A Compact Negative Group Delay Microstrip Diplexer with Low Losses for 5G Applications: Design and Analysis

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***Abstract*—A novel compact microstrip diplexer based on spiral cells is presented in this paper. The proposed resonator primarily consists of two spiral thin lines connected to a pair of coupled lines. This novel resonator is analyzed mathematically to find its behavior and tune the dimensions of the final layout easily. Using the analyzed resonator, two bandpass filters (BPFs) are designed. Then, a novel high-performance microstrip diplexer is obtained by designing and integrating these BPFs. The proposed diplexer boasts a remarkably small size of 0.004 λg2 and features flat channels with low insertion losses of only 0.048 dB and 0.065 dB. The maximum group delays of S_{21} and S_{31} are 0.31 ns and 0.86 ns, respectively, which are good values for modern communication system. Meanwhile, inside its passbands for some frequency ranges its group delays are negative. Thus, using this diplexer can decrease the signal dispersion. The first and second passbands are wide with 47.3% and 47.1% fractional bandwidths, respectively. Therefore, this diplexer can be easily used in designing high-performance radio frequency communication systems.**

***Index Terms*— 5G, Diplexer, Group delay, Microstrip.**

I. Introduction

There has been a growing demand for passive filtering microstrip devices with a planar structure and low cost by modern radio frequency (RF) communication systems (Jamshidi, et al., 2023; Yahya, Rezaei and Khaleel, 2021; Yahya and Rezaei, 2021; Rezaei and Yahya, 2022; Yahya, Rezaei and Nouri, 2020; Hosseini and Rezaei, 2020; Yahya and Rezaei 2020; Fadaee, et al., 2023; Afzali, et al., 2021). A microstrip diplexer is an electronic device that allows two different frequency bands to be transmitted and received simultaneously through a single antenna. It consists of two bandpass filters (BPFs) with different center frequencies, connected in parallel. The main application of a diplexer is in wireless communication systems, such as cellular networks and satellite communication. It enables the sharing of a single antenna for multiple frequency bands, reducing the number of antennas needed, and hence the cost and complexity of the system (Al-Majdi and Mezaal, 2023; Deng, Xu and Zheng, 2023; Chaudhary, Roshani and Shabani, 2023). Several different microstrip configurations are presented to create diplexers for wireless RF applications. A cross-band microstrip diplexer is presented in (Duan, et al., 2023). The dual-mode squared shape BPFs are used to obtain a microstrip diplexer in (Alnagar, et al., 2022). The common problems of the proposed diplexers in (Al-Majdi and Mezaal, 2023; Deng, Xu and Zheng, 2023; Chaudhary, Roshani and Shabani, 2023; Duan, et al., 2023; Alnagar, et al., 2022) are their high insertion losses and large dimensions. Based on a new resonator, a compact diplexer is proposed in (Yahya, Rezaei and Nouri, 2021) which works at 3 GHz and 1.4 GHz for S-band and L-band wireless applications. Various techniques have been employed to achieve microstrip diplexers, including folded open-loop ring resonators, stub-loaded coupled U-shape cells, meandrous and patch cells, a transmission line that is composite right/left handed and free of vias, and stub-loaded coupled open loops. These techniques have been applied to be effective in designing microstrip diplexers with desired characteristics such as high selectivity, low insertion loss, and compact size. Each of these techniques has its advantages and disadvantages and the selection of

