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A COMPACT MICROSTRIP QUADRUPLEXER USING SLOTLINE STEPPED IMPEDANCE STUB LOADED RESONATORS

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Abstract—In this paper, a novel compact quadruplexer is implemented by using slotline stepped impedance stub loaded resonators (SISLRs) in ground plane. Four folded dual-mode slotline SISLRs with one input and four output coupled line structures are designed at different frequencies for the quadruplexer operation. By properly adjusting the geometrical parameters of a single dual-mode slotline SISLR, its first two resonant frequencies can be controlled, and thus it can be utilized to implement a second-order bandpass filter when these resonant frequencies are suitably assigned. Furthermore, because the proposed quadruplexer utilizes the distributed coupling technique, a small circuit size can be obtained. As a result, the proposed quadruplexer occupies an extremely small area, i.e., $0.22\lambda_0 \times 0.25\lambda_0$ ($0.36\lambda_g \times 0.41\lambda_g$). Finally, good agreement between measurement and EM simulation verifies the design method successfully.

1. INTRODUCTION

Since multi-band and multi-service mobile communication systems play an important role in modern wireless applications, the research interest in multiplexers is increasing. To satisfy strict system requirements, multiplexers with high compactness, low loss, flexible passband frequencies and high isolation are always necessary. To this end, various design approaches have been proposed [1–17].

In [1], a novel high-isolation multiplexer utilizing stepped-impedance resonators (SIRs) was reported, which had a large circuit

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size due to the additional matching network. In [2], the authors presented low-temperature co-fired ceramic (LTCC) diplexer and triplexer, designed based on a parallel-coupled line filter connected with a capacitor. Since size reduction has become a significant issue in future mobile communication systems, these multiplexers are not small enough to be used. To reduce the circuit size, it is necessary to select proper resonators to reduce the circuit size since resonators are the basic components of a filter. For example, diplexers based on stepped impedance resonators (SIRs) [3–6], miniaturized open-loop resonators [7], spiral inductor resonators [8] and dual-mode SIR [9] have been proposed. In addition, two hairpin line filtering structures were proposed to form a diplexer, and a tapped open stub was used to introduce an attenuation pole to suppress the spurious response and achieve a high isolation between two bands [10]. In order to further reduce the circuit size, a common resonator configuration is proposed [11–13]. In this configuration, bandpass filters share the common resonator. However, the passband frequencies have to 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, numerous techniques were proposed to design microstrip multiplexers [14–25].

In this paper, a novel quadruplexer employing slotline stepped impedance stub loaded resonator is presented. Each channel of the proposed quadruplexer can be implemented with only one resonator, showing a small circuit size. Moreover, because the signal energy of each filter channel can be coupled through a common input coupled-line structure, the additional five-pole matching network is not needed anymore. As a result, the proposed quadruplexer occupies an extremely small area and achieves a significant size reduction.

2. RESONANCE PROPERTY OF THE SLOTLINE SISLR

Figure 1(a) shows the configuration of the proposed resonator. The substrate used in this study has a relative dielectric constant of 2.65, a thickness of 1 mm and a loss tangent of 0.004. The thickness of the metal is 0.035 mm. The slotline SISLR has different characteristic impedances of Z_1, Z_2 and Z_3 with the corresponding electrical lengths of θ_1, θ_2 and θ_3. It should be noticed that the slotline SISLR has opposite impedance characteristic compared with microstrip SISLR, which means that a narrow gap-width results in a lower impedance, while a wide gap width results in a higher impedance. As it is

