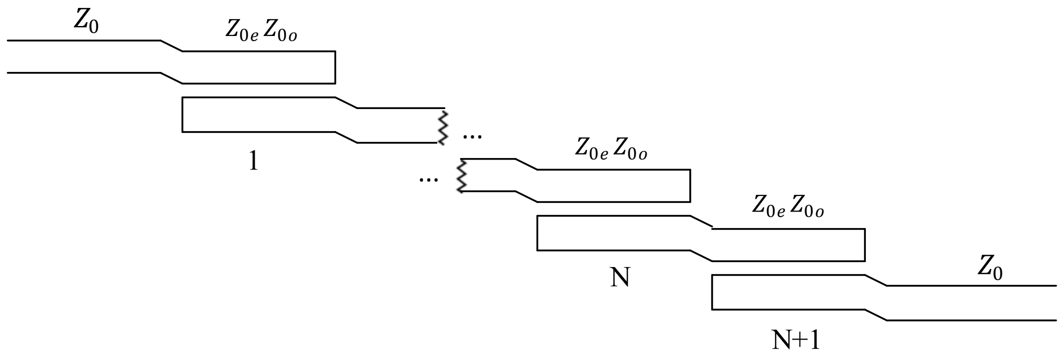

Figure 1. Layout for an N+1 Section Coupled Line BPF

N is the order of the filter. Each coupled line section functions as an admittance inverter, denoted by J. Equations 3 to 7 are applied in the design of a parallel coupled-line bandpass filter [13].

$$Z_0 J_1 = \sqrt{\frac{\Delta\pi}{2g_1}} \quad [3]$$

$$Z_0 J_n = \frac{\Delta\pi}{2\sqrt{g_n g_{n-1}}} \qquad \text{for n=2, 3,……,N} \quad [4]$$

$$Z_0 J_{N+1} = \sqrt{\frac{\Delta\pi}{2 g_N g_{N+1}}} \quad [5]$$

where $g_1, g_{2,} \dots\dots, g_N$ are element values of Chebyshev response. J_n is the admittance inverter constant. Z_0 represents the characteristic impedance of the transmission line being connected. Δ is fractional bandwidth. The even and odd mode impedances are calculated using equations 6 and 7 .

$$Z_{0e} = Z_0[1 + Z_0 J + (Z_0 J)^2] \quad [6]$$

$$Z_{0o} = Z_0[1 - Z_0 J + (Z_0 J)^2] \quad [7]$$

The dimensions of coupled microstrip lines that exhibit the desired even and odd mode impedances can be calculated by the equations 8 to 17 [14]. For a single microstrip line, the even and odd mode single characteristic impedances are:

$$Z_{0se} = \frac{Z_{0e}}{2} \quad [8]$$

$$Z_{0so} = \frac{Z_{0o}}{2} \quad [9]$$

The approximate expression for the shape ratio of the microstrip couplined line at the case w/h ≤ 2 is:

$$\frac{w}{h} = \frac{8\, e^{(A)}}{e^{2A} - 2} \quad [10]$$

$$\text{with } A = \frac{Z_c}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left\{0.23 + \frac{0.11}{\varepsilon_r}\right\} \quad [11]$$

At the case w/h > 2,

$$\frac{w}{h} = \frac{2}{\pi}\left\{(B-1) - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right]\right\} \quad [12]$$

$$\text{with } B = \frac{60\,\pi^2}{Z_c\sqrt{\varepsilon_r}} \quad [13]$$

where ε_r is the relative dielectric constant. The approximate expression for the spacing ratio of the microstrip coupled line is:

$$\frac{s}{h} = \frac{2}{\pi}\cosh^{-1}\left[\frac{\cosh\left(\frac{\pi}{2}\left(\frac{w}{h}\right)_{se}\right) + \cosh\left(\frac{\pi}{2}\left(\frac{w}{h}\right)_{so}\right) - 2}{\cosh\left(\frac{\pi}{2}\left(\frac{w}{h}\right)_{so}\right) - \cosh\left(\frac{\pi}{2}\left(\frac{w}{h}\right)_{se}\right)}\right] \quad [14]$$

where, $(w/h)_{se}$ and $(w/h)_{so}$ can be applied with the single microstrip line impedences, Z_{0se} and Z_{0so} as Z_c. By using s/h, the shpe ratio w/h can be obtained as equation 15.

