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A Miniaturized 3-dB Microstrip TRD Coupled-Line Rat-Race Coupler with Harmonics Suppression

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Abstract—A miniaturized microstrip rat-race coupler with harmonics suppression is proposed by using shorted trans-directional (TRD) coupled lines. The shorted TRD coupled lines consist of a set of capacitor-loaded $\lambda/4$ coupled microstrip lines with two shorts, which are used to replace the $3\lambda/4$ uniform transmission-line section (UTLS) in the traditional $3\lambda/2$ ring coupler for miniaturization. To attain perfect matching for any coupling factor of the TRD coupled lines, shorted TRD coupled lines are synthesized and the design equations are derived. To further reduce the ring size, T-type transmission-line equivalent circuits are also adopted to replace the $\lambda/4$ UTLS and associated with a transmission zero for harmonic attenuation. Using the proposed method, a microstrip ring coupler with 26.7% circuit size of a traditional one is fabricated and tested. The measured results show that the bandwidth for the return loss of better than 10 dB is 43.9% and that for isolation of better than 20 dB is 18.7% with a maximum isolation of 40.6 dB. There is no spurious passband up to the sixth harmonic of the design center frequency with more than 20 dB suppression from the third to fifth harmonics.

1. INTRODUCTION

A rat-race coupler is a four-port network with a 180° phase difference between the two output ports and can also be operated in phase at the outputs. It is widely adopted in practical microwave and millimeter wave circuits such as mixers [1], amplifiers [2], and antenna feeding networks [3, 4]. However, the traditional rat-race coupler, which consists of a $3\lambda/4$ and three $\lambda/4$ uniform transmission line sections (UTLS), has inherently large physical size. To reduce the size, a shorted $\lambda/4$ coupled-line section was firstly suggested replacing the $3\lambda/4$ UTLS by March [5]. In this paper, rat-race couplers of this type will be called coupled-line rat-race couplers. The design equations of the shorted coupled-line section were derived by Ahn and Kim [6]. Their design results show that the shorted coupled-line section is suitable to generate high-impedance ($200 \sim 350\,\Omega$) $3\lambda/4$ microstrip lines for microstrip rat-race couplers with high power-division ratios [7]. However, a low-impedance (e.g., $70.71\,\Omega$) $3\lambda/4$ microstrip line is required for 3-dB microstrip rat-race coupler. Table 1 gives the required even- and odd-mode impedances of the shorted coupled-line sections to realize a $70.71\text{-}\Omega$ $3\lambda/4$ microstrip line. It is seen that the required even- and odd-mode impedances of the shorted coupled-line sections are simultaneously decreased with the decrease of coupling coefficient C. As a result, the strip width W of coupled microsrtip lines can be chosen to be a proper value. However, the spacing between coupled microsrtip lines S is always less than 0.03 mm, which is relatively difficult to fabricate in a planar structure of microstrip lines with a standard printed circuit board (PCB) technology. To solve this problem, broadside [8], vertically [6] or Lange [9] coupled structures have been adopted. However, two output ports of the coupler with broadside-coupled structures are not on the same side so that vias are required to route the signals to the same side. Vertically coupled structures suffer from a complicated processing. Lange coupled structures need multiple coupled lines.

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Table 1. Design parameters of the shorted $\lambda/4$ coupled microsrtip lines to realize a 70.71-Ω $3\lambda/4$ microstrip line.

C (dB)	$Z_{0e}\,(\Omega)$	$Z_{0o}\,(\Omega)$	$\varepsilon_r = 2.65,\ h = 1.5\,\text{mm}$	
			W (mm)	S (mm)
−3	171.4	29.31	0.759	0.0192
−6	71.05	23.61	3.356	0.0196
−9	38.89	18.52	7.213	0.0200
−12	23.72	14.20	12.77	0.0203

Similar to the ideas of March [5], the $3\lambda/4$ UTLS can be replaced by a $\lambda/4$ transmission line plus a 180° phase inverter, which can be obtained from a coplanar waveguide (CPW) inverter [10], CPW-parallel stripline transition [11], CPW-slot line transition [12], microstrip-slot line transition [13], coplanar strip (CPS) twist [14] and asymmetrical CPS reverse-phase section [15]. Nonetheless, all the phase inverters cannot be easily implemented with traditional microstrip structures. In addition, left-handed transmission lines also can be used to replace the $3\lambda/4$ UTLS [16]. However, left-handed transmission lines are usually realized using lumped or quasi-lumped elements with complicated configurations [17].

