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Design of Compact and High-Isolation Quadruplexer With Novel Matching Network

QIANG SHAO AND FU-CHANG CHEN, (Member, IEEE)
School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510640, China

Corresponding author: Fu-Chang Chen (chenfuchang@scut.edu.cn)

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ABSTRACT A novel matching network to design quadruplexer is proposed in this paper. The matching network is comprised of two parts and each part consists of a short-circuited transmission line, an open-circuited transmission line, and a series transmission line. The matching network is analyzed to obtain the design curves, which lead to various design parameters. Using this matching network, the quadruplexer can be easily realized by the connection of different bandpass filters without further tuning. Systematic design procedure for quadruplexer is fully presented in this paper. To illustrate the concept, a quadruplexer is designed, fabricated, and measured. Simulated and measured results are found to be in good agreement with each other.

INDEX TERMS Bandpass filter, matching network, microstrip, quadruplexer.

I. INTRODUCTION

In recent years, with the great development of multi-band and multi-service mobile communication systems, the research in multiplexers has been popular. In order to meet the higher demands for the system, multiplexers with low loss, high isolation, compact size and flexible passband frequencies are imperative. To this end, various structures of multiplexers have been presented [1]–[20].

Regarding low losses, waveguide multiplexers have been presented in [1] and [2]. In order to achieve a high isolation, the matching network is crucial in the multiplexers design [3]–[7]. Weng *et al.* [3] demonstrated a dual-band diplexer using the branch matching network to feed the dual-band filters comprised of stepped impedance resonators and thus achieved high isolation. In [4], a triplexer was presented with high isolation due to the matching network based on the stepped-impedance resonators. A general design method for the matching circuits of multiplexers based on microstrip non-uniform transmission lines was presented in [5]. Lee and Itoh [6] presented a triplexer using a novel matching network comprised of a composite right/left handed transmission line. Deng *et al.* [7] proposed a high isolation multiplexer based on branch-line-shaped matching circuits. However, the additional matching network might also lead a large circuit size. In order to reduce the circuit size, proper resonators should be chosen since resonators are the basic components of a filter. Stepped impedance resonators were the most common resonators in the multiplexers design to reduce the size [8]–[11]. In [12], the spiral inductor resonators were presented to form the filters which help obtain a compact size. In [13] and [14], multi-mode resonators were used to design multiplexers. The further way to reduce the circuit size is to replace the conventional matching circuit with a common resonator [15]–[17]. In this method, bandpass filters share the common resonator. However, the passband frequencies should be designed at the resonant frequencies of the common resonator, thus the freedom in choosing passband frequencies is limited. Moreover, due to the limited coupling area available, this type of multiplexers only allows a small number of passbands to be implemented. Additionally, many other techniques were proposed to design multiplexers [18]–[20].

In this paper, a compact and high isolation quadruplexer with flexible passband frequencies is presented by utilizing the novel matching network. The detailed design process of the matching network is given based on our previous work [21], [22] in Section II. In Section III, the details about how to design each channel bandpass filter are given.

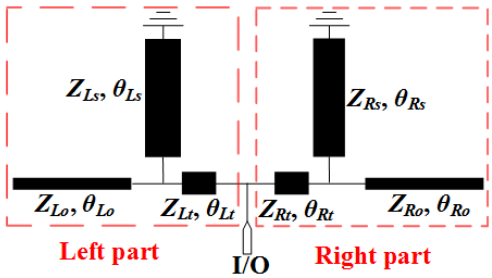

FIGURE 1. Proposed structure of matching circuit for quadruplexer.

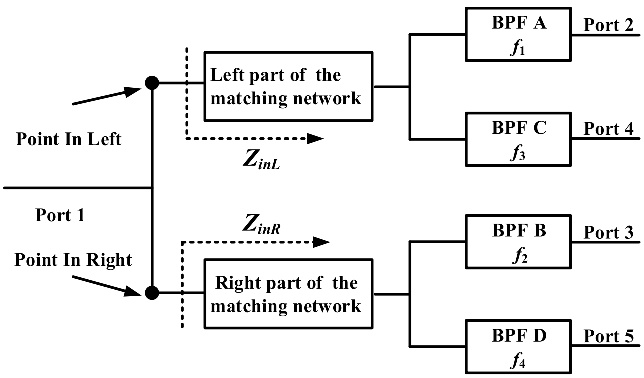

FIGURE 2. The proposed structure of quadruplexer.

