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Using Open Stubs and Tuning the Width of Output Microstrip Lines in a Balun Diplexer to Obtain Matching Output Impendence with a RF Output Transceiver

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Abstract—Two novel compact 2.6/5.2 GHz diplexers with high common-mode suppression are designed and fabricated on an FR4 substrate. The diplexers are based on two open-loop rectangle-ring (OLRR) resonators, and two different resonant frequencies are easily obtained by tuning the lengths of the OLRR resonators. In the past, the traditional balun diplexer needed a matching circuit to achieve low loss when transferring a signal to a radio frequency (RF) transceiver, because of unmatched impedances between them. To improve efficiency and lower the cost of circuit fabrication, we propose a novel method for tuning the output impedance of the balun diplexer so that it matches that of the RF transceiver. The resulting balun diplexer has two stub-loaded microstrip lines; the required output impedance can be tuned by changing the widths of the microstrip lines and stubs and adjusting the stubs' length and position. If the output impedance is well tuned, this balun diplexer is more efficient and less costly because a matching circuit is unnecessary.

1. INTRODUCTION

High-speed digital and analog microwave circuits increasingly feature differential designs and common-mode suppression due to their strong immunity to environmental noise. Compared with conventional single-ended circuits, balanced circuits can easily meet and even exceed requirements. Baluns — electrical devices that convert between a balanced and unbalanced signal and thereby enable the transition from unbalanced circuits to balanced ones — are used as interface devices [1–3]. Baluns can take many forms and may include devices that transform impedances. To miniaturize circuits, many researchers have tried integrating a filtering function into balun devices, yielding balun filters [4–7]. A diplexer is a passive device that implements frequency-domain multiplexing for two different frequencies. Low and high signals can thereby coexist on third ports without interfering with each other.

In the past, our team used a pair of half-wavelength folded open-loop rectangle-ring (OLRR) resonators and two microstrip lines to design a simple, compact balun bandpass filter (balun BPF). The center frequency of the balun BPF could easily be adjusted by changing the path length of the OLRR resonators [4]. Subsequently, we adopted an advanced design methodology to achieve a balun BPF with an excellent common-mode rejection ratio of over 25 dB in the passband by tuning the length of the open stubs [8]. We also investigated a simple, effective structure based on traditional coupled-line theory and folded OLRR resonators to design a balanced-to-unbalanced (balun) diplexer. The two resonant

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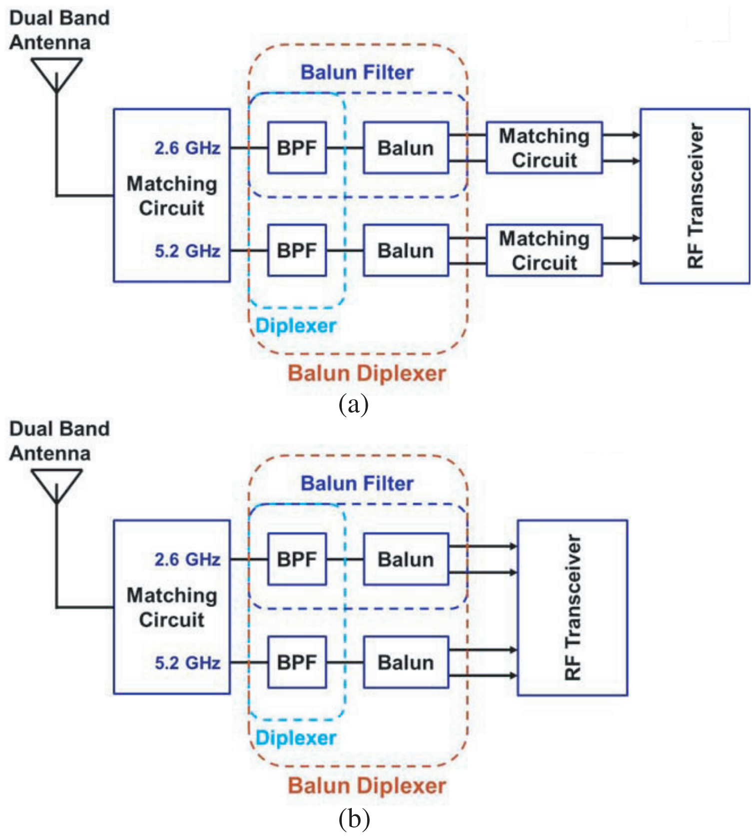


Figure 1. (a) A traditional balun diplexer needs a matching circuit to transfer a signal to an RF transceiver. (b) The proposed balun diplexer does not need a matching circuit to transfer signal.

frequencies of the balun diplexer were easily adjusted by changing the physical dimensions of the OLRR resonators and microstrip lines, and they had high common-mode suppression [9]; this was a traditional balun diplexer, which needed a matching circuit to transfer a signal from it to a radio frequency (RF) transceiver (see Fig. 1(a)). Yeung and Wu used an extracted-pole technique to create a transmission zero while also matching a filter with a complex load [10]; however, their designed circuit was complex and needed careful mathematical calculations to incorporate a complex load-matching function.

