

A Microstrip Bandpass Filter Using Parallel Coupled Lines for 2.4 GHz WiFi Application

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ABSTRACT

In this ever-evolving digital age, the need for wireless communication technology is becoming increasingly crucial in various sectors, such as commercial, industrial, educational, and even household. One of the most commonly used wireless technologies is WiFi (Wireless Fidelity), which enables high-speed wireless internet connections and supports user mobility efficiently. To ensure optimal WiFi performance, a frequency filter capable of selectively operating at specific frequencies, such as the 2.4 GHz band, is required. This study aims to characterize a bandpass filter for 2.4 GHz WiFi applications. The bandpass filter design employs a parallel coupled lines structure. Simulation results show that the filter has a center frequency of 2.45 GHz with a return loss of -28.6 dB, insertion loss of -1.61 dB, and a bandwidth of 93 MHz, which aligns with the specifications. However, measurement results after fabrication showed differences, namely a center frequency of 2.47 GHz, return loss of -25.65 dB, insertion loss of -3.55 dB, and bandwidth of 93 MHz. In conclusion, although the simulation performance meets the specifications, the fabricated performance shows deviations likely caused by fabrication tolerances. This research highlight the necessity of accounting for fabrication effects during the design stage. Designers are encouraged to include design margins or compensation strategies to ensure reliable real-world performance. Additionally, this study demonstrates that simulation results alone may not fully represent actual performance, emphasizing the need to bridge the gap between theoretical design and practical implementation.



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1. INTRODUCTION

In this ever-evolving digital age, the need for wireless communication technology has become increasingly important in commercial, industrial, educational, and household settings. One of the most commonly used wireless communication technologies is WiFi (Wireless Fidelity), which enables high-speed, wireless internet connections with a wide range. WiFi is a wireless communication device used to transmit data to the internet[1]. WiFi is a technology that uses electronic devices to transfer data across computer networks in an unrestricted manner (using radio signals)[2]. Based on this definition, WiFi is a wireless communication device that functions to transmit data to the internet network, utilizing electronic equipment in the process. Wireless communication requires devices to transmit and receive electromagnetic waves.

Wireless communication without a cable or nirkabel (WiFi) has become a basic requirement or new way of life for the general public. WiFi has radio frequencies of 2,400 – 2,483.5 MHz and 5,725 – 5,825 MHz, which

are specified in Regulation of the Minister of Communication and Information Technology Number 28 of 2015 about the limitations of technology and telecommunications that operate at radio frequencies of 2.4 GHz and/or 5.8 GHz, which must be adjusted in accordance with technological advancements and regulations regarding radio frequency[3].

The 802.11b/g/n Wi-Fi standard uses the 2.4 GHz frequency band, which covers the range from 2.400 MHz to 2.500 MHz, providing a total bandwidth of approximately 100 MHz[4]. This frequency has been the standard since the early development of Wi-Fi (IEEE 802.11b/g/n) and is still maintained by many smart device manufacturers due to its numerous advantages. One of the main reasons the 2.4 GHz WiFi band remains the preferred choice is its wider signal range and better wall penetration compared to higher Wi-Fi frequencies such as 5 GHz or 6 GHz.

Unwanted signal-filtering components are necessary to preserve WiFi signal quality and guarantee steady transmission. Typically, a microstrip filter is used on a printed circuit board (PCB), where a high frequency is transferred from one system component to another with a high efficiency. There are several types of microstrip filters that can be used, and the bandpass filter is the most common type. A bandpass filter is one that allows signals with particular frequencies to pass through while being constrained by high and low cutoff frequencies. It can also filter out noise that is located below the cutoff frequencies and above the cutoff frequencies[5].