In Section IV, a compact and high isolation quadruplexer is designed, fabricated and measured and the coherence between the simulated and measured results proves the effectivity of the design method. Lastly, Section V concludes this paper.

II. MATCHING NETWORK DESIGN

The proposed structure of the matching network for quadruplexer design is shown in Fig. 1, which is composed of the left part and the right part. The left part consists of an open-circuited stub (Z_{Lo}, θ_{Lo}), a short-circuited stub (Z_{Ls}, θ_{Ls}) and a series transmission line (Z_{Lt}, θ_{Lt}) and the right part is similarly comprised of an open-circuited stub (Z_{Ro}, θ_{Ro}), a short-circuited stub (Z_{Rs}, θ_{Rs}) and a series transmission line (Z_{Rt}, θ_{Rt}). Fig. 2 shows the proposed structure of quadruplexer using the novel matching network to feed the four channel bandpass filters. The central frequency of the four filters (BPF A, BPF B, BPF C, BPF D) is set as f_1, f_2, f_3 and f_4, respectively, wherein $f_1 < f_2 < f_3 < f_4$. The left part of the matching network feeds BPF A and BPF C, and the right part feeds BPF B and BPF D.

To minimize the interaction between channels and achieve high isolation, the matching network should satisfy the impedance requirement in a quadruplexer when the loading effect of the resonators is not taken into consideration, as follows

$$Z_{inL}@f_2,\ f_4 = \infty \tag{1}$$

$$Z_{inR}@f_1,\ f_3 = \infty \tag{2}$$

where Z_{inL}, Z_{inR} are the input impedance of the left part and the right part, respectively, as deduced below

$$Z_{inL} = -jZ_{Lt}\frac{Z_{Lo}Z_{Ls} - (Z_{Ls}Z_{Lt}\tan\theta_{Lo} - Z_{Lo}Z_{Lt}\cot\theta_{Ls})\tan\theta_{Lt}}{Z_{Ls}Z_{Lt}\tan\theta_{Lo} - Z_{Lo}Z_{Lt}\cot\theta_{Ls} + Z_{Lo}Z_{Ls}\tan\theta_{Lt}} \tag{3}$$

$$Z_{inR} = -jZ_{Rt}\frac{Z_{Ro}Z_{Rs} - (Z_{Rs}Z_{Rt}\tan\theta_{Ro} - Z_{Ro}Z_{Rt}\cot\theta_{Rs})\tan\theta_{Rt}}{Z_{Rs}Z_{Rt}\tan\theta_{Ro} - Z_{Ro}Z_{Rt}\cot\theta_{Rs} + Z_{Ro}Z_{Rs}\tan\theta_{Rt}} \tag{4}$$

Assuming $\theta_{Lt} < 90^\circ$, $\theta_{Lo} < 90^\circ$ and $\theta_{Ls} < 180^\circ$ and inspecting from (1) and (3), the matching condition of the left part of the network can be obtained as

$$\tan\theta_{\rm Lo} - R_{\rm ZL}\cot(\frac{\theta_{\rm Lo}}{R_{\theta L}}) + \frac{Z_{\rm Lo}}{Z_{Lt}}\tan\theta_{Lt} = 0 \tag{5}$$

$$\tan(R_{fL}\theta_{Lo}) - R_{ZL}\cot(\frac{R_{fL}\theta_{Lo}}{R_{\theta L}}) + \frac{Z_{Lo}}{Z_{Lt}}\tan(R_{fL}\theta_{Lt}) = 0 \tag{6}$$

where θ_{Lo} and θ_{Lt} are defined at f_2, and R_{ZL} (Z_{Lo}/Z_{Ls}), $R_{\theta L}$ (θ_{Lo}/θ_{Ls}) as well as R_{fL} (f_4/f_2) are the impedance ratio, the electrical length ratio and the ratio of the center frequencies of the two channels fed by the right part, respectively.

