A Novel Broad-Band Chebyshev-Response Rat-Race Ring Coupler

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***Abstract*— A novel broad-band rat-race ring coupler with a unit element at each port and an ideal phase inverter at one of the ring arms is proposed and analyzed. Design equations based on Chebyshev equiripple functions are derived. The design curves of equal or unequal power division are also presented. Theoretical data show that the bandwidth of unequal power division with a specific return-loss value increases as the power division ratio increases or decreases from unity. For a 180° hybrid with equal power division (3 dB) and 15-dB return loss, the proposed rat-race ring may have a bandwidth of 4 : 1. Three circuits of this novel rat-race ring are realized using finite-ground-plane coplanar waveguide. The measured results match very well with the theory.**

***Index Terms*—Finite-ground plane coplanar waveguide, phase inverter, uniplanar ring coupler.**

I. Introduction

The 180° hybrid ring coupler is a very useful circuit element in microwave circuits, such as mixer, multiplier, amplifier, beamformer, etc. However, the bandwidth of the conventional rat-race ring coupler is narrow. The conventional rat-race coupler comprises four ring arms. One of the ring arms contains a 180° phase shifter. Traditionally, this 180° phase shifter is formed by a $\lambda/2$ line section, and its phase shifting is 180° only at the center frequency. Many efforts have been made to make the bandwidth of rat-race ring coupler larger [1]–[8]. Most of them pay their attention by making a broad-band phase inverter (180° phase shifter). March [1] replaced the $3\lambda/4$ line section with a short-circuited $\lambda/4$ coupled-line section to make the bandwidth of the rat-race ring larger. The uniplanar type of circuit has many advantages for a broad-band rat-race ring. In [2]–[5], the combinations of coplanar waveguide (CPW) and coplanar strips (CPS's) or slot line were adopted to form a phase inverter, and it increases the bandwidth further. In those types of designs, the CPS direct cross-type phase inverter [2], [5] seems to be an ideal phase inverter (with infinity bandwidth theoretically). Even if an ideal phase inverter is used, the conventional rat-race ring coupler is still limited to a bandwidth of about 74% (2.2 : 1 bandwidth) for return loss better than 15 dB. When a rat-race ring coupler is realized with an ideal phase inverter, it physically looks like a 90° branch-line coupler. It is well known that the bandwidth of a 90° branch-line coupler can

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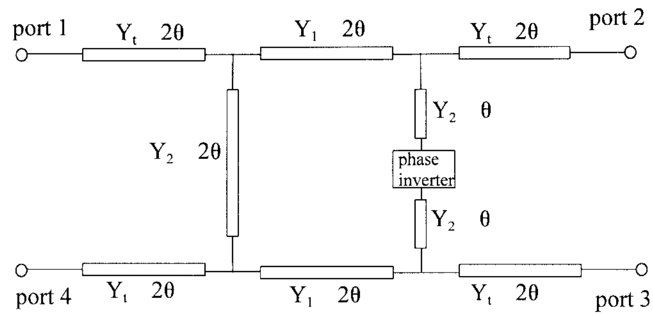

Fig. 1. Schematic circuit of the broad-band rat-race ring coupler.

be broadened by applying a multiple-section structure [9]. Increasing the number of sections, the bandwidth of a branch-line coupler increases accordingly. It seems like that same concept could be adopted here. Unfortunately, in this study, we find that the rat-race ring coupler could not have a similar multiple-section structure as a branch-line coupler has. The only possible way is to add a unit element with normalized admittance Y_t to each input/output (I/O) port, as shown in Fig. 1. With these unit elements, the response of a rat-race ring coupler could be increased from order two to order four. In [6], although the coupler has a unit element at each I/O port, the circuit after optimization does not show the fourth-order Chebyshev response and the bandwidth is only 50.7% with about 21-dB return loss. This is due to the fact that the phase inverter in [6] is a narrow-band phase inverter. By theoretical analysis, two criterions should be met to create the coupler showing a broader bandwidth. The first criterion is to realize an ideal phase inverter (or a phase inverter with enough bandwidth) with relatively low impedance. The second criterion is to increase the order of circuit response. When the order of freedom increases, the coupling function may fit to a specific frequency response with higher order. The bandwidth of the circuit may, therefore, be broadened. In short, we can say that narrow-band phase inverter limits the bandwidth of a conventional rat-race ring coupler. After solving the bandwidth problem of the phase inverter, increasing the order of the circuit response may still increase the bandwidth of a rat-race ring coupler. In this paper, we develop the solutions for the above-mentioned problems and provide a rigorous procedure to synthesize the circuit to a specified Chebyshev response. Theoretical analysis shows that a 15-dB return-loss bandwidth of 120% (4 : 1 bandwidth) can be achieved with this novel 3-dB rat-race ring coupler. Unequal power division may even have much broader bandwidth. Two practical problems