In the present study, we propose and investigate a generalized methodology for designing a novel, simple balun diplexer with high common-mode suppression. Two low-loss balun diplexers were designed with two pairs of folded OLRR resonators with the same physical dimensions, which were used to generate different resonant frequencies. Each pair of OLRR resonators was placed between two microstrip lines, which formed a perimeter whose length was about half the wavelength of the designed resonant frequency. The proposed balun diplexers had several advantages: low insertion loss, wide tunable range for the passband, large transmission zero, and simple structure.

A shunt open stub can reject unwanted harmonic frequencies and facilitate the transmission of desired passbands [11]. As mentioned above, we previously fabricated and investigated a new device with both filter-type and balun-type characteristics [8]; tuning the sizes of the open stubs and the length of the microstrip lines allowed the balanced impedance of a balun BPF to be tuned. Xue et al. proposed that a stub-loaded resonator not only has an extra degree of freedom to realize the desired coupling scheme but also can reduce the circuit size and enlarge the frequency separation of the first differential and common-mode resonant frequencies. They designed a balun filter with three $50\,\Omega$ ports based on a symmetric four-port balanced-to-balanced BPF [12].

In this study, we propose two novel balun diplexers and show that they have high common-mode suppression, low insertion loss, wide bandwidth, transmission zeros, and a simple structure, consisting of a stub-loaded resonator on two microstrip lines. The resulting balun diplexer has impedance matching that of the RF transceiver-to-transfer signal, as shown in Fig. 1(b). Because a matching circuit is unnecessary, this balun diplexer is more efficient and cheaper. To conclude the study, we fabricate two high-performance balun diplexers on an FR4 substrate to demonstrate the proposed structures.

2. DESIGN PROCEDURE

Each of the OLRR resonators was coupled with two microstrip lines (Fig. 2). Two balun diplexers with central frequencies of 2.6 GHz and 5.2 GHz for LTE band and WLAN band systems were designed to prove that the proposed dual resonance frequencies could be achieved using OLRR resonators and the discriminating coupling technique [13, 14]. The coupled structures resulted from different orientations of one pair of the OLRR resonators and the microstrip lines, which were separated by 0.2 mm (Figs. 4 and 5). Each of the OLRR resonators essentially acted as a folded half-wavelength resonator. Any coupling in these structures was due to proximity coupling, through fringe fields, the nature and extent of which could be controlled and used to determine the nature and strength of the coupling effect. By tuning the length of the microstrip lines to match the resonance of the fundamental mode, each of the OLRR resonators had maximum electric field density at the side with an open gap (g_{OLRR}) and maximum magnetic field density at the opposite side. Hence, highly efficient electrical coupling was obtained when the open sides of two coupled resonators were placed close together.

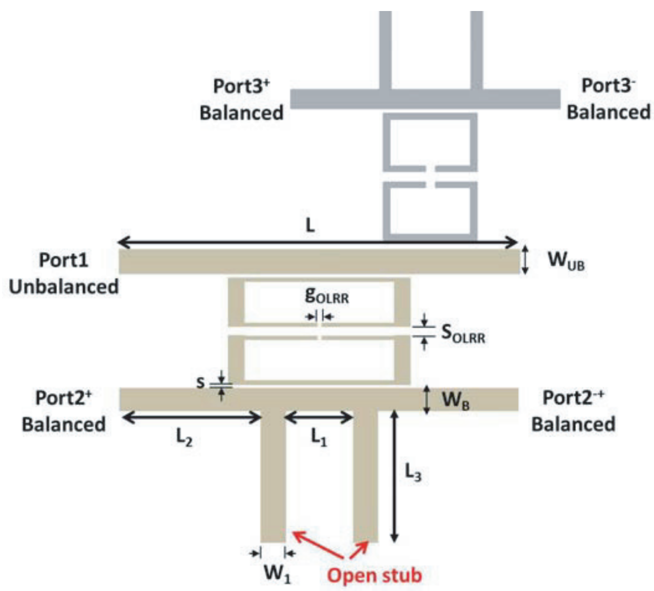


Figure 2. Layout of the designed balun BPF for simulation to find impedance variation.

The width and length of the microstrip lines and the position (L_1 and L_2 in Fig. 2) and length (L_3 in Fig. 2) of the open stubs are important influences upon the impedance of the designed circuits. First, we confirmed the optimum width and length of the microstrip lines, as shown in Figs. 4 and 5. Then, we changed the position and length of the open stubs to find variations in the impedance using simulation. The differently balanced impedances of the designed balun BPFs with open stubs are shown in Tables 1 and 2 (Smith charts) and Fig. 3. Table 1 and Fig. 3(a) show that when L_3 was unchanged, the impedance changed with variations in L_1 and L_2. Table 2 and Fig. 3(b) show that the impedance changed with variations in L_1, L_2, and L_3. These simulation results prove that we can tune the impedance by adding open stubs and suggest that using simulation we can also find the optimum width (W_B in Fig. 2) of the balanced-port microstrip line.