By solving (5) and (6), many selections for Z_{Lo}, R_{ZL}, $R_{\theta L}$, θ_{Lo}, Z_{Lt} and θ_{Lt} can be chosen to meet the matching condition. In order to simplify the design procedure, some parameters of the matching network can be preselected based on the analysis. First, $Z_{Lt} = 50\ \Omega$ and $\theta_{Lt} = 20^\circ$ are chosen because in this design the series transmission line (Z_{Lt}, θ_{Lt}) is only used to separate the two parts of network and thus can be arbitrarily selected. Then, in order to realize a large range of external quality factor (Q_e) of the filters, Z_{Lo} should be as large as possible, so in this design Z_{Lo} is preselected to be 131.4 Ω (corresponding width of the microstrip line on the proposed substrate is 0.3 mm). Therefore, R_{fL} is only affected by θ_{Lo}, R_{ZL} and $R_{\theta L}$ until now. Fig. 3 shows the design graph for the left part of the matching network based on (5) and (6). Once f_2 and f_4 are given, according to Fig. 3(a) a proper R_{ZL} with a specific R_θ can be obtained and at the same time θ_{Lo} can be confirmed according to Fig. 3(b). In general, all parameters of the matching network can be obtained once the design frequencies are set.

Similarly, parameters of the right part of matching network (θ_{Ro}, R_{ZR}, $R_{\theta R}$) can be also obtained according to Fig. 3 if f_1 and f_3 are given ($Z_{Rt} = 50\ \Omega$, $\theta_{Rt} = 20^\circ$ and $Z_{Ro} = 131.4\ \Omega$ are also preselected).

It should be mentioned that in practical design the loading effect of the resonators must be taken into consideration, and this will lead to a worse matching condition. The method of compensation by slightly adjusting the parameters of the matching network is used in the design, the detail process will be discussed in next Section.

III. BANDPASS FILTERS DESIGN

For the design of each channel bandpass filter, the primary question is to choose the proper resonators to generate the passbands of filters, because the spurious passbands of the bandpass filter can interfere with other filters' passbands.

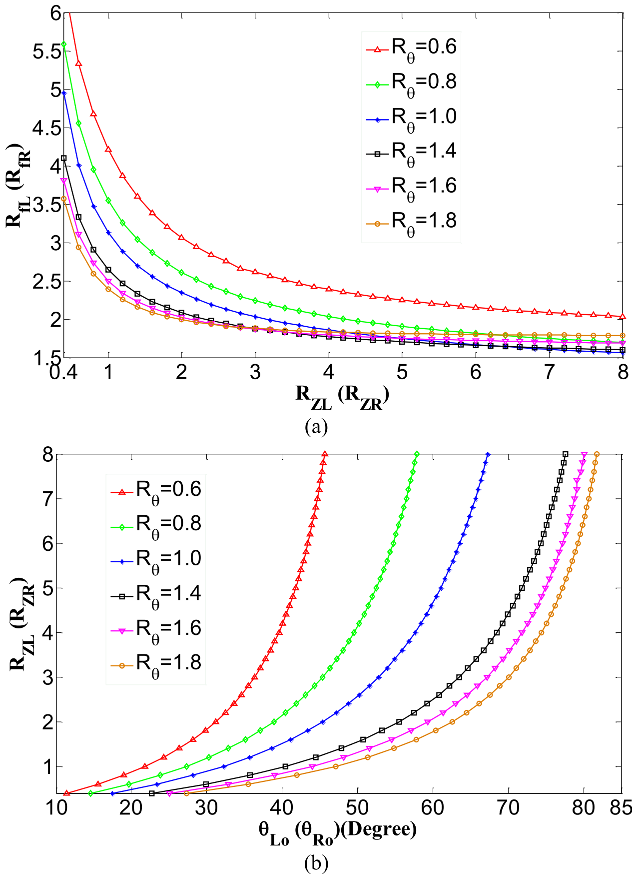

FIGURE 3. **Design graph of the matching network. (a) Solutions for R_f to R_Z with different R_θ. (b) Solutions for R_Z to θ_o with different R_θ.**

In order to prevent the passband of BPF D from operating at the spurious passbands of BPF A, BPF B and BPF C, the first spurious passbands of BPF A, BPF B and BPF C should be higher than the passband of BPF D. The half-wavelength uniform-impedance resonators and half-wavelength stepped impedance resonators are used to generate all the passbands of filters. Meanwhile, considering that the first spurious frequency of the half-wavelength uniform-impedance resonator is double of its fundamental resonant frequency, four useful cases are addressed below according to the various frequency ratios (f_4/f_3,f_4/f_2 and f_4/f_1).

