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Dual-Mode Diplexer with High Isolation Based on Amplitude and Phase Cancellation Technique

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Abstract—This paper presents a dual-mode diplexer with easy fabrication and high signal isolation based on amplitude and phase cancellation technique. The dual-mode structure enables a compact and easy asymmetrical frequency response which also requires considerable attenuation between the proximity in frequency of the transmitter and that of the receiver. Two back-to back dual-mode three-port diplexers and a 180° phase shifter are easily employed to construct the proposed device, which are combined to form a four-port dual-mode diplexer. A 180° phase shift in one branch can be achieved by delayed transmission line. The simulated and measured four-port dual-mode diplexers are designed at the operational frequency of Tx/Rx at 1.95 GHz and 2.14 GHz, respectively. The measured results of Tx/Rx dual-mode diplexer devices are presented of 48.5 dB Tx/Rx isolation. This four-port dual-mode diplexer achieves the isolation (S_{32}) more than 21.5 dB compared with a conventional three-port dual-mode diplexer.

1. INTRODUCTION

Diplexer is usually used in RF front-ends of several communications to discriminate two different signal frequency bands for transmitting (Tx) and receiving (Rx) channels while sharing a single antenna. A diplexer structure is composed of two bandpass filters with different passband frequencies. In multiband communications, filters and diplexers are currently required to design with compactness, light weight and high signal isolation. Microstrip bandpass filters can be easily mounted on a dielectric substrate and can provide a more flexible design of the circuit layout [1]. The square open-loop microstrip resonators filters are highly desirable in wireless communication systems with compactness and high performance [2]. A lot of efforts have been made on compact resonator filters and diplexers such as stepped impedance open-loop resonators [3], miniaturized open-loop resonator [4], and square open loop with stepped-impedance resonator [5].

In addition, it is challenging to design a diplexer with high signal isolation. Because when the signal transmitting power is high, the leakage of high signal power from transmitting channels increases. As a result of high transmitting signal, the channel interference between Tx/Rx ports can destroy Rx components. To increase high signal isolation while offering easy structure design, many research papers have been focused on increasing the signal isolation in diplexers. A variety of different filters and diplexers have been made for increasing the signal isolation in diplexers [6–11]. Normally, most common diplexer designs require high degree filters to achieve high Tx/Rx isolation, resulting in a very complicated filter design and fabrication process. An alternative technique to design a diplexer with low cost, high signal isolation and easy fabrication process was proposed by using a four-port network [12, 13]. To achieve the realized prototype, the technique for size reduction and high isolation signal by using dual-mode resonator was presented in [14]. Moreover, the considerable attenuation of

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transmitter signal in the receiver is also required to discriminate the proximity in frequencies of the transmitter and receiver. Asymmetric filter responses can be used to achieve this kind of requirement.

In this paper, a dual-mode diplexer with easy fabrication and high signal isolation is proposed based on amplitude and phase cancellation technique. The dual-mode structure enables a compact size and easy asymmetrical frequency response which also requires considerable attenuation between the proximity in frequency of the transmitter and that of the receiver. Two back-to-back three-port dual-mode diplexers and a 180° phase shifter are easily employed to construct the proposed device and are combined to form a four-port dual-mode diplexer. A 180° phase shift in one branch can be achieved by delayed transmission line to cancel the same amplitude signal but different phases in transmitter and receiver.

2. ANALYSIS OF DUAL-MODE RESONATOR FILTER

Dual-mode resonator filters are used to discriminate two different signal frequencies for Tx and Rx channels in three- and four-port diplexers. A four-port dual-mode diplexer can be designed by using two dual-mode diplexers with 180° different phases. This technique offers higher Tx/Rx signal isolation than a conventional three-port diplexer. To verify the new design technique, both dual-modes for Tx and Rx channels are presented in this section. The diplexer (four-port) design is based on the independent design of two diplexers as in following steps.

Step 1: design a dual-mode filter in Tx between ports 1 and 2 at center frequency of 1.95 GHz with 50 MHz bandwidth, and the transmission zero is produced at upper center frequency sideband.

Step 2: design a dual-mode filter in Rx between ports 2 and 3 at center frequency of 2.14 GHz with 50 MHz bandwidth, and the transmission zero is produced at lower center frequency sideband.

