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LTCC Filtering Rat-Race Coupler Based on Eight-Line Spatially-Symmetrical Coupled Structure

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ABSTRACT In this paper, a compact filtering rat-race coupler implemented in low-temperature co-fired ceramic (LTCC) technology is presented. In order to reduce the dimensions, the schematic and the coupling topology of a planar filtering rat-race coupler are first studied and then simplified to fit the 3-D multilayer LTCC structure. An eight-line spatially symmetrical coupled structure is, therefore, proposed to obtain the required coupling topology between resonators. Thus, the filtering rat-race coupler can be constructed only by using four resonators, which is only half that of the planar one. Consequently, the size could be reduced substantially. For validation, a design example centered at 3.5 GHz is simulated, fabricated, and measured. All the measured results are in good agreement with the full-wave simulation results. Besides, the size of the circuit is only $3.8 \times 4 \times 2.1$ mm^3, which demonstrates that by employing the eight-line spatiallysymmetrical coupled structure, the proposed rat-race coupler obtains good performance and compact size.

INDEX TERMS Rat-race coupler, low temperature co-fired ceramic (LTCC), filter, eight-line spatially-symmetrical coupling structure.

I. INTRODUCTION

Rat-race coupler is an essential component in many applications, such as balanced amplifiers, mixers and feed networks of antenna arrays [1], [2]. The conventional rat-race coupler is composed of three quarter wavelength and one three quarters wavelength transmission lines which occupies a large area. As a consequence, various methods to minimize the rat-race coupler have been reported. In [3]–[6], the transmission line sections in rat-race coupler are replaced with the complementary-conducting-strip lines [3], stub-loaded transmission lines [4], step-impedance sections [5], and slow-wave coupled lines [6] respectively. Compared with the conventional rat-race coupler, the overall size of these designs is effectively reduced. Also, phase inverters [7] and synthetic transmission lines [8] are proposed to shorten the length of the transmission lines. These structures utilize the cross of two transmission lines or defected ground structures which cannot be implemented easily on the single layer structure and the size reduction is limited. In order to further reduce the dimensions as well as overcome the shortages of planar structure, low temperature co-fired ceramic (LTCC) technology is therefore a good choice. Some 3-D rat-race couplers are demonstrated in [9]–[11]. They employ 180° coupled lines [9], T-equivalent sections [10] and lumped π-cells [11] in the horizontal and vertical layouts to design the component. Thus, considerable size reductions are observed.

In many applications, a rat-race coupler is cascaded with bandpass filters (BPFs). However, it is a great challenge to reduce the overall size of the cascaded components. Thus, co-design of two components which avoids interconnection mismatching and processes high integration has been presented and investigated [12], [13]. In order to get the dual functions of rat-race couplers and BPFs, the $\lambda/4$ and $3\lambda/4$ transmission lines of rat-race couplers are replaced by the resonators with electric and magnetic couplings [14]–[20]. The used resonators include quarter-wavelength resonators [14], [15], stepped-impedance resonators [16], dual-mode stub-loaded resonators [17], net-type resonators [18] and hairpin resonators [19]. In addition to size reduction, K and –K inverters with the filtering function are integrated into rat-race coupler to suppress harmonics simultaneously [20]. Good selectivity is observed and the stopband is extended to $5f_o$.

Similar to the single-function LTCC rat-race couplers [21], [22] or BPFs [23], [24], co-design of the rat-race coupler and BPF can also be implemented in LTCC technology to obtain more compact size. In [25], a LTCC filtering rat-race coupler is realized by cascading lumped filtering balun and power divider. However, the self-resonance of lumped elements limits their applications. In [26], magic-T with bandpass response operating at 24 GHz is implemented in LTCC technology. The in-phase and out-of-phase responses are accomplished by using the even and odd resonating modes of SIW cavities. But the cross sectional area is still relatively large which is about 1.18 $\lambda_g \times 1.26 \lambda_g$.

In this paper, a compact filtering rat-race coupler using distributed resonators is presented in LTCC technology. By using the proposed eight-line coupling structure in the 3-D technology, the device is composed of only four half-wavelength resonators. As compared to the planar filtering rat-race coupler in [20], the number of resonator is cut by half. Among them, every resonator is spatially coupled with other two resonators to realize the desired coupling topology which cannot be realized by planar circuit. Based on the proposed coupling scheme, the dual-function device is designed with the filter and rat-race coupler performance. The simulated and measured results are given to verify the proposed idea.