Case 1 ($f_4/f_3 < f_4/f_2 < f_4/f_1 < 2$)*:* In this case, the half-wavelength uniform-impedance resonators can be used to realize bandpass filters for all channels, and all the spurious passbands of BPF A, BPF B, BPF C are higher than the passband of BPF D.

Case 2 ($f_4/f_3 < f_4/f_2 < 2 \leq f_4/f_1$)*:* In this case, the first spurious passband of BPF A will be lower than or equal to the passband of BPF D if the half-wavelength uniform-impedance resonators are used. Therefore, the half-wavelength stepped impedance resonators should be used to realize BPF A to make its spurious passband higher than the passband of BPF D and the half-wavelength uniform-impedance resonators can be used to realize bandpass filters for the right channels and BPF C.

Case 3 ($f_4/f_3 < 2 \leq f_4/f_2 < f_4/f_1$)*:* In the same way, the half-wavelength stepped impedance resonators should be used to realize BPF A and BPF B to make their spurious passbands higher than the passband of BPF D and the half-wavelength uniform-impedance resonators can be used to realize BPF C and BPF D.

Case 4 ($2 \leq f_4/f_3 < f_4/f_2 < f_4/f_1$)*:* Similarly, the half-wavelength stepped impedance resonators should be used to realize BPF A, BPF B and BPF C to make their spurious passbands higher than the passband of BPF D and the half-wavelength uniform-impedance resonators can be used to realize BPF D.

The half-wavelength stepped impedance resonator can control its first spurious frequency easily by reasonably choosing the ratio of impedance [23]. In addition, the hairpin-line structure is used in the bandpass filter design to realize strong coupling and a compact size.

In this paper, the circuits are fabricated on a substrate with dielectric constant $\varepsilon_r = 2.55$, loss tangent $\delta = 0.0029$, and thickness $h = 0.8$mm. Fig. 4 shows the layout of the proposed quadruplexer, where all the channels are third-order filters. The central passband frequencies (fractional bandwidths) of the four bandpass channels (0.0432-dB ripple level) are selected to be 1.8 GHz (5%), 2.2 GHz (6%), 3.5 GHz (3%) and 4 GHz (3%), corresponding to $R_{fL} = 1.82$ and $R_{fR} = 1.94$. Based on the analysis above, $R_{ZL} = 3.5$, $\theta_{Lo} = 66.2\circ$ (f_2), $R_{\theta L} = 1.4$, $R_{ZR} = 4.65$, $\theta_{Ro} = 51.6\circ$ (f_1), and $R_{\theta R} = 0.8$ are chosen according to Fig. 3. The initial dimensions (mm) of the network without load is obtained by the full wave simulation carried out by Zeland IE3D, which are listed in Table 1. The initial values are a bit different from the one acquired from Fig. 3 because of the dispersion and discontinuity. Meanwhile, the half-wavelength stepped impedance resonators are used to realize the first and second channel filters and the half-wavelength uniform-impedance resonators are used to realize the third and fourth channel filters based on $f_4/f_3 < 2 \approx f_4/f_2 < f_4/f_1$. But in the practical design of this quadruplexer, in order to realize a compact size, the quarter-wavelength uniform-impedance resonators are used to replace the first and third resonators in the filters of the first and second channel considering that $f_4/f_2 < f_4/f_1 < 3$.

TABLE 1. **Main dimensions of the proposed matching network.**

Parameter	L_1	L_2	W_1	W_2	L_4	L_5	W_4	W_5
No load	12.25	18.6	3.8	3.7	18.0	17.25	0.3	0.3
Load resonator	13.75	16.7	3.3	3.1	18.0	17.25	0.3	0.3

Since the central frequencies and bandwidths of each channel are given, the physical parameters of the resonators can be obtained. Fig. 5 shows the extracted input external quality factor and coupling coefficients with respect to the corresponding physical parameters.

