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Dual-Band Microstrip Bandpass Filter for Wireless Applications

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Abstract

This study presents the design, simulation, and validation of a compact dual-band microstrip bandpass filter developed for wireless applications, operating within the 2.47–2.68 GHz and 5.02–5.45 GHz frequency ranges having operating frequencies at 2.6 GHz and 5.07 GHz. The filter utilizes edge-coupled square ring resonators along with split-ring structures to achieve improved frequency selectivity, low insertion loss, and reduced mutual interference between the bands. A 4th-order Chebyshev low-pass prototype with a 0.5 dB ripple serves as the basis for the design. Ansys HFSS (High Frequency Structure Simulator) is used to perform detailed electromagnetic simulations, helping to optimize physical parameters such as resonator lengths, coupling gaps, and feedline placements. This ensured the filter worked well at both frequency bands. The filter is fabricated on an Epoxy FR4 substrate with a dielectric constant of 4.4 and a thickness of 1 mm, the filter offers a cost-effective and compact solution while maintaining good return loss. Experimental validation using a Vector network analyzer showed close alignment with simulated results, confirming the accuracy and practical viability of the design.

Keywords: Wireless Applications, Bandpass, Dual-Band, Chebyshev Filter

1. Introduction

The increasing growth of wireless communication systems needs efficient frequency management. Bandpass filters, which allow signals within a designated frequency range to pass while blocking others, are fundamental to this functionality. Dual-band filters are particularly useful as they can support two distinct frequency bands at the same time, which is essential for multiservice and multiband communication systems where multiple communication standards operate concurrently within a single platform [1]. These filters play a key role in enabling the functioning of technologies such as mobile communication, Wi-Fi, Bluetooth [3], and emerging 5G networks. Microstrip technology is commonly used in the fabrication of such filters due to its low cost, compact form, and ease of integration with existing circuit designs.

The proposed bandpass filter employs edge coupling, where all the resonating elements are patterned on the top layer of the substrate. The coupling between adjacent square loop resonators is achieved through fringing electric fields along their edges, enabling effective energy transfer and mode excitation. This planar edge-coupled design allows compactness and ease of fabrication while supporting dual-band operation with good isolation between the bands.

This coupling technique helps in creating filters with enhanced performance characteristics. By carefully designing the resonant frequencies and the coupling structure, the filter can provide high selectivity and low insertion loss at these two bands [4], ensuring minimal signal degradation and optimal system performance.

The design of the filter relies heavily on the electromagnetic properties of the substrate and the geometry of the coupled microstrip lines [7], which can be tuned to meet the specific frequency requirements of a given application. By controlling the coupling strength and the physical dimensions of the lines, engineers can achieve the desired resonance at the two targeted frequencies, resulting in a high-quality bandpass filter.

Split-ring resonators (SRRs) are metamaterial-inspired structures consisting of concentric metallic rings with gaps, designed to exhibit strong resonance behavior within compact physical dimensions. In microstrip filter designs, SRRs are highly effective for creating bandpass characteristics due to their ability to support localized resonant modes. When arranged in proximity on the same substrate layer, SRRs facilitate edge coupling, allowing energy to be transferred between resonators through fringing electric fields along adjacent edges. This coupling mechanism contributes significantly to controlling the filter's passband properties, including bandwidth and insertion loss. Additionally, the symmetrical layout and gap placement in SRRs enhance selectivity and suppress unwanted frequencies [5], making them ideal for miniaturized and high-performance filter implementations in modern wireless systems.

2. Defining a Problem

The challenge of creating a Dual-Band Microstrip Bandpass Filter for Wireless Applications derives from the growing need for wireless communication systems to function well over various frequencies. Cell phones, Wi-Fi routers, and satellite communication are examples of wireless systems that need filters that can attenuate undesirable signals outside of two specific frequency bands while concurrently passing signals within those bands. High selectivity, low insertion loss, small size, and the capacity to function effectively at both frequency bands without causing appreciable interference between them are some of the obstacles that must be overcome when designing a dual-band microstrip bandpass filter. Furthermore, the filter needs to be made to satisfy the unique requirements of wireless applications, which include low cost, low power consumption, and system component integration. Optimizing the filter's performance for real-world scenarios and fine-tuning its resonant frequencies require precision, which adds to the challenge.