$$\frac{w}{h} = \frac{1}{\pi}\left\{\begin{matrix}\cosh^{-1}\left[\frac{1}{2}\left(\left(\cosh\left(\frac{\pi}{2}\,\frac{s}{h}\right) - 1\right) + \left(\cosh\left(\frac{\pi}{2}\,\frac{s}{h}\right) + 1\right)\cosh\left(\frac{\pi}{2}\left(\frac{w}{h}\right)_{se}\right)\right)\right] \\ -\left(\frac{\pi}{2}\right)\left(\frac{s}{h}\right)\end{matrix}\right\} \quad [15]$$

The effective dielectric constant is given by

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-0.5} \quad [16]$$

The guided wavelength of the quasi-TEM mode of microstrip is given by

$$l = \frac{c}{4 f_0 \sqrt{\varepsilon_{eff}}} \quad [17]$$

where c and f_0 are the speed of light in vacuum and the center frequency, respectively. Using the previously obtained even and odd mode characteristic impedances, the width and spacing of each pair of quarter-wavelength coupled sections can be determined using design equations 14 and 15.

Key Parameters in Filter Performance

Filters exhibit two primary types of losses: return loss and insertion loss. Return loss refers to the attenuation of the signal that is reflected within the passband due to impedance discontinuities in the transmission line caused by the filter. To ensure optimal performance, it is essential to evaluate the signal loss at the filter's output. Return loss is typically measured in decibels (dB), with higher values indicating better filter performance, as they correspond to lower signal reflections. The return loss in dB can be achieved by the equation 18 [15].

$$\text{Return Loss (dB)=-20}\ \log_{10}|s_{11}| \qquad [18]$$

s_{11} is the reflection coefficient, which represents the ratio of the reflected signal to the incident signal at the input port.

Insertion loss, on the other hand, represents the attenuation of the transmitted signal within the passband due to the presence of the filter on the transmission line. It is also measured in decibels (dB). For optimal filter performance, the input impedance of the filter should match the system's characteristic impedance, minimizing signal loss. A lower insertion loss value indicates better filter efficiency, as it ensures minimal signal attenuation. The insertion loss in dB can be obtained by the equation 19 [15].

$$\text{Insertion Loss (dB)=-20}\ \log_{10}|s_{21}| \qquad [19]$$

s_{21} is the transmission coefficient, which represents the ratio of the transmitted signal to the incident signal from the input port to the output port.

Another factor considered in this research is the shape factor. The shape factor of a filter is a measure of how sharply the filter transitions from the passband to the stopband. It is defined as the ratio of 30 dB rejection bandwidth to the 3 dB bandwidth. A lower shape factor (closer to 1) indicates a sharper filter response with better selectivity. The shape factor can be calculated by the equation 20 [16].

$$\text{Shape Factor} = \frac{\text{Bandwidth}_{30\ dB}}{\text{Bandwidth}_{3\ dB}} \qquad [20]$$

Design and Simulation of Parallel Coupled Line Bandpass Filters

The calculation process is relatively complex and lengthy. In this study, the performance of the filter is analyzed by varying different filter orders. A simulation was carried out with ADS software. The proposed coupled lined bandpass filter is designed at a center frequency of 3.9 GHz with FR4 substrate. The substrate parameters that are considered in this work are the relative dielectric constant (ε_r) of 4.4, substrate thickness (H) of 1.5 mm, thickness of metal layer (T) of 35 μm and dielectric loss tangent (TanD) of 0.002. The operating frequency range is 3.7 GHz to 4.2 GHz for C band satellite downlink.

Firstly, the third order parallel coupled BPF is designed and simulated. The element g values of the Chebyshe filter with 0.5 dB passband ripple [13] are as shown in table 1. The even-mode characteristic impedance, Z_{0e} and the odd-mode characteristic impedance, Z_{0o} can be calculated by using equations 1 to 7.

Table 1. Calculated Parameters for the Third Order BPF

Coupled Line	g_n	Z_0J_n	Z_{0e}	Z_{0o}
1	1.5963	0.3533	73.9047	38.5763
2	1.0967	0.1506	58.6626	43.6048
3	1.5963	0.1506	58.6626	43.6048
4	1.0000	0.3533	73.9047	38.5763

Using the even-mode and odd-mode impedance values along with the substrate parameters, the width (w), length (l), and spacing (s) of the parallel-coupled line bandpass filter can be determined using the LineCalc tool in ADS software. The employed coupled line is of the MCFL type. To ensure proper matching with the microstrip line, a 50 Ω characteristic impedance is connected to both ends.