Take the right part of quadruplexer as an example to show the design process of bandpass filters. The input external

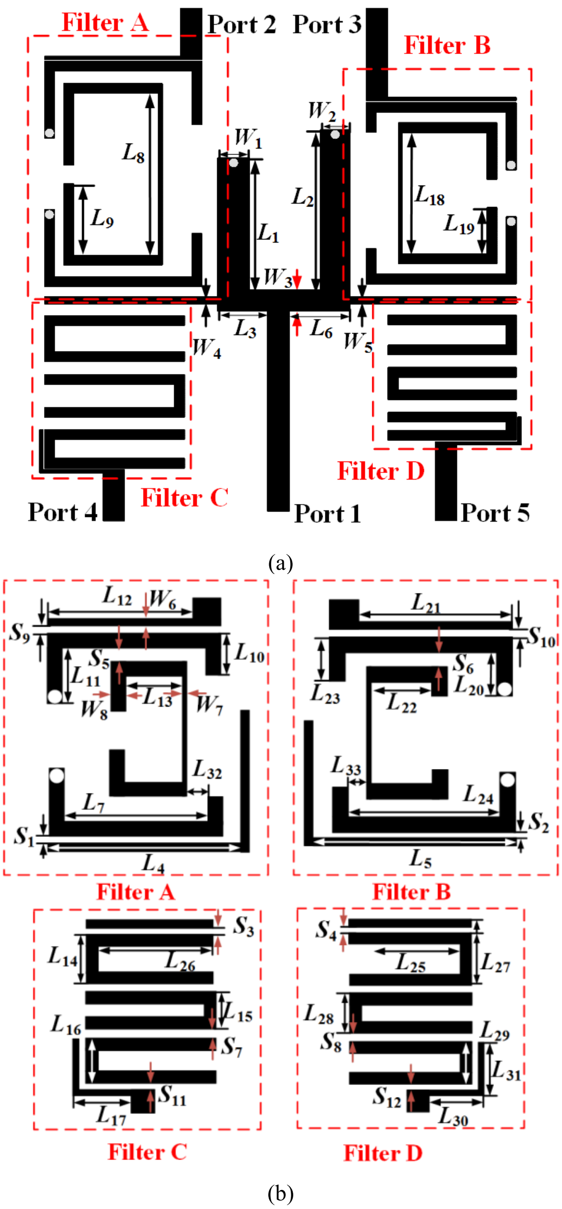

FIGURE 4. Layout of the proposed quad-channel diplexer (a) the main circuit (b) the detailed diagram of constituent elements.

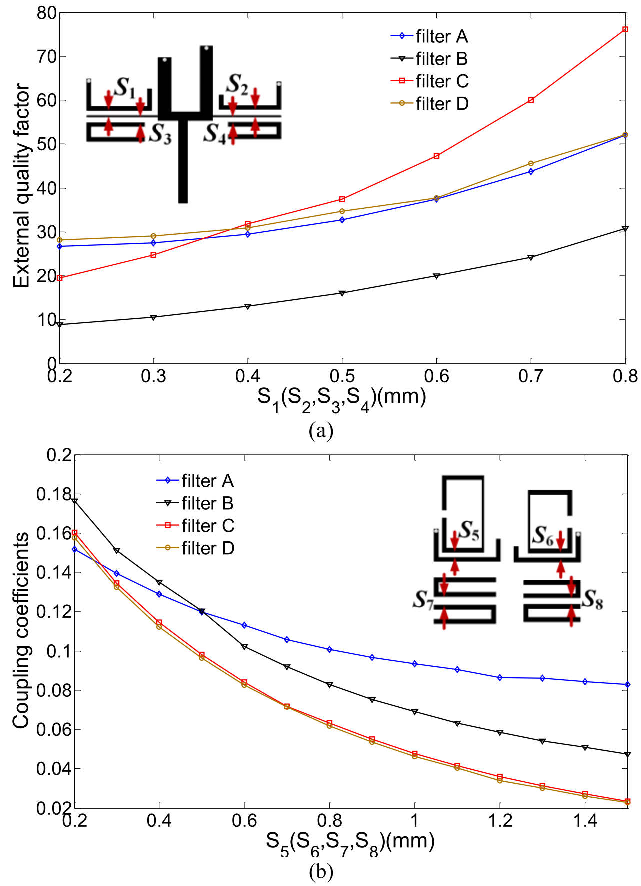

FIGURE 5. Extracted design parameters with respect to the corresponding physical parameters. (a) the input external quality factor. (b) Coupling coefficients.