Previous studies have designed bandpass filters for 2.4 GHz WiFi applications. Research by Abdulhamid and Mugambi (2019) used a parallel coupled lines topology but produced a wide bandwidth of around 240 MHz[6]. The design and simulation of a third-order lowpass filter were presented in a study conducted by Mhatre et al. in 2020. The resulting bandwidth was 615 MHz. Bandwidth frequency larger than the specific frequency reduces system performance and results in return loss and insertion loss values that do not meet specifications[7]. In 2016, Babu & Menon conducted research on the design of an open-loop resonator antenna filter for WiFi applications[8]. The result of this research was an open-loop resonator-based antenna filter. The filter has a passband at 2.45 GHz. The designed filter exhibits a passband characteristic at 2.48 GHz. A limitation of this study is that the resulting bandwidth is still quite wide at 500 MHz and does not yet meet the recommended bandwidth values for Wi-Fi.

The recommended bandwidth value for WiFi applications is 83.5 MHz–100 MHz[9]. (IEEE Standards Association, 2016). This study aims to develop and evaluate a parallel-coupled microstrip filter with a bandwidth of approximately 86–100 MHz and a center frequency of 2.45 GHz. Beyond achieving these design targets, this study also investigates the discrepancies between simulation and fabrication results.

2. METHOD

The method used in the design of this bandpass filter is parallel coupled lines with Type I Chebyshev response. Parallel coupled lines bandpass filters are one of the most popular filters in communication systems due to their ease of manufacture, ease of synthesis, low cost, and high practicality[10]. Parallel coupled microstrip lines are widely used in the design of microwave components, such as microstrip filters including bandpass filters[11]. Meanwhile, Chebyshev response is a filter response that has a steep roll-off while allowing ripple in certain parts of the frequency response[12]. Chebyshev Type I response can be seen in Figure 1.

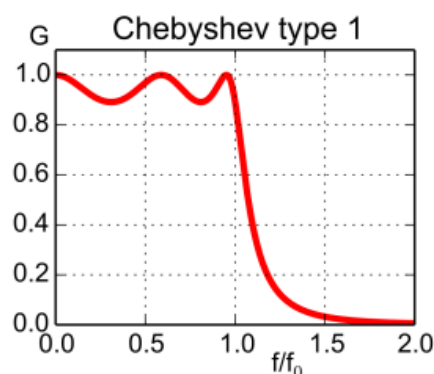


Figure 1. Chebyshev Type 1 Response

The figure shows the frequency response characteristics of a first-order Chebyshev filter, characterized by a ripple in the passband region before reaching the normalization frequency $f/f_0=1$. This ripple reflects amplitude fluctuations that are a distinctive feature of first-order Chebyshev filters as a consequence of the sharp transition to the stopband. After passing this frequency threshold, the amplitude drops sharply to near zero, indicating the filter's effectiveness in attenuating signals outside the desired region. This characteristic makes the Chebyshev Type 1 filter suitable for systems prioritizing a sharp transition slope despite tolerance for amplitude fluctuations in the passband. The value of the component with Chebyshev response can be determined using Equation (1) and Equation (2).

$$g_0 = g_{n+1} = 1 \quad (1)$$

$$g_i = 2 \sin\left(\frac{(2i-1)\pi}{2}\right) \quad (2)$$

In the equation, i is the order being calculated, and ϕ is equal to 180° . The value of the g component can also be determined as shown in Tabel 1.

Table 1. Chebyshev Component Values

Parameters	Value
g_0	1.000
g_1	0.4489
g_2	0.4078
g_3	1.108

There are several stages in designing this bandpass microstrip filter. The first stage is to determine the filter specifications. The second stage is to design and simulate the filter using CST Studio Suite software. The next stage is to fabricate and measure the optimized filter. The expected filter specifications are shown in Table 2.