II. MECHANISM OF THE FILTERING RAT-RACE COUPLER

Fig.1 (a) shows the structure of conventional rat-race coupler which is composed of three λ/4 transmission lines and one 3λ/4 line section with 70.7 Ω characteristic impedance. In [20], the open-loop filters are integrated in the conventional coupler, aiming to obtain the dual functions of rat-race coupler and BPF. As investigated in [27] and [28], there are two types of open-loop filters according to the feeding positions. When the feeding positions are anti-symmetrically placed at the BPF as shown in Fig.1 (b), it is named as 0° feed structure [27] and has −90° phase delay at the center frequency [28]. As for the non 0° feed structure in Fig.1(c), the feeding lines are located symmetrically and the phase delay from the input port to the output port is 90°. When the two types of open-loop filters are matched to 70.7 Ω, they could replace λ/4 and 3λ/4 transmission lines in Fig. 1(a). By using this method, a planar rat-race coupler with BPF response is realized as depicted in Fig. 1(d).

The planar filtering rat-race coupler is composed of four open-loop filters which processes eight half-wavelength resonators. However, when it is designed on the multilayer technology, the eight λ/2 resonators still occupy bulky size. In order to further reduce the area and take advantages of

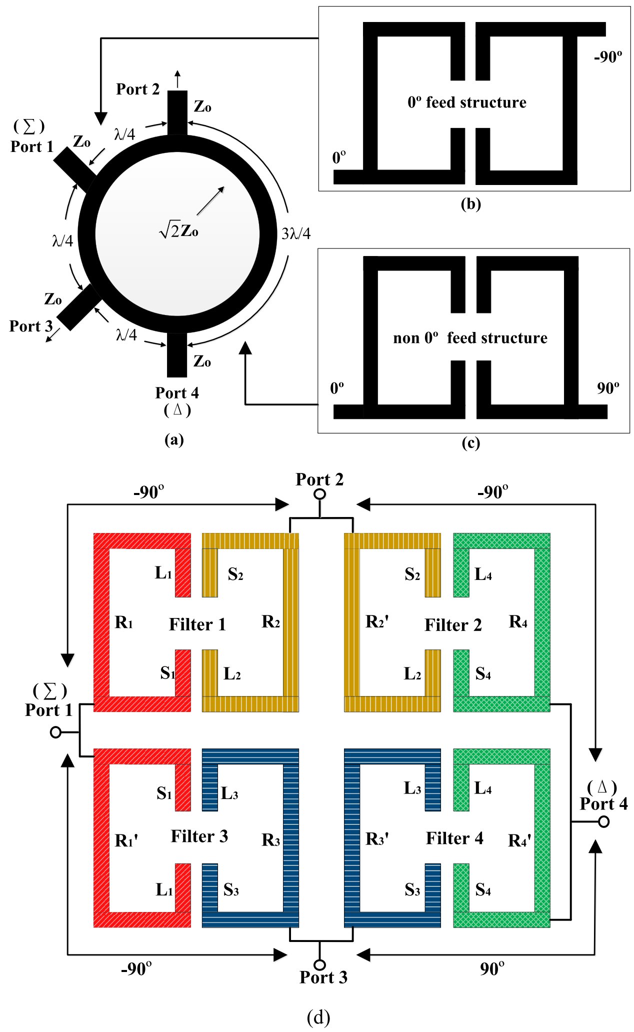

FIGURE 1. (a) Conventional rat-race coupler (b) Open-loop filters with 0° feed structure (c) Open-loop filters with non 0° feed structure [27], (d) Planar filtering rat-race coupler in [20].

3-D layout, the schematic and coupling topology should be carefully studied.

A. SCHEMATIC AND COUPLING TOPOLOGY

When the rat-race coupler with compact size is designed, the schematic and the coupling topology should be the same with those of planar circuit. Firstly, the schematic of planar filtering rat-race coupler is studied. As shown in Fig. 1(d), Resonators R_1 and R_1' are connected by Port 1. They are coupled with R_2 and R_3, respectively. Resonators R_4 and R_4' are connected by Port 4 and they are coupled with R_2' and R_3'. The schematic is depicted in Fig. 2(a).

