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Cross-Coupled Line Bandpass Filter Based on Modified Parallel-Coupled Line Structure

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Abstract

This paper presents a study of a narrow bandwidth of the bandpass filter with a cross-coupled line structure. This structure was designed to have a good filter selectivity with the transmission zeros and a simple design. Since the structure has a cross shape, cross-coupling between the resonators consequently occurs. This interferes with the passband of the filter. Optimization in the size of the coupled lines and transmission lines was done to minimize the interference. Rogers RT/duroid 5880 was used as a substrate to fabricate the bandpass filter to verify the proposed design. As a result, the fabricated cross-coupled line bandpass filter has an 80 MHz of 3 dB bandwidth with operating frequency ranges from 2.97 GHz to 3.05 GHz. The bandwidth is reduced by 20 % from the specification. It shows that the cross-coupled line structure can yield a narrow bandwidth. Based on the 3 dB bandwidth, the center frequency is shifted 0.33 % above the specification. Meanwhile, the return loss and insertion loss of the proposed bandpass filter successfully comply with the required specifications. In conclusion, the proposed bandpass filter can be applied to S-Band applications that require narrow bandwidth.

Keywords: bandpass filter, cross-coupled, s-band, parallel-coupled, microstrip.

I. Introduction

In a wireless communication system, the bandpass filter is one of the critical devices in the transmitter and receiver. The bandpass filter only selects the frequency according to the filter's passband and rejects the other frequency. It can also avoid interference with the system, hence, establishing a better quality of the communication is better. Some researchers have already designed the bandpass filter with different structures: multiband, narrow, wide bandwidth, and for various purposes.

In recent studies, the coupled-line structures are used by researchers to design a bandpass filter [1]–[11]. This structure is used to acquire the bandpass filter with wide bandwidth [1]–[6]. In [7], the folded coupled line technique successfully suppresses the second harmonic and provides a size reduction of 63 %. In [8], the side shorted coupled-line section topology was found to support the narrow bandwidth, while the cross-coupling effect in the adjacent coupled-line generates the transmission zero. The theoretical analysis of the microstrip short-circuited coupled-line resonator to dual-band bandpass filter was already demonstrated by [9]. The cross-coupled structure was also used by [10] to design a half mode SIW (substrate integrated waveguide) bandpass filter. It can reduce the physical size of the bandpass filter by up to 50 % compared to the conventional full-mode SIW resonator. To see the effect of the substrate, some substrates were used to design the bandpass filter using a parallel-coupled line bandpass filter method [11]. The filter using RO6010 was found to offer the best performance and compact size.

In S-Band frequency, various applications use a bandpass filter as an essential component. The design of a bandpass filter for S-Band applications has already been investigated in several studies [12]–[19]. The bandpass filter with the operating frequency of 3 GHz was designed to obtain a narrow bandwidth using a square resonator with folded coupled line method [12]. In S-Band radar application, the hairpin bandpass filter with dumbbell-DGS [13], octagonal shape [17], and square open-loop resonator [18] were proposed to block the unwanted frequency that suffers the performance of the radar system decrease. Also, in [19], the bandpass

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filter was designed for S-Band applications to acquire a wide bandwidth.

This paper proposes a narrow bandwidth bandpass filter using a cross-coupled line structure, as depicted in Figure 1. The proposed bandpass filter is constructed by four coupled lines. The parallel-coupled line bandpass filter is the base for designing the cross-coupled line bandpass filter, as shown in Figure 1. This bandpass filter consists of coupled lines that are arranged in parallel. We generate the cross-coupled line shape from the parallel-coupled line using a three-pole prototype. This method simplifies the cross-shape arrangement and bandpass filter fabrication. With this structure, it is interesting to see the adding coupling effect, especially in the center of the cross shape.

To optimize the structure of a cross-coupled line bandpass filter, the electromagnetic software simulation Advanced Design System (ADS) was used. The proposed bandpass filter was designed for S-Band application with a narrow bandwidth. The specifications of the bandpass filter are return loss of ≤ −10 dB, insertion loss of ≥ −3 dB, and bandwidth of 100 MHz. Finally, we fabricate and measure the proposed design to validate the design.

This paper is organized as follows. The first section gives an overview of the bandpass filter research, and the second section introduces the research method of the bandpass filter. The results and discussion are described in section three. Finally, the summary of this research is in section four.