The schematic diagram of the third order parallel coupled line bandpass filter is shown in figure 2.

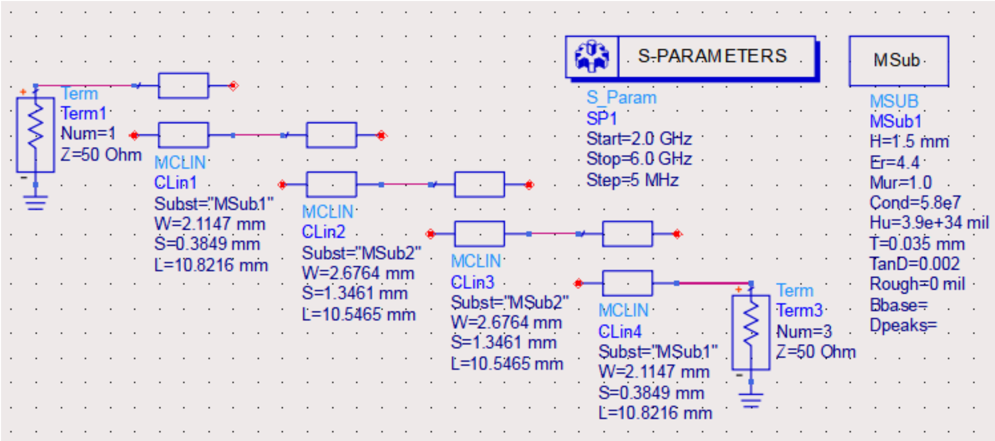

Figure 2 Schematic Diagram of the Third Order Parallel Coupled Line BPF

The calculated dimensions of transmission line is shown in table 2.

Table 2. Dimensions of the Third Order BPF

Coupled Line	w(mm)	s(mm)	l(mm)
1 and 4	2.1147	0.3849	10.8216
2 and 3	2.6764	1.3461	10.5465

Figure 3 shows the performance of the third order microstrip parallel coupled line bandpass filter. The filter has the lower cutoff frequency of 3.605 GHz and the upper cutoff frequency of 4.15 GHz measured at nearly -3 dB and thus, -3 dB bandwidth is 545 MHz. Marker m3 shows the lower frequency of 3.255 GHz and m4 indicates the upper frequency of 4.725 GHz measured at -30 dB attenuation and thus, bandwidth at -30 dB is 1470 MHz. According to equations 1 and 20, the center frequency is 3.87 GHz and the shape factor is 2.7. From marker m5, it can be observed that the filter has an insertion loss, s_{21} of -0.534 dB and a return loss, s_{11} of -16.32 dB, at the center frequency.

