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Design of a 5 GHz Microstrip Bandpass Filter Using the Coupled Line Method for Synthetic Aperture Radar (SAR)

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ABSTRACT

The remote sensing system, commonly referred to as radar, enables the monitoring of the Earth's surface by transmitting and receiving reflected microwave signals. With advancements in technology, remote sensing systems can now produce visual outputs in the form of 2D and even 3D images with high resolution. Synthetic Aperture Radar (SAR) has become one of the preferred methods for remote sensing. Using microwave signals, SAR radar is not exempt from disturbances such as out-of-band frequencies, interference, and other issues, which result in unclear radar images and noise. Therefore, a bandpass filter is required to filter signals in SAR radar systems. The proposed filter is designed using a microstrip layout. Microstrip filters offer advantages such as ease of design, the ability to operate at higher frequencies, low profile, and easy integration with other devices. The filter is designed using the couple line method, with a substrate having a dielectric constant of 2.17 and a thickness of 1.6 mm. The proposed design is tailored to the characteristics of SAR, targeting a filter frequency of 5 GHz with a narrow bandwidth of approximately 10 MHz. Simulation results indicate that the filter achieves a center frequency of 5.01 GHz, a bandwidth of 50 MHz, an insertion loss of -2.7 dB, and a return loss of -28 dB. Measurements of the fabricated filter show a center frequency of 5.03 GHz, a bandwidth of 18 MHz, an insertion loss of -2.8 dB, and a return loss of -15.11 dB. Based on these findings, the microstrip bandpass filter designed using the couple line method can be effectively used for SAR applications.

1. INTRODUCTION

The advancement of remote sensing technology has led to the availability of numerous satellites that enable the monitoring of Earth's surface dynamic[1]. The development of remote sensing instruments has utilized radar systems. Radio Detection and Ranging (Radar) operates using microwaves for detection purposes. Currently, radar technology has improved significantly, providing detection results in the form of much higher-resolution images. Synthetic Aperture Radar (SAR) is one type of radar capable of producing high-resolution images using microwaves with high frequencies ranging from 1 GHz to 40 GHz[2].

SAR radar systems, however, are not immune to noise and interference. Therefore, a band-pass filter is required to pass the desired frequency range[3]. Filters designed with sharp slopes can reduce noise that may interfere with filter performance[4]. The bandwidth of a filter influences the resolution of the transmitted signal. In radar systems, higher resolution is achieved with narrower filter bandwidths. The design of a band-pass filter is essentially influenced by the resistance value of resistors, the inductance of coils, and the capacitance of capacitors. Components are selected based on the desired filter characteristics. However, the use of components is limited at high frequencies due to size constraints and limitations in handling high power and voltage, making it challenging to design filters with desired characteristics.

The design of band-pass filters for high-frequency radar can be achieved using microstrip technology. In addition, microstrip filters can be designed with the desired bandwidth, including narrow bandwidths[5]. Microstrip filters can also be designed with sharp slope responses. The structure of a microstrip consists of a layered substrate and conductor[6], [7]. The dielectric substrate has specific properties, such as a relative dielectric constant (εr) and thickness (h), with a ground plane conductor beneath the substrate. Microstrip design involves adjusting the length and width of the conductor and selecting the appropriate substrate [8].

Numerous studies and research on microstrip band-pass filters have been conducted. Their development is evident from the increasing number of journals and papers in recent years, aiming to design filters with high performance and efficiency. Research by Velagaleti and Nalluri (2024) discusses a compact and customizable band-pass filter (BPF) design for satellite communication applications in the X-band and 5G networks (n77, n78, n79)[9]. Although this filter has advantages such as small size, low cost, and low insertion loss, it has limitations in its bandwidth, which is relatively wide at approximately 2.4 GHz with a center frequency of 5.2 GHz. This limitation makes the filter less ideal for applications requiring high selectivity and very narrow bandwidths, such as in Synthetic Aperture Radar (SAR) systems.

Research conducted by Jinjia (2023) designed a band-pass filter using an FR-4 substrate. With a semi-circular resonator and capacitive slots, this filter achieved a reflection loss of up to -31 dB and an insertion loss of -1.5 dB[10]. This filter offers a cost-effective and compact solution suitable for modern communication applications. However, it has drawbacks such as narrow stopband bandwidth, design complexity, and dependence on the FR-4 substrate, which limits flexibility. This research was also limited in real-world testing, with restricted resonance frequencies and scalability that need further development.