3. Aim and Objectives

The aim of the dual-band microstrip bandpass filter is to support multiple wireless technologies like LTE (Long Term Evolution), Wi-Fi, and Bluetooth by allowing efficient use of two frequency bands in compact and modern communication devices. The following are the key objectives to be considered during the design and implementation of the dual-band bandpass filter

- High selectivity is necessary to clearly separate the desired frequency bands, such as 2.6 GHz and 5.07 GHz, from unwanted signals, thereby minimizing interference and improving signal clarity.
- Minimizing insertion loss is important to ensure efficient signal transmission, as excessive loss can lead to reduced data rates and higher power consumption.

- Achieving a return loss below –10 dB ensures good impedance matching with connected components, which helps maintain signal integrity and prevents reflections.
- The filter design should support compactness to fit within the limited space available in modern wireless devices.
- Cost-effectiveness is essential for large-scale production and integration into consumer electronics where budget constraints are a key consideration.

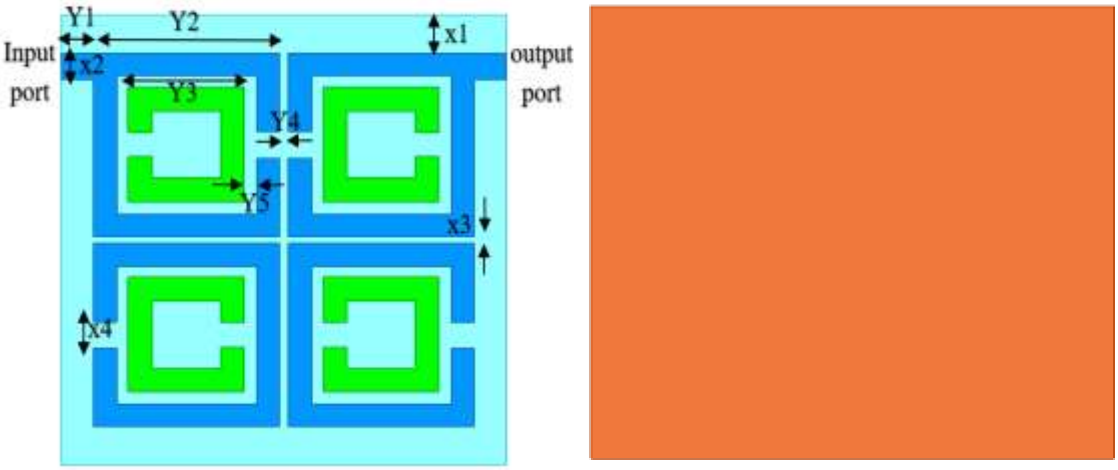
4. Methodology of the Bandpass Filter

The design and simulation of the dual-band bandpass filter were carried out using Ansys HFSS software, a powerful tool for electromagnetic analysis and design. The filter operates in two specific frequency bands: 2.47–2.68 GHz and 5.02–5.45 GHz, with operating frequencies of 2.6 GHz and 5.07 GHz, which are commonly used in wireless communication systems such as Wi-Fi, Bluetooth, 4G, and 5G. The dimensions of the filter are optimized in order to achieve the desired frequency response.

The proposed dual-band bandpass filter is built on an FR4 epoxy substrate ($\varepsilon r = 4.4$, thickness = 1 mm) with a 35 µm copper layer, making it a cost-effective and reliable choice for compact RF designs. Despite moderate dielectric losses due to a loss tangent of 0.02, the substrate offers suitable electrical performance at microwave frequencies.