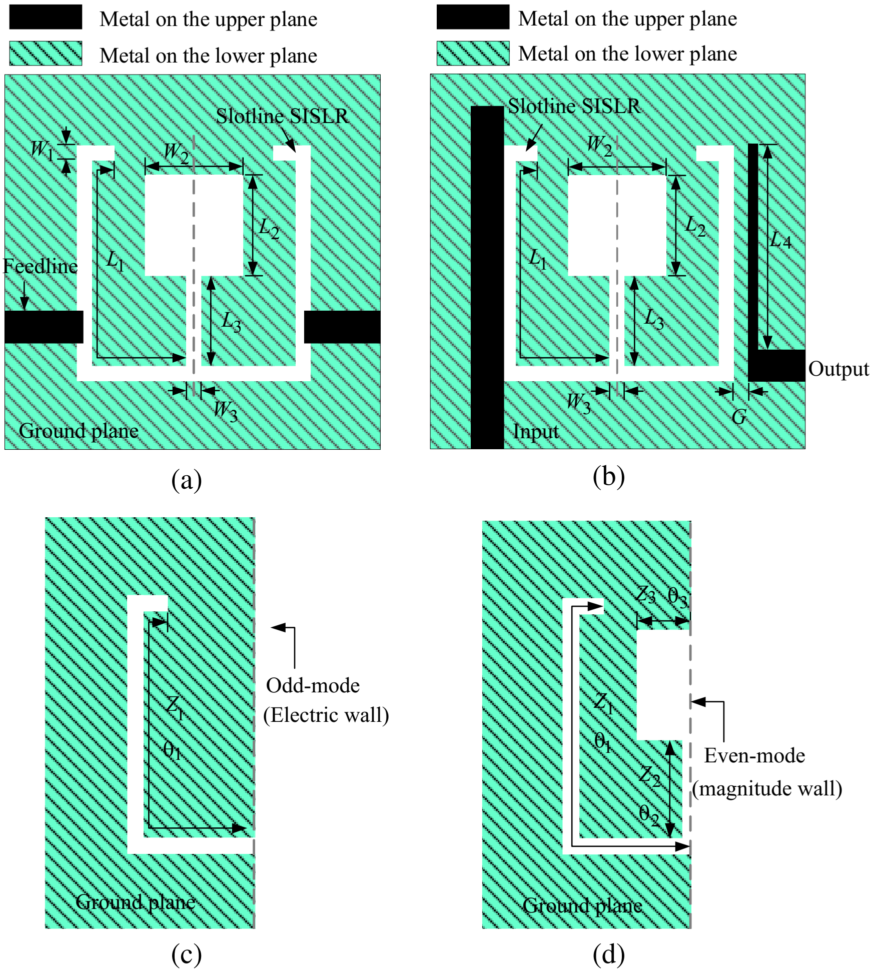


Figure 1. Circuit models for (a) dual-mode slotline SISLR. (b) Second-order slotline SISLR BPF. (c) Odd-mode for the slotline SISLR. (d) Even-mode for the slotline SISLR.

symmetric, the resonator can be analyzed by the even- and odd-mode method, respectively [26–29].

From the resonance condition ($Y_{in} = 0$), when the odd-mode (Figure 1(c)) is excited, the resonant frequencies can be obtained as follows:

$$f_{odd} = \frac{c}{4L_1\sqrt{\varepsilon_r}} \tag{1}$$

where c is the light speed in free space, and ε_r denotes the effective dielectric constant of the substrate. For even-mode (Figure 1(d)), the resonant frequency can be obtained as:

$$R_s \tan\theta_1 \tan\theta_2 \tan\theta_3 = \tan\theta_1 + R_z \tan\theta_2 + R_z R_s \tan\theta_3 \qquad (2)$$

where R_z and R_s are the impedance ratios, which are defined as $R_z = Z_1/Z_2$ and $R_s = Z_2/Z_3$, respectively. So, the fundamental frequency and the other higher-order mode frequencies can be determined by properly choosing a suitable combination of the admittance and the length ratios of the slotline SISLR. Besides that, It can be found that the larger are the impedance ratios, the longer distance is between the first and second spurious frequencies.

In addition, it can be observed from formulas (1)–(2) that the first two resonant modes of the slotline SISLR are non-coupling to each other. So the resonant frequencies of the two modes could be controlled separately. For the demonstration, frequency response simulation of the resonators with a weak coupling was carried out using the full-wave simulator IE3D. The parameters are: $L_1 = 22.7$ mm, $L_2 = 6.5$ mm, $L_3 = 6.3$ mm, $W_1 = 0.7$ mm, $W_2 = 7.4$ mm, $W_3 = 0.8$ mm. As shown in Figure 2, the even-mode resonant frequency can be adjusted by changing L_3 while keeping other dimensional parameters fixed. Meanwhile, the odd-mode frequency is slightly changed because the layout of the SISLR has been slightly changed. Thus, the first two resonant frequencies of the slotline SISLR can be well controlled by adjusting its structural parameters. This dual-mode characteristic is attractive because a simple second-order BPF can be implemented using a single dual-mode resonator, and hence the number of resonators required for a given order of filter can be reduced, resulting in a compact size.