A study conducted by Utami, Prakoso, and Santoso (2019) designed a band-pass filter using the coupled line method at a frequency of 5.8 GHz, focusing on the effects of conductor size changes on the filter parameters[11]. Another study by Ali Syahputra (2019) aimed to analyze the design of a band-pass filter for the Landsat 8 satellite. The design utilized parallel coupled lines within the X-band frequency range for radio frequency (RF) applications[12].

Research on band-pass filter design for SAR applications and coupled line band-pass filter designs has become a major focus for researchers. The authors are interested in designing a filter for SAR with specifications aligned with current radar requirements. The SAR frequency band used has a narrow bandwidth of 10 MHz, a high return loss greater than -3 dB, and an insertion loss of less than -15 dB. This research is expected to address the needs of SAR applications with high precision and selectivity

2. MATERIAL AND METHOD

In cellular networks, there are issues that can degrade the Quality of Service (QoS) of the network. These issues include noise, fading, and interference[13], [14]. To mitigate these problems, filters are required. Filters can separate signals based on frequency. There are four basic types of filters that can be used for signal separation: low-pass, high-pass, and band-pass filters. Band-pass filters are more recommended for signal filtering[15]. Band-pass filters are designed by combining the principles of low-pass and high-pass filters. They also adjust the center frequency that can pass through in the RF filter circuit[16], [17], [18]. The response used in the filter is Butterworth, which attenuates signals steeply and provides a response without ripples. The filter response is shown in Figure 1.

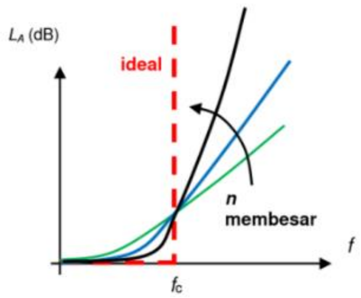


Figure 1. Butterworth Response

The filter design will use the couple line method. Strips are arranged parallel and close to each other, allowing them to be coupled with a specific coupling factor. The design of the couple line filter can be seen in Figure 2.

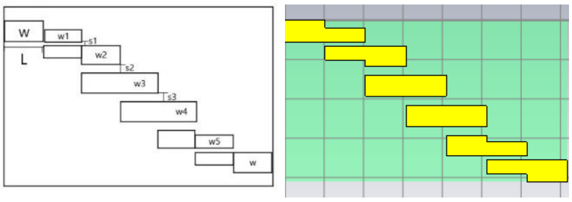


Figure 2. Filter Couple Line Design

The steps involve determining the parameters to be designed. To design a filter using the coupled line method, Equations (1), (2), and (3) can be used.

$$J_{01} = \sqrt{\frac{\pi BWn}{2g_o g_1}} \quad (1)$$

$$J_{j,j+1} = \frac{\pi BWn}{2\sqrt{g_o g_1}} \quad (2)$$

$$J_{n,n+1} = \frac{\pi BWn}{2\sqrt{g_o g_1}} \quad (3)$$

The BWn is obtained using Equation (4).

$$BW\ normal = \frac{\sqrt{ful - fl}}{fo} \quad (4)$$

Where the difference between the square roots of the cutoff frequencies is divided by the operating frequency used. Using the results of the above equations, the impedance in the circuit can be calculated using Equation (5) and Equation (6).

$$Z_{oo}|_{i,i+1} = Zo[1 - j_{i,i+1} + (ZoJj_{i,i+1})^2] \quad (5)$$

$$Z_{oe}|_{i,i+1} = Zo[1 + j_{i,i+1} + (ZoJj_{i,i+1})^2] \quad (6)$$

Thus, the resulting impedance can determine the size of the coupled line resonator. To obtain the length of the resonator plate filter LL, Equation (7) can be used.

$$L = \frac{(panjang\ gelombang)}{4} = \frac{\frac{c}{\sqrt{\varepsilon r}}}{4fo} \quad (7)$$

Where (εr) is the dielectric value of the substrate, (fo) is the center frequency, and (c) is the constant for the speed of light. The width of the transmission line can be calculated using Equations (8) and (9).

$$\frac{W}{h} = \frac{8e^A}{e^{2A} - 2} \quad (8)$$

$$A = \frac{Zo}{60}[\frac{\varepsilon r + 1}{2}]^{0,5} + \frac{\varepsilon r - 1}{\varepsilon r + 1}[0,23 + \frac{0,11}{\varepsilon r}] \quad (9)$$

[19]

The filter material uses the NPC-H220A substrate type, with substrate characteristics as shown in Table 1.