Step 3: then, a T-junction connects the two independent bandpass filters in the form of a three-port dual-mode diplexer.

Step 4: finally, the four-port dual-mode diplexer is based on two back-to-back dual-mode diplexers with coupled-feeders, which are combined to form a four-port diplexer. The delayed-line is used to tune the phase between ports 2 and 4 to achieve a 180° phase shift.

Dual-mode resonator filter design is based on a single mode open-loop resonator as in [15, 16] in which the single mode resonator focuses only on the odd mode resonance. Normally, an even mode resonance of single-mode resonator is present approximately at twice the fundamental resonant frequency, and even-mode is of little use in single band resonator filter synthesis. For this reason, even mode will emerge as the first spurious response which degrades the filter performance. On the other hand, the even mode of dual-mode filters may also be used as a doubly tuned circuit [17].

Consequently, an open-loop filter may be adjusted to act as a doubly-tuned filter. Based on the proposed structure in [17, 18], the even mode resonance can be moved close to the operating frequency band (the odd mode). Therefore, these two poles create a second-order response. The layout of the dual-mode filter is shown in Fig. 1. An open circuited stub is added and placed in the center of the filter to lower the even mode resonant frequency. The extended stub has no effect on the odd mode [17]. Hence, the two modes can be tuned independently.

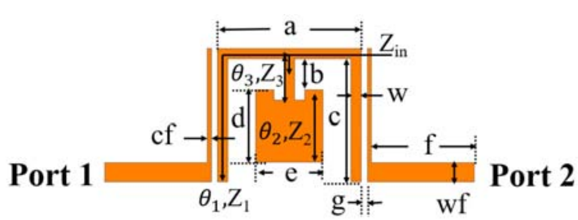


Figure 1. Schematic diagram of dual-mode microstrip stepped-impedance resonator.

The even and odd mode equivalent circuits at resonant mode are shown in Fig. 2. An open-circuited half wavelength type resonator is the even mode resonator while a short circuited quarter wavelength resonator is the odd mode one.

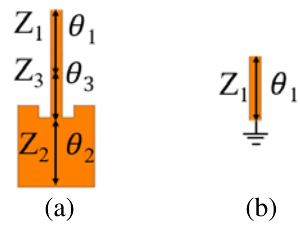


Figure 2. (a) Even-mode resonator (b) Odd-mode resonator.

The dual-mode resonator by using stepped impedance can be illustrated as an example design. The use of stepped impedances reduces the length of the open circuited stub. It can also be employed to achieve dual-mode performance [18]. The open circuited stub consists of two sections of different impedances as illustrated in Fig. 1. Dimensions were calculated using equations

$$\theta_1 \cong \frac{\pi}{2} \tag{1}$$

The stepped impedance stub (Z_2, Z_3) is connected to the middle of the resonator (Z_1), where αZ_2 and βZ_3 represent the even mode equivalent impedances of the sections with impedances Z_2 and Z_3. Let $R = \beta Z_3/\alpha Z_2$, so $R > 1$ for the stepped impedance resonator where $\beta Z_3 > \alpha Z_2$. The electrical length θ_2 is given approximately by [17].

$$\theta_2 = \cos^{-1}\left(\sqrt{\frac{R(R-1)}{(R^2-1)}}\right) \tag{2}$$

The electrical length (θ_3) of the open circuited stub may be defined from [17]

$$\theta_3 \cong (\pi + a\tan\left[-R\tan\left(\theta_2\right)\right]) - \left(\frac{c}{4f_{odd}\sqrt{\varepsilon}_{eff}}\right) \tag{3}$$

where θ_x ($x = 1$, 2, 3) corresponds to electrical length of section in Fig. 1, and c is the speed of light in vacuum.

For demonstration, the proposed dual-mode microstrip filters are based upon a U-shaped resonator loaded by a stepped impedance open stub. The filters are designed on an RT/Duroid substrate having thickness $h = 1.27$ mm with relative dielectric constant $\varepsilon_r = 6.15$. The filters were simulated by IE3D full-wave EM simulators. The resonator is coupled to the input and output ports with a feed structure having a linewidth (cf) and coupling spacing (g). The odd and even modes refer to as the first two resonating modes. These two modes can have the same or different modal frequencies which depend on the dimensions of the stepped resonator.