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technique depends on the particular requirements of the diplexer application. Folded open-loop ring resonators in (Feng, Zhang and Che, 2017), stub-loaded coupled U-shape cells in (Huang, et al., 2016), the meandrous and patch cells in (Rezaei and Noori, 2018), a transmission line that is composite right/left handed and free of vias in (Kumar and Upadhyay, 2019), and stub-loaded coupled open loops in (Rezaei, et al., 2019) are utilized to achieve microstrip diplexers. The patch and thin cells are combined in (Rezaei, Yahya and Jamaluddin, 2020) for designing a microstrip diplexer, which is suitable for GSM applications. The reported diplexers in (Zhou, et al., 2018; Rezaei and Noori, 2020; Danaeian, 2020; Roshani and Roshani, 2019; Rezaei, et al., 2019) have narrow channels. On the other hand, the common problem of the microstrip diplexers in (Feng, Zhang and Che, 2017; Huang, et al., 2016; Rezaei and Noori, 2018; Kumar and Upadhyay, 2019; Rezaei, et al., 2019; Rezaei, Yahya and Jamaluddin, 2020; Zhou, et al., 2018; Rezaei and Noori, 2020; Danaeian, 2020; Roshani and Roshani, 2019; Rezaei, et al., 2019) is their large implementation areas. Meanwhile, they could not improve group delay. Although group delay is important, only a few diplexer designers have made attempts to improve it. However, a number of designers of the other passive microstrip filtering devices have investigated group delay (Nouri, Yahya and Rezaei, 2020; Xu, Chen and Wan, 2020; Rezaei, Yahya and Nouri, 2023; Hayati, Rezaei and Noori, 2019; Hayati, et al., 2021; Liu, 2010; Chen et al., 2015; Noori and Rezaei, 2017; Lin, 2011). Since, the negative group delay circuits can be used to compensate dispersion, designing microwave circuits with a negative group delay is very important (Ahn, Ishikawa and Honjo, 2009; Chaudhary, Jeong and Lim, 2014; Ravelo, et al., 2020; Shao, et al., 2017).

This work presents the design of a diplexer for 5G mid-band applications, which utilizes a novel and compact microstrip structure. This diplexer operates at 1.86 GHz and 4.62 GHz, which are the two frequency bands of interest for 5G mid-band communication. The channels of this diplexer are wide and flat, ensuring that the signal loss is minimized and that the diplexer has a high selectivity. In addition, the group delays of S_{21} and S_{31} are negative at some frequencies, which is desirable for some specific applications. To achieve this design, a perfect mathematical method consisting of the resonator design is applied. This method allows for the tuning of the operating frequency and miniaturization of the diplexer simultaneously. The resonator is used to obtain two BPFs, which are then integrated to form the proposed diplexer. The resonator design plays a crucial role in the performance of the diplexer. The resonator is designed using a combination of a rectangular patch and a meander line. The rectangular patch acts as the radiating element, while the meander line is used to increase the resonant frequency of the patch. The resonator is then coupled to a microstrip transmission line to form a BPF.

The design of the BPF is optimized using a simulation tool, which allows for the adjustment of the dimensions of the resonator to achieve the desired frequency response. The optimized BPF is then integrated with another BPF to form the proposed diplexer. The final diplexer design is compact and has a low insertion loss, making it suitable for use in 5G mid-band communication systems. The performance of the proposed diplexer is confirmed using simulation and comparison with the other designs. The results show that the diplexer has a high selectivity and low insertion loss at the desired frequencies of 1.86 GHz and 4.62 GHz.

II. The Proposed Resonator: Design and Analysis

Fig. 1 depicts the proposed resonator and its approximated LC circuit. It includes a pair of coupled lines and two spiral cells. If we set the physical lengths of coupled lines equal to $2l_3$, then an approximated equivalent of them consists of the inductors and capacitors L_3 and C respectively. In this case, we assume that the equivalent of the physical length l_3 is the inductor L_3. Furthermore, the open ends of coupled lines are depicted by the capacitors C_o. The equivalent of spiral cell1 and the physical length l_1 is presented by L_1. Similarly, L_2 is an equivalent of spiral cell 2 and the physical length l_2.

The open end capacitors are small so that we can remove them for easier calculations. Under this condition, the equivalent impedance between the terminals (Z_{eq}) is:

$$Z_{eq} = \frac{1}{\dfrac{1}{\dfrac{1}{\dfrac{1}{(2j\omega L_3 + \frac{1}{j\omega C})} + j\omega C} + 2j\omega L_3} + j\omega C} + j\omega(L_1 + L_2) \quad (1)$$

Where ω is an angular frequency. After simplifying Equation (1), it can be written as:

$$Z_{eq} = \frac{1 - 3\omega^2 C(2L_3 + L_1 + L_2) + 4\omega^4 C^2 L_3 (L_3 + 2L_1 + 2L_2) - 4\omega^6 C^3 L_3^2 (L_1 + L_2)}{j\omega C(3 - 8\omega^2 L_3 C + 4\omega^4 C^2 L_3^2)} \quad (2)$$