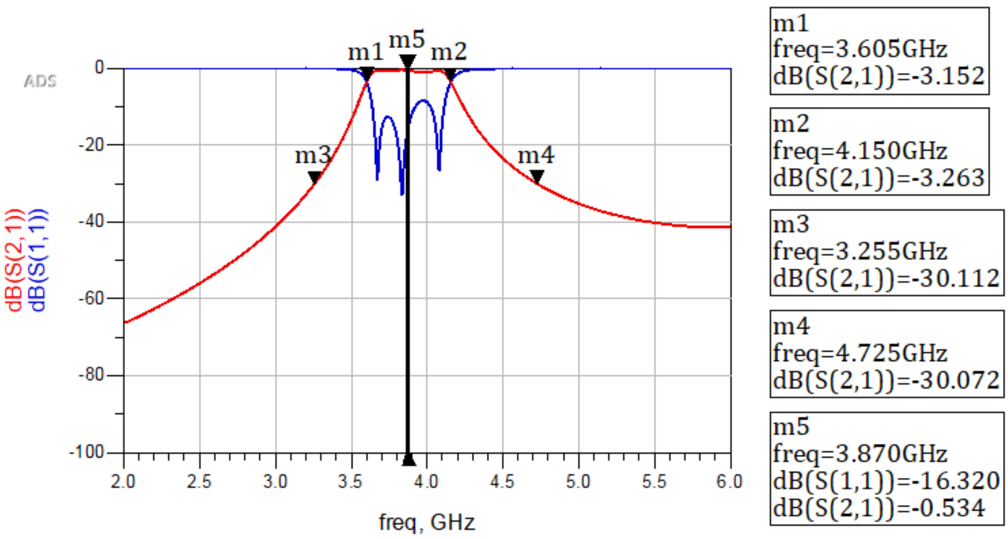

Figure 3 Result of the Third Order Parallel Coupled Line BPF

To analyze the performance, the microstrip parallel coupled line BPF is designed with five different orders. The design process of the filter for the remaining orders is the same as that of the third order BPF. The result of the fourth order BPF is shown in figure 4. The fourth order parallel coupled line BPF has -3 dB bandwidth of 505 MHz, a center frequency of 3.88 GHz, an insertion loss of -0.973 dB, a return loss of -10.812 dB and a shape factor of 1.9.

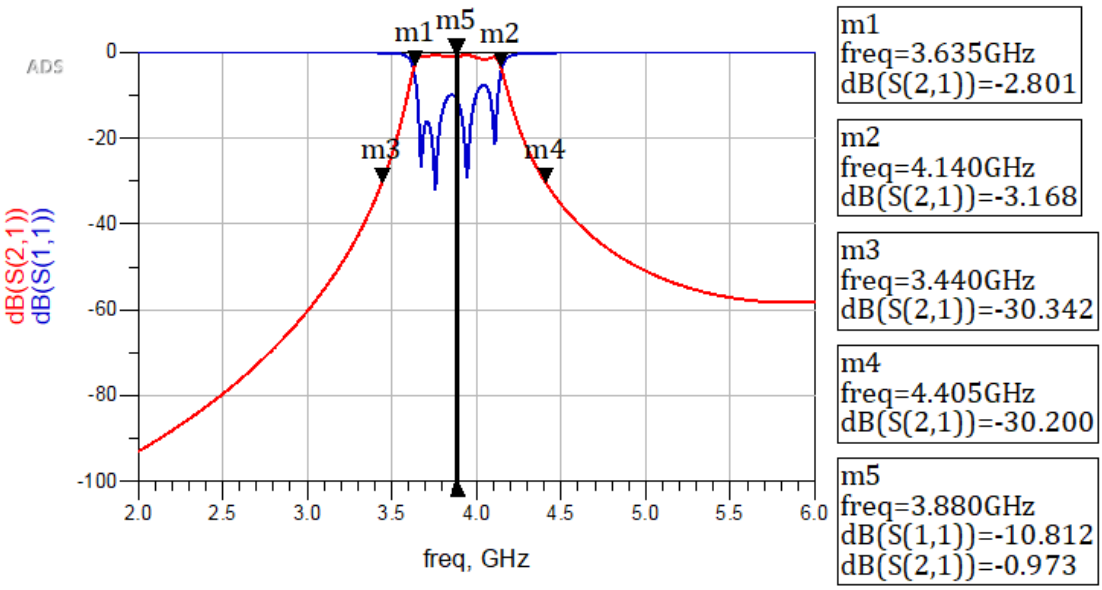

Figure 4 Result of the Fourth Order Parallel Coupled Line BPF

The result of the fifth order parallel coupled line BPF is illustrated in figure 5. The filter has -3 dB bandwidth of 490 MHz, a center frequency of 3.88 GHz, an insertion loss of -0.948 dB, a return loss of -14.654 dB and a shape factor of 1.6.