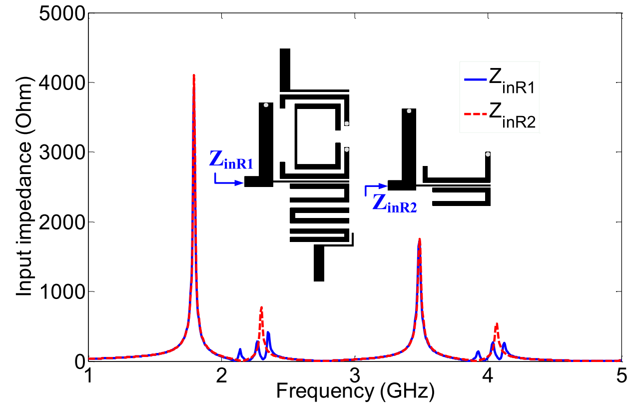

FIGURE 6. Simulated input impedance under different loading conditions.

quality factors of BPF *B* and BPF *D* are calculated as 14.19 and 28.39 with a third-order Chebyshev prototype according to the given bandwidth. Therefore, the dimensions of gaps between open-circuited stub and its adjacent resonators (S_2 and S_4) are set as 0.45 mm and 0.30 mm according to the input external equality factor as shown in Fig 5(a). Note that only the loading effect of the adjacent resonators coupled to open-circuited stub should be taken into consideration, but not all the resonators from bandpass filters. The resonators of BPF *B* and BPF *D* which are not coupled to open-circuited stub are nearly no influence on Z_{inR} at f_1 and f_3, because these resonators don't resonate at f_1 (1.8 GHz) and f_3 (3.5 GHz). Fig. 6 shows the simulated results of the input impedance under different loading conditions and the input impedances of different structure are almost the same around f_1 and f_3, which verifies the analysis. Therefore, it is only the adjacent resonators' influence on the matching network that should be considered.

In order to compensate the loading effect of the resonators, the input impedance of right part of the network is simulated and shown in Fig. 7 [22]. It can be found that $|Z_{inR}|$ is at

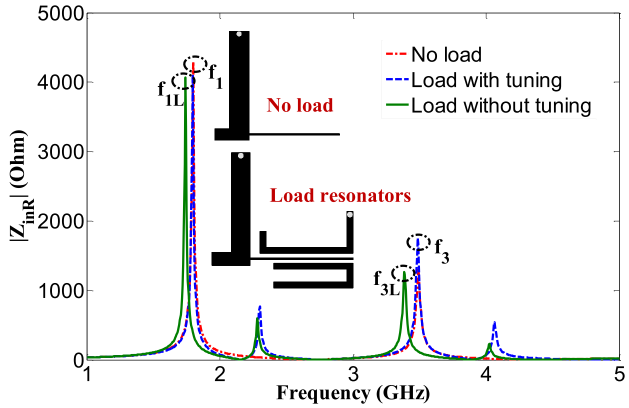

FIGURE 7. Simulated input impedance of right part of network in different condition.