The coupling capacitor C (in fF) is usually a small capacitor and the inductors are in nH ranges. To easy calculation, the following approximations can be used:

$$\begin{aligned} &3\omega^2 C(2L_3 + L_1 + L_2) \rangle\rangle 4\omega^4 C^2 L_3 (L_3 + 2L_1 + 2L_2) \\ &3\omega^2 C(2L_3 + L_1 + L_2) \rangle\rangle 4\omega^6 C^3 L_3^2 (L_1 + L_2) \\ &j\omega C(3 - 8\omega^2 L_3 C + 4\omega^4 C^2 L_3^2) \approx 3j\omega C \end{aligned} \quad (3)$$

The presented approximations in Equation (3) should be used for an angular frequency in GHz. By applying Equation (3) in Equation (2), the approximated equivalent impedance can be derived as follows:

$$Z_{eq} \approx \frac{1 - 3\omega^2 C(2L_3 + L_1 + L_2)}{3j\omega C} \quad (4)$$

Using Z_{eq}, the *ABCD* matrix of the proposed resonator (*T*) can be given by:

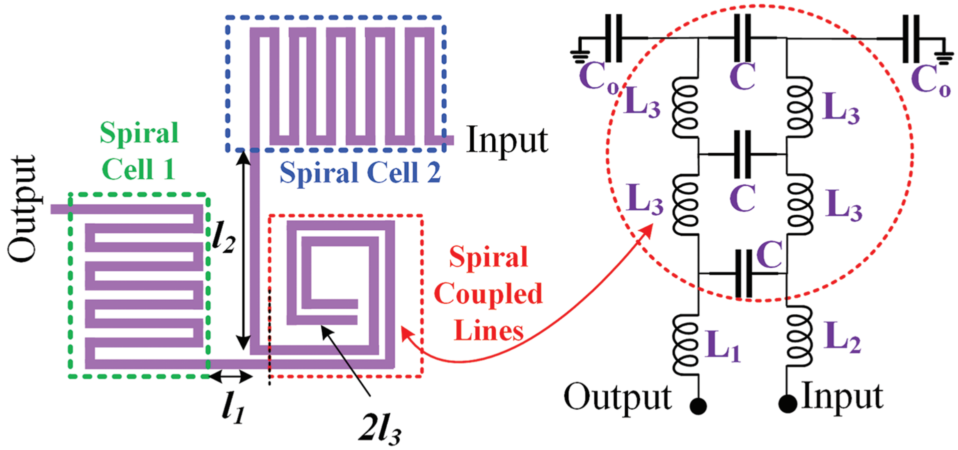

Fig. 1. Proposed basic resonator: Layout and equivalent LC model.

$$T=\begin{bmatrix} A & B \\ C & D \end{bmatrix}=\begin{bmatrix} 1 & \dfrac{1-3\omega^2 C(2L_3+L_1+L_2)}{3j\omega C} \\ 0 & 1 \end{bmatrix} \quad (5)$$

The *ABCD* matrix can be used to calculate the scattering parameters. For example S_{21} is calculated as follows:

$$S_{21}=\frac{6j\omega CZ_0}{6j\omega CZ_0+1-3\omega^2 C(2L_3+L_1+L_2)} \quad (6)$$

In Equation (6), Z_0 is the impedance of the terminals, which is 50 Ω for this work. At the operating frequency, the insertion loss should be a very small value. Since the insertion loss is $-20\log|S_{21}|$, for minimizing we can set $|S_{21}|=1$ as follows:

$$|S_{21}|=1\rightarrow 1-3(2\pi f_o)^2 C(2L_3+L_1+L_2)$$
$$=0\rightarrow f_0=\frac{1}{2\pi\sqrt{3C(2L_3+L_1+L_2)}} \quad (7)$$

In Equation (7), f_o is the operating frequency of the proposed basic resonator. If the gap of coupled lines is adjusted so that the capacitor C becomes in the range of 10^{-12} F, the inductors can be selected in the nH ranges. In this case, the operating frequency will be in GHz ranges. For a predetermined operating frequency, the values of L_1, L_2, and L_3 can be tuned with a high degree of freedom. Therefore, by adjusting the physical lengths of spiral cells, we can miniaturize the resonator size easily. Using the analyzed resonator, we presented two BPFs (BPF1 and BPF2). These filters and their frequency responses are presented in Fig. 2, where all dimensions are in mm. Moreover, the widths of all thin lines are 0.1 mm. The proposed BPFs are simulated on a Rogers RT/Duroid5880 substrate with 2.22 dielectric constant, tan(δ)=0.0009 and h = 31 mil. All simulation results are extracted using ADS software (EM simulator) in 5MHz linear steps. The information about the frequency responses is shortened in Table I.