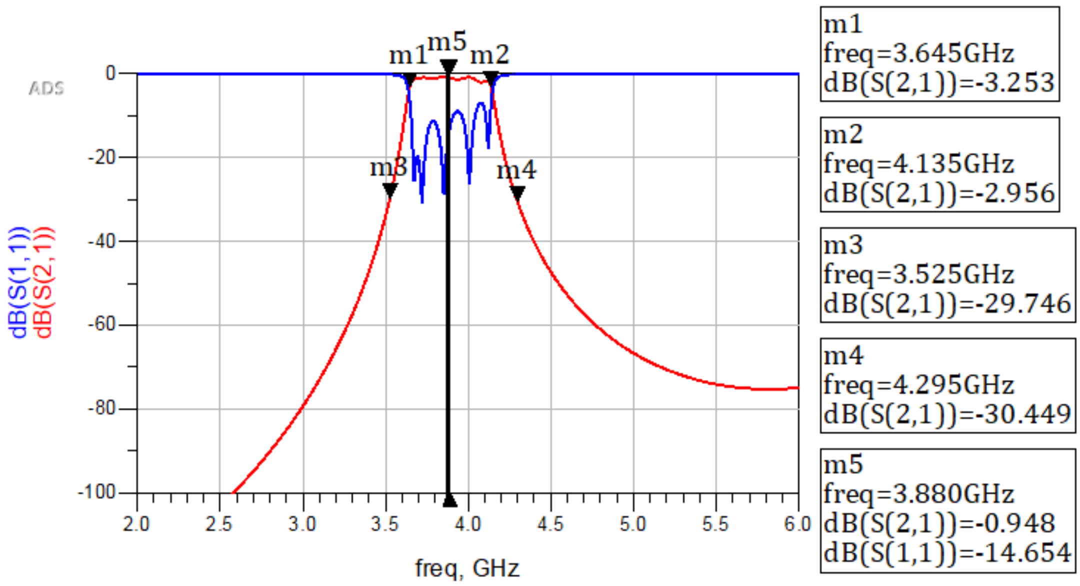

Figure 5 Result of the Fifth Order Parallel Coupled Line BPF

The result of the sixth order parallel coupled line BPF is shown in figure 6. The filter has -3 dB bandwidth of 480 MHz, a center frequency of 3.89 GHz, an insertion loss of -1.227 dB, a return loss of -12.401 dB and a shape factor of 1.4.

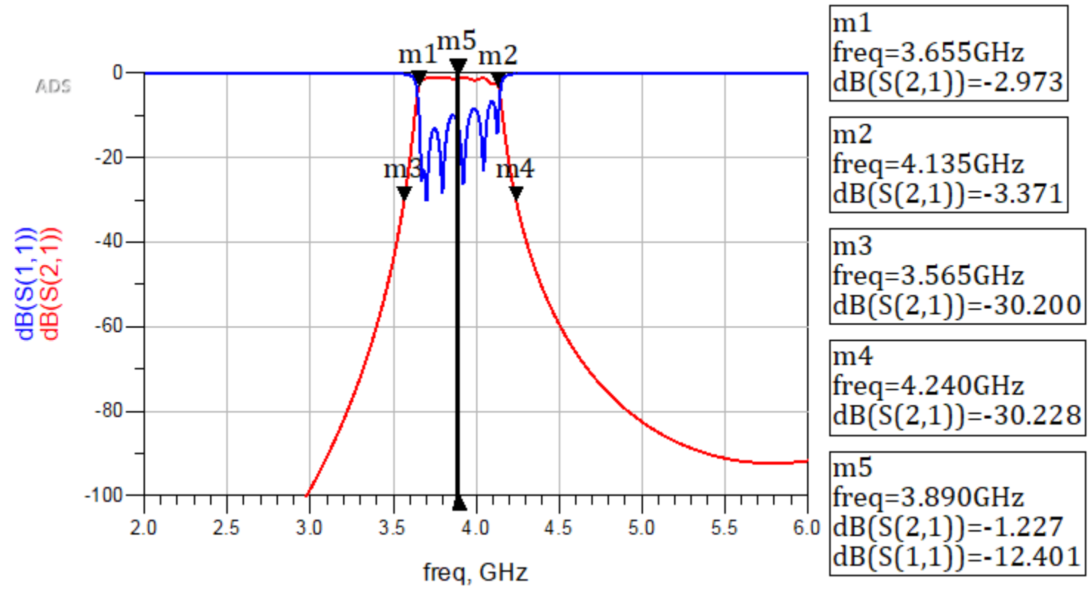

Figure 6 Result of the Sixth Order Parallel Coupled Line BPF

Figure 7 describes the result of the seventh order parallel coupled line BPF. The filter has -3 dB bandwidth of 465 MHz, a center frequency of 3.89 GHz, an insertion loss of -1.435 dB, a return loss of -12.18 dB and a shape factor of 1.3.