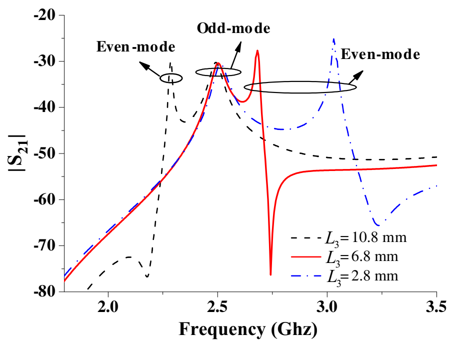


Figure 2. Resonant properties of the dual-mode slotline SISLR against L_3.

In addition, similar to the stepped impedance stub loaded resonator, the position of the inherent zero could be controlled to be located at the lower or higher side of the two modes while the resonant frequency of the odd-mode is lower or higher than the even-mode. This distinct characteristic could be used to improve the frequency selectivity.

3. BASIC THEORY OF QUADRUPLEXER

Figure 3(a) describes the coupling schemes of the conventional quadruplexer, where each black node and white node represent a single resonator and source/load, respectively. The solid lines between nodes represent the direct coupling path. Each channel can be designed independently. However, the circuit size is very large. The proposed one is shown in Figure 3(b), which can be implemented with only four dual-mode resonators. Moreover, the signal energy of each filter channel can be coupled through a common input coupled-line structure and, thus, no additional five-pole matching network is needed for the quadruplexer design. As a result, the proposed quadruplexer occupies an extremely small area and achieves a significant size reduction. Hence, here we choose the structure shown in Figure 3(b) to achieve the desired quadruplexer.

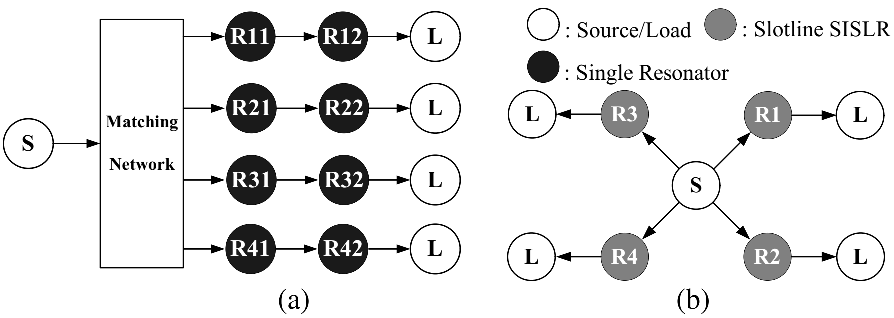


Figure 3. Coupling scheme of a quadruplexer with four two-order BPFs. (a) Conventional structure. (b) Proposed structure.

4. DESIGN OF A QUADRUPLEXER BASED ON SLOTLINE SISLR

The circuit configuration of the quadruplexer is shown in Figure 4. As can be seen, the quadruplexer is composed of four folded slotline

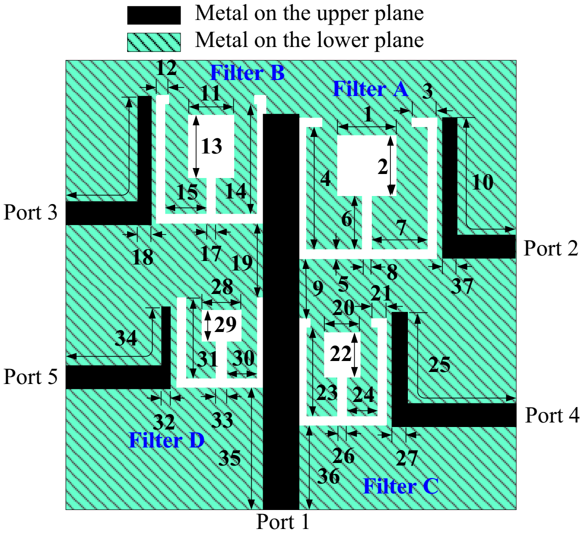


Figure 4. Layout of the proposed quadruplexer.