For our proposed balun diplexer, the lengths of the OLRR resonators were used as frequency controllers of two resonant frequencies and different physical dimensions of microstrip lines for

Table 1. Variations in the balanced impedance as L_1 and L_2 were changed.

Types	W_{UB}	W_{B}	W_1	L_1	L_2	L_3	Balanced Impedance, Ω at 2.6 GHz
T1	2	1.5	2	11.5	11.25	9.5	$71 - j6$
T2	2	1.5	2	14.5	8.25	9.5	50
T3	2	1.5	2	17.5	5.25	9.5	$40 - j6$

Table 2. Variations in balanced impedance as L_1, L_2, and L_3 were changed.

Types	W_{UB}	W_{B}	W_1	L_1	L_2	L_3	Balanced Impedance, Ω at 2.6 GHz
T1	2	1.5	2	14.5	8.25	12.5	$19 + j45$
T2	2	1.5	2	14.5	8.25	9.5	53
T3	2	1.5	2	14.5	8.25	6.5	$113 - j35$
T4	2	1.5	2	11.5	11.25	9.5	$71 - j6$
T5	2	1.5	2	17.5	5.25	9.5	$40 - j6$

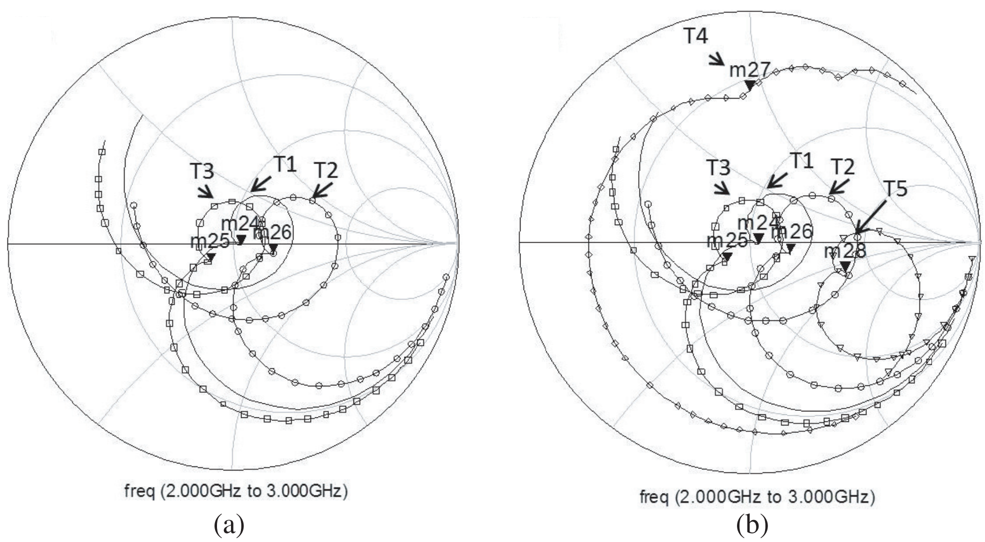
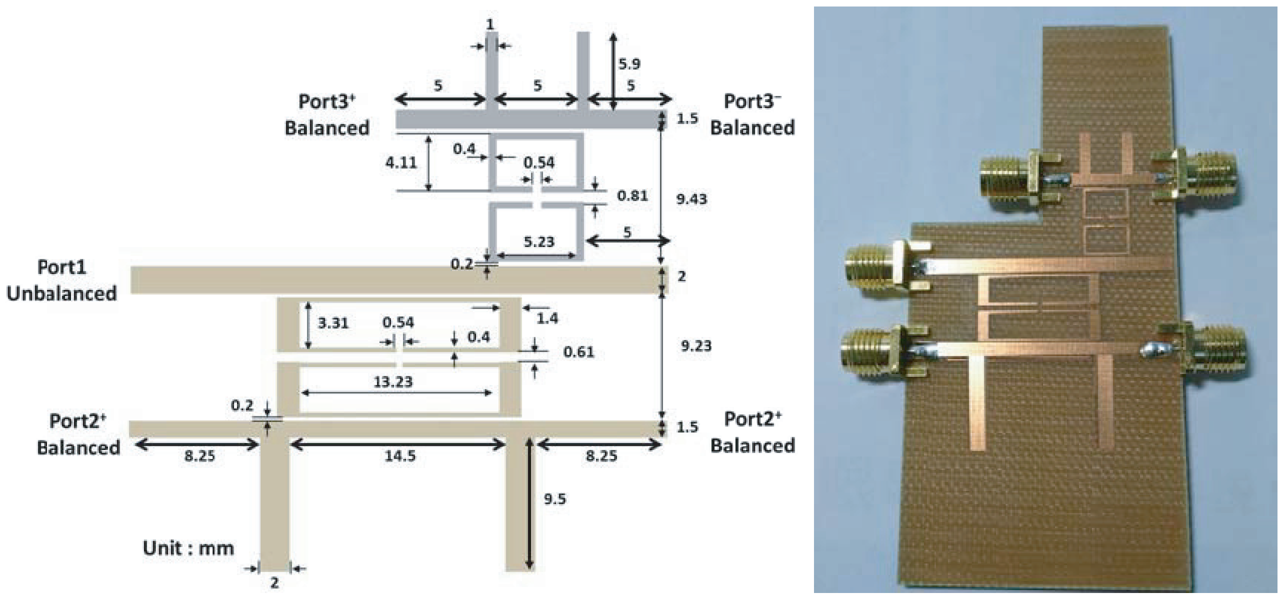