Table 1. Filter design values

Parameters	**Filter dimensions**
Substrate length	25mm
Substrate width	25mm
Thickness of the substrate	1mm
Y1	1.8mm
Y2	10.4mm
Y3	6.5mm
Y4	0.6mm
Y5	0.7mm
X1	1.9mm
X2	1.5mm
X3	0.4mm
X4	1.4mm



(a) (b)

Figure 1. Design of the microstrip bandpass filter, (a) top view, (b) bottom view

Numerical modeling is essential in microstrip filter design, enabling engineers to simulate and optimize key parameters like insertion loss, return loss, and bandwidth before fabrication. For dual-band filters, accurate modeling is crucial due to the complex interactions of multiple resonators. This design uses four cross-coupled square resonators [2] to enhance selectivity and generate transmission zeros near the passbands, improving out-of-band rejection. While simulations provide valuable insights, experimental validation through prototyping is necessary to verify real-world performance. A fourth-order Chebyshev low-pass prototype was employed, and its lumped elements were transformed into a distributed microstrip layout to achieve the desired frequency response [6].

$$\mathrm{FBW} = \frac{(f_2 - f_1)}{f_0} * 100 \tag{1}$$

$$M_i, M_{i+1} = M_{n-i,n-i+1} = \frac{\mathrm{FBW}}{\sqrt{g_i + g_{i+1}}}, \text{for } i = 1 \text{ to } m-1 \tag{2}$$

$$M_{m,m+1} = \frac{\mathrm{FBW} * J_m}{g_m}, \quad M_{m-1,m+2} = \frac{\mathrm{FBW} * J_{m-1}}{g_{m-1}} \tag{3}$$

The fractional bandwidth (FBW) is defined as the ratio of the difference between the upper (f_2) and lower (f_1) cutoff frequencies to the center frequency (f_0). In low-pass prototype filters, parameters like gi (lumped capacitance) and Ji (characteristic admittance of the inductor) are used to determine the coupling matrix, which influences how energy flows between resonators. The resulting coupling coefficients (Mi) indicate the strength of interaction between resonators, where stronger coupling increases bandwidth and weaker coupling narrows it. In dual-band filters, this concept is applied to both passbands to maintain balanced performance at each center frequency.

Coupling coefficients like M12 = M21 and M34 = M43 are achieved through a combination of electric and magnetic coupling by adjusting the spacing and orientation of resonators. Magnetic coupling alone, as seen in M23 = M32, is effective when resonators are closely placed to support mutual inductance. Negative coupling, such as M14 = M41, is introduced between non-adjacent resonators through electric coupling, creating a 180° phase shift that generates transmission zeros and enhances selectivity. Impedance-based coefficients (Mm, m+1) ensure proper matching with 50-ohm ports, while the use of four open-loop resonators with a 6.5 mm inner ring length further improves filter selectivity.

5. Design Steps of the Bandpass Filter

The design and realization of the proposed dual-band bandpass filter are carried out through the following steps:

Step 1: The design process begins with a Chebyshev low-pass prototype featuring a 0.5 dB ripple to ensure a sharp roll-off. This prototype provides normalized element values (g-values) for constructing the coupling matrix. It serves as the foundational model from which the dual-band filter is derived through appropriate transformations.

Step 2: A lumped-element model is constructed using ideal inductors and capacitors to replicate the filter's frequency response. This stage facilitates the analysis and validation of the filter's behavior in an idealized circuit environment.

Step 3: The lumped-element circuit is converted into a distributed-element design using microstrip transmission line structures. This conversion accounts for electromagnetic wave propagation and is essential at microwave frequencies.

Step 4: A microstrip layout is developed using square resonators with appropriate coupling arrangements to realize dual-band operation. Critical parameters such as line width, resonator dimensions, and coupling gaps are optimized through electromagnetic simulation. This ensures targeted frequency response, minimal insertion loss, and sufficient return loss.

Step 5: The optimized layout is fabricated on an FR4 substrate. SMA (Sub Miniature version A) connectors are mounted at the input and output ports to enable measurement. The final prototype is evaluated using a vector network analyzer to verify compliance with design specifications.

6. Simulation Results

The simulation of the bandpass filter is performed using full-wave analysis in Ansys HFSS. Key parameters such as return loss (S11), insertion loss (S21), and electromagnetic field distribution are evaluated to ensure the filter meets the design requirements. The simulated results confirm effective performance within the target bands around 2.6 GHz and 5.07 GHz.