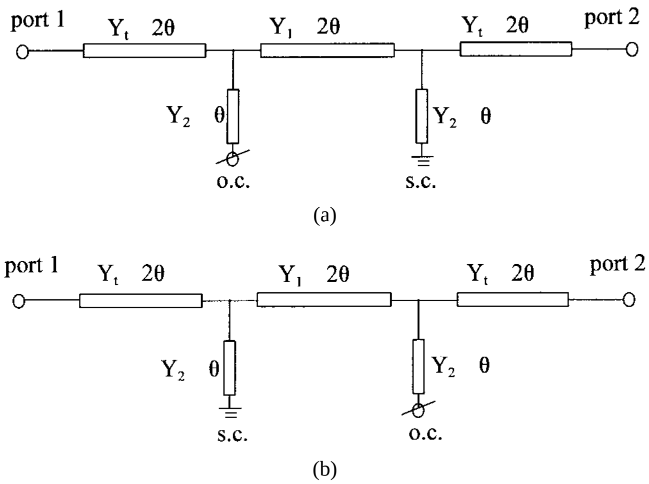

Fig. 2. (a) Even- and (b) odd-mode equivalent circuits of the broad-band rat-race ring coupler.

should be solved in the realization of our rat-race ring. Realization of low impedance line (3-dB coupler with 15-dB return loss having the line impedance as low as 32 Ω) is the first problem. The design of ideal phase inverter with low impedance line is the second problem. Among the planar transmission lines, the finite-ground-plane CPW (FCPW) and broadside line can solve these problems simultaneously. Three prototype 3-dB rat-race ring hybrids using FCPW are realized with center frequency of 5 GHz. Measured results match very well with the theoretical predictions.

II. Theoretical Analysis of the Coupler

Based on the normal-mode analysis and using the even–odd-mode analysis technique, the even- and odd-mode equivalent circuits of the proposed rat-race ring coupler are shown in Fig. 2(a) and (b). In Figs. 1 and 2, the ring admittance Y_1, Y_2, and the unit element admittance Y_t are normalized values, which is normalized to system admittance Y_0. The $ABCD$ matrices for the even- and odd-mode circuits shown in Fig. 2(a) and (b) are

$$\begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} = \frac{1}{(1-t^2)^3} \begin{bmatrix} A_3(t^2) & tB_2(t^2) \\ tC_3(t^2) & D_3(t^2) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} A_o & B_o \\ C_o & D_o \end{bmatrix} = \begin{bmatrix} D_e & B_e \\ C_e & A_e \end{bmatrix} = \begin{bmatrix} D & B \\ C & A \end{bmatrix} \tag{2}$$

where $t = j \tan\theta$ and A_3, C_3, D_3, and B_2 represent the third- and second-order polynomials of t^2, respectively. The S-parameters of the four-port network are

$$S_{11} = S_{22} = \frac{B-C}{A+B+C+D} = \Gamma \tag{3a}$$

$$S_{21} = S_{12} = \frac{2}{A+B+C+D} = T \tag{3b}$$

$$S_{31} = S_{42} = 0 \tag{3c}$$

$$S_{41} = \frac{A-D}{A+B+C+D} = \frac{2(Y_1/Y_2)}{A+B+C+D} \tag{3d}$$

$$S_{32} = \frac{D-A}{A+B+C+D} = \frac{-2(Y_1/Y_2)}{A+B+C+D}. \tag{3e}$$

It is obvious that the output-power division ratio is

$$R = \frac{|S_{41}|^2}{|S_{21}|^2} = \frac{|S_{32}|^2}{|S_{12}|^2} = \left(\frac{Y_1}{Y_2}\right)^2. \tag{4}$$

Assuming that the input is matched well in the passband, for conservation of energy, we have

$$|T|^2\left[(Y_1/Y_2)^2 + 1\right] \approx 1. \tag{5}$$

Now, consider the function

$$F = \frac{|\Gamma|}{|T|\sqrt{R+1}} \tag{6}$$

which approximately equals to the reflection coefficient in the passband because the denominator $|T|\sqrt{R+1}$ is very close to unity [see (5)]. The deviation is small if the ripple in the passband is small. The insertion-loss function can be shown as follows:

$$P_L = 1 + |F|^2 = 1 + \left\{\frac{|B-C|}{2\sqrt{R+1}}\right\}^2. \tag{7}$$

The insertion-loss function can be specified by a different mathematical function. The responses of the coupler will follow the characteristics of the mathematical function.