When the 3-D technology is utilized to design the rat-race coupler, the number of resonators could be reduced. R_1 can replace R_1 and R_1'. Similarly, R_2 and R_2', R_3 and R_3' are replaced by resonators R_2 and R_3. Then R_1 is coupled to R_2 and R_3 simultaneously as shown in Fig. 2(b). R_4 and R_4' are also replaced by one resonator and it is coupled to R_2 and R_3

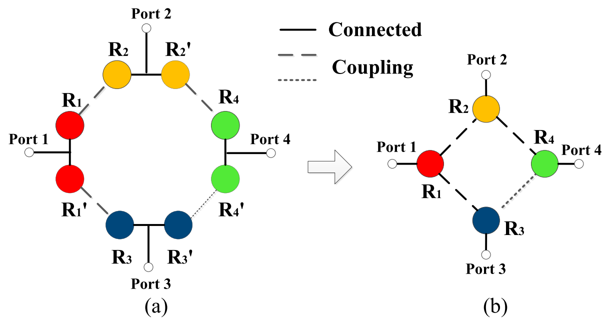

FIGURE 2. The schematic of filtering rat-race coupler (a) the basic planar circuit (b) the schematic with four resonators.

at the same time. The four ports are tapped at the resonators. It can be found that the schematic in Fig. 2(a) and (b) have the same functions. However, only four resonators are utilized which means that by making use of 3-D technology, the number of resonators decrease in half theoretically.

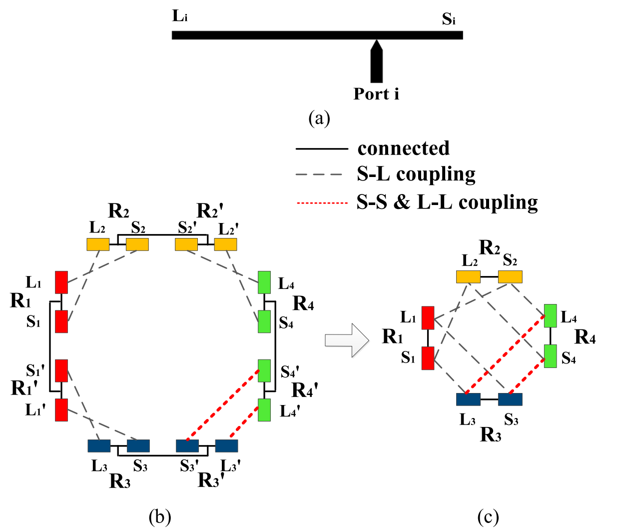

FIGURE 3. Coupling topology (a) Resonator denotes; (b) Coupling topology of the planar rat-race hybrid using eight resonators; (c) Coupling topology of four resonators.

If four resonators are utilized to construct the rat-race coupler, they should obtain the same coupling topology with that of the planar circuit. Thus, the coupling topology of planar filtering rat-race coupler is taken into consideration. In order to conveniently analyze the coupling topology in Fig. 2, the $\lambda/2$ resonators i and i′ (i = 1, 2, 3 and 4) are separated into two parts with different lengths reference to the port position as shown in Fig 3 (a). The longer and shorter parts are denoted as L_i and S_i, respectively. The coupling between the longer and shorter parts is represented as $L_i - S_j$ (i, j = 1, 2, 3 and 4) coupling, and the $L_i - L_j$ and $S_i - S_j$ coupling denotes the coupling between two longer parts and two short parts, respectively. The coupling scheme of the planar rat-race coupler is depicted in Fig. 3(b). Because Filters 1 and 2 are 0° feed structure, the longer part of R_1 is coupled to the shorter part of R_2 which is named as $L_1 - S_2$ coupling. At the same time, S_1 is coupled to L_2. What's more, $L_i - S_j$ (i, j = 1, 2, 3) couplings are also found between $R'_1 - R_3$ and $R'_2 - R_4$ which are connected by the dashed line. However, Filter 4 is non 0° feed structure which leads to $S'_4 - S'_3$ and $L'_4 - L'_3$ couplings through the red dotted line between R'_3 and R'_4.