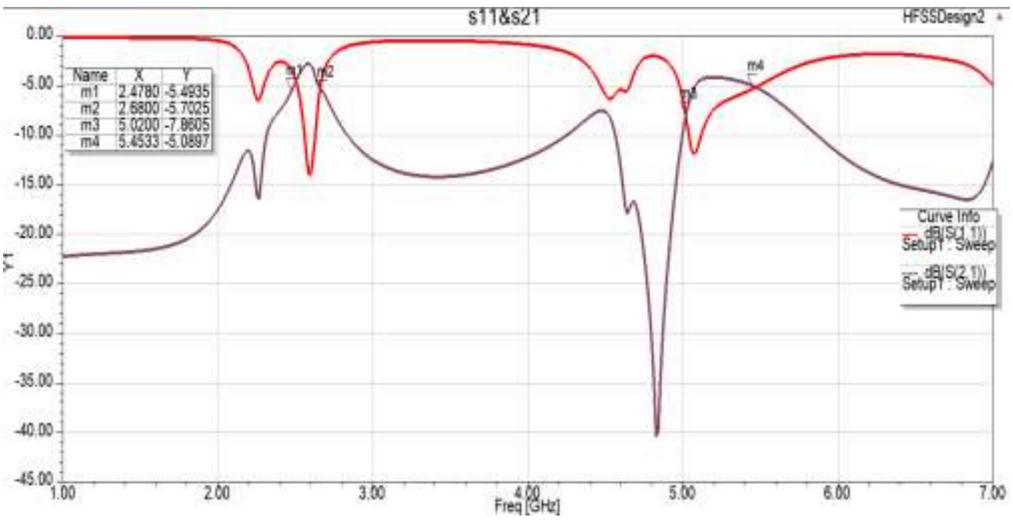


Figure 2. |S11 | (dB) & |S21| (dB) Vs Frequency (GHz) in Ansys HFSS Simulation

The results displayed in Figure 2 include important characteristics like the return loss (S11), insertion loss (S21), and the overall frequency response, which demonstrate the performance of the dual-band bandpass filter. The S11 parameter, which represents return loss, shows sharp dips below –10 dB between 2.47-2.68 GHz and 5.02-5.45 GHz, indicating good impedance matching and minimal reflection in both bands. The S21 parameter, representing insertion loss, displays two clear peaks at the same center frequencies, confirming efficient signal transmission with low insertion loss in the passbands.

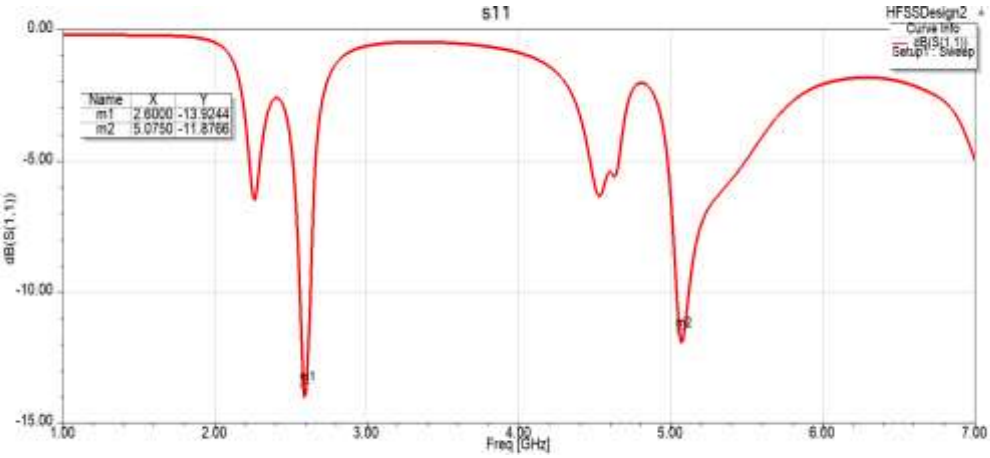


Figure 3. |S11 | (dB) Vs Frequency (GHz) in HFSS Simulation

The results displayed in Figure 3 include s11 (return loss) characteristics. A low S11 value, typically expressed in decibels (dB), indicates that most of the input signal is transmitted through the filter rather than being reflected, which is desirable for efficient signal processing. The return loss at two operating frequencies is -13 dB at 2.6 GHz and -11 dB at 5.07 GHz.