Table 2. Filter Parameter Specifications

Parameters	Value
Center frequency	2.45 GHz
Return loss	≤ -10 dB
Insertion loss	> -3 dB
Bandwidth	83.5 MHz-100 MHz

Software called CST Studio Suite was used to design and simulate the filter. With a substrate thickness (h) of 1.6 mm, a dielectric constant (ϵ_r) of 2.17, a copper thickness of 0.035 mm, and a loss tangent ($\tan-\theta$) of 0.0005, this microstrip-based bandpass filter was designed. Table 3 shows the size of each connected line.

Table 3. Optimization of Coupled Lines Dimensions in Microstrip Filters

Dimensions	Size (mm)
L0	10
L1	23
L2	23.9
L3	21.5
W0	4.8
W1	3.3
W2	2.8
W3	3
S1	0.3
S2	1.4
S3	2.7

According to Table 3, the design of the bandpass filter prototype can be viewed in Figure 2.

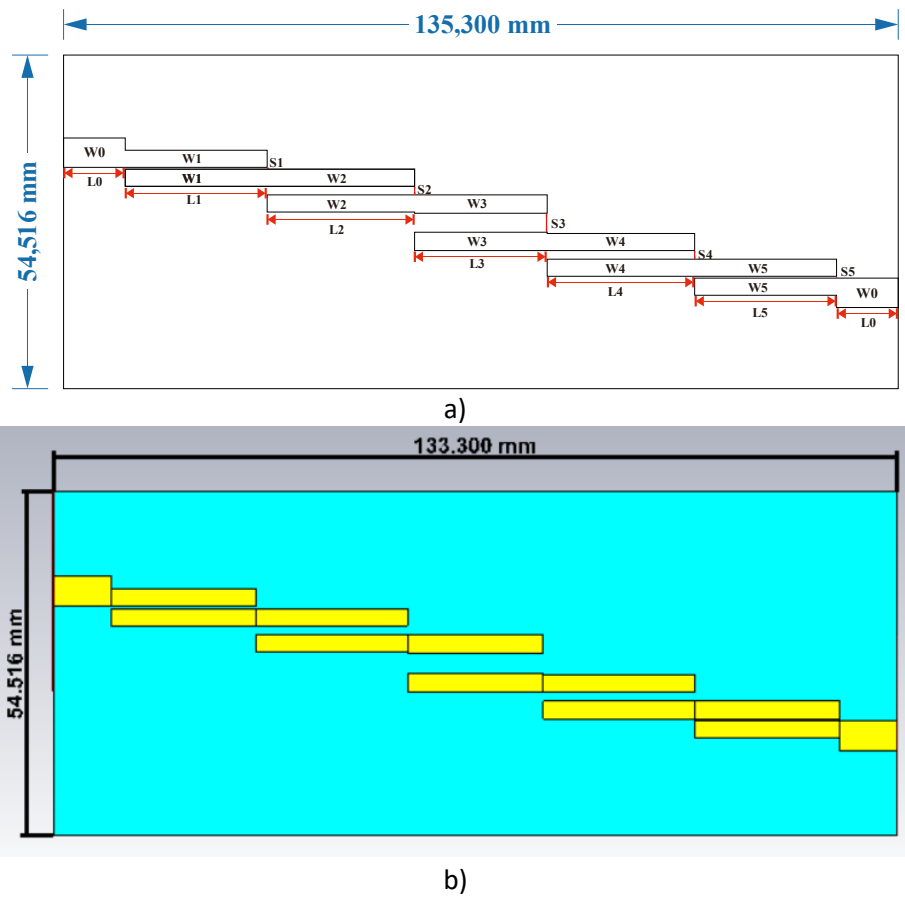


Figure 2. Bandpass filter design model a) Design Parameters, and b) Design

Figure 2 shows a design model of a microstrip bandpass filter with a parallel-coupled line structure. Figure a) displays geometric dimensions such as length, width, and coupling distance, while Figure b) shows a physical representation of the structure on the substrate.

3. RESULTS AND DISCUSSION

The The optimized microstrip filter was fabricated, and its parameters were measured under real conditions. The measurement was conducted to evaluate the performance of the fabricated filter compared to the simulation results. The physical form of the fabricated filter is shown in Figure 3.