The operation of resonant frequencies against the length of stepped impedance resonator has been investigated using IE3D full-wave EM simulators. The dual-mode resonator is designed to achieve the desired resonant frequencies. The fundamental frequency is fixed by the length of U-shaped resonator (a and c). Even-mode characteristic can be achieved by adjusting the length of loaded stepped open circuit stub (d and e). Two input/output microstrip lines with 50 Ω characteristic impedance are used to feed the proposed dual-mode stepped stub loaded resonator. The dimensions of dual-mode resonator filter are detailed in Table 1. As can be seen in Fig. 3, the stepped open-stub loaded length does not affect the S_{21} response at odd-mode resonant frequency as shown in Fig. 3(a) at 1.95 GHz and in Fig. 3(b) at 2.14 GHz, while the even-mode resonant frequency is flexibly controlled by changing the length of stepped-impedance (d). An inherent transmission zero (TZ) can be easily tuned to optimize the response. The TZ causes an asymmetric response. It can be illustrated that the TZ is produced as a direct result of the open-circuited stub. When the even mode resonant frequency appears below that of the odd mode, the TZ actually occurs on the lower stopband. This property can be used to improve selectivity of either the upper or lower stopband.

The microstrip dual-mode resonator filters are designed at the operational frequency 1.95 GHz and 2.14 GHz for Tx and Rx modules, respectively, with 20-dB bandwidth of 50 MHz (FBW = 2.6% at

Table 1. Dimensions of microstrip dual-mode resonator filter.

Dimensions	$\mathbf{R_X}$ **= 1.95 GHz**	$\mathbf{T_X}$ **= 2.14 GHz**
Resonator width (w)	1 mm	1 mm
Feed width (wf)	1.87 mm	1.87 mm
Coupling-feed width (cf)	0.4 mm	0.4 mm
Space between coupling-feed and dual-mode resonator (g)	0.6 mm	0.6 mm
Resonator length (a)	14 mm	14 mm
Resonator length (b)	3 mm	2 mm
Resonator length (c)	11.9 mm	9.89 mm
Patch length (d)	7 mm	8.95 mm
Patch width (e)	6.55 mm	9 mm
Feed length (f)	10 mm	10 mm

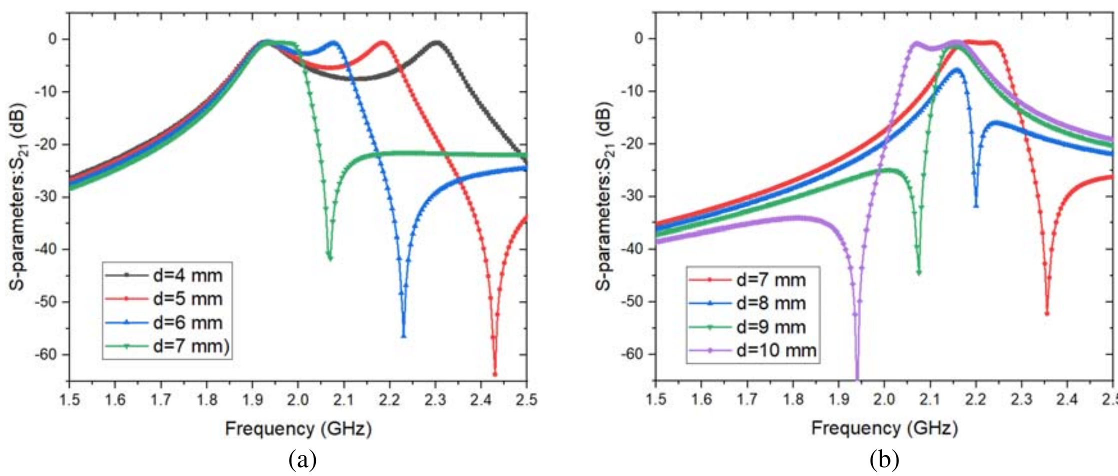
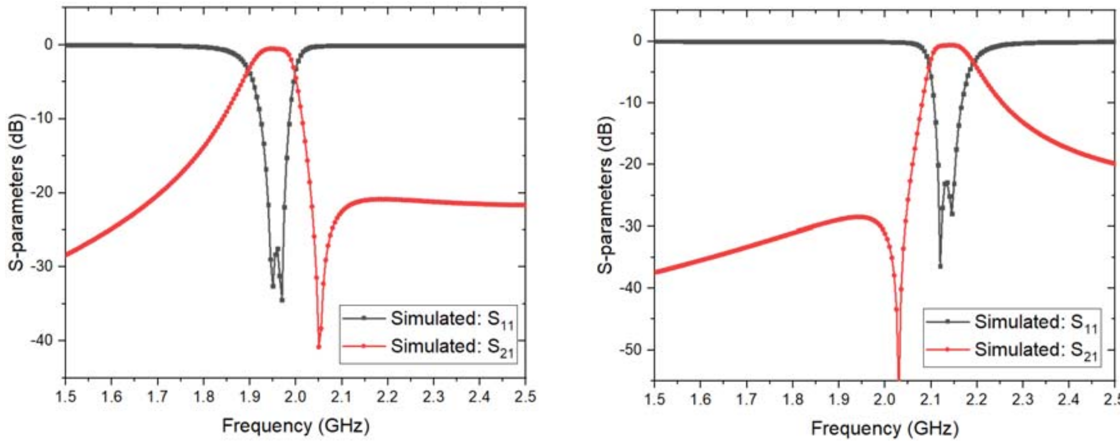