As shown in Table I, both filters have low insertion losses which was the purpose of our mathematical analysis. The maximum group delays of S_{21} for both filters are low. By integrating the proposed BPFs, our diplexer can be obtained as shown in Fig. 3. We did not change the dimensions of our filters in the final diplexer structure. Therefore, all dimensions are in mm and the widths of all thin lines are 0.1 mm. Both filters are connected directly without needing to any extra matching circuits. Thus, the overall size is saved again. The proposed diplexer has a total size of just 11.3 mm × 5.7 mm (equivalent to 0.004 λ_g^2), with λ_g being the guided wavelength calculated at the first operating frequency of the presented diplexer.

The important parameters in determining the frequency response are specified, which are shown in Fig. 3 as l_A, l_B, S_C, S_D, l_E, and l_F. The frequency responses as functions of these parameters are shown in Fig.4. As shown in this figure, by decreasing the physical length of spiral cell l_A, the insertion loss at the lower channel will be increased. However, we should try to increase the dimensions of this cell so that it does not lead to an increase in the overall size. Since spiral cell B is directly connected to the common port, its dimension has a direct impact on the both channels. Decreasing the length of this cell increases the insertion loss at the lower channel. Increasing the length of spiral cell B shifts the first channel to the left. However, it creates some harmonics inside the higher channel. Changing the gaps between coupled lines S_C and S_D affects the insertion losses of the first and second passbands, respectively. Changing the physical lengths l_E and l_F has no impact on the first channel. However, reducing the lengths l_E and l_F destroys the second passband.

III. Results and Comparison

Fig. 5a and b show the simulated scattering parameters of the designed diplexer. Operating at 1.8 GHz and 4.6 GHz, the introduced diplexer exhibits exceptionally low insertion losses of only 0.048 dB and 0.065 dB, respectively. Both channels are flat and wide, where both of them have 47% fractional bandwidths (FBW). Meanwhile, The lower and upper channels exhibit return losses of 43.8 dB and 27.6 dB, respectively. The isolation of the output ports is better than −19.88 dB from DC to 7 GHz. As can be seen, after the first channel we could suppress harmonics up to 7GHz

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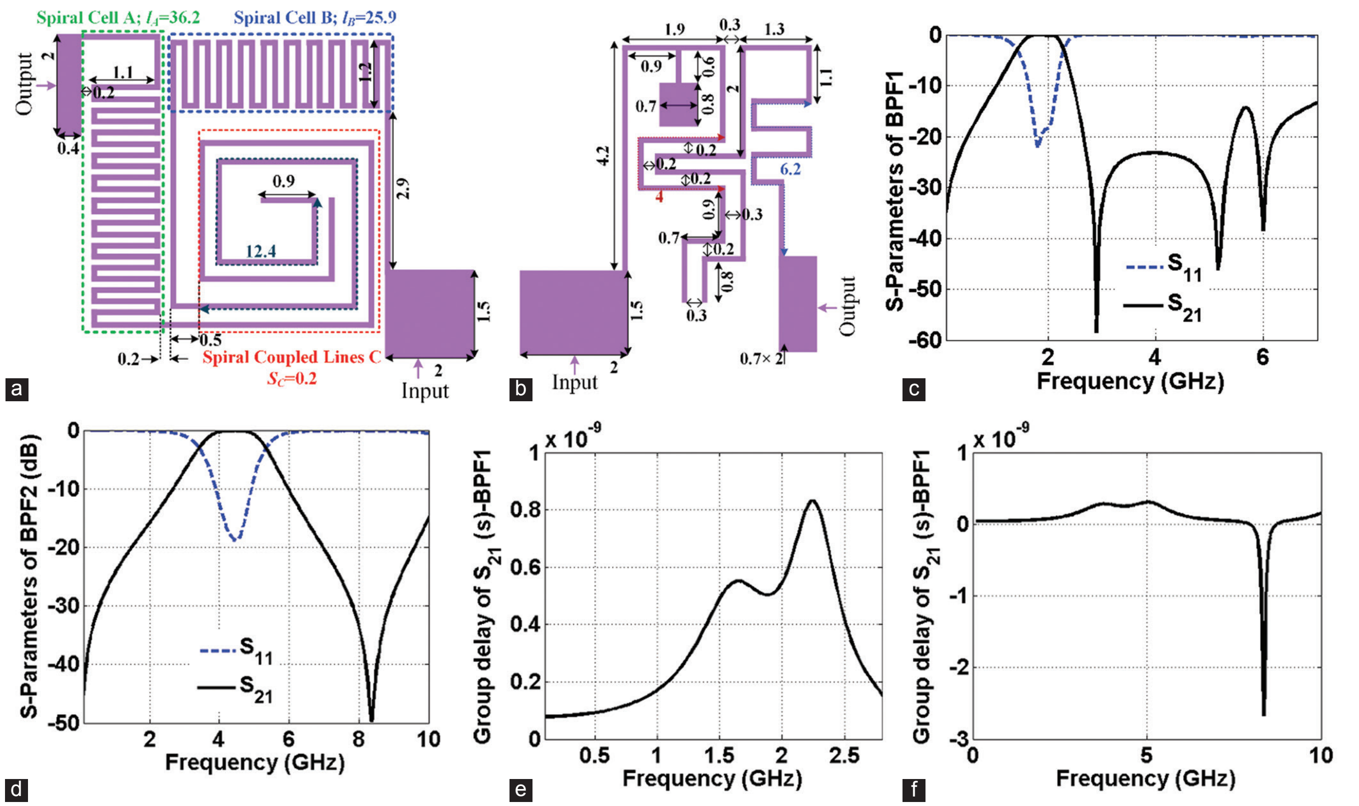