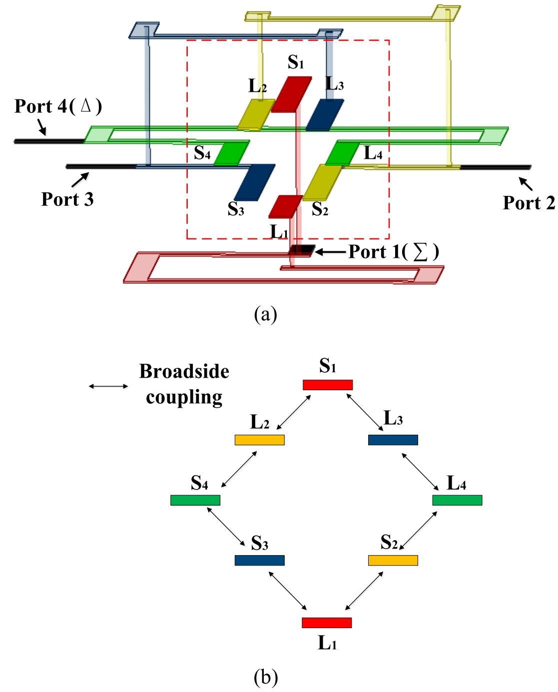

FIGURE 4. Eight-line spatially-symmetrical coupled structure. (a) 3-D structure (b) Sectional view.

In order to get the same dual-functions, the coupling topology using four resonators should be identical with that in Fig. 3(b). It is depicted in Fig. 3(c). The longer part of R_1 should be coupled to S_2 and S_3 to realize $L_1 - S_2$ and $L_1 - S_3$ couplings. Meanwhile, S_1 of R_1 should be coupled to L_2 and L_3 simultaneously. The couplings between R_4 and R_2 are also $L_4 - S_2$ and $S_4 - L_2$ couplings. Whereas, the couplings between R_4 and R_3 are different. As shown in Fig. 3(c), $L_4 - L_3$ and $S_4 - S_3$ couplings in red dotted line should be realized. It can be seen that the coupling topology in Fig. 3(c) has the same coupling scheme with eight resonators. However, it cannot be achieved in the planar process. Even in the 3-D technology, the conventional multi-layer layout cannot meet the requirements.

B. EIGHT-LINE SPATIALLY-SYMMETRICAL COUPLED STRUCTURE

In order to realize the compact rat-race coupler, the coupling topology using four resonators as shown in Fig.3 (c) should be arranged appropriately. In our design, taking advantages of vertical and horizontal layout of LTCC technology, eight-line spatially-symmetrical coupled structure is presented and employed to realize the complicated coupling topology.

The diagram of the filtering rat-race coupler is depicted in Fig. 4(a). The four resonators in different colors are located in different layers. The eight open ends are distributed as eight-line spatially-symmetrical coupled structure as shown in the dashed box. Among them, the shorter and longer open ends of R_1 labeled as S_1 and L_1 are placed at the top and bottom positions. S_4 and L_4 of resonator 4 are located the left and right sides. In the meanwhile, S_2, L_2 and S_3, L_3 are appropriately settled down in the middle nodes. All of the couplings between the open ends are broadside couplings. Each resonator at different layers is connected by the metallized vias.

Fig. 4(b) is the side view of eight-line spatially-symmetrical coupled structure. In the figure, L_1 of resonator R_1 is symmetrically coupled to S_2 and S_3. S_1 is coupled to L_2 and L_3. Thus, R_1 is symmetrically coupled to R_2 and R_3 which is L-S coupling. In the meanwhile, the coupling between R_4 and R_2 is also L-S coupling which employs the couplings of $L_4 - S_2$ and $S_4 - L_2$. However, the coupling between resonators R_4 and R_3 is $S_4 - S_3$ and $L_4 - L_3$ couplings. It can be found that the structure in Fig. 4(a) has two advantages. Firstly, it perfectly achieves the required coupling topology of Fig. 3(c) in a simplified method. Secondly, the coupling strength between every two resonators can be easily adjusted by the relative positions of the resonators. As shown in Fig.4 (b), the coupling strength between $R_1 - R_2$ and $R_1 - R_3$ can be adjusted by symmetrically displacing S_1 and L_1 in the vertical direction. Similarly, the coupling strength of $R_4 - R_2$ and $R_4 - R_3$ can be altered by symmetrically adjusting S_4 and L_4 in the horizontal direction.

Consequently, by utilizing the eight-line spatially- symmetrical coupled structure, only four resonators are employed in the compact rat-race coupler. It significantly reduces the overall size of the circuit. What's more, the proposed coupling structure fulfills the required complicated coupling in an easy layout.