Besides the $3\lambda/4$ UTLS can be miniaturized, there are many methods for size reduction of both $\lambda/4$ and $3\lambda/4$ UTLS, such as meander lines [18], arbitrary electrical-length UTLS [19] and equivalent circuits [20–25]. For the meander-line method, the level of miniaturization is determined by the number of meandering sections and the tightness of the meandering. However, each meander section adds four discontinuities (bends) deteriorating the input matching and isolation, and tight meandering results in increased parasitic coupling among transmission lines [26]. For the arbitrary electrical-length method, the $\lambda/4$ UTLS in traditional rat-race coupler have been changed to be $\lambda/8$, $\lambda/6$, and $5\lambda/36$ for 3-dB couplers with $5\lambda/4$, $7\lambda/6$ and $19\lambda/18$ circumferences, respectively. However, up to now, the method is only used to design 3-dB couplers [19]. For the equivalent-circuit method, Π-type [6, 20, 23], T-type [25, 26] or stepped-impedance transmission line [22] equivalent circuits have been used. However, equivalent circuits can be only used when the original length of UTLS is less than $\lambda/2$. Thus, the $3\lambda/4$ UTLS requires two or more equivalent circuits. Among the previous methods [22–28], the Π- and T-type equivalent circuits can be easily used to suppress harmonics [29].

The trans-directional (TRD) coupled line shown in Figure 1 was firstly introduced with periodically capacitor-loaded coupled microstrip lines by Shie et al. [30]. One important advantage of the TRD coupled line is that tight coupling (e.g., 3 dB) can be easy to implement with weakly coupled microstrip lines. Another advantage is that the through and coupled ports of the TRD coupled line are on the same conductor strip, which is different from traditional parallel-coupled lines. When the through and coupled ports are connected with short loads, the input and output ports of the $\lambda/4$ TRD coupled line

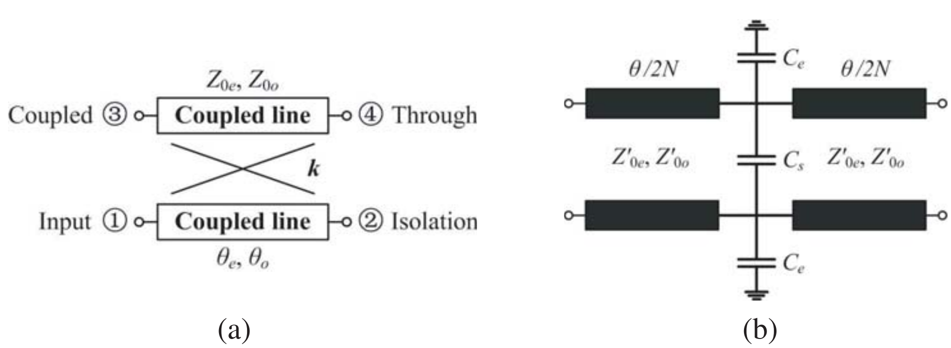


Figure 1. Topology of the TRD coupler. (a) Schematic of the TRD coupler. (b) One unit cell of capacitor-loaded coupled lines.

also be on the same conductor strip result in a small insertion loss and produce a phase shift equal to 270°. Thus, the shorted $\lambda/4$ TRD coupled line is introduced to replace the $3\lambda/4$ UTLS of the rat-race coupler for miniaturization in this paper. To attain perfect matching for any coupling factor of TRD coupled lines, design formulas for shorted $\lambda/4$ TRD coupled lines are derived. To further reduce the size of rat-race couplers, T-type transmission-line equivalent circuits are also adopted to replace the $\lambda/4$ UTLS and associated with a transmission zero for harmonic attenuation. Details of the miniaturized rat-race coupler design and both the theoretical and experimental results are given and discussed.

2. CIRCUIT STRUCTURE AND DESIGN THEORY

Figure 2 shows the proposed configuration of the miniaturized rat-race coupler with harmonics suppression, which consists of a shorted $\lambda/4$ TRD coupled line and three T-type transmission-line sections. The shorted $\lambda/4$ TRD coupled line is a TRD coupler (as shown in Figure 1) with the through and coupled ports connected with short loads, which is used to replace the $3\lambda/4$ UTLS in the traditional rat-race coupler. Three T-type transmission-line sections are used to replace the $\lambda/4$ UTLS in the traditional rat-race coupler.