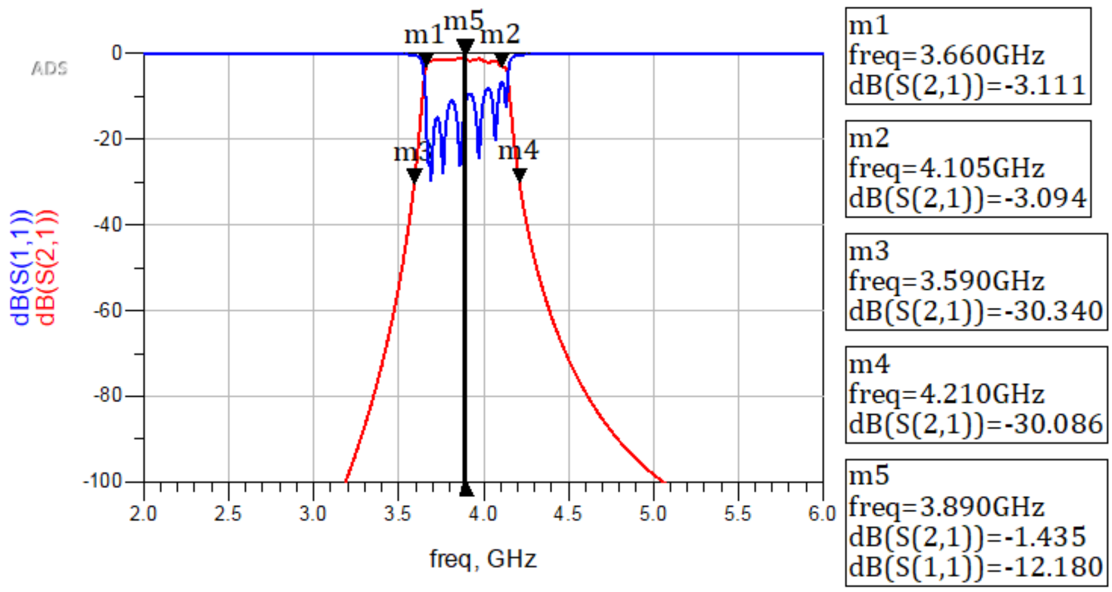

Figure 7 Result of the Seventh Order Parallel Coupled Line BPF

C. Performance Analysis of the Filter with Five Different Orders

The comparison of the return loss, s_{11} of the microstrip parallel coupled line BPF with five different orders is shown in figure 8. All filters exhibit a flat response in the passband, with minimal attenuation, which is expected. The higher-order filters (6th and 7th order, in cyan and blue) exhibit a much steeper roll-off, meaning they attenuate unwanted frequencies more rapidly. The lower-order filters (3rd order, in red) have a gradual roll-off and provide less rejection in the stopband. Higher-order filters provide sharper transitions and better out-of-band rejection, but they are typically more complex to design and may introduce more group delay.

A fifth order filter provides a steeper roll-off compared to third and fourth-order filters. This means better selectivity and improved attenuation of unwanted frequencies. From the graph, the fifth order filter (magenta curve) shows a significant attenuation in the stopband, reaching below -60 dB at around 3 GHz and 5 GHz.