Fig. 2. Proposed bandpass filters (BPFs) and their simulated frequency responses, (a) BPF1, (b) BPF2, (c) BPF1 frequency response, (d) BPF2 frequency response, (e) group delay of BPF1, and (f) group delay of BPF2.

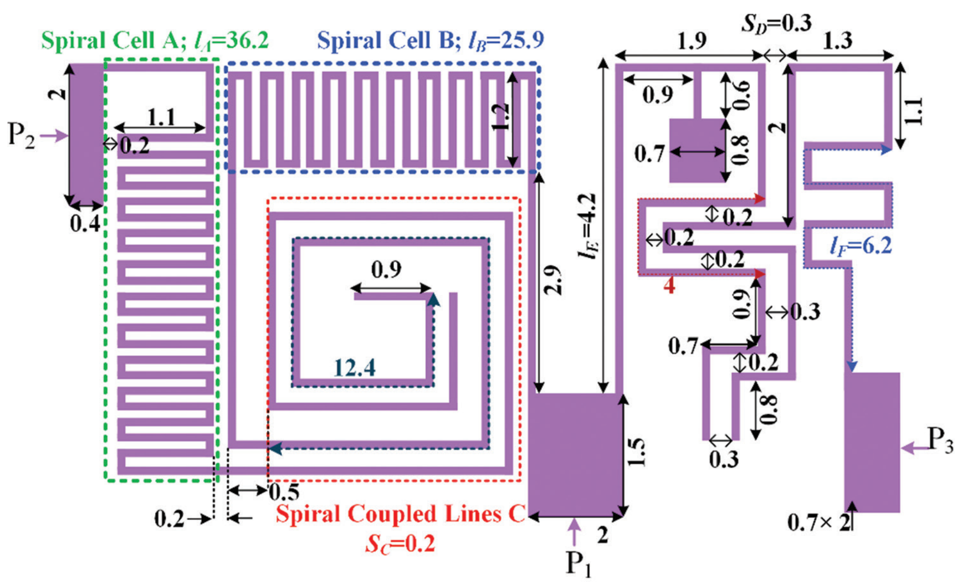

Fig. 3. Layout of the proposed microstrip diplexer.

with −14.4 dB maximum level. Consequently, it is capable of suppressing harmonics from the first up to the sixth harmonics after the lower passband. The group delays of S_{21} and S_{31} (related to the suggested diplexer) are presented in Fig. 5c and d. As can be seen, in some frequencies inside the channels, the group delays have negative values which is an advantage (Ahn, Ishikawa and Honjo, 2009; Chaudhary, Jeong and Lim, 2014; Ravelo, et al., 2020; Shao, et al., 2017). At the lower and upper channels, the maximum group delays are 0.3 ns and 0.8 ns, which are acceptable for modern wireless communication systems.