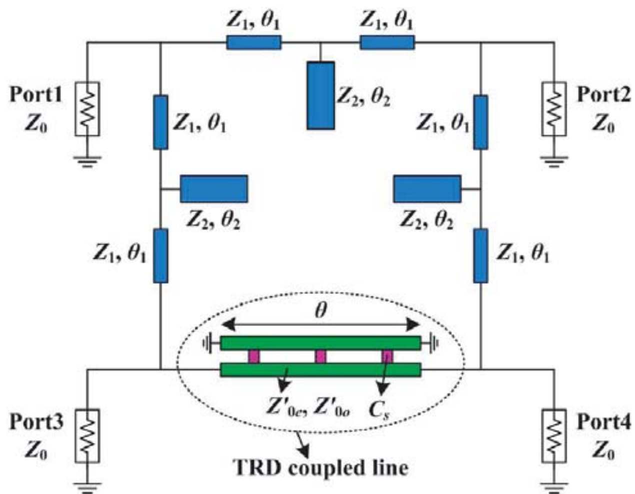


Figure 2. Configuration of the proposed rat-race coupler.

According to the even- and odd-mode analysis of TRD coupled line in [30], the even- and odd-mode electrical lengths of the TRD coupled line are $\theta_e = \pi/2$ and $\theta_o = 3\pi/2$, respectively. When the through and coupled ports of the TRD coupled line are connected with short loads, the four-port network becomes a two-port network, and the $ABCD$ matrix elements of which can be derived by using the network theory in [31] as

$$A = D = \frac{Z_{0o}\cot\theta_e + Z_{0e}\cot\theta_o}{Z_{0o}\csc\theta_e + Z_{0e}\csc\theta_o}, \tag{1}$$

$$B = j\frac{2Z_{0e}Z_{0o}}{Z_{0o}\csc\theta_e + Z_{0e}\csc\theta_o}, \tag{2}$$

$$C = j\frac{Z_{0e}^2 + Z_{0o}^2 + 2Z_{0e}Z_{0o}(\csc\theta_e\csc\theta_o - \cot\theta_e\cot\theta_o)}{2Z_{0e}Z_{0o}(Z_{0o}\csc\theta_e + Z_{0e}\csc\theta_o)}, \tag{3}$$

where Z_{0e} and Z_{0o} are the even- and odd-mode impedances of the TRD coupled line, respectively.

Applying the TRD operation condition of $\theta_e = \pi/2$ and $\theta_o = 3\pi/2$, the $ABCD$ matrix of the shorted TRD coupled line can be simplified as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & -j\dfrac{2Z_{0e}Z_{0o}}{Z_{0e}-Z_{0o}} \\ -j\dfrac{Z_{0e}-Z_{0o}}{2Z_{0e}Z_{0o}} & 0 \end{bmatrix}. \tag{4}$$

In order to match the shorted TRD coupled line to a $3\lambda/4$ transmission line with a characteristic impedance of Z_t with $A = D = 0$, $B = -jZ_t$, and $C = -j/Z_t$ [32]. Therefore, equivalent condition is found as

$$Z_t = \frac{2Z_{0e}Z_{0o}}{Z_{0e} - Z_{0o}}. \tag{5}$$

Usually, coupling factor k of the TRD coupled line is defined as

$$k = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}. \tag{6}$$

Based on Equations (5) and (6), even- and odd-mode impedances of the TRD coupled line are derived as

$$Z_{0e} = Z_t \frac{k}{1-k}, \tag{7}$$

$$Z_{0o} = Z_t \frac{k}{1+k}. \tag{8}$$

Equations (7) and (8) imply that the coupling factor k of the TRD coupled line can be flexibly chosen. When k is chosen, the even- and odd-mode analysis can be used to determine the coupled line impedance Z'_{0e}, Z'_{0o}, and the loaded capacitor C_s of the TRD coupled line, as shown in Figure 2.