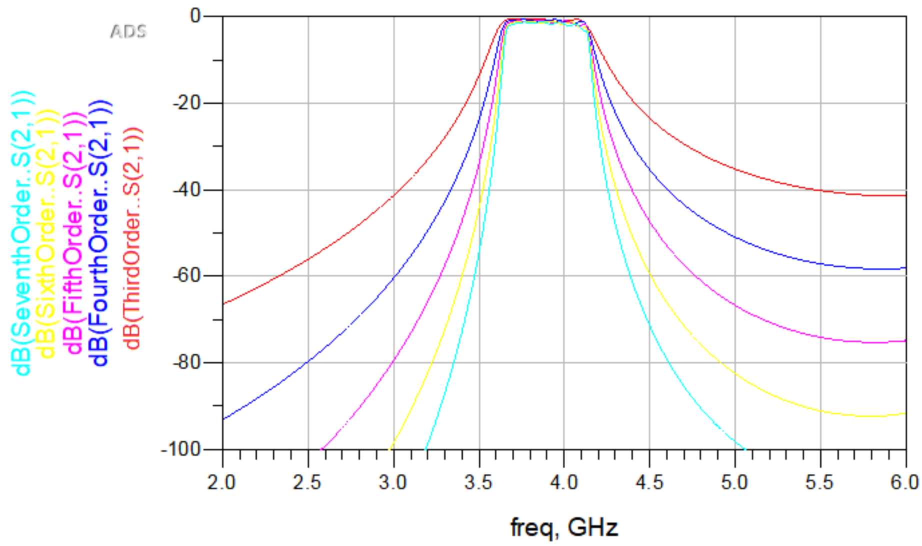

Figure 8 The Comparison of the Insertion Loss

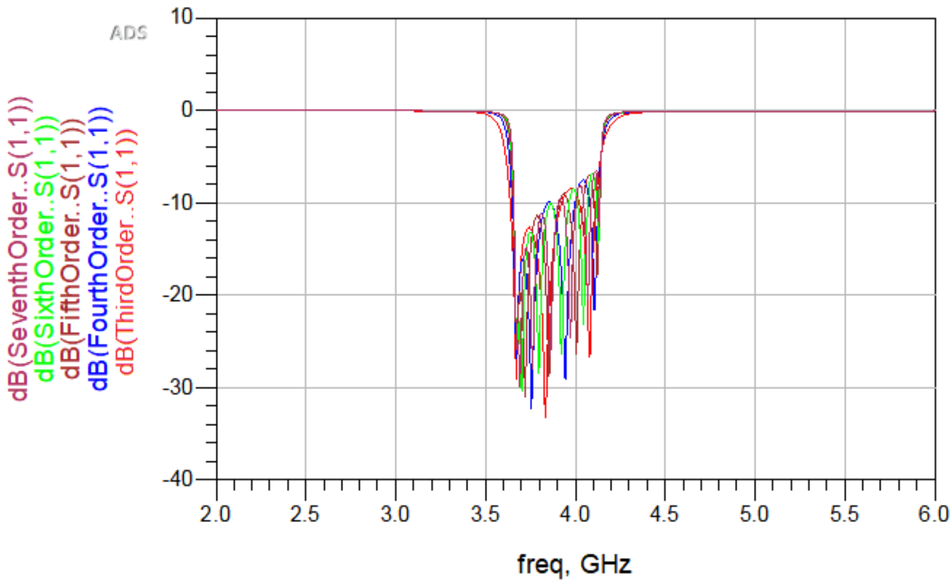

Figure 9 The Comparison of the Return Loss

Figure 9 shows the comparison of the insertion loss, s_{11} of the microstrip parallel coupled line BPF with five different orders. The s_{11} curves show deep dips (notches) in the passband, meaning low return loss and good impedance matching in this range. The fifth order filter (green curve) shows a deep notch around 4 GHz, confirming effective impedance matching. Higher-order filters (6^{th} and 7^{th}) show more pronounced notches and ripples in the stopband. Some oscillations in the stopband indicate potential parasitic effects or coupling issues, which are common in high-order filters. The fifth order filter provides a good compromise between deep passband notches (good matching) and minimal ripples in the stopband.

Performance comparison of different order bandpass filters for C-band satellite receiver is shown in table 3.

Table 3. Performance Comparison of Different Order Bandpass Filters for C-Band Satellite Receiver

Parameter	3^{rd} Order BPF	4^{th} Order BPF	5^{th} Order BPF	6^{th} Order BPF	7^{th} Order BPF
Center Frequency (GHz)	3.87	3.88	3.88	3.89	3.89
Insertion Loss (dB)	-0.534	-0.973	-0.948	-1.227	-1.435
Return Loss (dB)	-16.32	-10.812	-14.654	-12.401	-12.18
Bandwidth (MHz)	545	505	490	480	465
Shape Factor	2.7	1.9	1.6	1.4	1.3

According to table 3, the fifth order parallel coupled line bandpass filter provides the best trade-off between performance, insertion loss, return loss, and complexity. It offers lower insertion loss than the sixth and the seven orders for better signal transmission.

It provides good impedance matching (-14.654 dB return loss) to reduce reflections. Its 490 MHz bandwidth effectively covers C-band satellite signals while reducing unwanted interference.

It has a good shape factor (1.6), ensuring a sharp roll-off without excessive design complexity. Thus, for the C-band satellite receiver system, the fifth order BPF is the optimal choice, delivering high performance while remaining practical for implementation.