SISLR filters with one input and four output coupled-line structures (filter A, B, C and D). Herein, each resonator can provide a path coupled signal energy from source to loads at around resonance and no coupling between resonators is introduced. It should be noted that each filter can be designed individually to generate the desired passband before combining the four as a quadruplexer. Besides that, it deserves mentioning that the quadruplexer, which has a second-order bandpass response, is composed of four dual-mode resonators. Thus, about four resonator spaces are saved as compared with the conventional second-order bandpass quadruplexer based on the uniform impedance resonators. By combining the four filters and making use of a common input coupled-line structure, size reduction can be significantly achieved.

The design procedure for the quadruplexer is given as follows:

1) Design four single-band second order bandpass filters. The circuit model is shown in Figure 1(b). The passband bandwidth of each narrow-band dual-mode resonator filter can be determined by properly assigning the two resonant modes of the resonator at adjacent frequencies into passband. The absolute bandwidth of the second-order filter based on the dual-mode slotline SISLR is close to the first two resonance frequencies and the center frequency is approximately the arithmetic average of them. Thus, the physical dimensions of the four dual-mode resonators can then

be easily determined based on the desired center frequencies and bandwidths.

2) To determine the input/output (I/O) coupling structures. As known to all, a stronger coupling can be obtained with a smaller gap, a narrower coupled-line, or a longer coupled-line. Thus, given, i.e., 50-ohm line, the gaps (G) and lengths (L_4) of the I/O coupled-lines are then adjusted to achieve the given bandwidth.

3) Combine the four bandpass filters into a quadruplexer by sharing one input feeding line. In this design, in order to have a compact configuration, filters A and B (the lowest and the second lowest frequency ones) are firstly placed on the different sides near the open end of the input coupled-line. Then filters C and D are placed in the next available areas along the input coupled-line with stronger currents at their operating frequency bands. It should be noted that the loading effect between channels is very small. The simulated results of a single-band bandpass filter (2.4 GHz), a diplexer (2.4 and 3.5 GHz), a triplexer (2.4, 3.5, and 4.2 GHz), and a quadruplexer (2.4, 3.5, 4.2, and 5.2 GHz) are shown in Figure 5. From the single-band bandpass filter fixed at the upper right to the quadruplexer as shown in Figure 5, the channels are constructed one by one clockwise. For example, the only difference between the quadruplexer and the triplexer is the added dual-mode resonator and the output feeding line at port 5 for the fourth channel. The loading effect is negligible since the newly added resonators have little effect on the existing channels. Moreover, it can be further extended to develop a multiplexer with more operation channels by inserting more filter sections.

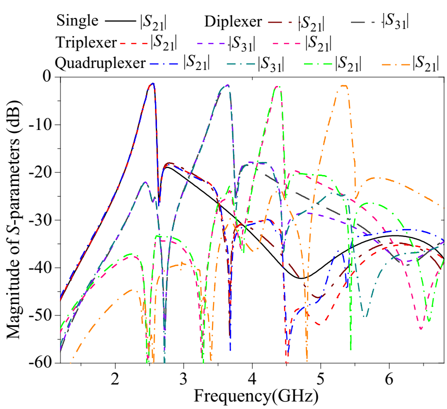


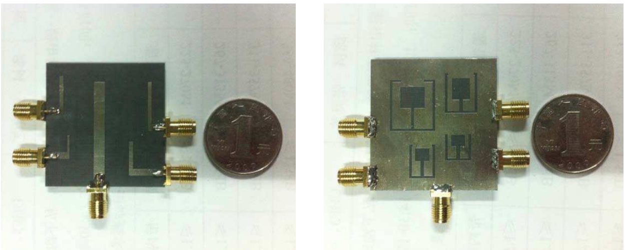
Figure 5. Simulated S parameters of a single-band BPF, diplexer, triplexer and quadruplexer.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Following the synthesis procedure in Section 4, a compact size and high isolation second-order bandpass quadruplexer is fabricated, and the design geometric parameters are listed in Table 1. The proposed quadruplexer was measured by an Agilent's 8719ES Network Analyser. Figure 6 is a photograph of the fabricated quadruplexer. The size of the proposed quadruplexer is $28\,\text{mm} \times 31\,\text{mm}$, i.e., only about $0.22\lambda_0 \times 0.25\lambda_0$ ($0.36\lambda_g \times 0.41\lambda_g$), where λ_0 and λ_g are the free-space wavelength and guided wavelength on the substrate at the center frequency of

Table 1. Optimal dimensions (in mm) of each part of the quadruplexer.

