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# Design of a Miniaturized Microstrip Diplexer Based on Hairpin and Short Stub for 5G and Wi-Fi Communications

**Soufiane Achraou*, Alia Zakriti, Souhaila Ben Haddi, and Mohssine El Ouahabi**

**Abstract**—This paper focuses on designing and manufacturing a compact microstrip diplexer, which operates at 3.5 GHz and 5 GHz for 5G and Wi-Fi applications, respectively. Indeed, two bandpass filters are combined to create the proposed diplexer. For making bandpass filters compact, a hairpin resonator is suggested and developed into an E-shaped resonator. To attain the central frequencies, a short microstrip stub loading the E-shaped resonator is proposed. The filters were combined by a coupling junction to form the final diplexer. The proposed diplexer exhibits good isolation that is better than 40 dB in the whole operational frequency band. Additionally, the passband insertion losses are about 1 dB, and the return losses are about 20 dB and 26 dB at the two channels, respectively. Moreover, the final size of the manufactured diplexer is $30 \times 25\,\mathrm{mm}^2$ ($0.6\lambda_g \times 0.52\lambda_g$). These results confirm that the suggested diplexer is suitable for the demanded applications.

## 1. INTRODUCTION

Mobile communication is advancing at a rapid speed due to the increased demand for cell phones. Indeed, several high-performance passive microwave components such as antennas, filters, and diplexers are required to fulfill this demand [1–6]. Diplexer is a three-port component that combines or separates multiple signals at different frequency bands, allowing them to share the same transmission path. A microstrip diplexer is achieved by using microstrip transmission lines to implement bandpass filters in a specific configuration. The filters are designed to pass or block signals within a certain frequency range, allowing the diplexer to separate or combine the signals as needed. Moreover, microstrip diplexer is commonly used in telecommunications due to its compact size, low cost, and ease of manufacture compared to other types of diplexers.

The large size and insufficient performance of the microstrip diplexers referenced in [7–9] are considered the common disadvantages. The designed diplexer in [7] is based on two bandpass filters and novel zigzag junction for 5G and Wi-Fi applications. This diplexer exhibits good insertion losses and compact size about $30 \times 17\,\mathrm{mm}^2$, but it presents low return loss. In [8], a high isolation microstrip diplexer is presented. The design is based on two interdigital bandpass filters combined with a T-junction for Industry 4.0. Their results depict high insertion losses at both channels. The presented diplexer in [9] combines two pairs of open-loop resonators. They have both large size and high insertion losses. The diplexer in [10] has an absolutely enormous size of approximately $75 \times 14\,\mathrm{mm}^2$. In [11], a coupled stepped impedance is used to realize a microstrip diplexer for the digital communication systems and Industrial Scientific and Medical bands at 1.8 GHz and 2.45 GHz, respectively. The design has a large area about $47{\times}24\,\mathrm{mm}^2$ and high insertion losses at two bands. Consequently, electronic researchers are constantly motivated to propose feasible strategies and adequate interventions in order to create miniaturized topologies with excellent performances.

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* Corresponding author: Soufiane Achraou (sachraou6@gmail.com).
The authors are with the Laboratory of Sciences and Advanced Technology, Department of Civil and Industrial Sciences and Technologies, National School of Applied Sciences, Abdelmalek Essaâdi University, Tetuan, Morocco.

In this paper, a compact microstrip diplexer is proposed using two developed resonators and a coupling junction for 5G and Wi-Fi applications. The proposed diplexer's main goal is to resolve problems of recently published diplexers. The design process is structured as follows. First, a hairpin resonator is proposed and developed into an E-shaped resonator. A short microstrip stub is added to the E-shaped resonator, to attain the central frequencies 3.5 GHz and 5 GHz. Second, the bandpass filters are combined using a coupling junction to realize the diplexer. Finally, the prototype of our microstrip diplexer is fabricated and measured to validate the EM-simulation.

## 2. DIPLEXER DESIGN ANALYSIS

As mentioned above, the diplexer is an essential component of wireless communication systems. It is a passive RF component designed to separate or combine two signals having two different frequencies. Its topology essentially includes two bandpass filters designed independently as shown in Figure 1. Moreover, a junction is used for combining the proposed filters [12].