II. RESEARCH METHOD

The proposed bandpass filter was designed based on the parallel-coupled microstrip bandpass filter. The structure of a parallel-coupled microstrip bandpass filter used a half-wavelength line resonator. This design uses a three-pole Chebyshev prototype with a 0.1 dB ripple. The prototype parameter is listed as follows [20]:

- $g_0 = g_4 = 1.0$
- $g_1 = g_3 = 1.0315$
- $g_2 = 1.1474$

we use a three-pole prototype because it consists of four coupled lines. Thus, it can be modified like a cross-shaped.

The bandpass filter has a frequency center of 3 GHz.

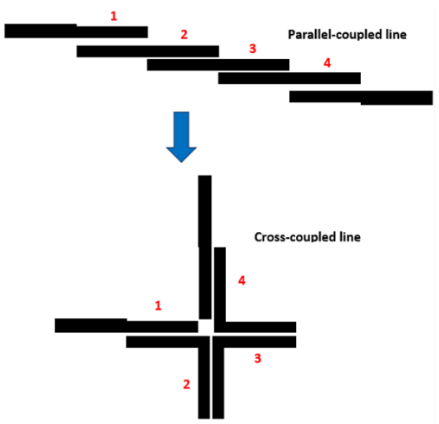


Figure 1. The modification of parallel-coupled line bandpass filter.

For calculating the resonator filter, we first determined the FBW with the filter bandwidth of 100 MHz using (1) [21].

$$FBW = \frac{f_2 - f_1}{f_0} \; with \; f_0 = \frac{f_1 + f_2}{2} \quad (1)$$

where FBW is the fractional bandwidth of the bandpass filter, f_0 is the frequency center, f_1 is low frequency, and f_2 is high frequency. From the bandwidth value of 100 MHz, the low and high frequencies can be determined.

In the next step, using (2) to (4) [21], the even mode and odd mode characteristic impedances of coupled lines resonators were calculated.

$$\frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi FBW}{2_{g_n g_{n+1}}}} \quad (2)$$

$$(Z_{0e})_{j,j+1} = \frac{1}{Y_0}\left[1 + \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right] \quad (3)$$
$$for \; j = 0 \; to \; n$$

$$(Z_{0o})_{j,j+1} = \frac{1}{Y_0}\left[1 - \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right] \quad (4)$$
$$for \; j = 0 \; to \; n$$

where $j_{n,n+1}$ is the characteristic admittances of J inverters, Y_0 is the characteristic admittance of the terminating lines, Z_{0e} is even mode characteristic impedance, and Z_{0o} is odd mode characteristic impedance.

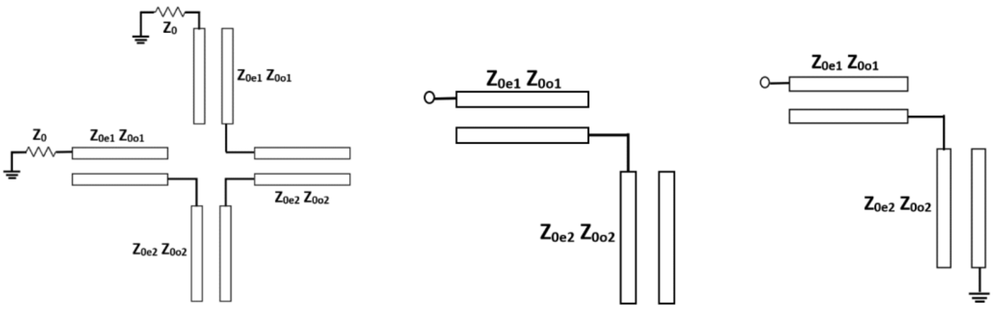
From the results of even- and odd mode characteristic impedance, the calculation of the coupled microstrip lines dimensions was performed using the LineCalc software from Keysight. Finally, the coupled lines were arranged like cross shapes, and the electromagnetic software simulation was used to verify the proposed design.

III. RESULTS AND DISCUSSION

Based on (1) to (4), the results of even- and odd mode characteristic impedances are shown in Table 1. The data of characteristic impedances from Table 1 and the substrate parameters are required to find the dimensions of the coupled microstrip lines. RT/duroid 5880 was used as a substrate with the substrate thickness of 1.575 mm, copper thickness is 0.035 mm, the dielectric constant of 2.2, and the electric tangent delta of 0.0009. Those parameters of the substrate, and even and odd mode characteristic impedance are required for LineCalc software. The LineCalc software was used to calculate the physical length of the coupled line. The results are depicted in Table 1.