To verify the advantages of the designed microstrip diplexer, a comparison was made with the previously reported microstrip diplexers. The comparison was based on the main diplexer parameters such as insertion loss, operating frequency, return loss, group delay, and FBW. The obtained

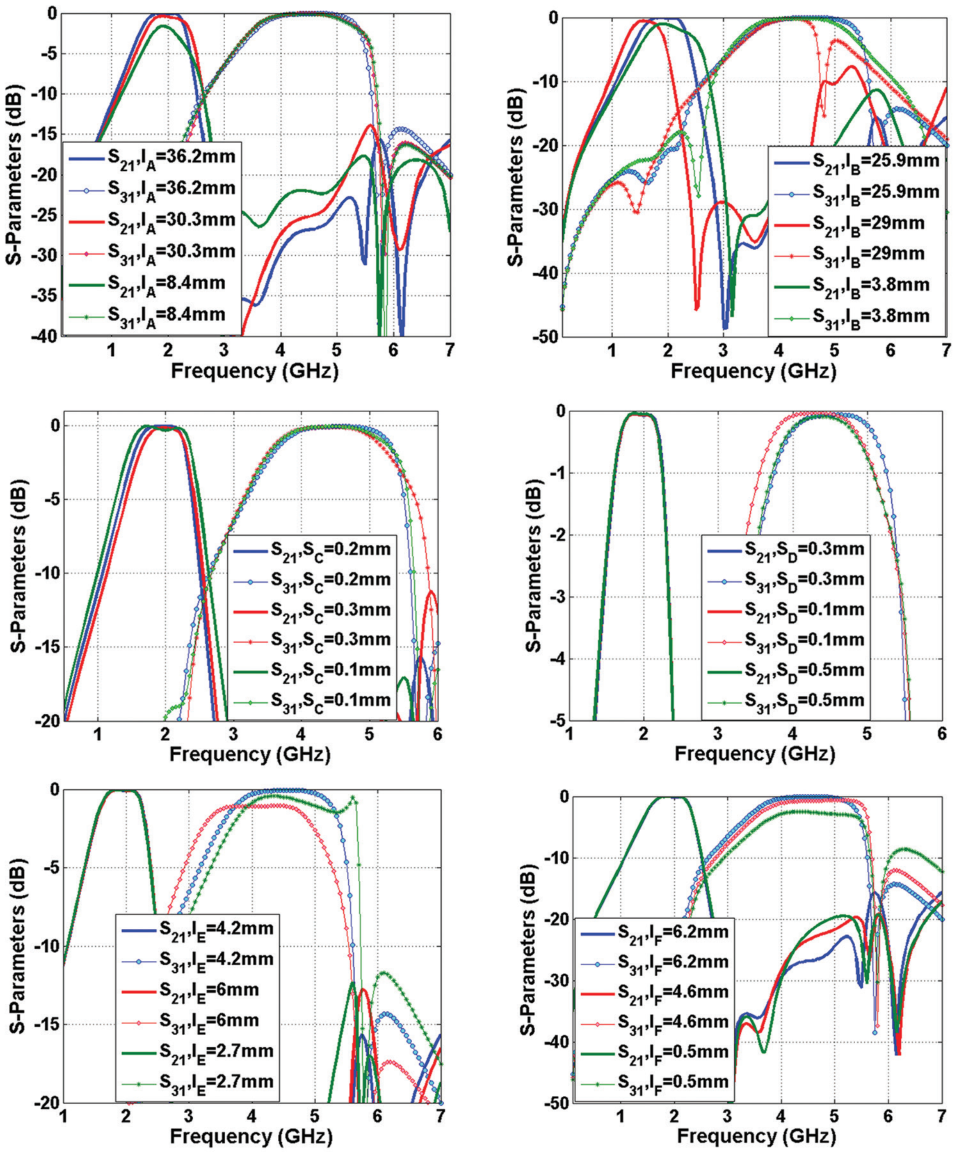

Fig. 4. Frequency responses of the proposed diplexer as functions of *lA, lB, SC, SD, lE*, and *lF*.