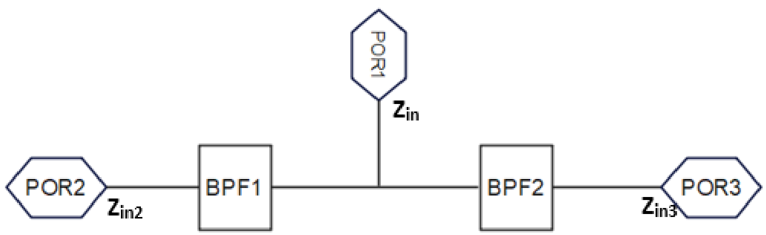



**Figure 1.** Typical diplexer.

Assuming that the diplexer is lossless and connected to real load $Z_0$ at its three ports, the scattering parameters can be determined as follows [13]:

$$\mathbf{S11} = \frac{\mathbf{Z_{in}} - \mathbf{Z_0}}{\mathbf{Z_{in}} + \mathbf{Z_0}}$$

$$|\mathbf{S_{21}}| = \sqrt{\frac{\mathbf{P_{L2}}}{\mathbf{P_A}}} = \sqrt{\frac{\mathbf{P_{in2}}}{\mathbf{P_A}}} = 2\sqrt{\mathbf{Z_0 R_0}\left(\mathbf{Z_{in2}^{-1}}\right)}\left|\frac{\mathbf{Z_{in}}}{\mathbf{Z_{in}} + \mathbf{Z_0}}\right|$$

$$|\mathbf{S_{31}}| = \sqrt{\frac{\mathbf{P_{L3}}}{\mathbf{P_A}}} = \sqrt{\frac{\mathbf{P_{in3}}}{\mathbf{P_A}}} = \mathbf{2}\sqrt{\mathbf{Z_0 R_0}\left(\mathbf{Z_{in3}^{-1}}\right)}\left|\frac{\mathbf{Z_{in}}}{\mathbf{Z_{in}} + \mathbf{Z_0}}\right|$$

where $Z_{in2}$, $Z_{in3}$, $Z_{in}$, and $R$ are impedances at the input of the upper filter, lower filter, both filters, and load impedance of port (50 ohm), respectively.

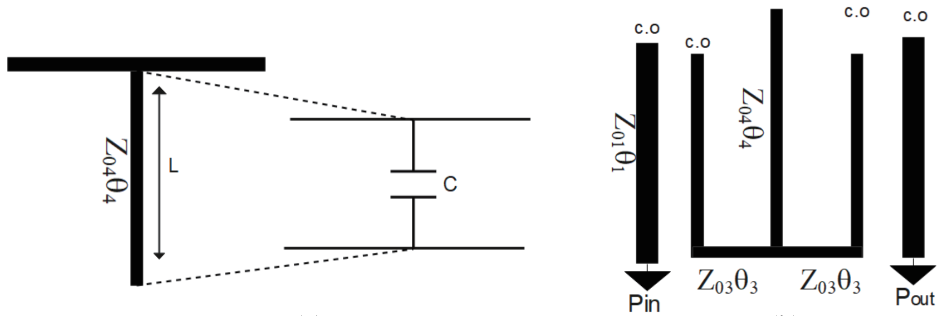
The first step in designing a compact diplexer is to choose a small resonator structure having a bandpass response. Accordingly, the open-end folded hairpin resonator structure was chosen due to its compact size in comparison to the conventional hairpin resonator, without excessive degradation of the resonator quality factor. The folded open-end or termed an internal coupled-line is used to introduce the capacitance effect where the resonance frequency can be adjusted easily by trimming its length and impedance [14, 15]. The shorted E-shaped resonator and its equivalent circuit are shown in Figure 2 [16, 17]. Its modeling approach is depicted in Figure 3.