Part Number	1	2	3	4	5	6	7	8	9	10
Dimensions	7.4	6.5	3.4	14.3	0.7	6.3	5.8	0.8	4.1	18.2
Part Number	11	12	13	14	15	16	17	18	19	20
Dimensions	5.4	1.0	6.6	10.9	3.7	14.7	1.0	1.3	6.4	4.3
Part Number	21	22	23	24	25	26	27	28	29	30
Dimensions	0.9	3.9	8.8	2.7	19.1	1.0	1.3	4.1	3.5	2.6
Part Number	31	32	33	34	35	36	37			
Dimensions	7.3	0.7	1.1	12.5	9.1	3.8	1.2			



(a) (b)

Figure 6. Photograph of the fabricated quadruplexer. (a) Top view. (b) Bottom view.

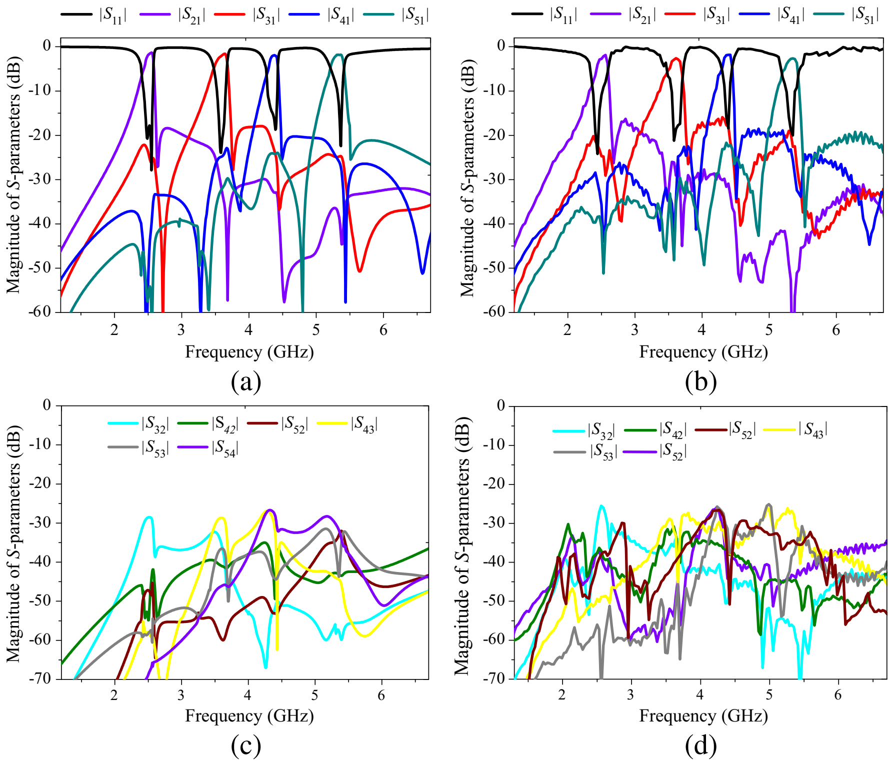


Figure 7. Response of the fabricated quadruplexer. (a) Simulated insertions and return losses. (b) Measured insertions and return losses Return losses. (c) Simulated isolation characteristic. (d) Measured isolation characteristic.

channel one, respectively. The simulated and measured results are shown in Figure 7. The simulated centered and fractional bandwidth are $f_{0a} = 2.5\,\text{GHz}$, $f_{0b} = 3.5\,\text{GHz}$, $f_{0c} = 4.3\,\text{GHz}$, $f_{0d} = 5.3\,\text{GHz}$, and $FBW_a = 4.7\%$, $FBW_b = 5.2\%$, $FBW_c = 3.3\%$, $FBW_d = 3.7\%$, respectively, where the subscripts a, b, c and d denote the first, second, third and fourth channel filter, respectively. In the measurements, the four channels are centered at 2.55/3.59/4.34/5.32 GHz, with the fractional bandwidths of 4.8%, 5.2%, 3.4% and 3.6%, respectively. The measured insertion losses at the channel center frequencies are 1.85 dB, 2.53 dB, 1.82 dB and 2.68 dB, respectively, while the measured passband return losses are all better than 17 dB. The insertion loss would be mainly attributed to the conductor loss. The measured isolations amongst channels were over 26 dB as shown in Figure 7(d).