According to the even- and odd-mode analysis in [30], the loaded capacitor C_e, as shown in Figure 1(b), becomes zero when the electrical length of the coupled line θ equals to be $\pi/2$. Then, the even- and odd-mode impedance (Z'_{0e} and Z'_{0o}) of coupled microstrip lines and the loaded capacitor C_s, as shown in Figure 2, can be derived as

$$Z'_{0e} = Z_t \frac{k}{1-k}, \tag{9}$$

$$Z'_{0o} = \frac{Z_t k}{(1+k)\sqrt{\dfrac{2\sin(\theta') + b_o\cos(\theta') - b_o}{2\sin(\theta') + b_o\cos(\theta') + b_o}}}, \tag{10}$$

$$C_s = \frac{b_o}{2\omega Z'_{0o}}, \tag{11}$$

$$\theta' = \frac{\pi}{2N}, \tag{12}$$

$$b_o = \frac{2\left(\cos\theta' - \cos 3\theta'\right)}{\sin\theta'}, \tag{13}$$

where parameter N is the number of the loaded capacitor C_s.

It is noted that Equations (7) and (8) for the shorted TRD coupled structure seem similar to the design equations for the traditional $\lambda/4$ shorted coupled structure [6]. However, by loading capacitors C_s, the required odd-mode impedance Z'_{0o} of coupled microstrip lines for the shorted TRD coupled structure is much larger than that (Z_{0o}) for the traditional parallel-coupled structure [6], as shown in Figure 3.

Figure 3 gives the required even- and odd-mode characteristic impedances of the coupled microsrtip line as a function of the coupling factor k of the $\lambda/4$ TRD coupled line to realize a $3\lambda/4$ transmission line with $Z_t = 70.71\,\Omega$. It is seen that when $N = 3$ and $k < 0.577$, the required even-mode impedance Z'_{0e} is less than odd-mode impedance Z'_{0o}, which cannot be realized with coupled microsrtip lines. Thus, the coupling factor k of the $\lambda/4$ TRD coupled line should be greater than 0.541, 0.577, 0.707 for the number of the loaded capacitors $N = 4$, 3, and 2, respectively. Furthermore, with the increase of k, even-mode impedance Z'_{0e} increases faster than odd-mode impedance Z'_{0o}. This implies that a greater k needs a tighter coupling of the coupled microsrtip line.

Figure 4 gives the required C_s of loaded capacitors as a function of the coupling factor k of the $\lambda/4$ TRD coupled line to realize a $3\lambda/4$ transmission line operated at 1.0 GHz with $Z_t = 70.71\,\Omega$. It is observed that when $N = 3$, the required C_s is from 2.86 to 2.35 pF in the range of k from 0.577 to 0.800. Due to available capacitors existing as discrete components, three operation points (0.631, 2.7 pF), (0.717, 2.5 pF) and (0.770, 2.4 pF) can be actually adopted when $N = 3$. Also, three operation points (0.610, 2.5 pF), (0.653, 2.4 pF) and (0.757, 2.2 pF) can be used when $N = 4$. Table 2 gives Z'_{0e} and Z'_{0o} at enabled operation points for different N. It is found that when $N = 3$ or 4, the required coupled microsrtip line for $\lambda/4$ TRD coupled structure can be easy to implement with a standard PCB technology.

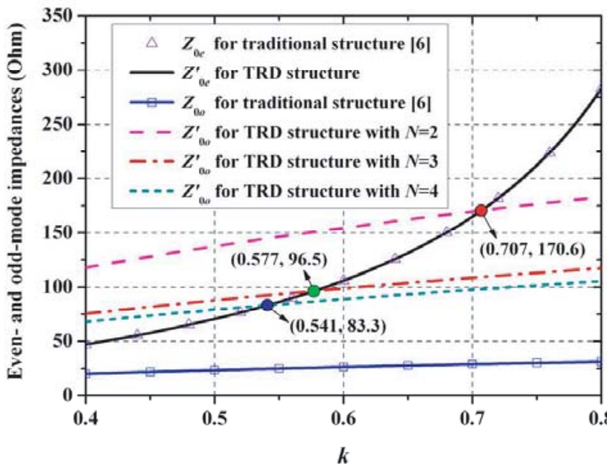


Figure 3. Even- and odd-mode characteristic impedances of the coupled microsrtip line as a function of k.