The coupler in Fig. 1 could be synthesized to have a equiripple response. According to Levy and Lind's [9] analysis, if S_{31} and S_{42} (the isolation of the coupler) are assumed to be zero in the passband, the synthesis procedure can be largely simplified. In our circuit, however, this is already satisfied for all frequencies [see (3c)]. Now, let us define the center frequency of our hybrid ring by setting Y_t, Y_1, and Y_2 length to be $\lambda/4$ (i.e., $\theta = 45°$ in Fig. 1). Using the method similar to Riblet [10], the return loss and coupling could be synthesized simultaneously. The equiripple response, which was described by Riblet [10], Carlin, and Kohler [11], has the form as shown in

$$P_L = 1 + h^2 \cdot \left\{\frac{\left(1+\sqrt{1-x_c^2}\right)T_n(x/x_c) - \left(1-\sqrt{1-x_c^2}\right)T_{n-2}(x/x_c)}{2\sqrt{1-x^2}}\right\}^2 \tag{8}$$

where $x = \cos 2\theta$, $x_c = \cos 2\theta_c$, and h is the parameter to control the ripple level.

In order to fit (7) to this equiripple response, we must set $n = 4$. Therefore, we have four return-loss dips in the passband of $-x_c \le x \le x_c$. After some manipulations, we have

$$\frac{Y_t^4 - Y_1^2 - Y_2^2}{Y_2 Y_t^2 \sqrt{R+1}} = 2h \tag{9a}$$

$$\frac{2Y_t\left(Y_t^2 - 1\right) + \left(Y_1^2 + Y_2^2\right)\left(Y_t^2 - 2\right) - Y_t^2 - 2Y_1Y_2 + 2Y_t^4}{Y_2 Y_t^2 \sqrt{R+1}} = \frac{6\sqrt{1-x_c^2} + 10}{x_c^2}\, h \tag{9b}$$

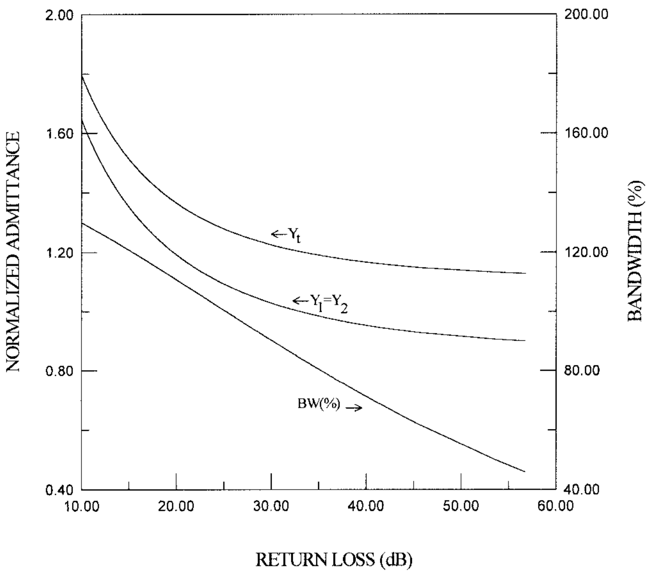

Fig. 3. Normalized admittance Y_1, Y_2, Y_t, and bandwidth (%) versus return loss (dB) for equiripple response (four return-loss dips) 3-dB ring coupler.

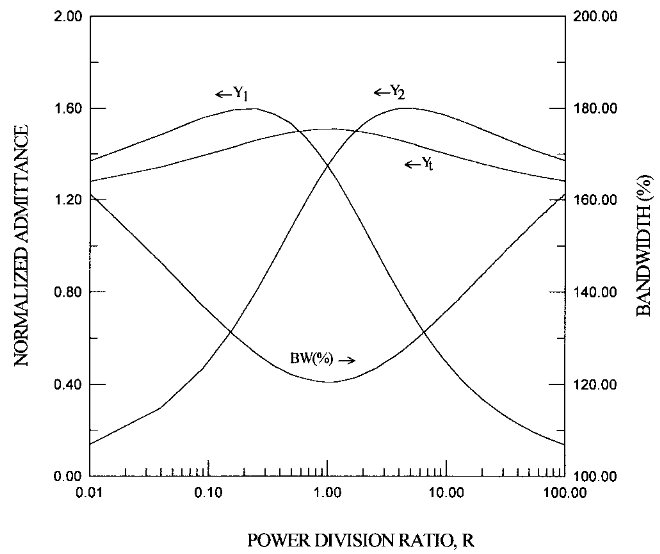

Fig. 4. Normalized admittance Y_1, Y_2, Y_t, and bandwidth (%) versus power division ratio R for 15-dB return loss and equiripple response (four return-loss dips).

$$\frac{\left(Y_t^2-1\right)(Y_1+Y_2)(2Y_t+Y_1+Y_2)-Y_t^2+Y_t^4}{Y_2Y_t^2\sqrt{R+1}} = \frac{8\sqrt{1-x_c^2}+8}{x_c^4}\,h. \tag{9c}$$