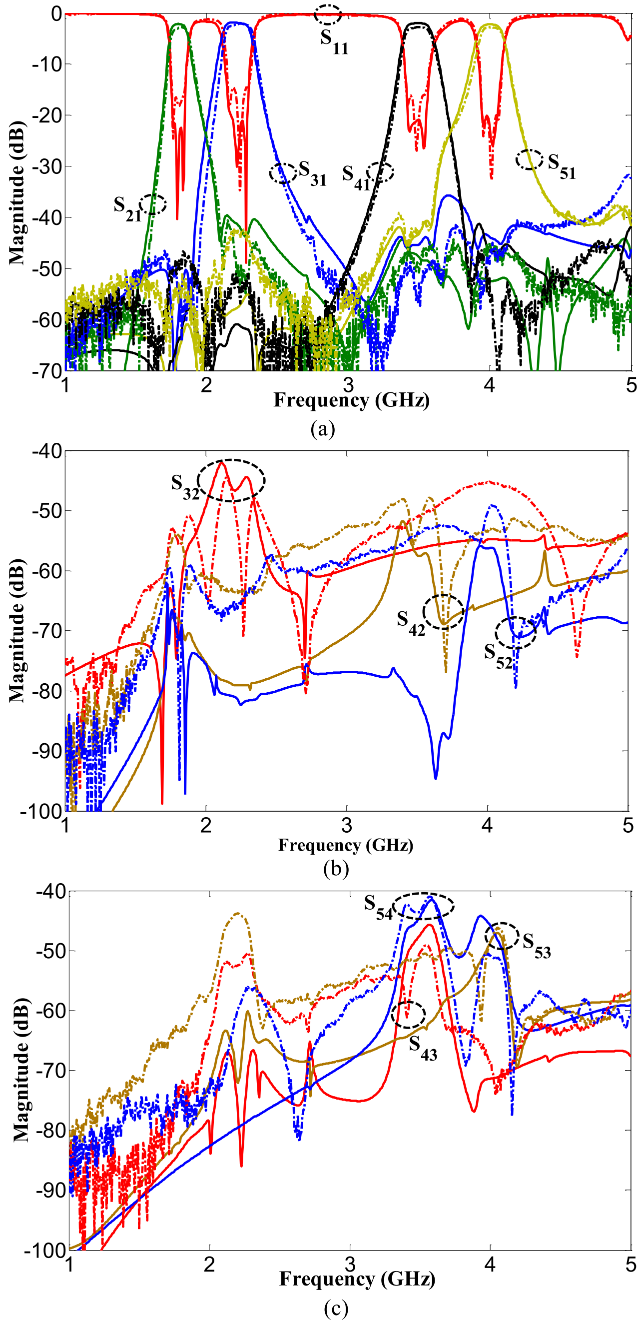

FIGURE 8. Simulated and measured results of the fabricated quadruplexer (solid lines: simulated results; dash-dotted lines: measured results). (a) S_{11}, S_{21}, S_{31}, S_{41} and S_{51}. (b) S_{32}, S_{42} and S_{52}. (c) S_{43}, S_{53} and S_{54}.

peak value at 1.8 GHz (f_1) and 3.5 GHz (f_3) if no resonator is loaded, which meets the matching condition. When the uniform impedance resonator and the stepped impedance resonator are loaded, the peak values of input impedance are deviated a little from f_1 and f_3, as shown in Fig. 7 The new frequencies of the peak value are marked as f_{1L} and f_{3L}. These deviations can be compensated by adjusting the length and impedance of the short-circuited stub (θ_{Rs}, Z_{Rs}) without changing the open-circuited stub (θ_{Ro}, Z_{Ro}). By properly changing θ_{Rs} and Z_{RS} (Table 1 also shows the dimensions of right part network with loaded resonators after tuning), the peak values can be tuned to be f_1 and f_3 again, as shown in Fig. 7. If the new frequency ratio (f_{3L}/f_{1L}) is larger than (f_3/f_1), Z_{RS} should be reduced to obtain a higher impedance ratio according to Fig. 3, while θ_{Rs} should be accordingly tuned to change the position of the peak value. It is worthy to mention that the input external quality factor will be slightly changed when the parameters of the matching network are adjusted, and this little deviation can be easily tuned by adjusting the gaps between open-circuited stub and its adjacent resonators.

At last, since the loading effect of resonators has been compensated by adjusting the parameters of the matching network, BPF *B* and BPF *D* can be designed independently while using the adjusted matching network as the input feeding structure. Similarly, the coupling coefficients of BPF *B* and BPF *D* are calculated as 0.062 and 0.031, so the dimensions of gaps between the adjacent resonators (S_6 and S_8) are set as 1.2 mm and 1.3 mm according to the Fig 5(b) to meet the corresponding channel bandwidths. The dimensions of gaps between the resonators and output feeding lines can be also easily obtained.

In the same way, the left part of the quadruplexer can be also designed easily.

IV. QUADRUPLEXER DESIGN

Based on the foregoing design process, a quadruplexer with compact size and high isolation is presented. Table 2 shows the main optimized parameters (mm) of quadruplexer in Fig. 4. The whole design process of quadruplexer can be concluded as follows: 1) Choose the proper resonators and obtain the initial parameters of matching network once all passband central frequencies are given. 2) Then take the loading effect into consideration and adjust the parameters of the matching network to compensate the loading effect. 3) Design each channel filter using the adjusted matching network as the feeding structure, tune the coupling strength to meet the required bandwidth of each passband.

Fig. 8 shows the simulated and measured results. The measured minimum insertion losses for the four channels are

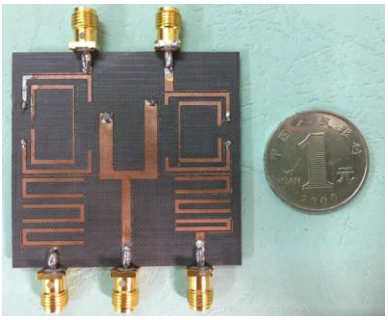

FIGURE 9. Photograph of the fabricated quadruplexer.