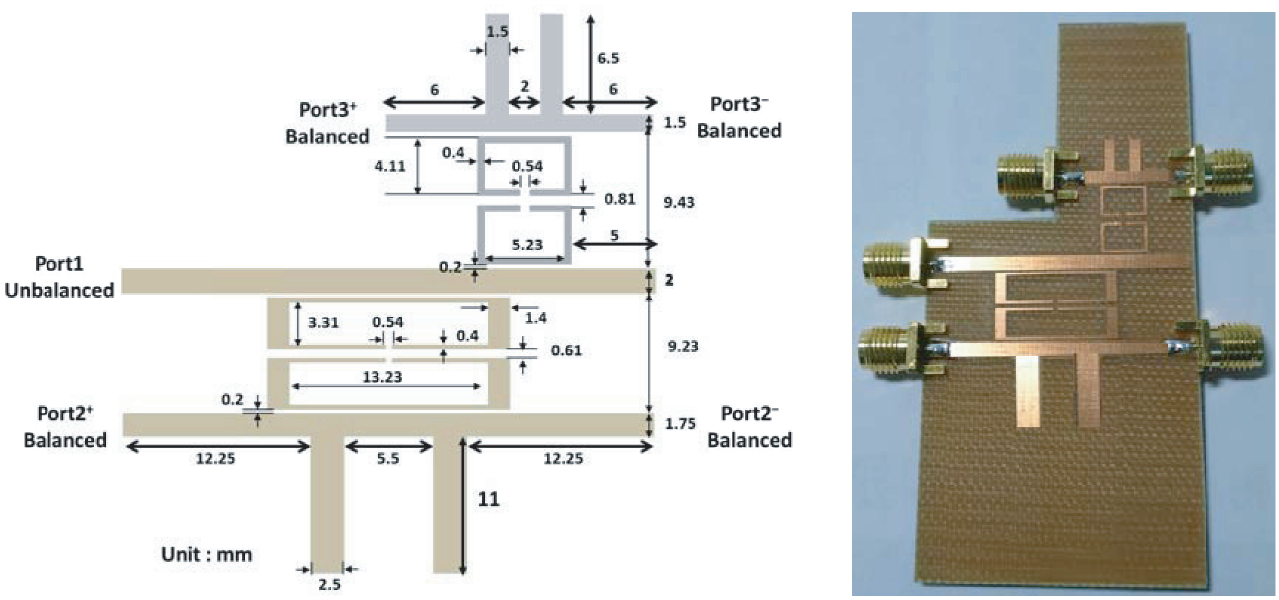
Figure 3. Simulation results for $50\,\Omega$ impedance as a function of varying the lengths in Fig. 2: (a) L_1 and L_2 in Table 1; (b) L_1, L_2, and L_3 in Table 2.

discriminative coupling [8, 9]. The center valley of the OLRR resonators for the two different resonant frequencies had to be positioned at the proper location to obtain maximum magnetic coupling. The two pairs of OLRR resonators had maximum electrical field densities near their open ends and maximum magnetic field densities around the center valleys of the output microstrip lines. Based on transmission line theory, the balun diplexer had the structure of two stub-loaded microstrip lines. The optimum design parameters for our designed balun BPFs are shown in Figs. 4 and 5. The balun diplexer in Figs. 4(a) and 4(b) was designed for both 2.6 and 5.2 GHz, with a balanced impedance of $50\,\Omega$, and the balun diplexer in Figs. 5(a) and 5(b) was designed for both the 2.6 and 5.2 GHz with a balanced impedance of $100\,\Omega$. The required output impedance could also be changed by tuning the widths of the microstrip lines and stubs and by changing the stubs' lengths and positions. For example, the widths of the output microstrip lines were 1.5 mm for both 2.6 and 5.2 GHz in the circuit with a balanced impedance of 50 Ω (Fig. 4), but the widths of the output microstrip lines were 1.0 and 1.75 mm for 2.6 and 5.2 GHz (Fig. 5) in the circuit with a balanced impedance of 100 Ω. The widths of the open tubes were 1.0 and 2.0 mm for 2.6 and 5.2 GHz in the circuit with a balanced impedance of 50 Ω (Fig. 4), and the widths of the open tubes were 1.5 and 2.5 mm for 2.6 and 5.2 GHz in the circuit with a balanced impedance of 100 Ω (Fig. 5).