Table 1. Types and Characteristics of Substrate

Substrate Parameters	Value

Tangen Loss	0.0005
Substrate Thickness	1.6 mm
Dielectric Constant (εr)	2.17

The filter material uses the NPC-H220A substrate type, with substrate characteristics as shown in Table 1. The design for the microstrip filter for SAR can be seen in Figure 3.

Figure 3. Flowchart of Device Design

Figure 3 illustrates the flowchart of the steps in designing the filter. The process begins by determining the parameters to be designed, followed by designing the filter in software and running simulations. If the results meet the target, the filter will be printed. If the results do not meet the target, the parameters will be adjusted, and simulations will be repeated until the simulation results match the target. The target or specifications of the filter to be achieved can be seen in Table 2.

Tabel 2. Filter Specifications

Parameters	Value
Center Frequency	5 GHz
Return Loss	<-10 dB
Insertion Loss	>-3 dB
Bandwidth	10 MHz

The data will be analyzed by observing the effect of each filter parameter on the changes in the size of the microstrip filter. The appropriately sized filter will be printed and tested using measuring instruments. A comparison of filter parameters between simulation and fabrication will also be conducted.

3. RESULTS AND DISCUSSION

From the research conducted, the results consist of simulation and real measurement data. The simulation data were obtained from variations in the filter size variables, including length, width, and gap size in the filter design. The comparison of filter size variables with filter parameters can be seen as follows. The simulation results show the response of return loss, insertion loss, bandwidth, and center frequency concerning the length of the coupled line. The microstrip filter simulation results are shown in Figure 4.

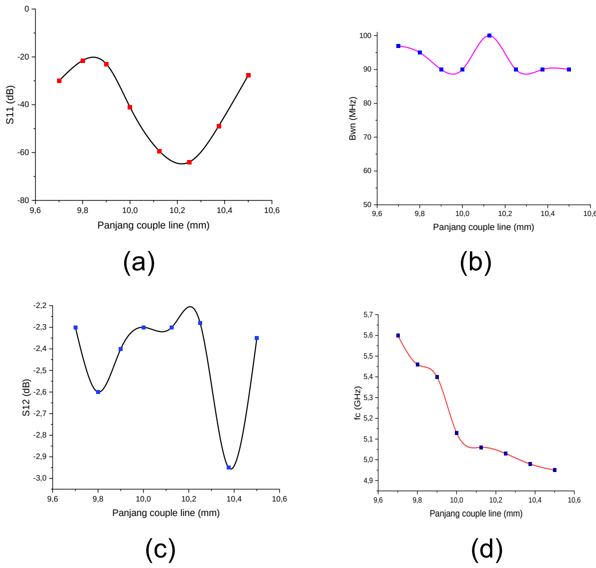


Figure 4. Plot the simulation results against the change in the length of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

The analysis shows a tendency for the center frequency to change in a negative linear trend. By setting the operating frequency, the dimensions of the coupled line in the filter can be determined. The relationship between the operating frequency and the length of the coupled line can be expressed as negative linear[20].

The width of the coupled line is divided into two parts: the first width is at the input and output of the coupled line filter, while the second width depends on the width of the coupled line at each order. The analysis of the changes in width ww in the filter can be seen in Figure 5.

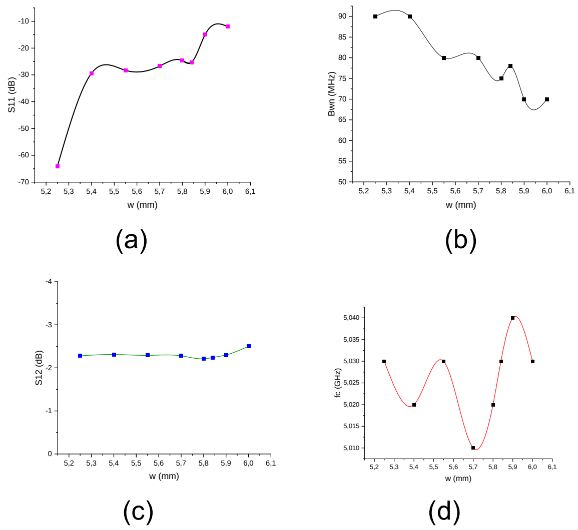


Figure 5. Plot the simulation results against the change in the w of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

Changes in the width w of the coupled line affect the return loss and bandwidth parameters. The return loss value exhibits a positive linear relationship with changes in the width w, while the bandwidth parameter exhibits a negative linear relationship. The width of the coupled line influences the return loss parameter, where the return loss value indicates the ratio of reflected to transmitted power in the filter.