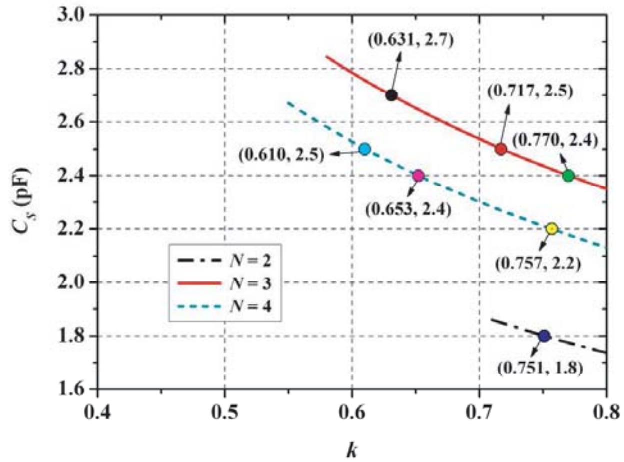


Figure 4. Required C_s of loaded capacitor as a function of k.

Table 2. Design parameters of the shorted $\lambda/4$ TRD coupled line operated at 1.0 GHz with $Z_t = 70.71\,\Omega$.

N	k	C_s (pF)	Z'_{0e} (Ω)	Z'_{0o} (Ω)	$\varepsilon_r = 2.65$, $h = 1.5$ mm	
					W (mm)	S (mm)
2	0.751	1.8	213.3	176.8	0.09	2.36
3	0.631	2.7	120.9	102.1	0.82	2.80
	0.717	2.5	179.2	110.2	0.36	1.08
	0.770	2.4	236.7	114.8	0.16	0.62
4	0.610	2.5	110.6	90.0	1.08	2.37
	0.635	2.4	123.0	92.3	0.90	1.78
	0.757	2.2	220.3	102.3	0.23	0.56

T-type transmission line equivalent circuits were used to replace $\lambda/4$ UTLS of the traditional rat-race coupler for miniaturization [25], but three sections of the T-type circuits are in a limit of equal electrical length. In order to improve the design flexibility, the electrical length of the shunt stub is different from the two other transmission line sections as shown in Figure 2 for flexible control of the transmission zero. $ABCD$ matrix elements of the modified T-type circuit can be derived as:

$$A' = D' = \cos^2\theta_1 - \sin^2\theta_1 - \frac{Z_1 \sin\theta_1 \cos\theta_1 \tan\theta_2}{Z_2}, \tag{14}$$

$$B' = jZ_1 \left(2\sin\theta_1\cos\theta_1 - \frac{Z_1 \sin^2\theta_1 \tan\theta_2}{Z_2}\right), \tag{15}$$

$$C' = j\left(\frac{2\sin\theta_1\cos\theta_1}{Z_1} + \frac{\cos^2\theta_1 \tan\theta_2}{Z_2}\right), \tag{16}$$

In order to match the modified T-type circuit to a $\lambda/4$ transmission line with a characteristic impedance of Z_t with $A' = D' = 0$, $B' = jZ_t$, and $C' = j/Z_t$ [32]. Therefore, equivalent condition are found as

$$Z_1 = Z_t \cot\theta_1, \tag{17}$$

$$Z_2 = Z_t \frac{\cos^2\theta_1 \tan\theta_2}{\cos 2\theta_1}. \tag{18}$$

The solution of Equations (17) and (18) is not unique, which implies that many T-type circuits can be used in the design of the miniaturized rat-race coupler.

3. PARAMETERS ANALYSIS

Based on the previous theoretical analysis, electrical parameters of the proposed circuit can be easily calculated with Equations (9)–(13), (17) and (18). For observation of the effect of the electrical parameters, the Advanced Design System (ADS) circuit simulator will be used to analyze the proposed coupler in this section.

3.1. Effect of the Coupling Factor of the TRD Coupled Line

Figure 5 gives the effect of the coupling factor k of the $\lambda/4$ TRD coupled line on the S-parameters of the proposed 3-dB rat-race coupler with $N = 3$, $\theta = 90°$, $\theta_1 = 24.5°$, $\theta_2 = 25.4°$, $Z_1 = 154.7\,\Omega$, and $Z_2 = 42.5\,\Omega$. It is seen that perfect matching and isolation characteristics are obtained by using the derived equations for any coupling factor of the TRD coupled lines. The 10-dB return loss and $\pm 10°$ phase ripple bandwidths are slightly increased with the increase of k. Therefore, the choice of operation points of the shorted $\lambda/4$ TRD coupled line mostly relies on the available capacitors and realizable coupled microstrip lines.