Figure 3. Simulated response of transmission zero located at (a) upper side band of the center frequency of 1.95 GHz (b) lower side band of the center frequency of 2.14 GHz with different length of loaded stepped-impedance.

1.95 GHz, 2.3% at 2.14 GHz). The passband insertion loss (IL) is less than 0.5 dB and 0.6 dB for Tx and Rx bands, respectively. The return losses (RLs) in both channels are better than 20 dB in the passband as shown in Figs. 4(a) and 4(b).

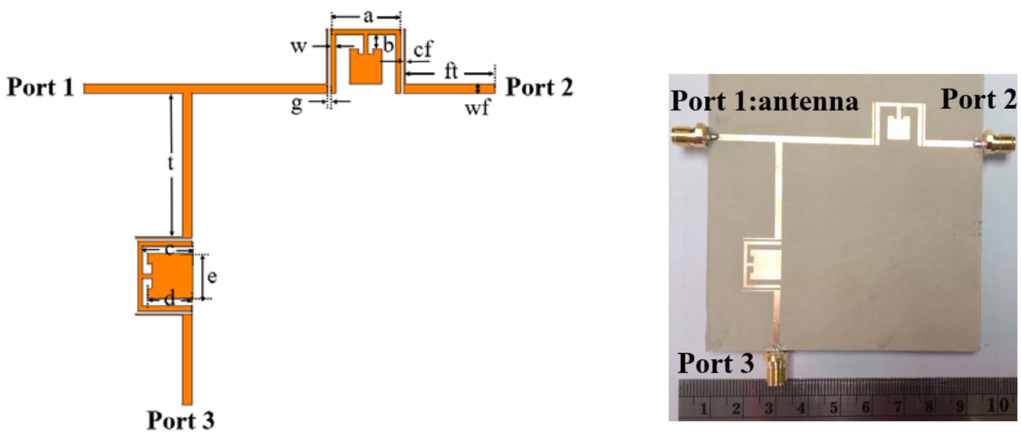
3. THREE-PORT DUAL-MODE DIPLEXER DESIGN

The structure of proposed dual-mode diplexer is shown in Fig. 5(a). Two filters are interconnected by an appropriately designed matching circuit of T-junction that has the width of 50 Ω line. The diplexer geometry is optimized at the T-junction for better return loss performance in both the channels. Fullwave simulator IE3D is used to perform electromagnetic (EM) simulations. A photograph of the fabricated diplexer is shown in Fig. 5(b). Measurements are carried out using Agilent Vector Network Analyzer. The dimensions of dual-mode diplexer are listed in Table 2. Fig. 6(a) presents insertion losses (S_{21}, S_{31}) of 1.5 dB and 1.25 dB, and return losses (S_{11}) better than 24.2 dB and 22.5 dB, at 1.95 GHz and 2.14 GHz, respectively. Fig. 6(b) shows the isolation performance of the proposed diplexer. The dual-mode diplexer presents an out-of-band rejection better than 27 dB isolation (S_{32}) over the frequency



(a) (b)

Figure 4. Simulated RL and IL results of dual-mode resonator filter (a) at 1.95 GHz (b) at 2.14 GHz.