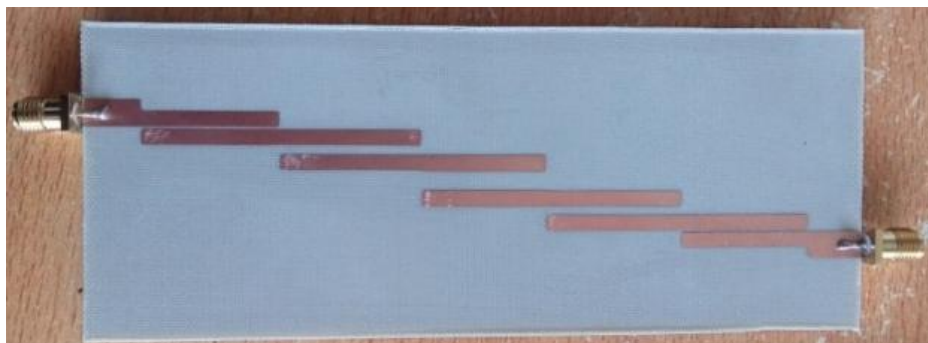


Figure 3. Filter Fabrication

Figure 3 shows the fabricated filter with dimensions optimized based on simulation results. The filter is connected to two 50-ohm ports. The fabricated filter has dimensions of 135.3 mm in length, 54.116 mm in width, and 2.65 mm in thickness. The filter's performance was measured using a Fieldfox RF Vector Network Analyzer. A comparison of the simulation and measurement results is displayed in Figure 4.

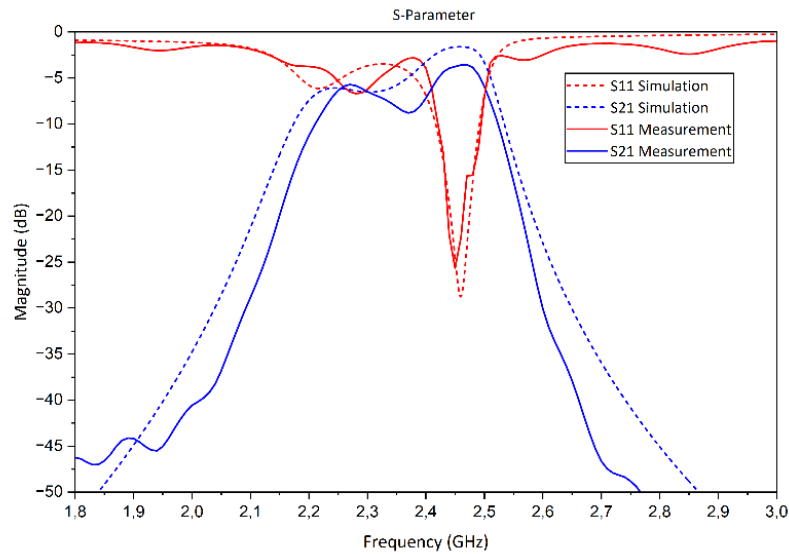


Figure 4. Simulation Results and Measurements of Microstrip Bandpass Filters

Figure 4 shows the simulation and measurement results of return loss and insertion loss, where S11 is the return loss and S21 is the insertion loss. There is a shift in the return loss and insertion loss values. For more details, see Figures 5 and 6.