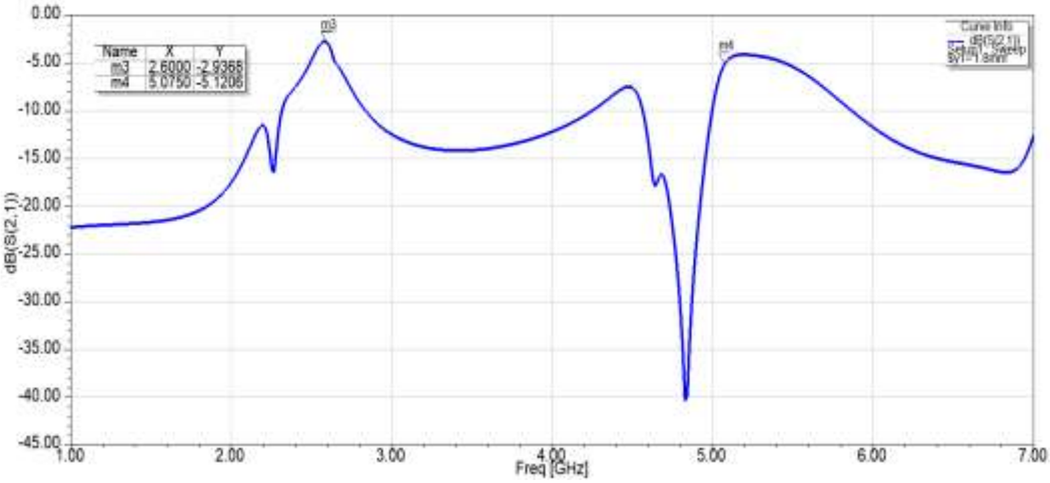


Figure 4. |S21| (dB) vs Frequency (GHz) in HFSS simulation

The results displayed in Figure 4 include s21 (insertion loss) characteristics. For a filter -3 dB point is commonly used to define the bandwidth of each passband, as it represents the frequency range where the signal power remains within 50% of its peak transmission. In this plot, two passbands are clearly visible around 2.6 GHz and 5.07 GHz. The insertion loss at these operating frequencies is -2.93 dB and -5.12 dB respectively. The designed filter exhibits a fractional bandwidth of 8.15% at 2.6 GHz with a corresponding bandwidth of 210 MHz and a quality factor of 12.26. Similarly, at 5.07 GHz, the fractional bandwidth is 8.21%, with a bandwidth of 430 MHz and a quality factor of 12.17. These values indicate that the filter maintains consistent performance across both bands, offering a balanced trade-off between bandwidth and selectivity.

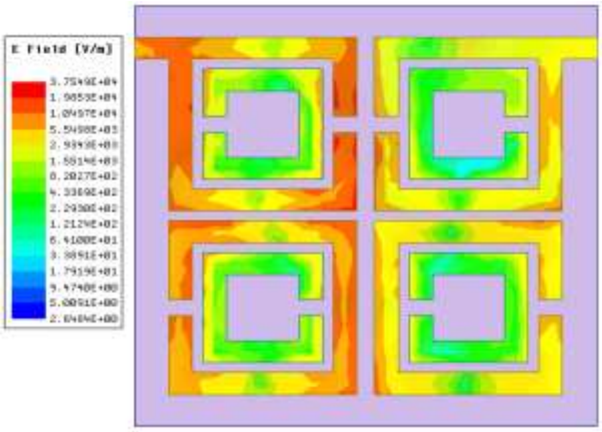


Figure 5. Representation of the electric field intensity of the dual-band bandpass microstrip filter

The above figure represents the electric field intensity simulated in HFSS. The graphical and vectorial depiction of the electric field strength, current density, and S parameters were its primary goals [7]. The field distribution is influenced by resonant structures like split ring resonators, which resonate at specific frequencies.

In Figures 5 and 6, the characteristics of the electric field intensity and current density displayed by the 4-pole cross-coupled structure filter using split-ring resonators. The distribution and behavior of the electric field inside the filter structure are depicted visually in these illustrations.