(a) (b)

Figure 5. (a) Layout (b) photograph of three-port dual-mode diplexer.

range. The excess losses in the measurements are believed due to SMA connectors and fabrication errors.

4. FOUR-PORT DUAL-MODE DIPLEXER DESIGN

The topology of 4-port dual-mode diplexer is formed of two conventional three-port dual-mode diplexers joined back-to-back and a 180° phase shifter, as illustrated in Fig. 7(a). The geometry of four-port dual-mode diplexer is illustrated in Fig. 7(b). The design technique is based on two diplexers joined back-to-back to form the four-port diplexer. A 180° phase shifter is embedded in one of the channel filters between port 2 and port 4. To achieve such a phase shifter, a half wavelength delayed-line is adopted, as shown in Fig. 7(b). A phase shift of $180° \pm 2°$ is achieved across the Tx and Rx bands. A photograph of the fabricated four-port dual-mode diplexer is pictured in Fig. 7(c). The dimensions of the microstrip four-port dual-mode diplexer are detailed in Table 3.

The measured and simulated results of the four-port dual-mode diplexer are shown in Fig. 8(a). The measured in-band return loss is better than l6 dB in the first passband (1.95 GHz) and 2 dB in the second passband (2.14 GHz), respectively. The insertion losses are approximately 1.15/1.20 dB at the two passbands. The simulation and measurement results are in good agreement. The comparison of signal isolation, S_{32}, of four-port dual-mode diplexer and three-port dual-mode diplexer isolation

Table 2. Dimensions of three-port microstrip dual-mode resonator diplexer.

Dimensions	**R_X = 1.95 GHz**	**T_X = 2.14 GHz**
Resonator width (w)	1 mm	1 mm
Feed width (wf)	1.87 mm	1.87 mm
Coupling-feed width(cf)	0.4 mm	0.4 mm
Space between coupling-feed and dual-mode resonator (g)	0.6 mm	0.6 mm
Resonator length (a)	14 mm	14 mm
Resonator length (b)	3 mm	2 mm
Resonator length (c)	11.9 mm	9.89 mm
Patch length (d)	7 mm	8.95 mm
Patch width (e)	6.55 mm	9 mm
Feed length (ft)	19.8 mm	19.8 mm
T-junction length (t)	29.35 mm	27.05 mm

Table 3. Dimensions of four-port microstrip dual-mode resonator diplexer.

Dimensions	**R_X = 1.95 GHz**	**T_X = 2.14 GHz**
Resonator width (w)	1 mm	1 mm
Feed width (wf)	1.87 mm	1.87 mm
Coupling-feed width (cf)	0.4 mm	0.4 mm
Space between coupling-feed and dual-mode resonator (g)	0.6 mm	0.6 mm
Resonator length (a)	14 mm	14 mm
Resonator length (b)	3 mm	2 mm
Resonator length (c)	11.9 mm	9.89 mm
Patch length (d)	7 mm	8.95 mm
Patch width (e)	6.55 mm	9 mm
Feed length (ft)	19.8 mm	19.8 mm
T-junction length (t)	29.35 mm	27.05 mm
Delayed-line length (k)	18.4 mm	
Microstrip line length (m)	5.58 mm	
Delayed-line length (n)	17.7 mm	

Table 4. Comparison of proposed four-port dual-mode diplexer with the state-of-the arts diplexer.