The input, output, and hairpin admittance matrices of the resonator are respectively determined as follows [13]:

$$[Y_1] = \begin{bmatrix} \cot g\theta_1 & jZ_{01}\tan\theta_1 \\ j\dfrac{\tan\theta_1}{Z_{01}} & 1 \end{bmatrix} \quad [Y_2] = \begin{bmatrix} \cot g\theta_2 & jZ_{02}\tan\theta_2 \\ j\dfrac{\tan\theta_2}{Z_{02}} & 1 \end{bmatrix}$$

$$[Y_3] = \begin{bmatrix} 2\cot g(\theta_3) + \cot g(\theta_4) & -2jZ_{03}\tan(\theta_3) - jZ_{04}\tan(\theta_4) \\ 2j\dfrac{\tan(\theta_3)}{Z_{03}} + \dfrac{j}{Z_{04}}\tan(\theta_4) & 3 \end{bmatrix}$$

where $\theta_i$ is the propagation constant of line $i$.




(a) (b)

**Figure 2.** (a) The equivalent circuit. (b) The E-shape resonator BPF.

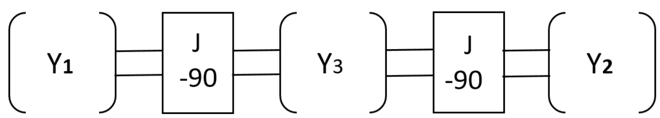



**Figure 3.** The empirical model.

## 3. MICROSTRIP BAND-PASS FILTER DESIGN

Figure 4 depicts the proposed configuration of the microstrip bandpass filter. It consists of an E-shaped resonator and two feedlines. The presented filter is simulated using CST MicrowaveStudio with an FR4 dielectric substrate having a relative dielectric constant $\varepsilon_r = 4.3$ and a thickness $h = 1.56$ mm. Table 1 illustrates the dimensions of our bandpass filters. Moreover, the overall response of the BPF is associated with the coupling coefficient, which is directly related to the spacing between the coupled lines.

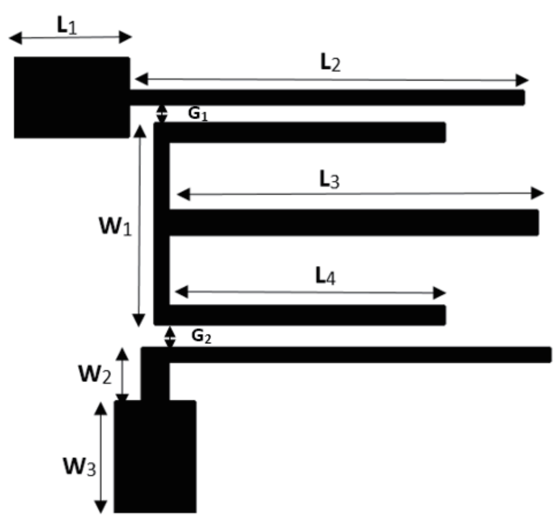
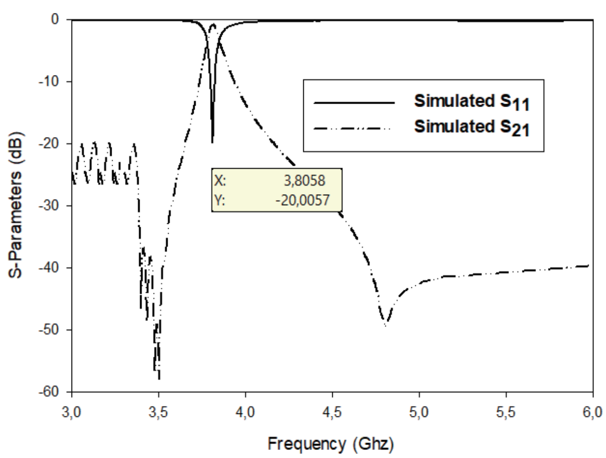