A contour plot or color map representing the electric field intensity illustrates the differing electric field strengths in various filter sections. Conversely, the current density shows how the movement of regions of high and low current density is highlighted by electrical current flowing through the filter construction. One can better comprehend the filter's electromagnetic behavior and performance by examining these numbers, especially considering the split-ring resonators' distinctive layout and construction.

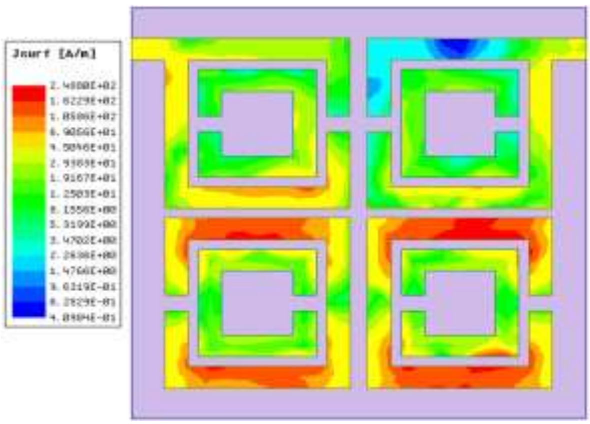


Figure 6. Representation of the current density distribution of the dual-bandpass filter

7. Measured Results

The fabricated prototype is tested using SMA connectors and measured with a vector network analyzer (VNA). The measured S-parameters closely align with the simulated results, demonstrating good impedance matching and low insertion loss across both bands. This validates the accuracy of the simulation model and confirms the practical feasibility of the proposed design.

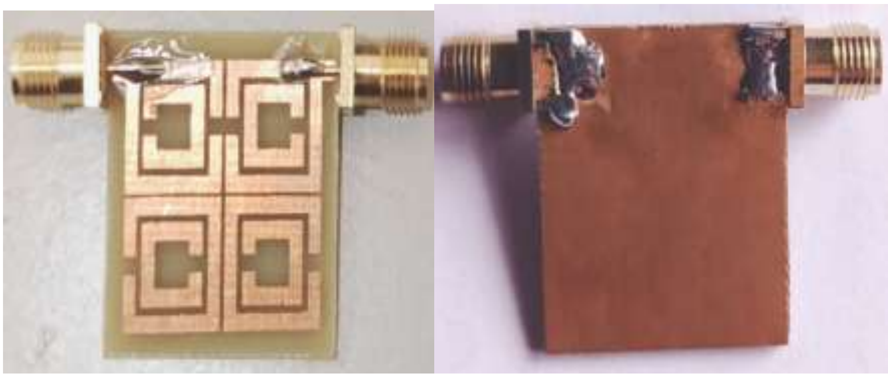


Figure 7. Top and bottom view of the fabricated filter

The fabricated dual-band bandpass filter is implemented on an FR4 substrate with 1mm thickness and is equipped with SMA ports. These connectors allow the filter to be easily interfaced with vector network analyzers (VNA).