(a) (b)

Figure 4. (a) Layout pattern and (b) photograph of the designed balun BPF with about 50-Ω balanced impedance based on OLRR resonators.



(a) (b)

Figure 5. (a) Layout pattern and (b) photograph of the designed balun BPF with about 100-Ω balanced impedance based on OLRR resonators.

3. EXPERIMENTAL PROCEDURE

The balun diplexers were designed and fabricated on an FR4 substrate with a relative permittivity of 4.4. The thickness between the two electrodes was 1.0 mm. The balun diplexers were based on a pair of half-wavelength OLRR resonators (Figs. 4 and 5). Magnetic coupling was easily achieved when each coupled resonator's side with maximum magnetic field was placed next to the other's [8, 9]. The simulation results showed that the optimum coupling space between the microstrip lines and the OLRR resonators was 0.2 mm and between the two OLRR resonators was 0.61 mm. Once the correct position was chosen, the center frequency of the designed balun diplexers could be accurately controlled at the desired frequencies of 2.6 GHz and 5.2 GHz. The simulation results showed good match in input impedance, as well as good amplitude and phase balances between the two output ports and the two wide passbands, respectively. Finally, SMA connectors were welded onto the input/output transmission lines of the fabricated balun diplexers, and the microwave properties were measured using a network analyzer (Agilent-N5071c).

4. RESULT AND DISCUSSIONS

The balun diplexer with no open stubs was used in simulations at 2.6 and 5.2 GHz with an impedance of 250 Ω. We also obtained measured results for the balun diplexer with no open stubs at 2.6 GHz with an impedance of 150 Ω and 5.2 GHz with an impedance of 150 Ω [9]. To match the dual-feed input/output transmission lines, the resonators were designed based on the length of a $1/2\lambda g$ open-loop resonator. According to the relative permittivity $\varepsilon_r(4.4)$ of the FR4 substrate, the ideal fundamental guided wavelength of the resonator can be calculated using Eq. (1) [15]:

$$V = C \times (\varepsilon_r)^{-0.5} = f \times \lambda g \tag{1}$$

In the past, we made designs based on the geometries and responses of a typical straight-line type (TSLT) resonator with different numbers of open stubs [11]. Basically, more open stubs in a filter were employed to obtain a deeper rejection and a wider stopband. However, the number of open stubs was important, as having too many pairs would influence the passbands and having too few pairs would make them unable to prevent unwanted responses. We used two open stubs for each OLRR resonator to improve the filtering effect of the designed filter [11]. In the present study, we also used two open stubs.

The balun diplexer in Fig. 4 was designed for both 2.6 GHz and 5.2 GHz with a balance impedance of 50 Ω. Therefore, the measured output balance impedances for 2.6 and 5.2 GHz were 38 and 50 Ω,

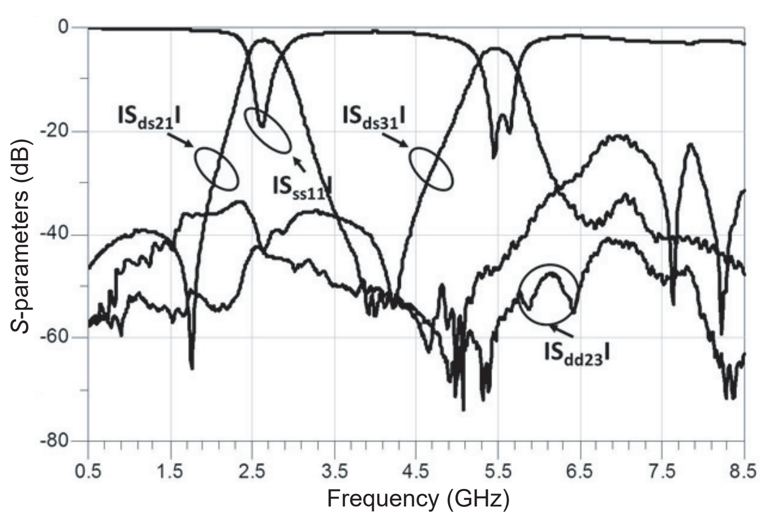


Figure 6. Measured and simulated frequency response of differential-mode response for the proposed balun diplexer with a 50 Ω microstrip line.