**Figure 4.** The proposed BPF.

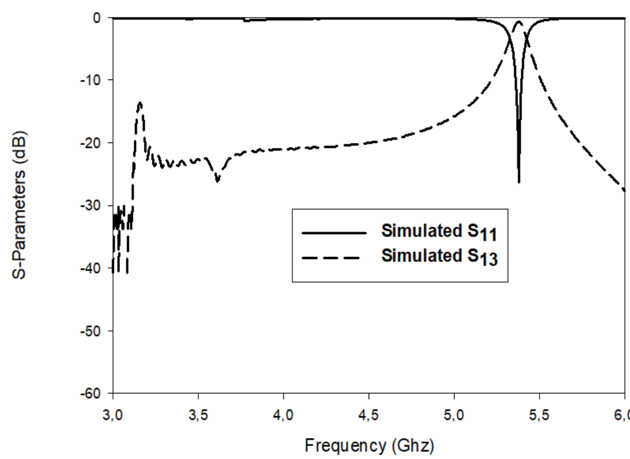
The $S$-parameters results of both bandpass filters (BPFs), as illustrated in Figure 5, show that our designed resonators operate at 3.7 GHz and 5.4 GHz, respectively. They exhibit good performance in terms of $S$-parameters. The return loss is more than 20 dB, and the insertion losses are less than 1 dB. In order to keep the same dimensions while obtaining the central frequencies for the required applications, a short microstrip stub is placed at the center of the resonators for both filters, with diameters of 3.4

**Table 1.** Dimensions of the proposed filter.

| Parameter | Values of BPF1 (mm) | Values of BPF2 (mm) |
|---|---|---|
| **L1** | 4.5 | 4.5 |
| **L2** | 15 | 15 |
| **L3** | 14 | 9 |
| **L4** | 10.5 | 7.8 |
| **W1** | 7.6 | 8.25 |
| **W2** | 2 | 2 |
| **W3** | 4.5 | 4.5 |
| **G1** | 0.7 | 0.6 |
| **G2** | 0.9 | 0.5 |



(a)



(b)

**Figure 5.** The simulated $S$-parameter result of the two proposed BPFs without short stub.

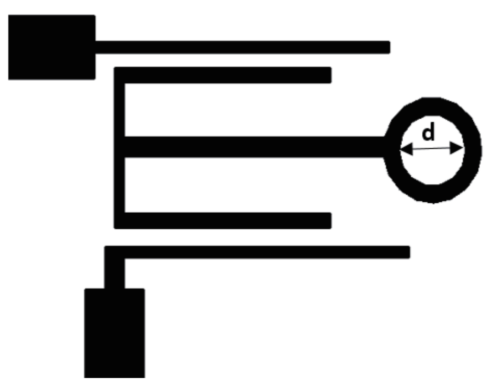
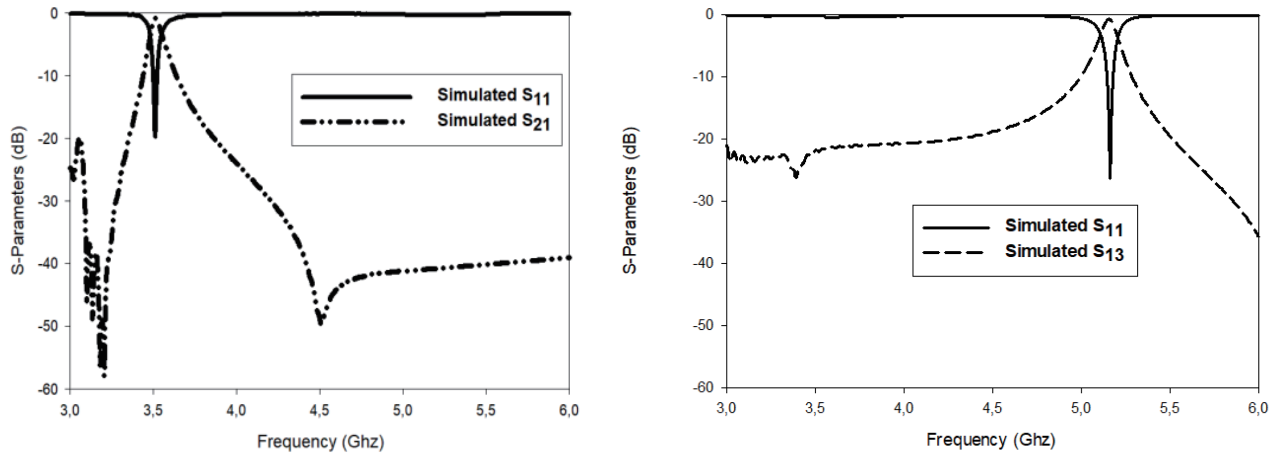



**Figure 6.** The proposed BPF with short stub.

and 2.4, respectively, as shown in Figure 6. The simulated $S$-parameter results of the two proposed BPFs with short stubs are illustrated in Figure 7.