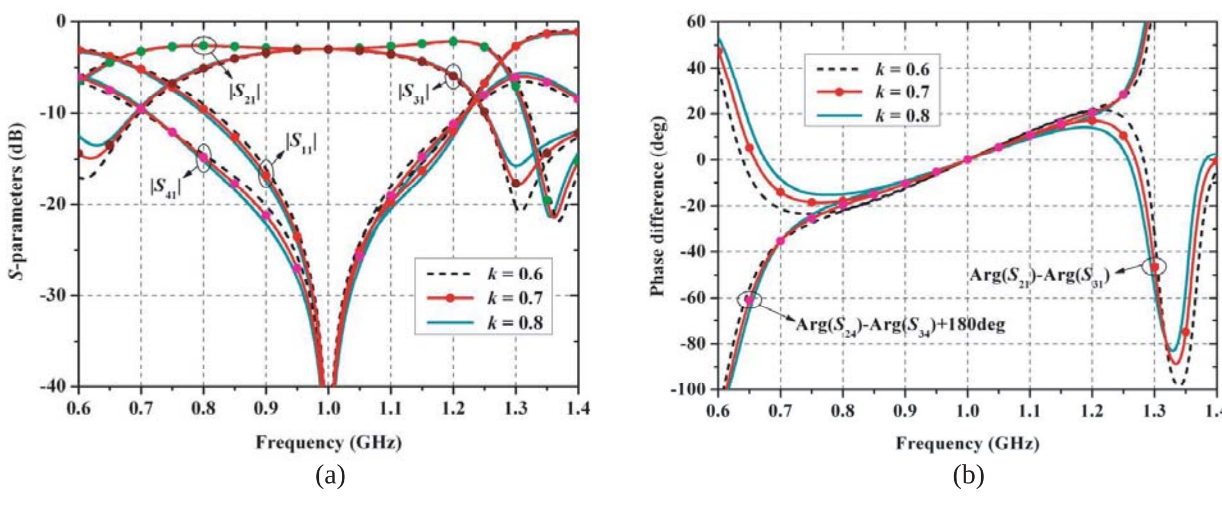
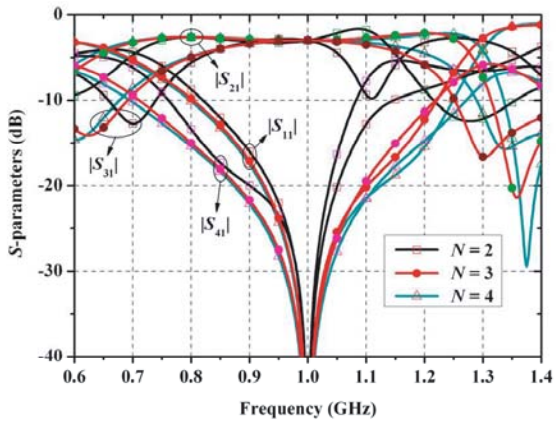


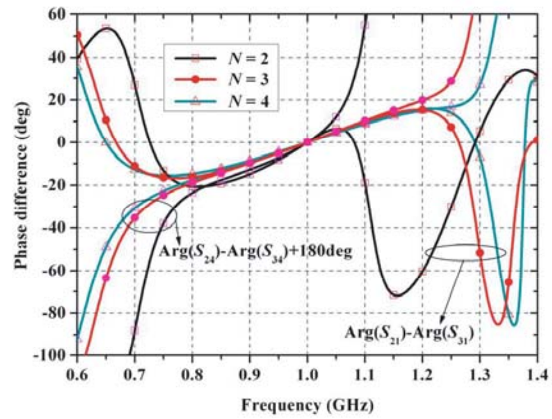
Figure 5. Effect of k on the S-parameters of the proposed rat-race coupler. (a) Amplitude responses. (b) Phase responses.

3.2. Effect of the Number of the Loaded Capacitors

Figure 6 gives the effect of number N of the loaded capacitors on the S-parameters of the proposed 3-dB rat-race coupler with $\theta = 90°$, $\theta_1 = 24.5°$, $\theta_2 = 25.4°$, $Z_1 = 154.7\,\Omega$, and $Z_2 = 42.5\,\Omega$. It is observed that the larger the number of loaded capacitors is, the wider the operation bandwidth is. However, 10-dB return loss and $\pm 10°$ phase ripple bandwidths increase little when the number of the loaded capacitors changes from three to more. Thus, a three-cell design is selected as a compromise between bandwidth and complexity.