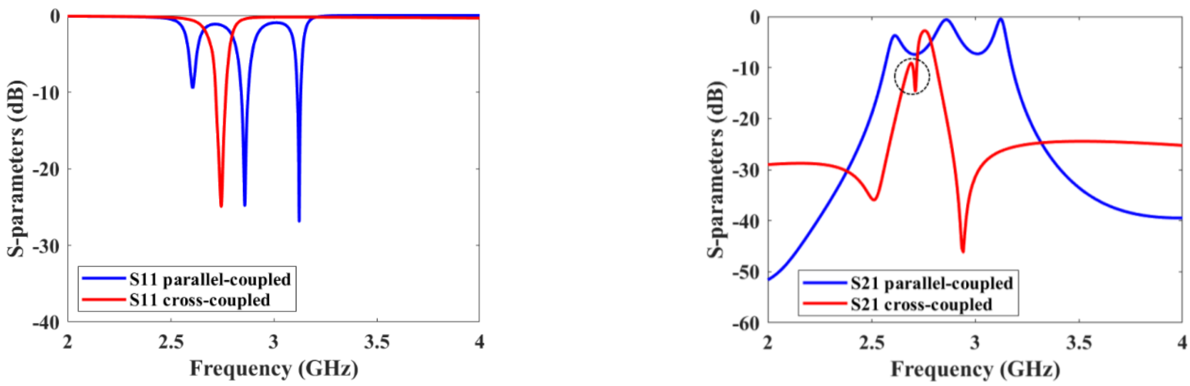
TABLE 1
CIRCUIT DESIGN PARAMETERS OF THREE-POLE OF THE PARALLEL-COUPLED FILTER.

J	*$J_{j,j+1}/Y_0$*	*$(Z_{0e})_{j,j+1}$ (Ω)*	*$(Z_{0o})_{j,j+1}$ (Ω)*	*W_j (mm)*	*S_j (mm)*	*l_j (mm)*
0	0.2275	63.9628	41.2128	4.2212	0.6260	18.4326
1	0.2124	62.8757	41.6357	4.2908	0.7077	18.4074
2	0.2124	62.8757	41.6357	4.2908	0.7077	18.4074
3	0.2275	63.9628	41.2128	4.2212	0.6260	18.4326



(a) (b) (c)

Figure 2. (a) Ideal circuit of the cross-coupled bandpass filter; (b) even mode equivalent circuit; and (c) odd mode equivalent circuit.



(a) (b)

Figure 3. The S-parameters results before optimization: (a) S_{11} of parallel-coupled and cross-coupled line bandpass filter; (b) S_{21} of parallel-coupled and cross-coupled line bandpass filter.

Afterward, we modified the structure from the parallel-coupled bandpass filter design to become a cross-coupled line structure as depicted in Figure 2(a). Figure 2(b) and Figure 2(c), respectively, are even- and odd mode equivalent circuits. We simulated the parallel-coupled microstrip bandpass filter and the proposed design using ADS software to investigate the proposed design. Based on the data of physical length from LineCalc software, we arranged the coupled lines as shown in Figure 1.

Figure 3 shows the simulation results of s-parameters of the parallel-coupled microstrip bandpass filter and cross-coupled line bandpass filter. Figure 3(a) shows the simulation results of S_{11}, and Figure 3(b) shows the simulation results of S_{21}. From Figure 3(a) and Figure 3(b), the parallel-coupled microstrip bandpass filter results are still not adequate. These results were obtained before the optimization. The center frequency of the proposed design is about 2.756 GHz with the insertion loss (S_{21}) of -2.780 dB and the return loss (S_{11}) of -16.754 dB. The best return loss obtained is -24.960 dB at a frequency of 2.745 GHz. Also, from Figure 3(b), it can be seen the effect of the interaction between the coupled lines in the center of the structure. The coupling causes interference described by the S_{21} result with a circle sign. However, the filter's slope exhibits a good performance with the transmissions zero caused by the coupling. We measured the bandwidth from -3 dB of insertion loss, as shown in Figure 4; a bandwidth of 21 MHz was obtained. In the next step, we optimized the design to meet the specification of the bandpass filter and to minimize the effect of interference.