D. Optimization Result and Discussion

The next phase involves performing an optimization and tuning process to enhance filter performance. This begins by accurately setting up the optimization parameters. Key specifications such as insertion loss, return loss, and the allowable ranges for the width, length, and spacing of each coupled line are configured based on the design requirements. The optimization and tuning are executed using ADS software, employing the Goal and Optimization Controller. The optimized dimensions of the fifth order BPF are shown in table 4.

Table 4. Optimized Dimensions of the Fifth Order BPF

Coupled Line	w(mm)	s(mm)	l(mm)
1	1.0811	0.5376	13.3922
2	3.3774	0.4133	6.7519
3	9.9725	0.7446	15.3323
4	5.2139	0.4016	5.6741
5	3.8425	1.1677	13.8102
6	1.0815	0.4000	8.1475

The optimized result of the fifth order parallel coupled line BPF is illustrated in figure 9. It can be seen that the optimized center frequency is 3.94 GHz, aligning well with the C-band satellite communication range (3.7–4.2 GHz). Low insertion loss (-0.625 dB) means minimal signal attenuation, ensuring maximum signal strength reaches the receiver. This is a significant improvement compared to higher-order filters that typically have insertion losses above 1 dB. Deep return loss (-31.443 dB) at the center frequency means excellent impedance matching. This ensures maximum power transfer with minimal reflections, improving system efficiency. The -3 dB bandwidth is approximately 565 MHz (from 3.67 GHz to 4.235 GHz), which provides sufficient bandwidth for C-band satellite applications. The filter has a shape factor value of 1.7, which confirms that the optimized fifth order bandpass filter achieves a good balance between selectivity and bandwidth efficiency**,** making it a strong candidate for C-band satellite receiver applications**.**

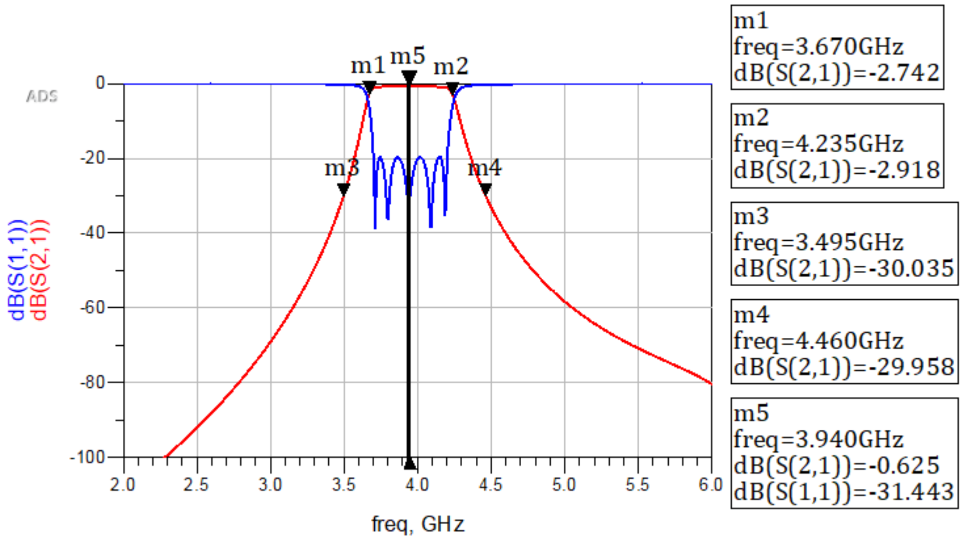

Figure 9 The Optimized Result of the Fifth Order Parallel Coupled Line BPF

E. Conclusion

In this work, a microstrip parallel coupled line bandpass filter was designed and analyzed across different filter orders. The optimized fifth order bandpass filter successfully meets the design requirements for C-band satellite receiver applications, providing an optimal balance between insertion loss, return loss, bandwidth, and stopband rejection. With a low insertion loss of -0.625 dB, a deep return loss of -31.443 dB, a bandwidth of 565 MHz, and a shape factor of 1.7, the filter ensures efficient signal transmission, minimal power loss, and strong interference suppression. The achieved sharp roll-off and impedance matching make it highly effective for real-world satellite communication systems. Overall, this design demonstrates a high-performance and reliable filtering solution for C-band satellite receivers, ensuring improved system efficiency and signal integrity.

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