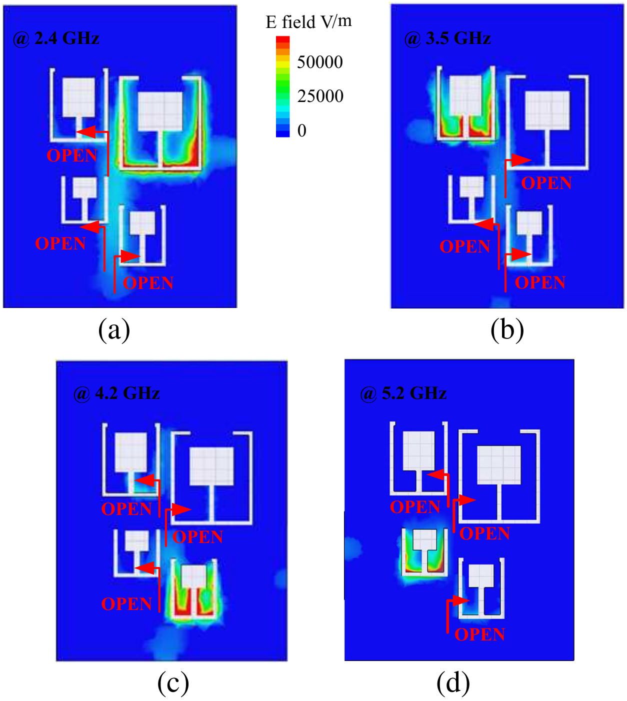


Figure 8. Electric field distributions for (a) the first channel @ 2.4 GHz. (b) The Second channel @ 3.5 GHz. (c) The third channel @ 4.2 GHz. (d) The fourth channel @ 5.2 GHz.

The electric field distributions of the proposed quadruplexer are shown in Figure 8. Figure 8(a) shows that the high current density is located at the first channel (2.5 GHz) whereas the other passband channels are considered as open circuits. Contrarily, Figure 8(b) presents that the high current density is located at the second passband channel (2.45 GHz) whereas the other passband channel is considered as open circuit. The current density distribution of the third passband channel and the fourth passband channel shown in Figures 8(c) and 8(d) respectively are similiar as those of the first two passband channels. These performances verify that the quadruplexer has high isolations.

Table 2 compares the performances of the proposed quadruplexer with the previous multiplexers. As it can be seen, the proposed UWB BPF has the advantage of high isolation and compact size. As a result, it is quite useful in future wireless communication system.

Table 2. Comparison between the proposed quadruplexer and other multiplexers.

Ref.	Channels	Filter order	Isolation (dB)
[13]	2	4	> 30
[14]	3	4	> 33
[15]	6	4	> 30
[16]	4	4	> 35
[17]	3	3	> 35
This work	4	2	> 26
Ref.	**Passband insertion loss (dB)**	**Fractional bandwidth (%)**	**Circuit size (λ_0^2)**
[13]	2.8/3.2	3.8/3.3	0.19×0.31
[14]	3.4/3.6/3.6	5.4/5.6/5	0.43×0.51
[15]	2.2/3.1/3.2/2/2.8/3	10/10/10/10/10/10	1.42×0.56
[16]	2.3/2.6/2.5/2.5	6.5/7/6.6/7.5	0.44×0.48
[17]	2.7/2.5/1.8	6.6/7.3/8.2	0.12×0.4
This work	1.85/2.53/1.82/2.68	4.8/5.2/3.4/3.6	0.22×0.25

6. CONCLUSION

In this study, a simple and efficient method to design a compact size and high isolation quadruplexer is presented. The detailed design procedure is given. By locating the slotline SISLR of each channel properly, the harmonics of the resonators can be suppressed effectively. Furthermore, the loading effect among the four channels is negligible, so that the implementation of a quadruplexer becomes convenient. Moreover, the passband frequencies can be placed arbitrary unless the center frequencies of any two out of the four channels are very close and overlap with each other. The proposed configuration with more channels is ready to be applied to multiplexers. The above features make the proposed scheme attractive in multiplexer design. Therefore, these circuits are particularly suitable for multiband and multiservice applications in future mobile communication systems.

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