(a)



(b)

Figure 6. Effect of N on the S-parameters of the proposed rat-race coupler. (a) Amplitude responses. (b) Phase responses.

4. IMPLEMENTATION AND PERFORMANCE

To validate the proposed method, a miniaturized 3-dB rat-race coupler operated at 1.0 GHz has been designed and implemented on a 1.5 mm-thick substrate with a relative dielectric constant of 2.65. In this case, the impedance of the microstrip line on the circumference of the traditional rat-race coupler will be $Z_t = 70.71\,\Omega$ [32]. Thus, the line width of the traditional ring coupler is 2.28 mm, the circumference of the whole ring 309.7 mm, and required circuit area 79.9 cm^2. To reduce the size of the coupler, the first step is to replace the $3\lambda/4$ UTLS with the shorted $\lambda/4$ TRD coupled line. Then, T-type circuits are used to replace the $\lambda/4$ UTLS.

Based on theory analysis of the shorted TRD coupled line, k, N, and θ are chosen to be 0.717, 3, and 90°, respectively, for easy implementation. Then, the calculation for even- and odd-mode characteristic impedances of the coupled microsrtip line and loaded capacitor are $Z'_{0e} = 179.2\,\Omega$, $Z'_{0o} = 110.2\,\Omega$, and $C_s = 2.5$ pF with Equations (9)–(13). Lastly, using the transmission line synthesis tool *ADS Linecalc*, the strip width and spacing between coupled microsrtip lines are calculated to be 0.36 and 1.08 mm, respectively.

To reduce circumference discontinuities, the characteristic impedance of arm section for T-type equivalent circuits is chosen to be $Z_1 = 154.7\,\Omega$ for same strip width with coupled microsrtip lines. Then, T-type circuit parameters are calculated to be $\theta_1 = 24.5°$, $\theta_2 = 25.4°$, and $Z_2 = 42.5\,\Omega$ with Equations (17) and (18). Also, the physical dimensions of T-type circuits are calculated with *ADS Linecalc*. However, optimal physical dimensions of transmission lines must take account of the distributed capacitance effect of the open stubs at the ends and inductive effect of vias. Therefore, the HFSS EM software is used to obtain the final dimensions. At last, the dimensions of the miniaturized 3-dB rat-race coupler are found and implemented as follows: $W = 0.3$ mm, $W_1 = 0.3$ mm, $W_2 = 5.2$ mm, $S = 1.1$ mm, $L = 51.0$ mm, $L_1 = 29.4$ mm, and $L_2 = 14.0$ mm with $C_s = 2.4$ pF. The photograph of the fabricated 3-dB rat-race coupler is shown in Figure 7(a). The effective circuit area of the miniaturized coupler is 16.0 cm^2, which is only 26.7% of that of the traditional rat-race coupler. This means significant size reduction.

To validate the design, the S-parameter of the fabricated rat-race coupler was measured with an Agilent N5230A network analyzer. Figure 7 gives the simulated and measured S-parameters of the proposed rat-race coupler. The measured return loss of more than 10 dB is in the frequency range of 0.825–1.289 GHz (about 43.9%); the measured power division $|S_{21}|$ and $|S_{31}|$ at the design center frequency of 1.0 GHz are -2.89 and -3.64 dB, respectively. The measured bandwidth for the isolation $|S_{41}|$ of better than 15 dB is 32.2% (0.809–1.120 GHz), and that for the isolation of better than 20 dB is 18.7% (0.883–1.065 GHz) with a maximum isolation of 40.6 dB at 0.983 GHz. It is seen from Figure 7(c) that in-phase ($\angle S_{21} = \angle S_{31}$) and out-of-phase ($\angle S_{34} - \angle S_{24} = 180°$) characteristics are obtained at

0.967 GHz. The frequency shift between the simulated and measured results is 3.3%, which seems acceptable and is mainly due to inaccurate values of the 2.4-pF capacitors used in the fabricated prototype. In addition, it is found from Figure 7(d) that the transmission zero introduced by the open stub appears around 4.3 GHz. As a result, the upper stopband is extended from 2 to 6 GHz with the suppression level better than 10 dB. Table 3 compares the proposed coupler with some previous publications.

Table 3. Comparison between the proposed coupler and the existing microstrip designs.