TABLE I
SUMMARIZED SIMULATION RESULTS OF THE PROPOSED BPFs

Filters	BPF1	BPF2
f_o (GHz)	1.82	4.5
Insertion loss (dB)	0.042	0.098
Return loss (dB)	22.66	18.8
Maximum harmonic level (dB)	−15	−15
Last frequency with suppressed harmonics (GHz)	6.94	10
Maximum group delay at passband (NS)	0.83	0.3
Fractional bandwidth (%)	50.14	28.2

BPF: Bandpass filters, NS: Not significant

results of the comparison are summarized in Tables II and III. In the comparison tables, the parameters f_o, IL, RL, and FBW are the operating frequency, insertion loss, return loss, and FBW, respectively. In addition, index 1 corresponds to the first channel, while index 2 corresponds to the second channel. According to Table II, the designed diplexer has significant advantages over the previously reported microstrip diplexers. It has the smallest size and the widest channels, with the lowest insertion losses and best return loss at all channels. These results demonstrate the effectiveness of the designed novel compact structure in achieving high performance microstrip diplexers. In Table III, the group delay of our diplexer is compared with the previous passive filtering microstrip devices. It was found that the group delay of the designed diplexer is better than all of the previously reported devices. This indicates that the diplexer has better phase characteristics, which is essential for applications such as signal processing and data communication. Overall, the comparison results demonstrate that the designed microstrip diplexer using the novel compact structure has significant advantages over the previous microstrip diplexers in terms of size, performance, losses, and group delay. These advantages make it a promising candidate for use in wireless

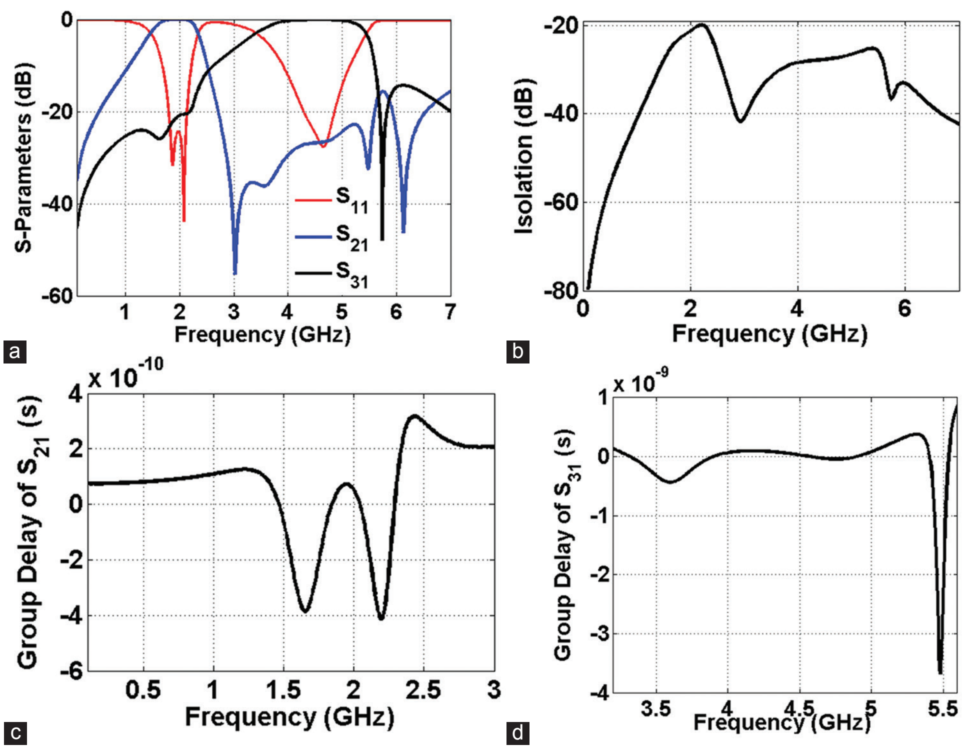

Fig. 5. Proposed diplexer, (a) scattering parameters, (b) S_{23}, (c) group delay of S_{21}, and (d) group delay of S_{31}.