The simulation results for changes in gap size at each order can be plotted on the graph shown in Figure 6.

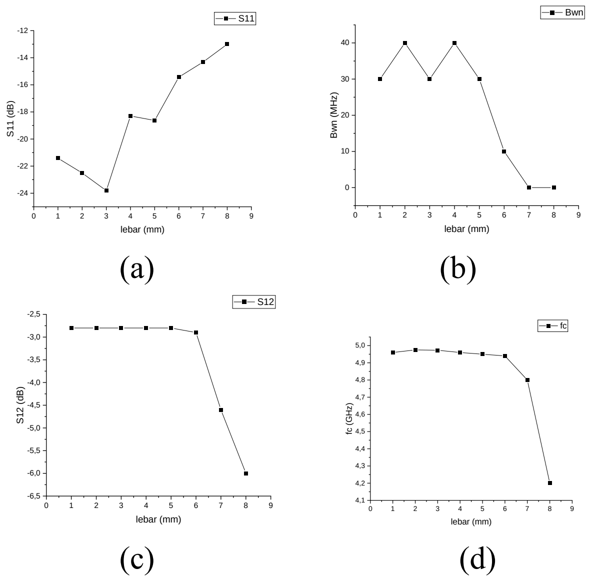


Figure 6. Plot the simulation results against the change in the w orde of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

The analysis results indicate that changes in the width w at different orders can affect the center frequency negatively in a linear manner and the return loss positively in a linear manner. By varying the width of the coupled line, it is possible to achieve the accuracy of all filter parameters according to the desired characteristics.

Variations in the gap size are simulated, and their effects on the filter parameters are observed. The simulation results for changes in the gap s1 in the coupled line filter can be seen in Figure 7.

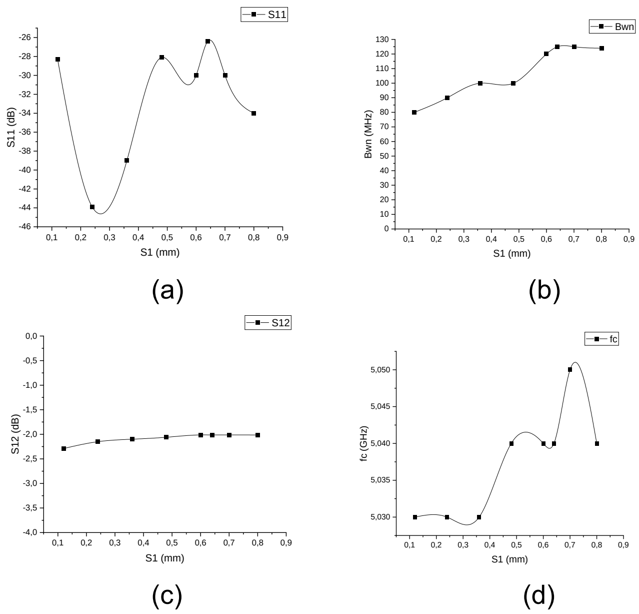


Figure 7. Plot the simulation results against the change in the s1 of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

From the graph, the insertion loss parameter shows a more complex pattern, with polynomial characteristics that increase along with changes in the gap s1. This indicates that even though the s1 values fluctuate, the insertion loss consistently increases, following a nonlinear pattern that reflects higher signal transmission losses at specific frequencies.

The simulation results for changes in the gap s2 in the coupled line can be seen in Figure 8.