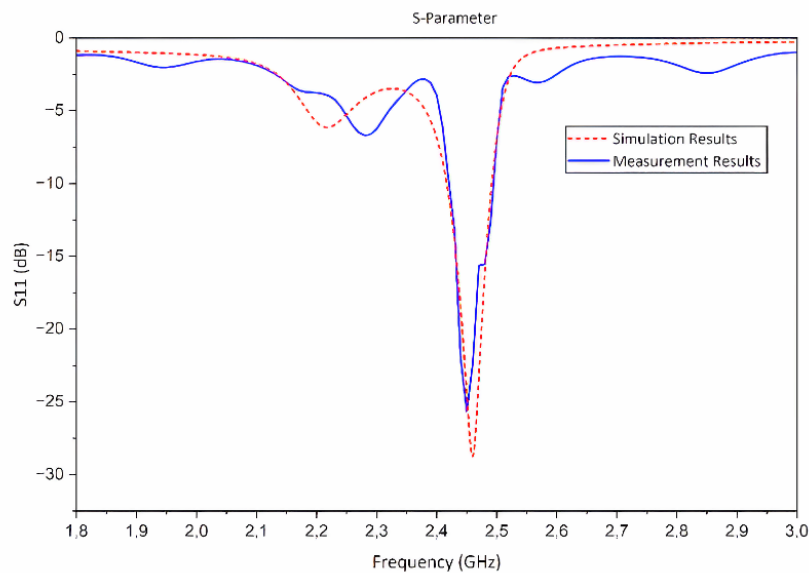


Figure 5. Simulation and Measurement Results of Return Loss

Figure 5 shows that the measured return loss value decreased compared to the simulation and optimization results. At an operating frequency of 2.458 GHz, the simulation results displayed a return loss value of -28.6 dB, but the optimization results fabrication a value of -25.65 dB at the same frequency. Despite the decrease, the return loss value from the fabrication results still shows good performance as it remains well below the minimum standard threshold of -15 dB, indicating that the impedance matching between the port and the filter structure is still effective [10]. Similarly, the insertion loss measurement results also show a shift in the

measurement results. A comparison of the insertion loss simulation results and measurement results is shown in Figure 6.

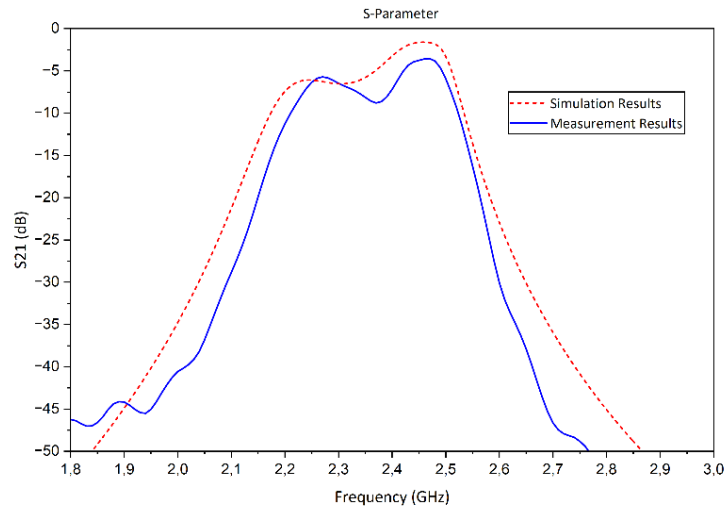


Figure 6. Simulation and Measurement Results of Insertion Loss

Figure 6 shows the simulation results of insertion loss -1.61 dB with a center frequency of 2.45 GHz. The measurement results show that the insertion loss value decreased to -3.55 dB with a center frequency of 2.47 GHz. The bandwidth value in the simulation is 93 MHz and the measurement bandwidth value is 90 MHz.

Based on the simulation analysis results, the microstrip filter design successfully met the targeted specifications, namely return loss of -28.6 dB, insertion loss of -1.61 dB, bandwidth of 93 MHz, and center frequency of 2.45 GHz. This indicates that the design is theoretically optimal. However, the measurement results of the fabricated filter differed from the simulation results. The simulation results show a return loss value of -28.6 dB. The measured return loss value is -25.65 dB. The simulation results show an insertion loss value of -1.61 dB with a center frequency of 2.45 GHz. The measurement results indicate that the filter performance has deteriorated, as evidenced by an increase in the insertion loss value to -3.55 dB with a center frequency of 2.47 GHz. The bandwidth value in the simulation is 93 MHz, and the bandwidth measurement value is 90 MHz.