III. IMPLEMENTATION

In order to verify the proposed idea, a rat-race coupler with bandpass responses is designed and implemented in LTCC technology. The design procedure is similar to the filtering coupler proposed in [20]: (1) with a given operating frequency, choose the proper lengths for the half wavelength resonators; (2) tune the coupling strengths among the adjacent resonators and I/O tapped port position to obtain the required bandwidth. The characteristics of the structure are illustrated and the experiment results are given.

A. IMPLEMENTATION

Fig. 5(a) and Fig. 5(b) are the 3-D structure and side view of the proposed filtering rat-race coupler. As shown in these two figures, the circuit is composed of four $\lambda/2$ resonators which are distributed in eleven metal layers. Resonator 1 in red color is meandered and etched in metal layers 2, 3, 5, and 9. The metallized vias connect the resonator in different layers.

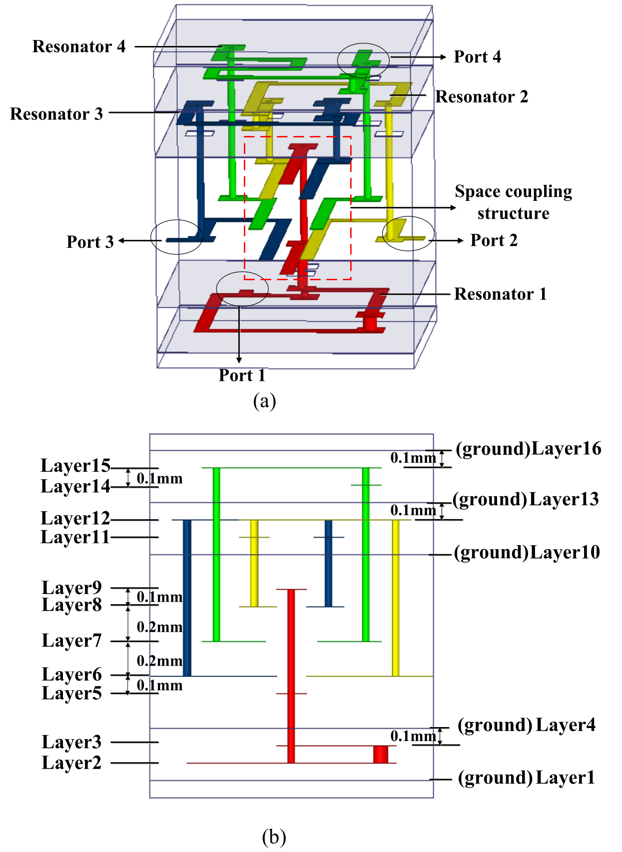

FIGURE 5. The proposed LTCC filtering rat-race coupler. (a) 3-D view. (b) side view.

The sum input port Port 1 is taped at the resonator in layer 2. Resonators R_2 and R_3 in yellow and blue color respectively are placed in metal layers 6, 8, 11 and 12. The two output ports Port 2 and Port 3 are located at layer 6. Resonator 4 in green color is located in metal layers 7, 14 and 15. The difference port 4 is tapped at Resonator 4 in layer 15. Layers 1, 4, 10, 13 and 16 are the common ground of the striplines, which also act as the block wall to separate the unwanted coupling. It can be found that, the proposed 3-D eight-line spatially-symmetrical coupling scheme in Fig. 5 is realized by broadside coupling which is located in metal layers 5, 6, 7, 8, 9.

Fig. 6 shows the planar layout on each layer. The LTCC substrate is Ferro A6-M with a dielectric constant of 5.9 and a loss tangent of 0.002. The design parameters are determined as follows (all in mm): $L_1 = 3.8, L_2 = 4, L_3 = 3.2, L_4 = 2.9,$ $L_5 = 0.4, L_6 = 0.6, L_7 = 1.4, L_8 = 2, L_9 = 2.4, L_{10} = 1.3,$ $L_{11} = 3.2, L_{12} = 2.4, L_{13} = 0.22, L_{14} = 3, L_{15} = 3,$ $L_{16} = 3, L_{17} = 1.9, L_{18} = 1.1, L_{19} = 1.9, L_{20} = 1.4,$ $L_{21} = 1.4, L_{22} = 0.8, L_{23} = 2.25, L_{24} = 0.8, L_{25} = 0.35,$ $L_{26} = 2, L_{27} = 0.9, L_{28} = 0.7, L_{29} = 0.9, L_{30} = 1.25,$ $L_{31} = 1.8, L_{32} = 1, W_1 = W_2 = 0.4, W_3 = 0.5, W_4 = 0.4,$ $W_5 = 0.6, W_6 = 0.9, S_1 = 0.4$. The circuit size of the LTCC wafer is $3.8 \times 4 \times 2.1$ mm^3.