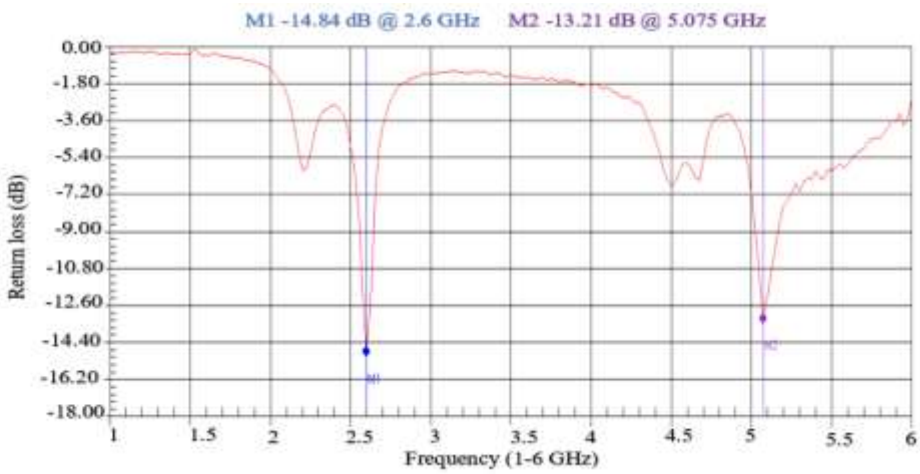


Figure 8. Measured |S11| dB vs frequency

Figure 8 above shows the measured return loss (S11) of the dual-band bandpass filter that was made. Due to measurement errors and connection losses, the observed findings and the calculated results only differ slightly in magnitude. Return loss values below -10 dB are seen at both operational frequencies, 2.6 GHz, and 5.07 GHz, suggesting good impedance matching and negligible signal reflection in both bands.

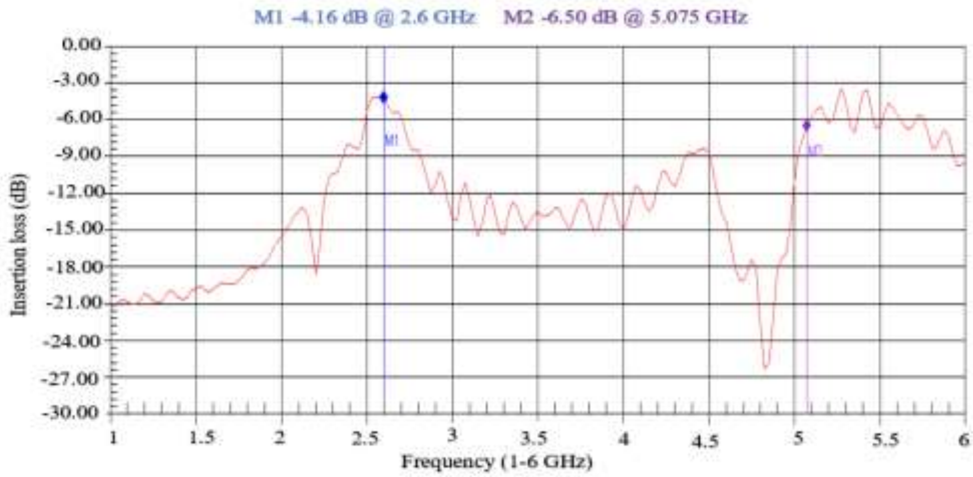


Figure 9. Measured |S21| dB vs frequency

Figure 9 shows the measured insertion loss (S21) of the fabricated dual-band bandpass filter, which closely matches the simulation results. While more ripples are observed between the first and second bands compared to the simulation, they are minor and do not significantly impact the filter's performance.

Figure 10. Snapshot of fabricated filter tested with network analyzer

Figure 10 shows the proposed dual-band bandpass filter, which is tested with a network analyzer represents successful testing of the bandpass filter operating at two frequency bands, and the simulation and measured results are approximately equal, which indicates the filter is effectively operating with good impedance matching.

Table 2. comparison between simulated and measured results

Parameters	Simulated results	Measured results
S11 dB (at 2.6GHz)	-13.92	-14.84
S21 dB (at 2.6GHz)	-2.93	-4.16
S11 dB (at 5.07GHz)	-11.87	-13.21
S21 dB (at 5.07GHz)	-5.12	-6.50

8. Conclusion

The dual-band microstrip bandpass filter designed for wireless applications with frequency ranges of 2.47-2.68 GHz and 5.02-5.45 GHz demonstrates a successful implementation for modern communication systems. The filter is designed in Ansys HFSS software and fabricated using FR4 epoxy substrate, which is cost-effective and suitable for high-frequency applications despite its relatively lower dielectric constant. The first frequency band, spanning from 2.47 GHz to 2.68 GHz, has a fractional bandwidth of 8.15%, providing a broader passband, which is advantageous for accommodating variations in signal frequency and ensuring better system tolerance. The second band, from 5.02 GHz to 5.45 GHz, has a fractional bandwidth of 8.21%, which is also effective for wireless applications. These bandwidth characteristics indicate that the filter is optimized for dual-band operation, offering good selectivity and performance within the specified frequency ranges, making it suitable for various wireless communication applications, such as Wi-Fi, Bluetooth, and other wireless standards.

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