The measurement results show that the filter does not fully meet the design specifications, specifically the increased insertion loss value. An insertion loss value of -3.55 dB indicates a significant reduction in the transmitted signal power. An insertion loss of -3.55 dB means that more than 55% of the power is lost, which is very poor and making this filter suboptimal for Wi-Fi applications.

As part of the performance evaluation, this study compares the results obtained with those of several previous studies on 2.4 GHz Wi-Fi applications. The comparison is based on key filter parameters, namely center frequency, bandwidth, return loss, and insertion loss. The results of this comparison are presented in Table 4.

Table 4. Comparison with Some Previous Works

Ref.	Center frequency (GHz)	Bandwidth (MHz)	Return Loss/ S11 (dB)	Insertion Loss / S21 (dB)
[6]	2.4 GHz	240	< -15	-2
[7]	N/A	615	-35	N/A
[8]	2.48 GHz	500	-20	N/A
Pro.	2.45 GHz	90	-25.65	-3.75

Based on Table 4, previous studies generally yielded bandwidths far exceeding the 2.4 GHz Wi-Fi standard (83.5 – 100 MHz), particularly in the 240 – 615 MHz range, indicating low filter selectivity. In this study, the bandwidth obtained was 93 MHz in simulation and 90 MHz in measurement, indicating good compliance with the specified standard. Return loss values of -28.6 dB (simulation) and -25.65 dB (measurement) indicate excellent impedance matching at the operating frequency. Meanwhile, the insertion loss value increased from $-$

1.61 dB (simulation) to -3.75 dB (measurement). The difference between the measurement results and the simulation results is caused by several factors. First, the software used assumes ideal conditions, whereas in reality, losses exist [13]. Second, there are dimensional differences between the design results and the fabrication results in CST Studio Suite. Connected microstrip filters are highly sensitive to size reduction. Fabricating this type of filter is quite challenging due to errors caused by random factors and other unaccounted-for parameters [14]. Third, there is loss in the coaxial cable used to connect the microstrip filter to the VNA used for measurement.

4. CONCLUSION

The design of a microstrip bandpass filter for 2.4 GHz WiFi applications was successfully carried out using a parallel coupled lines structure, with simulation results showing performance in line with specifications, namely a return loss of -28.6 dB and an insertion loss of -1.61 dB at a center frequency of 2.45 GHz with a bandwidth of 93 MHz. However, fabrication results showed a performance degradation, with return loss of -25.65 dB and insertion loss of -3.55 dB at a center frequency of 2.47 GHz with a bandwidth of 90 MHz. This study provides important insights for practitioners and engineers regarding the impact of fabrication tolerances in microstrip filter design, particularly for structures with very narrow coupling gaps (e.g., 0.3 mm). The observed discrepancies between simulation and measurement results highlight the necessity of considering the "fabrication gap" during the design stage. Therefore, it is recommended that designers incorporate adequate design margins or apply compensation techniques to minimize performance degradation in real-world implementations. This study also emphasizes the need for further evaluation of the accuracy of simulation models in predicting filter performance at 2.4 GHz when fabrication tolerances are taken into account. Future research may focus on developing more accurate analytical approaches that better represent real fabrication conditions, thereby enabling more reliable and practical filter designs.

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DECLARATIONS

Authorship contribution

Deli Anggraini: Conceptualization, methodology, formal analysis, software and writing -original draft.

Pakhrur Razi, Yulkifli, and Khairi Budayawan: Validation, writing –review and editing.

Competing Interest

The authors **declare** no conflict of interest in this study.

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Ethical Clearance

There are no human subjects in this manuscript, and informed consent is not applicable.

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