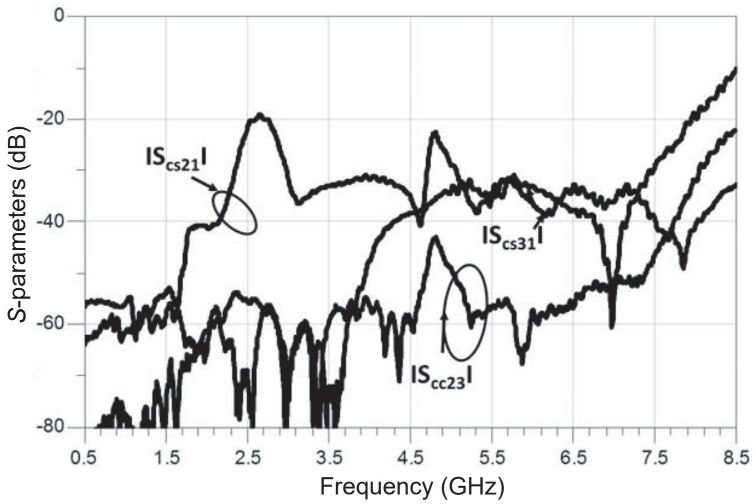


Figure 7. Measured and simulated frequency response of common-mode response for the proposed balun diplexer with a 50 Ω microstrip line.

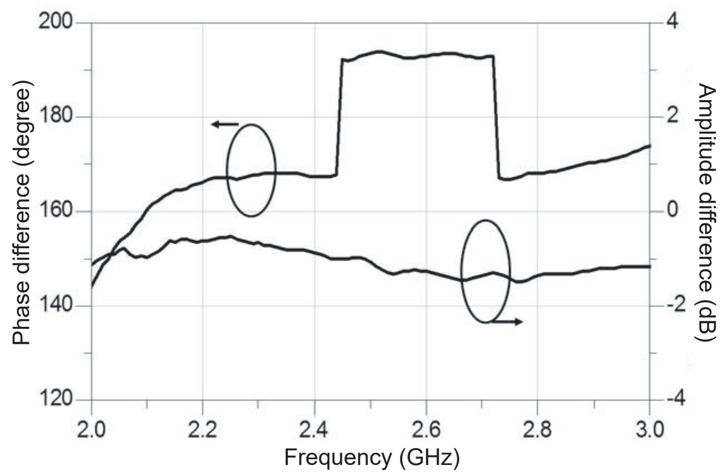


Figure 8. Phase difference and amplitude difference of the designed balun diplexer with a 50 Ω microstrip line for the 2.6 GHz low band.

respectively. The balun diplexer was 35×39.06 mm, as shown in Fig. 4. The measured differential-mode and common-mode results are shown in Figs. 6–9. In differential-mode operation, the low passband was centered at 2.65 GHz with a 1 dB bandwidth of 240 MHz or 9.05%. The minimum insertion loss, including SMA connectors, was 2.32 dB. The high passband was centered at 5.47 GHz with a 1 dB bandwidth of 340 MHz or 6.21%. The minimum insertion loss, including SMA connectors, was 4.28 dB. The differential-mode isolation between ports 2 and 3 was larger than 40 dB, while for the common-mode signal, the insertion loss was below 20 dB in the two operation bands. Fig. 8 shows the full-wave simulated and measured results for the phase and amplitude differences for the circuit. For the low band, the amplitude difference was below 1.48 dB and the phase difference was within $180 \pm 13°$. For the high band, the amplitude difference was below 0.49 dB, and the phase difference was within $180 \pm 4°$. The small differences between the simulated and measured results were mainly caused by fabrication error (circuit etching), the SMA connector, and numerical error.

The balun diplexer in Fig. 5 was designed for both 2.6 and 5.2 GHz with a balance impedance of 100 Ω. Therefore, the measured output balance impedances for 2.6 and 5.2 GHz were 50 Ω and 30 Ω, respectively. The balun diplexer was 35×41.41 mm, as shown in Fig. 5. The measured differential-mode