References	Types	Degrees	Frequency (GHz)	Insertion loss (dB)	Isolation (dB)	Ports no.
[8]	Dual-mode resonator	2	1.95/2.14	1.2/1.5	> 35	3
[9]	Quarter-wavelength resonators	2	1.8/2.4	1.1/1.18	> 40	3
[10]	Open-loop single-mode	2	2.44/3.52	1.43/1.59	> 42	3
[11]	Low-temperature co-fired ceramic (LTCC)	3	3.55/5.55	1.74/2.37	> 40	3
This work	Dual-mode resonator	2	1.95/2.14	1.15/1.2	> 48.5	4

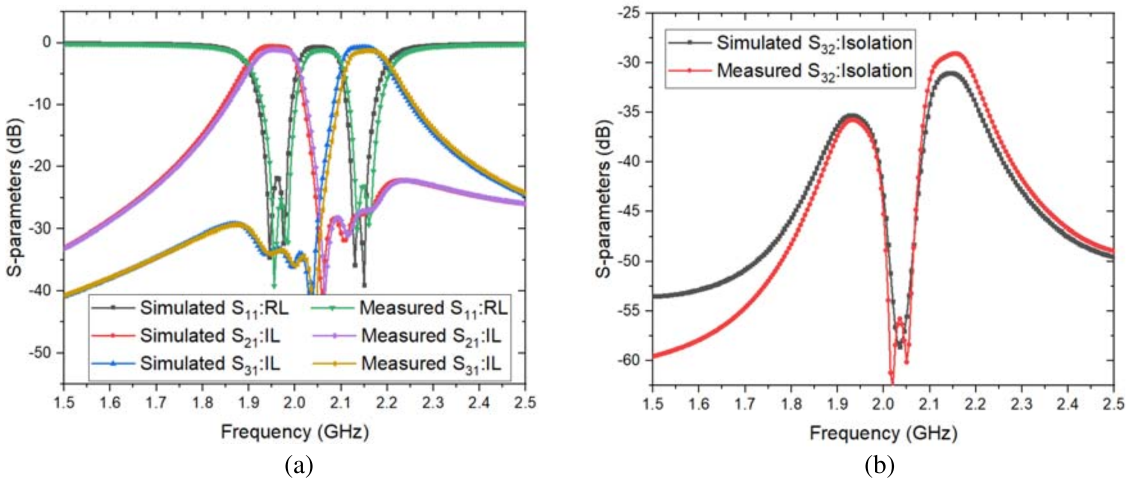


Figure 6. Comparison between simulated and measured results of (a) RL and IL of three-port dual-mode diplexer (b) isolation (S_{32}) of three-port dual-mode diplexer.