TABLE II
Comparison between the Designed Diplexer and the Previous Works

References	f_{o1}–f_{o2} (GHz)	IL_1–IL_2 (dB)	RL_1–RL_2 (dB)	FBW_1%–FBW_2%	Size (λg^2)
This diplexer	1.86–4.62	0.048–0.065	43.8–27.6	47.3–47.1	0.004
Al-Majdi and Mezaal, 2023	2.84–4.08	0.7–0.9	21.2–17	1.41–2.2	-
Deng, Xu and Zheng, 2023	16–18.3	1.3–1.36	19–17	2.5–2.3	-
Chaudhary, Roshani and Shabani, 2023	2.1–5.1	0.3–0.4	10–18	14–4	0.083
Duan, et al., 2023	-	1.6–2.6	15.6–15	-	-
Alnagar, et al., 2022	1.82–2	1.1–1.2	35–45	3.2–3	0.26
Yahya, Rezaei and Khaleel, 2021	1.4–3	0.06–0.07	28.6–20	47–45	0.004
Feng, Zhang and Che, 2017	0.9–1.8	1.4–2.3	15–20	6.1–4	0.089
Huang, et al., 2016	2.3–2.72	1–0.9	20–20	6.1–5.8	0.127
Rezaei and Noori, 2018	0.8–0.9	0.28–0.29	21.2–24.3	3.2–3.2	0.01
Kumar and Upadhyay, 2019	3.5–5.6	0.87–1.25	17–15.5	21.2–13.29	0.12
Rezaei, et al., 2019	1.6–2.1	0.1–0.16	33–22	16.8–11	0.054
Rezaei, Yahya and Jamaluddin, 2020	0.78–1.85	0.17–0.30	19–21	12.5–4.2	0.026
Zhou, et al., 2018	1.8–2.4	0.5–0.2	12–20	-	0.04
Rezaei and Noori, 2020	1–1.3	0.21–0.21	32–25	4.6–4.6	0.018
Danaeian, 2020	2.4–3.5	1.45–1.55	13–30	5.9–8.8	0.029
Roshani and Roshani, 2019	0.9–2.6	0.7–0.5	19.6–22	-	0.017
Rezaei, et al., 2019	2.12–3.94	0.25–0.26	18.45–17.47	5.7–6.5	0.038

communication systems and other applications requiring high-performance diplexers.

IV. Conclusion

In this paper, the mathematical design, simulation, and optimization of a microstrip diplexer with a high performance is proposed. An estimated LC model of the proposed basic structure is analyzed to find the scattering parameters. Subsequently, the operating frequency of the basic resonator is calculated to help the miniaturization and tune the resonance frequency simultaneously. The designed diplexer operates at 1.86 GHz and 4.62 GHz, which makes it suitable for the mid-band 5G applications. It occupies a compact size of 64.4 mm^2. The other advantages of this diplexer are low insertion and return losses, wide FBW, flat channels, and low group delays, while the isolation between the output ports is acceptable. Moreover, after the lower channel, the harmonics are suppresses from the 1st up to 6th harmonics.

TABLE III
Group Delays Comparison (*: Approximated values).

References	Type	Maximum group delays at each channel
This work	Bandpass-bandpass diplexer	0.31 ns, 0.86 ns
Jamshidi, et al., 2023	Lowpass-bandpass diplexer	0.34 ns, 1.7 ns, 0.34 ns
Al-Majdi and Mezaal, 2023	Bandpass-bandpass diplexer	4 ns*, 3 ns*
Yahya, Rezaei and Nouri, 2021	Bandpass-bandpass diplexer	0.94 ns, 0.48 ns
Rezaei, et al., 2019	Bandpass-bandpass diplexer	Maximum 2.6 ns for both channels
Danaeian, 2020	Bandpass-bandpass diplexer	1.5 ns, 0.8 ns
Nouri, Yahya and Rezaei, 2020	Bandpass-bandpass diplexer	3.15 ns, 2.98 ns
Xu, Chen and Wan, 2020	Lowpass-bandpass triplexer	1.62 ns, 1.75 ns, 2.07 ns
Rezaei, Yahya and Nouri, 2023	Lowpass-bandpass diplexer	1.43 ns, 1.68 ns
Hayati, Rezaei and Noori, 2019	Lowpass-bandpass diplexer	2 ns, 1.24 ns
Hayati, et al., 2021	Lowpass-bandpass diplexer	0.65 ns*, >2.5 ns*
Liu, 2010	Tri-channel bandpass filter	Better than 8 ns at all channels
Chen, et al., 2015	Lowpass-bandpass triplexer	1.5 ns, 6 ns, 4.4 ns
Noori and Rezaei, 2017	Quad-channel bandpass diplexer	2.76 ns, 3.31 ns, 0.91 ns, 2.15 ns
Lin, 2011	Quad-channel bandpass filters	9 ns, 6 ns, 6 ns, 5 ns

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