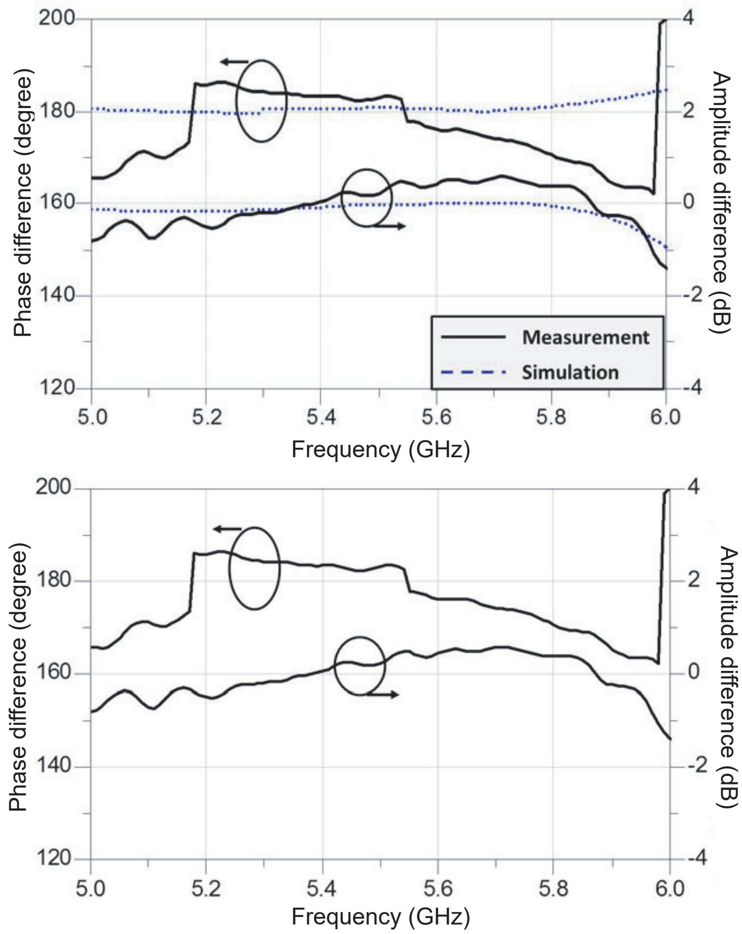


Figure 9. Phase difference and amplitude difference of the designed balun diplexer with a 50 Ω microstrip line for the 5.2 GHz high band.

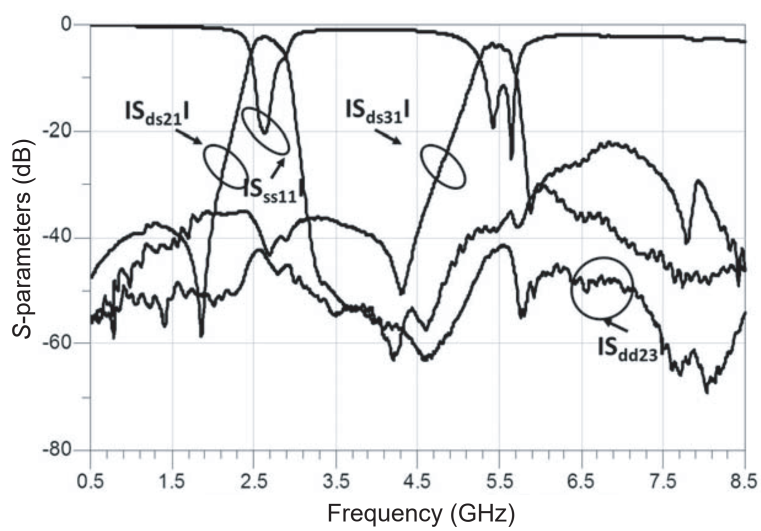


Figure 10. Measured and simulated frequency response of differential-mode response for the proposed balun diplexer with a 100 Ω microstrip line.

and common-mode results for the proposed balun diplexer are shown in Figs. 10–13. For differential-mode operation, the low passband was centered at 2.64 GHz with a 1 dB bandwidth of 235 MHz or 8.9%. The minimum insertion loss, including SMA connectors, was 2.34 dB. The high passband was centered at 5.46 GHz with a 1 dB bandwidth of 330 MHz or 6.04%. The minimum insertion loss, including SMA connectors, was 4.01 dB. The differential-mode isolation between ports 2 and 3 was larger than 40 dB, while for the common-mode signal, the insertion loss was below 20 dB in the two operation bands. Fig. 6 shows the full-wave simulated and measured results of the phase and amplitude differences for the circuit. For the low band, the amplitude difference was below 0.08 dB and the phase difference was within $180 \pm 2°$. For the high band, the amplitude difference was below 0.93 dB and the phase difference was within $180 \pm 7°$. The small differences between the simulated and measured results were mainly caused by fabrication error (circuit etching), the SMA connector, and numerical error.

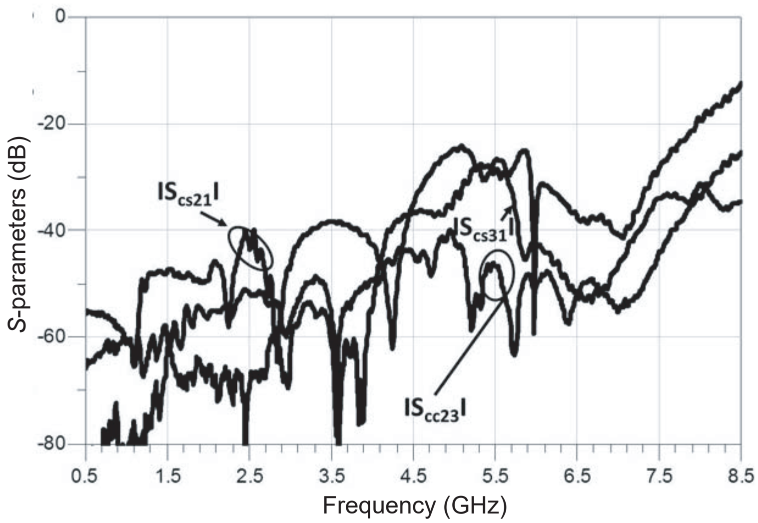


Figure 11. Measured and simulated frequency response of common-mode response for the proposed balun diplexer with a 100 Ω microstrip line.