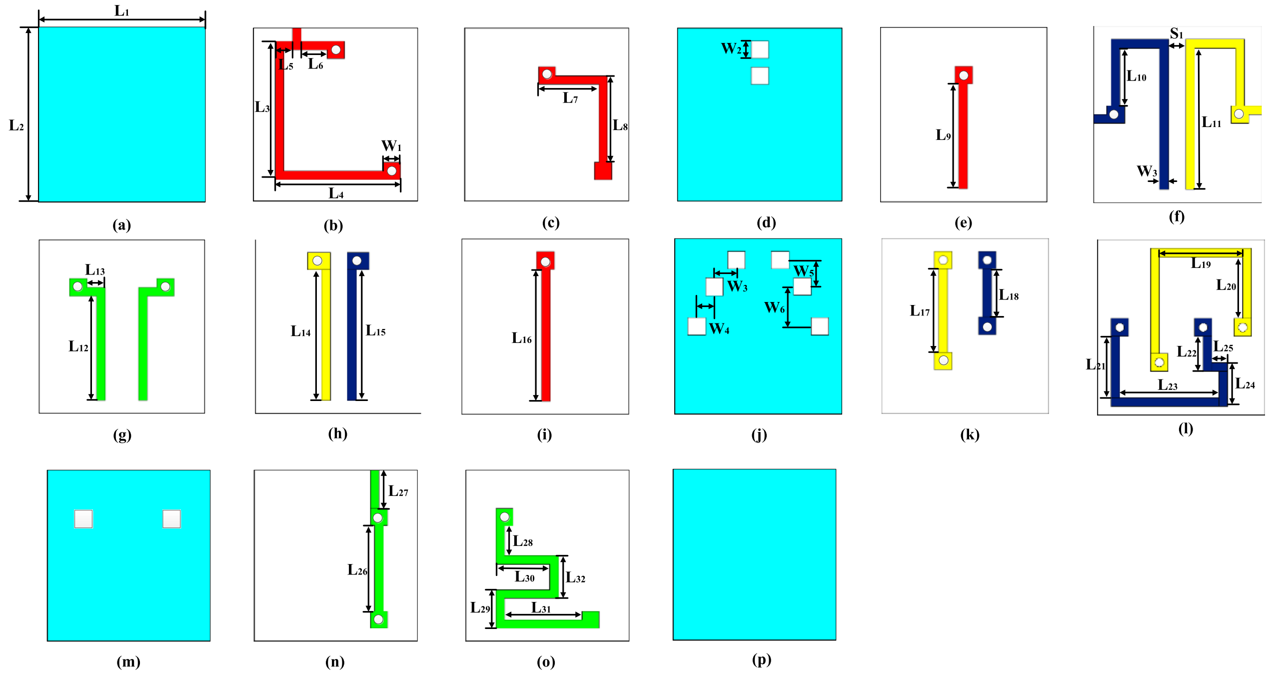

FIGURE 6. Layout of the proposed filtering rat-race coupler. (a) Layer 1. (b) Layer 2. (c) Layer 3. (d) Layer 4. (e) Layer 5. (f) Layer 6. (g) Layer 7. (h) Layer 8. (i) Layer 9. (j) Layer 10. (k) Layer 11. (l) Layer 12. (m) Layer 13. (n) Layer 14. (o) Layer 15. (p) Layer 16.

TABLE 1. Comparison of various filtering rat-race coupler.