The resonator operating at the lower frequency 3.5 GHz should have a wide upper rejection band to




(a) (b)

**Figure 7.** The simulated $S$-parameter result of the two proposed BPFs with short stub.

avoid interference with the higher frequency. Similarly, the resonator operating at the higher frequency 5 GHz should have a wide lower rejection band to obviate the intrusion with the lower frequency.

## 4. APPLICATION FOR DIPLEXER

As explained in the preceding section, the design process of a diplexer consists of two essential steps. The first one is the design of two microstrip bandpass filters, and the second one is to combine the proposed filters with corresponding networks. In this context, a coupled junction is used to combine the designed filters, as depicted in Figure 8. Indeed, the simplicity of this type of junction guarantees a compact design and good electrical performance. The simulation results of the proposed diplexer are shown in Figure 9. Generally, the frequency response shifts when two band-pass filters are combined [18, 19]. Consequently, each element of the circuit must be precisely optimized. As presented in the first section, the gap between the sorted E-shaped resonator and the feedline can also influence the simulation results. The final size of the designed diplexer is approximately $30 \times 25\,\text{mm}^2$.

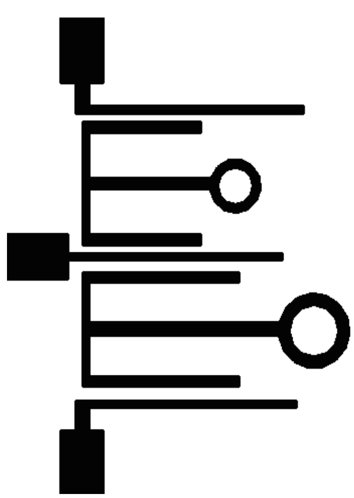


**Figure 8.** Structure of the proposed diplexer.

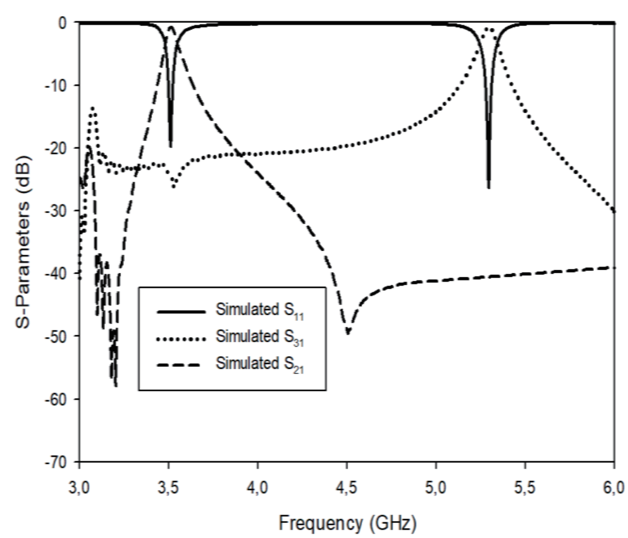



**Figure 9.** Simulation results of reflection and transmission coefficients.

The designed diplexer, shown in Figure 8, is simulated using EM-simulation and manufactured by the circuit board plotter LPKF ProtoMat E33 as depicted in Figure 10. FR4 is the substrate used with a thickness of 1.6 mm, a loss tangent of 0.025, and a relative permittivity of 4.3. The central frequencies 3.5 GHz and 5 GHz are chosen due to the 5G and Wi-Fi communications frequency bands presented in the literature.