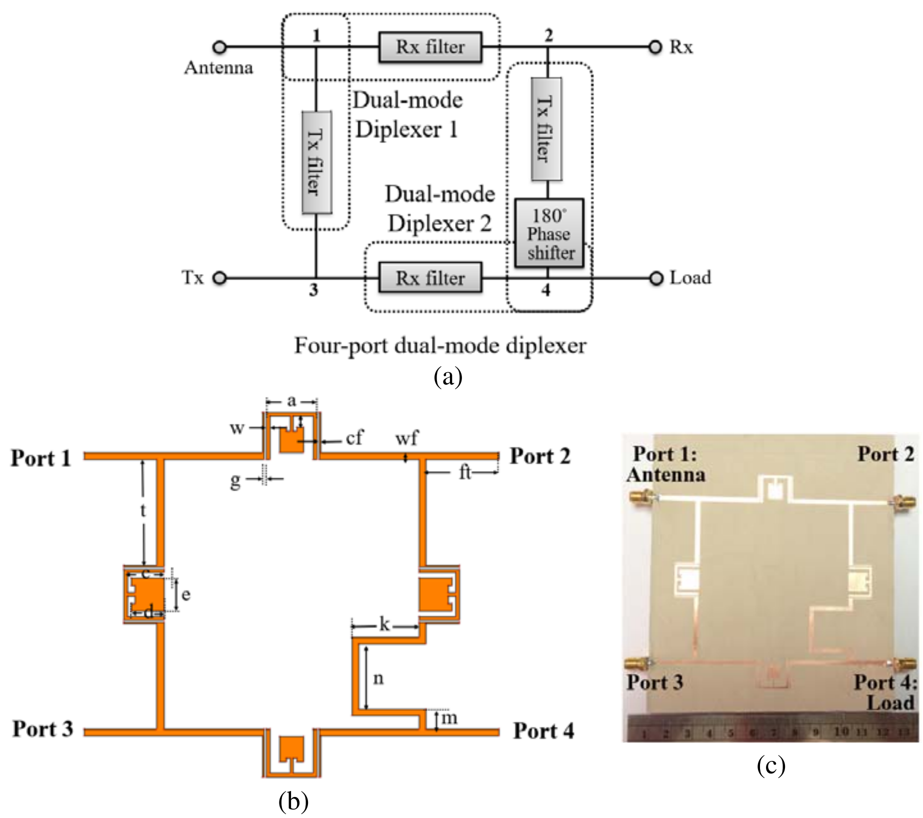


Figure 7. (a) Topology (b) layout (c) photograph of four-port dual-mode diplexer.

between Rx and Tx bands is shown in Fig. 8(b). The measured signal isolation of the conventional three-port dual-mode diplexer is 27 dB, and it is 48.5 dB for the four-port dual-mode diplexer.

To compare the size of the proposed four-port dual-mode diplexer, a conventional four-port diplexer [13] is simulated by using a single-mode microstrip open loop resonator. The total number of degrees required in a single-mode bandpass filter can be reduced by half for dual-mode resonator. High signal isolation between the Tx and Rx modules is achievable by only using one resonator filter

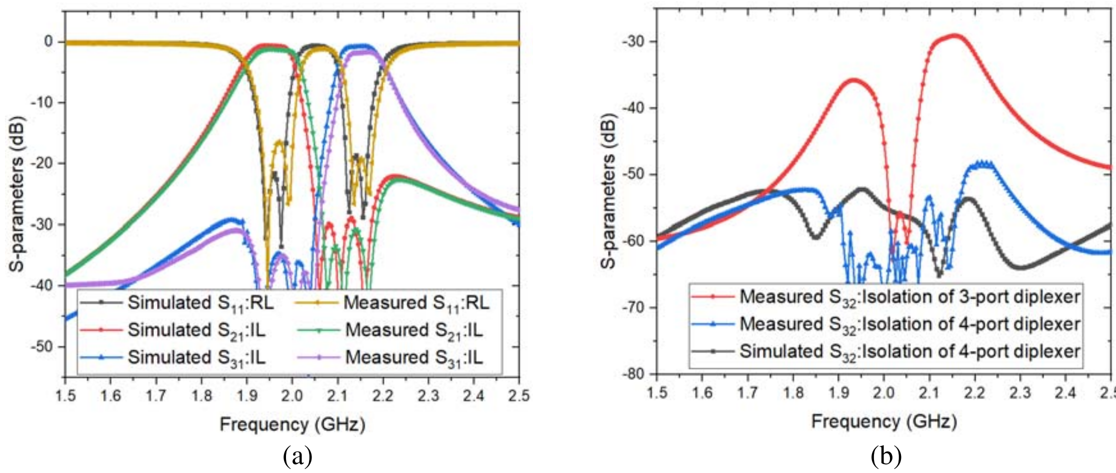


Figure 8. Comparison between simulated and measured results of (a) RL and IL of four-port diplexer (b) isolation (S_{32}) between three-port diplexer and four-port diplexer.

topology. Moreover, four-port microstrip dual-mode diplexer still reduces overall signal losses with the same or better isolation than the existing state-of-the art diplexers [13].

Table 4 shows the comparison of several three-port diplexers and the proposed four-port dual-mode diplexer. It can be seen that the proposed four-port dual-mode diplexer exhibits good in-band performance and high isolation.

5. CONCLUSIONS

A dual-mode diplexer with easy fabrication and high isolation based on amplitude and phase cancelation technique is proved here. A compact dual-mode bandpass filter with an asymmetric frequency response is easily realized to design with two extremely close frequency bands. The high signal isolation is achieved by using two back-to-back dual-mode diplexers. A 180° phase shift in one branch can be easily achieved by delayed transmission line. The microstrip four-port dual-mode diplexer can enhance the isolation (S_{32}) more than 21.5 dB compared to the conventional diplexer. Finally, the proposed four-port dual-mode diplexer offers a simple structure, which allows low complexity design and easy fabrication process.

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