Ref.	Frequency (GHz)	Fabrication technology	Design method	IL(dB)	FBW(%)	Mag.(dB) imbalance	Phase (°) imbalance	Overall size
[14]	1.5	PCB	Coupled Resonators	2.6	3.5	0.6/0.8	8.7	0.29*0.15 λ_g^2
[15]	2.4	PCB	Coupled Resonators	0.7	10	0.7/1.0	2	0.30*0.12 λ_g^2
[16]	2.4/5.8	PCB	Stepped-impedance resonators	1.0/1.4	4.6/5.2	0.6	9.5	0.41*0.39 λ_g^2
[17]	1.5	PCB	Stub-loaded resonators	3	4	-0.9 to 0.2	12	0.31*0.22 λ_g^2.
[18]	2	PCB	Net-type resonators	1.3	5	N.A.	0.9 @ CF	0.153*0.195 λ_g^2
[19]	2.4	PCB	Hairpin Resonators	1.9	4.9	N.A.	0.8 @ CF	0.196*0.212 λ_g^2
[20]	0.47	PCB	Lumped elements	1.2	12	0.1	4.5	0.095*0.117 λ_g^2
[25]	2.5	LTCC	Quasi-lumped elements	2.27	10	0.5	2	7.8*4.3*1 mm^3
[26]	24	LTCC	Rectangular cavity	2.2	6	0.25	6	7.5*7.95*0.93 mm^3
This work	3.5	LTCC	Distributed resonators	1.8/1.5	14	0.25/0.15	5	3.8*4 *2.1 mm^3

CF: Center Frequency.

B. EXPERIMENT

In order to measure the LTCC circuit, the designed filtering rat-race coupler is packaged and mounted on the PCB board as shown in Fig. 7. The PCB test board is Rogers RO4003 with the relative dielectric constant of 3.38, the thickness of 0.508 mm and the loss tangent of 0.0027. There are four 50 ohm transmission lines connecting the LTCC circuit and testing ports. The top and bottom ground of the test board is connected by the metalized via holes which are symmetrically placed on each side of the transmission lines to avoid undesired surface current. The measurement is accomplished by using 8753ES network analyzer.

Fig. 8(a) and (b) depict responses of the proposed filtering rat-race coupler when the sum and difference ports are excited, respectively. As shown in Fig. 8 (a), when Port 1 is excited, the center frequency is located at 3.5 GHz with 1 dB FBW of 14.2%. Within the passband, the measured S_{21} and S_{31} are around $-(3 + 1.8)$ dB. And the imbalance

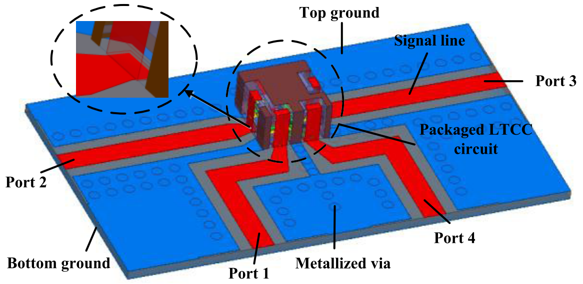

FIGURE 7. 3-D view of the proposed LTCC filtering rat-race coupler with test PCB board.

between S_{21} and S_{31} is smaller than 0.25 dB. The in-band return loss is better than 20 dB. There are two transmission zeros near the passband which featuring good selectivity.

When the signal is excited in Port 4, the measured results are shown in Fig. 8(b). The 1 dB FBW is 14.9% reference to the center frequency of 3.5 GHz. S_{34} and S_{24} are $-(3 + 1.5)$ dB with imbalance less than 0.15 dB. The measured S_{44} is better than 10 dB and the out-of-band rejection is better than 20dB. The measured isolation between two input ports is higher than 20 dB within the operation frequency band. Comparing with the simulated result, the FBW is wider and the insertion loss is a bit higher than the simulated results of 3+1.2 dB and 3+1.0 dB, which is mainly attributed to the fabrication tolerance. Thus, the coupling between resonators is stronger in practical fabricating process. Fig. 8 (c) shows that when port 1 is excited, the phase difference between the two output ports is $0° \pm 4°$ in operating frequency band. When port 4 is excited, the phase difference between the two output ports is $180° \pm 4°$. The measured results demonstrate that the device could provide in-phase and out-of-phase outputs with filtering response simultaneously.

C. COMPARISON

Table I lists the comparion of various filtering rat-race couplers which include the devices on PCB and LTCC technology. it can be found that, the insertion loss of the proposed rat-race coupler is about 1.5 dB which is comparable with that on PCB technology. The measured magnitude and phase difference are 0.25 dB and 5°, respectively. It keeps a good balanced performance. Thus, the measured performance of the proposed devices has a comparable performance with that of PCB technology. Howerver, it processes more compact dimensions due to the multilayer structure.