The layout of the cross-coupled line microstrip bandpass filter after optimizing the design is shown in Figure 5. The dimensions of the proposed bandpass filter can be seen in Table 2. The inset picture in Figure 5 displays the zoom of the center of the cross-coupled line. As shown in Figure 5, the 50 Ω connectors are connected to port 1 and port 2 as input and output.

Figure 6 depicts the fabricated cross-coupled line bandpass filter. Two SMA connectors were soldered to the input and output ports of the bandpass filter. To evaluate the performance of the cross-coupled line bandpass filter, the Advantest R3370 Network Analyzer was used to measure the bandpass filter, as shown in Figure 7. The measurement yields the s-parameters data such as insertion loss (S_{21}, S_{12}) and return loss (S_{11}, S_{22}).

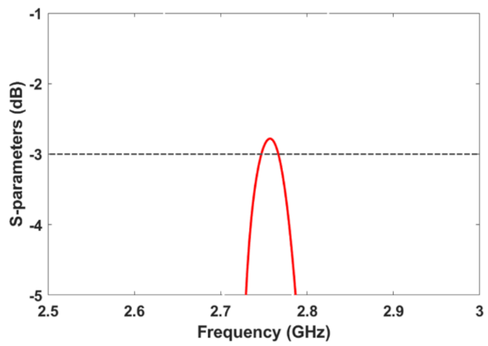


Figure 4. The bandwidth at -3 dB of insertion loss.

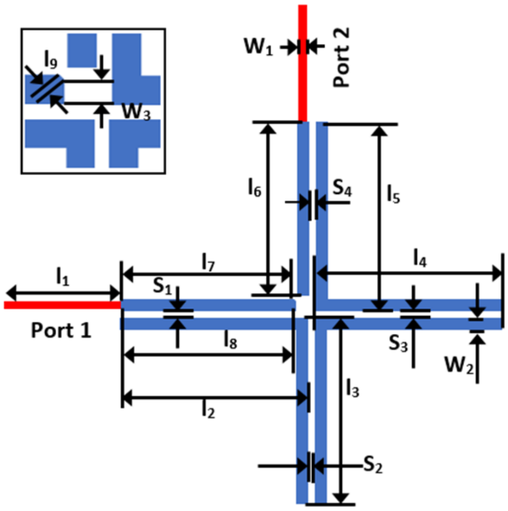


Figure 5. Layout of the proposed cross-coupled line bandpass filter.

TABLE 2
CIRCUIT DESIGN PARAMETERS OF THE THREE-POLE PARALLEL-COUPLED FILTER.

Variable	Dimensions (mm)
W_1	1.2
W_2	2.6
W_3	2.1
l_1	13
l_2	20.196
l_3	20.14
l_4	20.117
l_5	20.181
l_6	17.55
l_7	16.55
l_8	17.55
l_9	1.118
S_1	0.321
S_2	0.3126
S_3	0.321
S_4	0.3126

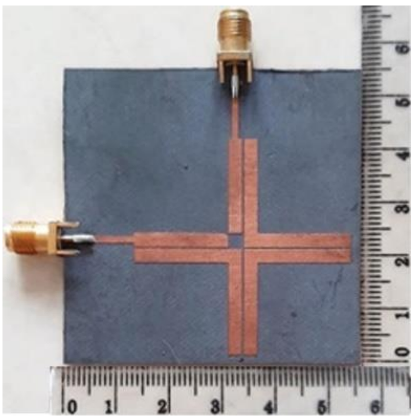


Figure 6. The fabricated cross-coupled line bandpass filter.

We compared the data from simulation and measurement to see the difference. Figure 8 shows the insertion loss and the return loss of both simulation and measurement, respectively.

From the insertion loss results of the simulation and measurement in Figure 8(a), it is indicated that the best

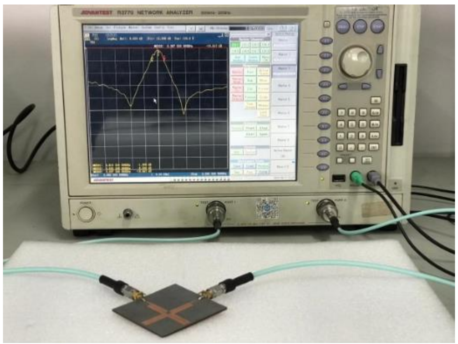


Figure 7. Measurement of the bandpass filter.