References	Electrical length of ring	Relative area	Design complexity	Harmonic suppression	Bandwidths	
					Return loss (> 15 dB)	Isolation (> 15 dB)
Conventional	540°	100%	Less	No	40.0%	46.2%
[16]	285°	33.0%	More	No	39.0%	78.0%
[19]	380°	50.7%	Less	No	10.6%	38.0%
[21]	183°	30.1%	More	No	50.0%	45.0%
[22]	250°	21.5%	Less	Yes	26.9%	35.2%
[23]	240°	31.0%	Less	Yes	25.0%	25.0%
[24]	N/A	12.9%	Most	Yes	18.8%	18.8%
[25]	300°	32.9%	Less	Yes	32.2%	31.0%
This work	237°	26.7%	Less	Yes	27.3%	32.2%

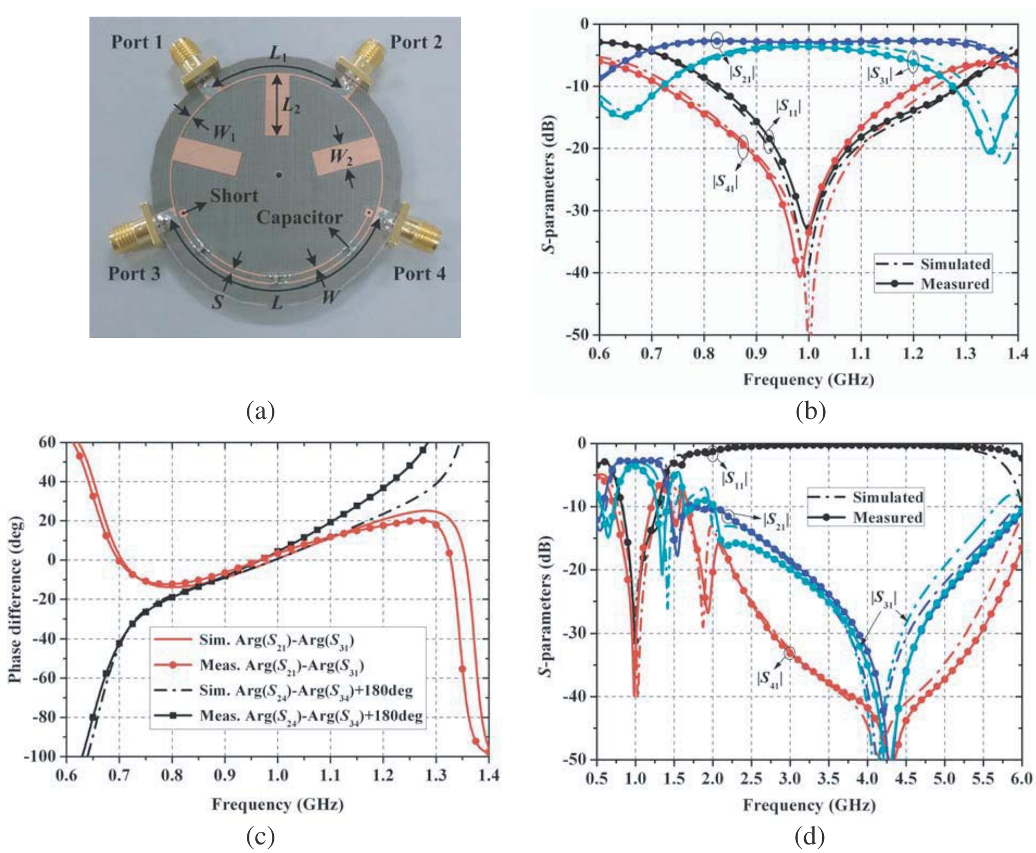


Figure 7. Photograph and S-parameters of the proposed 3-dB rat-race coupler. (a) Photograph. (b) Narrowband amplitude responses. (c) Narrowband phase responses. (d) Broadband amplitude responses.

5. CONCLUSIONS

In this article, a miniaturized rat-race coupler with harmonics suppression was proposed by replacing the $3\lambda/4$ and $\lambda/4$ UTLS in the traditional $3\lambda/2$ ring coupler with the shorted $\lambda/4$ TRD coupled line and T-type circuits, respectively. To attain perfect matching for any coupling factor of TRD coupled lines, shorted TRD coupled lines were synthesized, and the design equations were derived. Using the proposed method, a ring coupler with electrical length of 237° was implemented. The fabricated coupler has 26.7% circuit size of a traditional one. In addition, the proposed coupler is not only suitable for common PCB processes but also realizable with microstrip technology.

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