Furthermore, the proposed design is compared to some LTCC filtering rat-race couplers. As shown in Table I, our proposed rat-race coupler has the smallest cross sectional area (similar volume) comparing to that in [25] and [26]. However, it can be found that the proposed device has the smallest insertion loss of 1.8 dB and the most balanced magnitude of 0.25 dB. By utilizing eight-line spatially-symmetrical coupled structure, the proposed filtering rat-race coupler

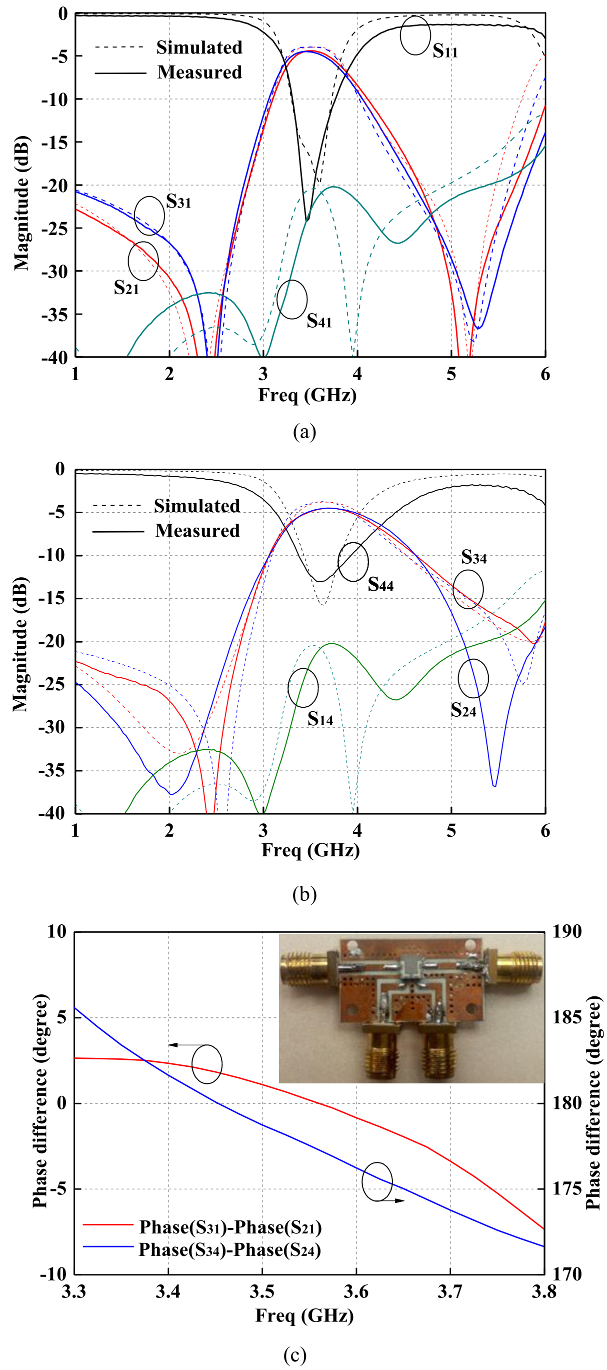

FIGURE 8. Simulated and measured performance of the proposed filtering rat-race coupler (a) with sum input, (b) with difference input; (c) phase difference.

enhances the symmetry of the layout and thus the performance is better than other designs.

IV. CONCLUSION

In this work, a compact filtering rat-race coupler has been designed. The eight-line spatially-symmetrical coupled structure has been proposed to satisfy the desirable schematic and coupling topology. Then the rat-race coupler in the LTCC technology has been constructed by only four resonators. By utilizing the 3-D coupling structure, the circuit process compact overall size. Low insertion loss and magnitude and phase imbalance have been observed due to the highly symmetrical layout. It is believed that the proposed compact and dual-functional device is suitable in the modern wireless and mobile communication systems.

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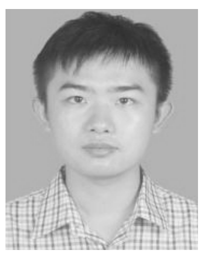

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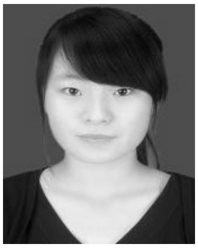

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