insertion loss is -0.703 dB at a frequency of 3.053 GHz (simulation) and -1.803 dB at a frequency of 3.010 GHz (measurement). Meanwhile, the insertion losses at the working frequency obtained from the simulation and the measurement are -1.632 dB and -1.941 dB, respectively. Figure 8(b) represents the return loss of the bandpass filter. The simulation and measurement exhibit a good performance of return loss. The smallest return loss of the simulation is -37.74 dB at the frequency of 2.98 GHz. On the other hand, a return loss of -19.4 dB at a frequency of 2.98 GHz was obtained from the measurement. The bandpass filter has two transmissions zero, as depicted in Figure 8(a), which is marked with a dotted circle. In the simulation, the transmissions zero are at a frequency of 2.614 GHz and 3.416 GHz with -48.14 dB and -57.57 dB of insertion loss, respectively. Then, in the measurement, the transmissions zero are at frequencies of 2.6 GHz and 3.36 GHz with -46.87 dB and -54.43 dB of insertion loss, respectively.

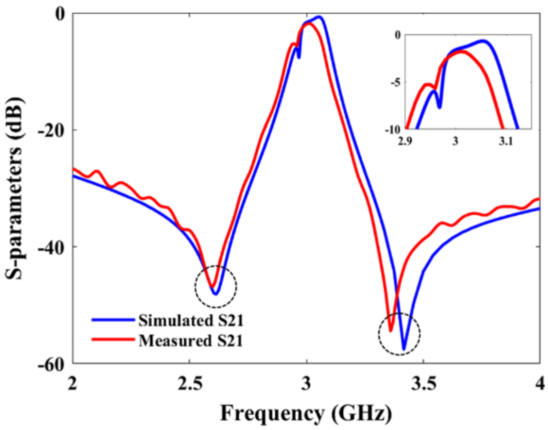
We obtained the bandwidth of 104 MHz in the simulation and 80 MHz in the measurement, as shown in Figure 9. The bandwidth was calculated from -3 dB of S_{21}. Using the bandwidth, the center frequency was calculated. The center frequency is shifted about 32 MHz and 10 MHz above the specification both in the simulation and measurement, respectively. The fabricated cross-coupled line bandpass filter results have a good agreement with the specification, except for the frequency center and bandwidth. The current density at a frequency of 3 GHz is depicted in Figure 10, where excitation occurs from port 1. This figure shows the concentration of current at each coupled line.

Therefore, to obtain better results, we optimized the size of coupled lines and ports. The frequency was shifted by changing the length (l) of the coupled lines. It relates to the function of λ. To make the cross-coupled line structure, the length of the half-wavelength was required to be longer than the parallel-coupled line structure. So, it caused the center frequency to shift to the lower frequency. By reducing the length, we can obtain the desired frequency. Changing the width (W) of coupled lines and ports affects the impedance value used for the matching process. The bandwidth can be optimized by modifying the distance between the coupled lines (S). We adjusted the value of S to be smaller than the initial design to increase the bandwidth. However, the limitation of the fabrication process must be considered.

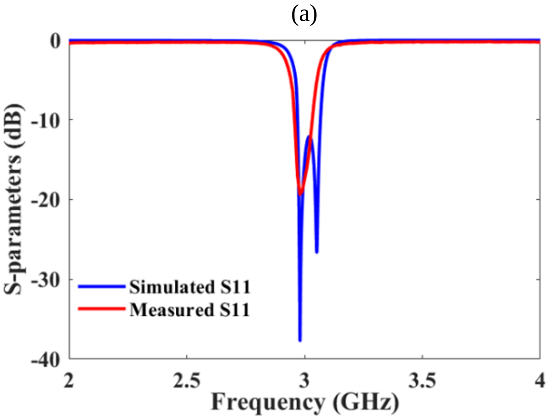
The minimal distance between lines is about 0.3 mm in the fabrication process.The l_9 depicted in the inset picture in Figure 5 shows that the line is not at a right angle. It is to avoid connection occurring with the coupled line on it.

In Figure 3, the interference arises when the structure becomes a cross-coupled line. The coupling effect causes it in the center of the structure. Overall, by optimizing the size of the coupled lines and ports, the interference problem can be minimized as we can see in Figure 8(a). In this design, the coupling effect in the center of the structure has a negative and positive impact. We found that the coupling caused the interference in the passband, but the slope became steep and had transmissions zero. Moreover, this structure only generated narrow bandwidth. The steep slope was obtained only using a three-pole prototype of the filter, so, large numbers of poles were not required. Finally, by reducing the number of poles, the size decreases according to the pole prototype.