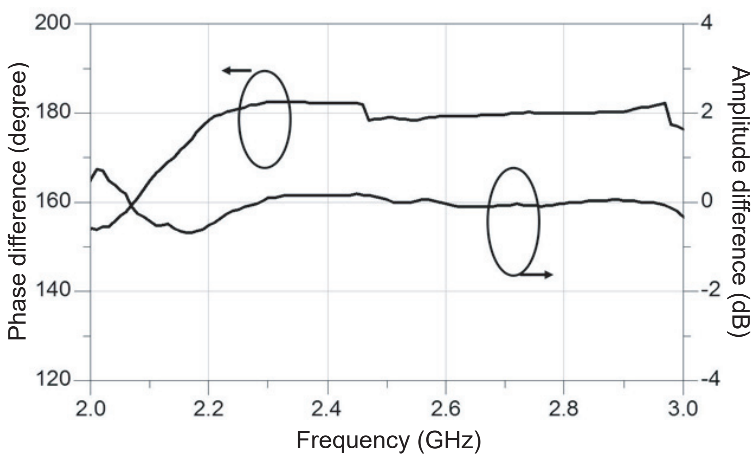


Figure 12. Phase difference and amplitude difference of the designed balun diplexer with a 100 Ω microstrip line for the 2.6 GHz low band.

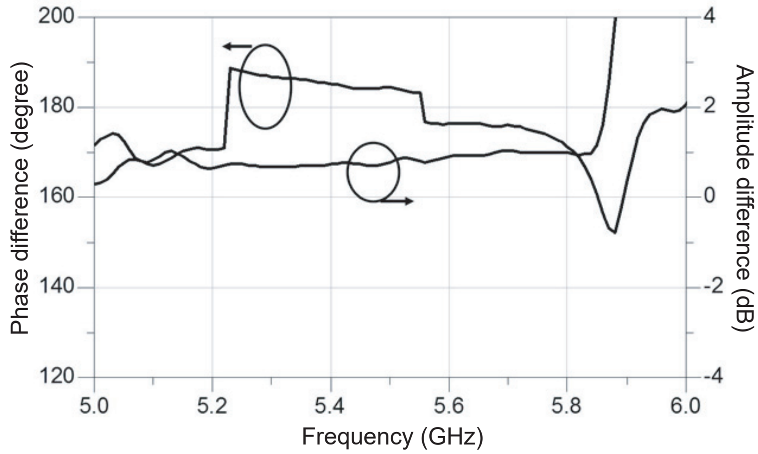


Figure 13. Phase difference and amplitude difference of the designed balun diplexer with 100 Ω microstrip line for the 5.2 GHz high band.

5. CONCLUSIONS

In this study, two parameters were used to tune the output impedances of the designed balun diplexers. The first parameter was the width of the output microstrip lines, and the second was the lengths, widths, and positions of two open stubs on the output microstrip lines. The balun diplexer in Fig. 4 (Fig. 5) was designed for both 2.6 and 5.2 GHz with a balance impedance of 50 Ω (100 Ω). The measured output balance impedances for 2.6 and 5.2 GHz were 38 and 50 Ω (50 Ω and 30 Ω), respectively. The dimensions of the proposed balun diplexer were 35×39.06 mm (35×41.41 mm). For differential-mode operation, the low passband was centered at 2.65 GHz (2.64 GHz) with a 1 dB bandwidth of 240 MHz or 9.05% (235 MHz or 8.9%). The minimum insertion loss, including SMA connectors. was measured to be 2.32 dB (2.34 dB). The high passband was centered at 5.47 GHz with a 1 dB bandwidth of 340 MHz or 6.21% (330 MHz or 6.04%). The minimum insertion loss, including SMA connectors, was 4.28 dB (4.01 dB). The differential-mode isolation between ports 2 and 3 was larger than 40 dB, while for the common-mode signal, the insertion loss was below 20 dB in the two operation bands. For the low band, the amplitude difference was below 1.48 dB (0.08 dB) and the phase difference was within $180 \pm 13°$ ($180 \pm 2°$). For the high band, the amplitude difference was below 0.49 dB (0.93 dB) and the phase difference was within $180 \pm 4°$ ($180 \pm 7°$). We have proven that we can use open stubs and tune the width of the output microstrip lines to tune the output impedance of a balun diplexer. Hence, with the appropriate output impedance, the designed balun diplexer does not need a matching circuit to transfer a signal to an RF transceiver.

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