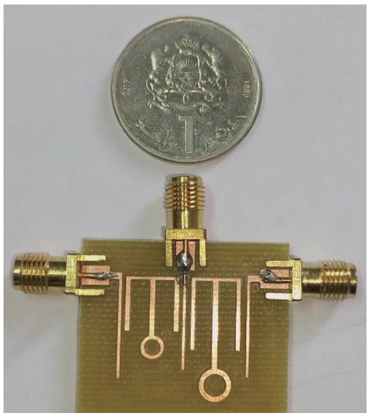


**Figure 10.** Microstrip diplexer prototype.

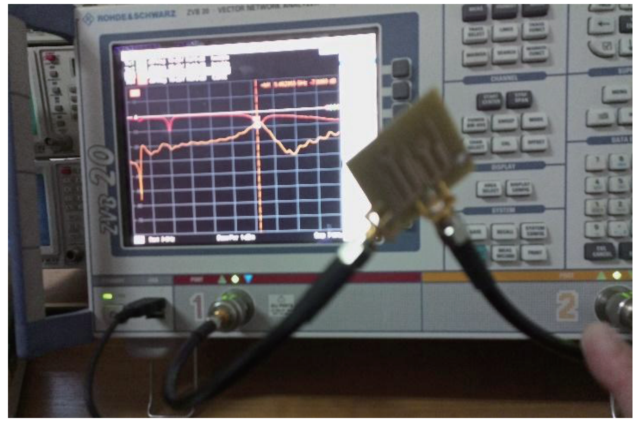


**Figure 11.** Measurement of the designed diplexer.

## 5. RESULTS AND DISCUSSION

A Rohde and Schwarz ZVB 20 vector network analyzer, as indicated in Figure 11 measured the $S$-parameters of our designed diplexer. Furthermore, this analyzer is able to measure elements that operate between 1 GHz and 20 GHz.

Figures 12 and 13 show the transmission coefficients ($S_{21}$–$S_{31}$) and the reflection coefficients ($S_{11}$), while Figure 14 depicts the measured and simulated isolations $S_{23}$. As seen from these graphs, the simulated and measured results show a significant correlation. Accordingly, the insertion loss of the first frequency 3.5 GHz and the second frequency 5 GHz is about 1 dB, while the return loss at both operating frequencies is more than 20 dB. The isolation between channels is better than 30 dB. Moreover, the fractional bandwidths at lower and higher frequencies were around 1,9% and 1,8%, respectively. These results confirm that the proposed diplexer design is suitable for the required applications.