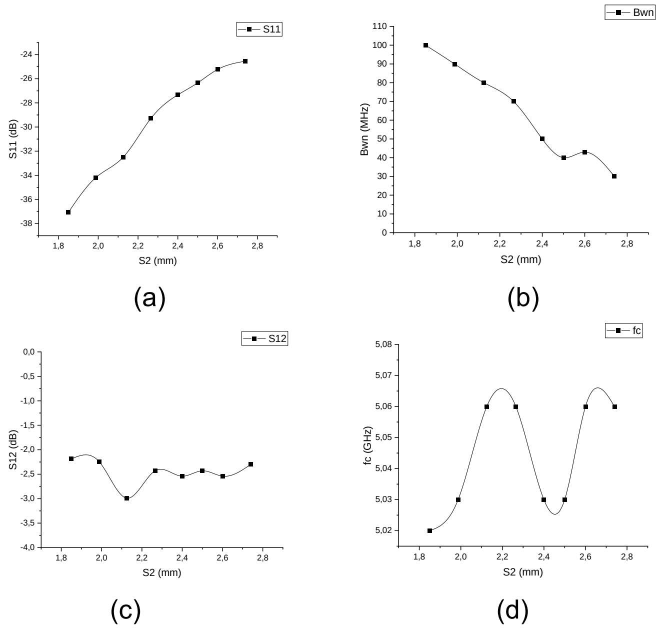


Figure 8. Plot the simulation results against the change in the s2 of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

The return loss parameter shows a positive linear relationship, where the return loss value increases as the gap s2 size increases. The bandwidth shows a negative linear relationship, with the bandwidth narrowing as the s2 gap value increases, indicating that the filter becomes more selective at certain frequencies as the gap dimensions change.3.4 Effect of Time on the percentage of degradation of the Congo Red

The gap is varied in the simulation, and its effects on the filter parameters are observed. The simulation results for changes in the gap s3in the coupled line can be seen in Figure 9.

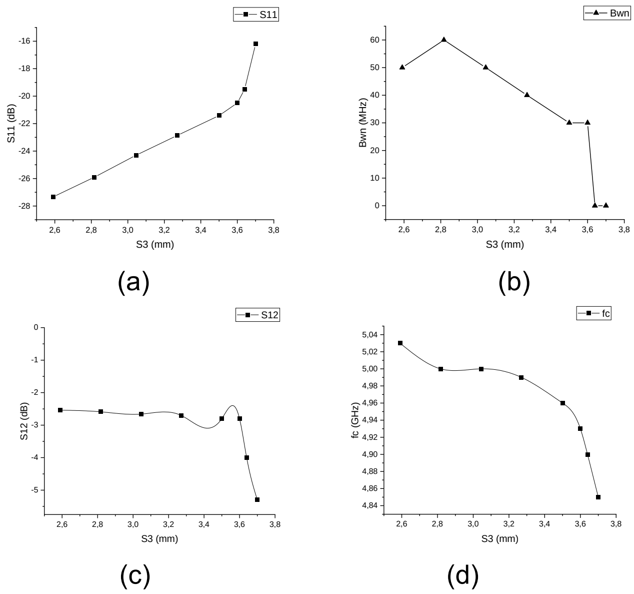


Figure 9. Plot the simulation results against the change in the s3 of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

The changes in the gap size s3 affect four parameters with different linear relationships. The insertion loss initially increases, indicating that each increase in s3 causes a sharp rise in insertion loss. Conversely, the bandwidth significantly decreases, showing a large reduction as s3 increases. The second insertion loss also decreases linearly but shows a slower change. The center frequency also gradually decreases, reflecting a small reduction in frequency as s3 increases. Overall, these parameters demonstrate the diverse impacts of changes in s3 on the system's performance.

After conducting the analysis, the filter size with the corresponding parameter response was obtained. The optimized microstrip filter was then fabricated and the filter parameters were measured in real conditions. The fabricated filter is shown in Figure 10.

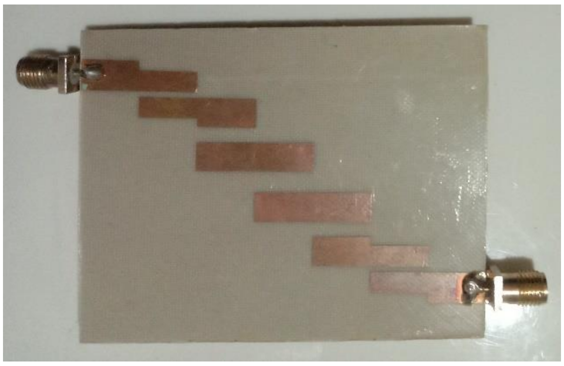


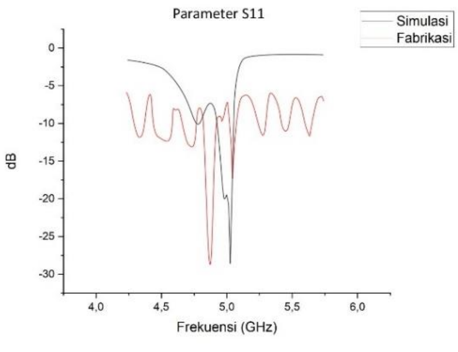
Figure 10. Plot the simulation results against the change in the s3 of the couple line return loss (a), bandwidth (b), insertion loss (c), center frequency (d).