TABLE 2. Main dimensions of the proposed quadruplexer.

L_3	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}	L_{15}	L_{16}	L_{17}
5.2	6.36	14.3	16.9	7.44	6.6	9.0	14.12	8.83	4.74	4.43	3.99	6.6
L_{18}	L_{19}	L_{20}	L_{21}	L_{22}	L_{23}	L_{24}	L_{25}	L_{26}	L_{27}	L_{28}	L_{29}	L_{30}
12.7	4.86	8.0	13.37	8.83	3.05	13.57	12.28	13.53	4.14	3.34	2.89	6.68
L_{31}	L_{32}	L_{33}	W_3	W_6	W_7	W_8	S_1	S_2	S_3	S_4	S_5	S_6
2.91	3.1	2.35	2.2	0.3	0.39	1.00	0.31	0.57	0.46	0.39	1.25	1.1
S_7	S_8	S_9	S_{10}	S_{11}	S_{12}							
1.33	1.35	0.2	0.25	0.2	0.2							

TABLE 3. Comparison with previous work FBW: Fractional bandwidth; IL: Insertion loss; RL: Return loss; ISO: Isolation

Ref.	Pass-band	Order	FBW (%) / IL(dB)	RL (dB)	ISO (dB)	Size (λg^2)
[4]	3	4	5.35/5.6/5.04	>10	>32.5	0.7× 0.83
			3.38/2.94/3.23			
[5]	3	5	12.2/4.25/7.3	>10	>35	0.97× 1.13
			< 3			
[7]	4	4	6.3/6.45/6.34/6.6	>15	>34	1.14×1.13
			3.1/2.86/2.86/2.76			
[8]	4	2	3.5/3.5/4/4	>10	>25	0.59×0.31
			2.9/ 2.88/2.75/ 2.7			
[10]	4	2	3.4/2/2.5/2.5	>11	>31	0.16×0.31
			3.05/3.1/3.14/3.23			
This work	**4**	**3**	**7.8/9.1/5.7/5.0**	**>15**	**>40**	**0.44× 0.45**
			2.8/2.1/ 2.8 /2.8			

2.8 dB, 2.1 dB, 2.8 dB and 2.8 dB, while the return losses are 16.5 dB, 14.5 dB, 16 dB and 20 dB, respectively. The measured 3 dB bandwidths are found to be 1.74 to 1.88 GHz (7.8%), 2.13 to 2.33 GHz (9.1%), 3.4 to 3.6 GHz (5.7%) and 3.92 to 4.12 GHz (5.0%), respectively. The measured isolation is larger than 40 dB between 1-5 GHz. Fig. 9 shows the photograph of the fabricated quadruplexer, the size of which is 50.0 mm × 51.5 mm. Table 3 shows the comparison with previous work in term of performance and circuit size, where λ_g is the guided wavelength at the first channel frequency. Compared with previous work, this work can provide a higher isolation and moderate circuit size. In addition, each channel filter of the quadruplexer can be designed independently once the passbands frequencies and bandwidth are given, which greatly simplifies the quadruplexer designs.

V. CONCLUSION

A systematic design procedure of quadruplexer by using the novel matching network is presented in this paper. By slightly tuning parameters of the matching network to compensate the loading effects of resonators, each channel bandpass filter of the quadruplexer can be designed independently. A compact and high isolation quadruplexer is realized by the connection of bandpass filters without much tuning. For validation, a quadruplexer is designed, fabricated and measured. Coherence between the simulated and measured results proves the effectivity of the matching network.

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QIANG SHAO received the B.S. degree in information engineering from Shantou University, Shantou, China, in 2015. He is currently pursuing the Ph.D. degree with the South China University of Technology. His research interests include microwave filters and associated RF circuits for microwave and millimeter-wave applications.

FU-CHANG CHEN (M'12) was born in Fuzhou, China, in 1982. He received the Ph.D. degree from the South China University of Technology, Guangzhou, China, in 2010. He is currently an Associate Professor with the School of Electronic and Information Engineering, South China University of Technology. His research interests include the synthesis theory and design of microwave filters and associated RF modules for microwave and millimeter-wave applications.