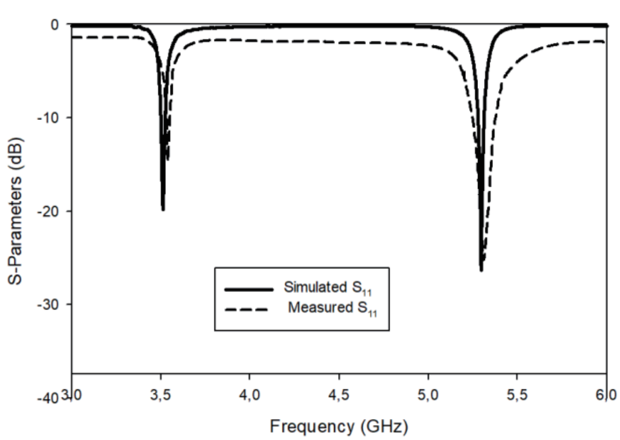



**Figure 12.** Simulated and measured $S_{11}$.

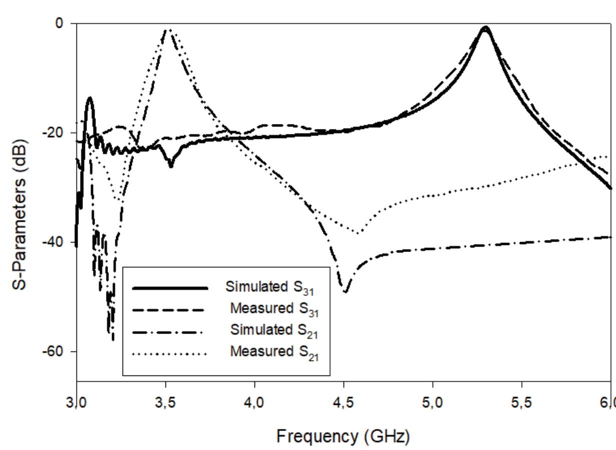



**Figure 13.** Simulated and measured $S_{21}$ and $S_{31}$.

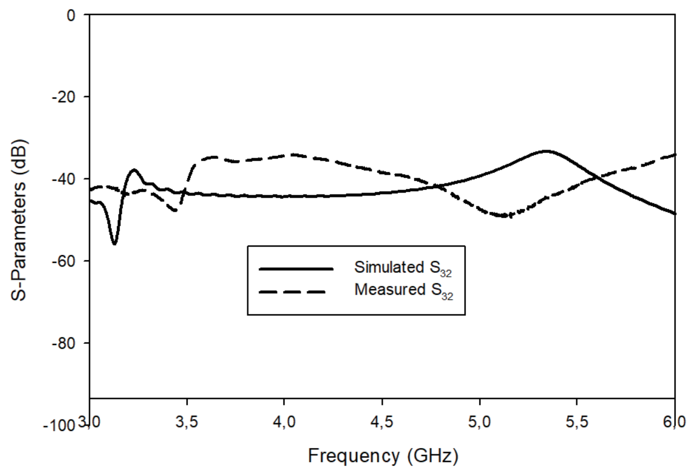



**Figure 14.** Simulated and measured $S_{23}$.

**Table 2.** Comparison performances.

| Refs | Lower/higher channels (GHz) | Insertion losses (dB) | Isolation (dB) | Return loss (dB) | Size ($\mathbf{mm^2}$) |
|---|---|---|---|---|---|
| [8] **2022** | 3.5/5 | 0.43/0.48 | $> 20$ | $> 20$ | $30 \times 17$ |
| [7] **2022** | 2/3.7 | 2.2/1.9 | $> 50$ | $> 20$ | $34 \times 32$ |
| [20] **2021** | 2.22/2.95 | 1.14/1.42 | $> 30$ | $> 20$ | $32 \times 34$ |
| [21] **2017** | 3.55/5.55 | 1.74/2.37 | $> 40$ | $> 20$ | $19 \times 17$ |
| [22] **2019** | 2.88/3.29 | 0.36/0.46 | $> 20$ | $> 20$ | $32 \times 28$ |
| [15] **2018** | 2.41/3.61 | 1.46/2.15 | $> 20$ | 23.5/18 | $31.6 \times 7.34$ |
| [23] **2018** | 2.6/3.3 | 0.85/1.28 | $> 20$ | 28/23 | $39.2 \times 11.5$ |
| [12] **2017** | 4.78/5.77 | 1.8/2.3 | $> 20$ | 20/14 | $25 \times 15$ |
| [24] **2018** | 2.95/4.92 | 1.47/1.43 | $> 40$ | 16/28 | $30 \times 20$ |
| **This work** | 3.5/5 | 1/1 | $> 40$ | $> 20$ | $30 \times 25$ |

Table 2 compares our designed diplexer to other diplexers mentioned in the literature. As seen, the presented diplexer has low insertion losses in both channels compared to [5, 10, 13, 20, 21, 24] and high isolation compared to [6, 10, 13, 22, 23]. Furthermore, compared to [5] and [20], the proposed diplexer has a smaller size of $30 \times 25\,\mathrm{mm}^2$.

## 6. CONCLUSION

A novel microstrip bandpass diplexer was designed, fabricated, and measured in this paper. The proposed topology of hairpin bandpass filter was developed into an E-shaped resonator to solve the problem of large size. Furthermore, a short stub is placed to control the resonance frequencies 3.5 GHz and 5 GHz. As a result, good return losses are obtained at both channels. In addition, our designed diplexer exhibits low insertion losses at operating frequencies compared with other works. The realized diplexer's topology offers advantage of simplicity of implementation. Furthermore, it has a small size and good features, making it suitable for 5G and Wi-Fi applications.

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