The size of each dimension of the coupled line can be seen in Table 3.

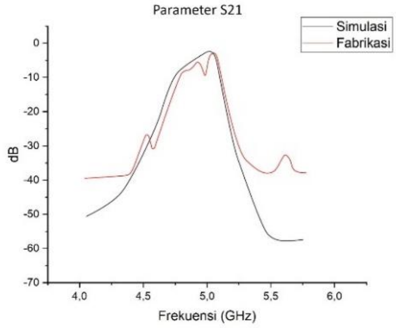
Table 3. Optimized Couple Line Filter Dimensions

L	s1	s2	s3	W	w1	w2	w3	w4	w5
10,25 mm	0,8 mm	2,4 mm	3,5 mm	5,5 mm	3,8 mm	5,3 mm	5,3 mm	5,3 mm	3,8 mm

The filter performance is measured using a VNA (Vector Network Analyzer). The comparison between the simulation results and the measurements is shown in Figure 11.



(a)



(b)

Figure 11. Return loss Simulation and Fabrication Results(a), insertion loss Simulation and Fabrication Results(b).

In Figure 11 (a), the return loss value from the measurement shows a reduction compared to the simulation results. The optimized return loss value is -28 dB at 5.02 GHz, while the measured value is -15.11 dB at 5.01 GHz. Although there is a reduction in the return loss value, the fabricated result still matches the filter design characteristics, where the return loss value is << -15 dB. Figure 11 (b) shows the comparison of insertion loss, bandwidth, and center frequency values of the filter. The center frequency of the fabricated filter shifts from the optimized simulation result. The simulation center frequency is 5.016 GHz, while the fabricated center frequency is 5.031 GHz. The bandwidth in the fabricated filter is reduced compared to the simulation, with the simulation bandwidth being 50 MHz, while the fabricated bandwidth is 18 MHz, which is closer to the designed characteristic of 10 MHz. The insertion loss in the fabricated filter is slightly increased compared to the simulation, with the simulation result being -2.76 dB, and the fabricated result being -2.8 dB. Thus, the filter operates at a center frequency of 5.031 GHz with a bandwidth of 18 MHz, insertion loss of -2.8 dB, and return loss of -15.11 dB.

The differences between the measurement results and the simulation results are due to several factors. First, the software used assumes ideal conditions, while in reality, losses exist. Second, during fabrication, unintended dimensional changes occur, causing deviations in the fabrication values, especially for high frequencies, which are very sensitive. Third, during measurements, electromagnetic waves are used, which can be affected by emissions and disturbances, such as reflections, external wave influences, and equipment with precision and additional components like cables. Despite these discrepancies, the filter still functions well.

4. CONCLUSION

Based on the research conducted, it can be concluded that the length of the coupled line affects the center frequency of the microstrip filter in a negative linear manner, while the width of the coupled line influences the return loss and bandwidth, where return loss exhibits a positive linear relationship and bandwidth shows a negative linear relationship with the width of the coupled line. Changes in the gap s1 affect insertion loss in a polynomial manner, while gaps s2 and s3 influence other parameters such as bandwidth, insertion loss, and return loss with both negative and positive linear relationships depending on the gap changes. The measurement results show that the filter operates at a center frequency of 5.03 GHz with a bandwidth of 18 MHz, insertion loss of -2.8 dB, and return loss of 15.11 dB. For future research, it is recommended to maximize bandwidth, insertion loss, and the shape of the response with a sharp slope to optimize the performance of the microstrip filter. The study could also explore design variations, such as adjusting the position of the coupled line or modifying the ground design, to enhance the overall parameter response.

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DECLARATIONS

Authorship contribution

Syukri Fajrin: Conceptualization, methodology, formal analysis, software and writing -original draft. **Asrizal, Mona Berlian Sari and Khairi Budayawan**: Validation, writing–review and editing.

Competing Interest

The authors **declare** no conflict of interest in this s This research does not involve humans as subjects.tudy.

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Ethical Clearance

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

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