Table 3 illustrates the comparison between the proposed design and the previous works on the bandpass filter. It can be seen that this work has two transmission zeros. Compared to [18], the insertion loss of the proposed design is better.



(a)



(b)

Figure 8. The S-Parameters Results of The Proposed Bandpass Filter (a) Simulation and Measurement Results of S_{21} (b) Simulation and Measurement Results of S_{11}.

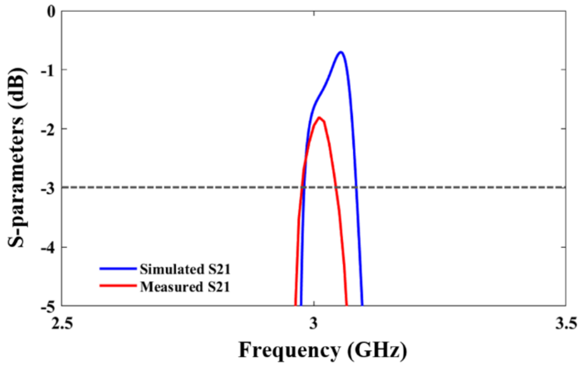


Figure 9. The Simulated and Measured Bandwidth at -3 dB of Insertion Loss.

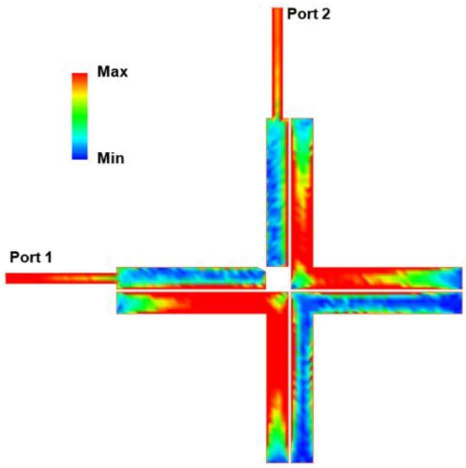


Figure 10. Current Density at Frequency of 3 GHz.

TABLE 3
THE PERFORMANCE COMPARISON OF THE BANDPASS FILTER.

Ref.	***Freq. Center* (GHz)**	**S_{21} (dB)**	***BW* (MHz)**	***Transmission Zero***
[12]	3	-1.949	12	1
[13]	2.93	-0.836	170	1
[17]	2.862	-1.566	340	1
[18]	3.185	-3.561	200	2
This work	3.01	-1.794	80	2

IV. CONCLUSION

The bandpass filter was designed and realized using the cross-coupled line structure. This structure is a modification of the parallel-coupled microstrip bandpass filter. The proposed bandpass filter has a simpler design compared with the parallel-coupled line design. The addition of the coupling in the center of the cross shape interferes with the passband. The optimization using electromagnetic software simulation successfully minimized the interference. Also, by the addition of the coupling in the center of the cross shape, the number of pole prototypes used in the filter design can be decreased. It is shown by the steep slope of the bandpass filter for a three-pole prototype bandpass filter design that has comparable performance with a design containing larger numbers of the pole. As a result, the realization and simulation results of return loss and insertion loss have a good agreement with the specification. However, the center frequency of both simulation and realization is shifted above the specification, i.e., 1.07 % and 0.33 %, respectively. The bandwidth of the realization bandpass filter decreases by 20 % from the specification. The fabrication process yields insignificant changes in the performance of the s- parameters compared with the simulation. The proposed bandpass filter successfully selects narrow bandwidth which can be applied to S-Band applications, such as S-Band radar. The bandpass filter can be put before the antenna resulting in a filtered signal before the signal processing process. A potential progression of this work is to employ the folding technique in an attempt to minimize the size of the bandpass filter, especially for the application in low frequency.

DECLARATIONS

Conflict of Interest

The authors have declared that no competing interests exist.

CRediT Authorship Contribution

Fajri Darwis: Conceptualization, methodology, investigation, writing – original draft, writing – review & editing; Enjel Al Birr Rahayu: Software, formal analysis, investigation, writing – original draft; Sutrisno: Conceptualization, investigation, writing – review & editing; Hanny Madiawati: Investigation, writing – review & editing; Taufiqqurrachman: Funding acquisition, writing – review & editing; Arie Setiawan: Writing – review & editing; Erry Dwi Kurniawan: Writing – review & editing; Yusuf Nur Wijayanto: Funding acquisition, writing – review & editing.

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