If we fix the ring admittance Y_1, the admittance Y_2 is determined by the power-division ratio corresponding to (4). There are three unknown variables related to three equations in (9), which can be solved numerically. Fig. 3 shows the plot of Y_1, Y_2, Y_t, and bandwidth (%) versus return loss for 3-dB power-division (i.e., $Y_1 = Y_2$) rat-race ring. The 120% bandwidth for return loss better than 15 dB or 130% bandwidth for return loss better than 10 dB can be achieved. The relationship between h and return loss is

$$RL = 10\,\log\left(1+1/h^2\right)\ \text{dB}. \tag{10}$$

Fig. 4 shows the computed results for different power-division ratio and for 15-dB return loss. It is clear that the bandwidth increases as the power-division ratio increases or decreases from unity (equal power division) and, of course, the realization of circuit is more difficult. Figs. 3 and 4 provide the useful information for designing the 180° ring hybrid.

Riblet [10] also described an optimum, even, equiripple, function having a double zero at zero. If this type of function is chosen to specify the coupler, there will be three return-loss dips instead of four, as in previous derivation. We summarize the procedures as follows.

The values of the function

$$\frac{\left(a+\sqrt{a^2-1}\right)T_n(x)-\left(a-\sqrt{a^2-1}\right)T_{n-2}(x)}{2\sqrt{a^2-x^2}} \tag{11}$$

vary between ± 1 over the range $-1 \le x \le 1$. Let x_0 be the zero of this function nearest to the origin, then when $n = 4$,

$$T_2(x_0) = \cos\,2\,\cos^{-1}x_0 = \frac{1-\sqrt{1+8Z^4}}{4Z^2} \tag{12}$$

where $Z = a+\sqrt{a^2-1}$.

The function

$$R_n\left[\left(a^2-x_0^2\right)x^2+x_0^2\right]\Big/2\sqrt{a^2-x_0^2}\,\sqrt{1-x^2} \tag{13}$$

varies between ± 1 over the range $\pm\sqrt{1-x_0^2}/\sqrt{a^2-x_0^2}$ with a double zero at $x = 0$, where $R_n\left(y^2\right) = ZT_n(y) - Z^{-1}T_{n-2}(y)$.

Therefore, the insertion-loss function for the optimum, even, equiripple, response has the form

$$P_L = 1+h^2 \cdot\left\{R_n\left[\left(a^2-x_0^2\right)x^2+x_0^2\right]\Big/2\sqrt{a^2-x_0^2}\,\sqrt{1-x^2}\right\}^2. \tag{14}$$

Applying this function to the insertion-loss function of a rat-race ring coupler, we find that

$$\frac{Y_t^4-Y_1^2-Y_2^2}{Y_2Y_t^2\sqrt{R+1}} = h\left[8Zx_0^4-\left(8Z+2Z^{-1}\right)x_0^2+Z+Z^{-1}\right]\Big/\sqrt{a^2-x_0^2} \tag{15a}$$

$$\frac{2Y_t\left(Y_t^2-1\right)+\left(Y_1^2+Y_2^2\right)\left(Y_t^2-2\right)-Y_t^2-2Y_1Y_2+2Y_t^4}{Y_2Y_t^2\sqrt{R+1}} = h[16Z(a^2-x_0^2)x_0^2-(8Z+2Z^{-1})(a^2-x_0^2)]\Big/\sqrt{a^2-x_0^2} \tag{15b}$$

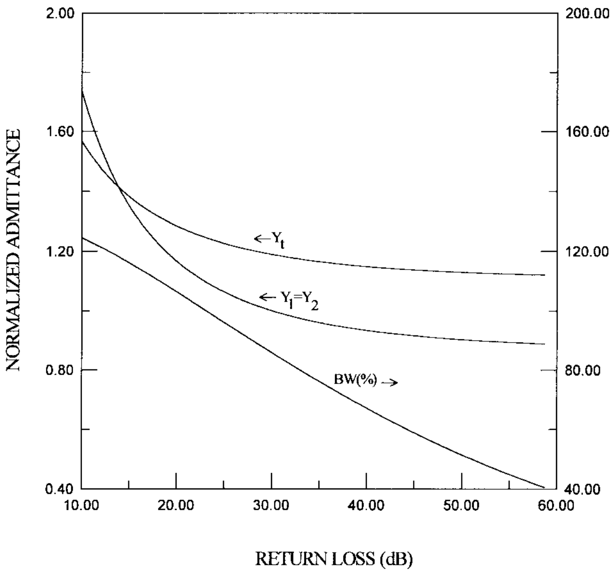

Fig. 5. Normalized admittance Y_1, Y_2, Y_t, and bandwidth (%) versus return loss (dB) for equiripple response (three return-loss dips) 3-dB ring coupler.

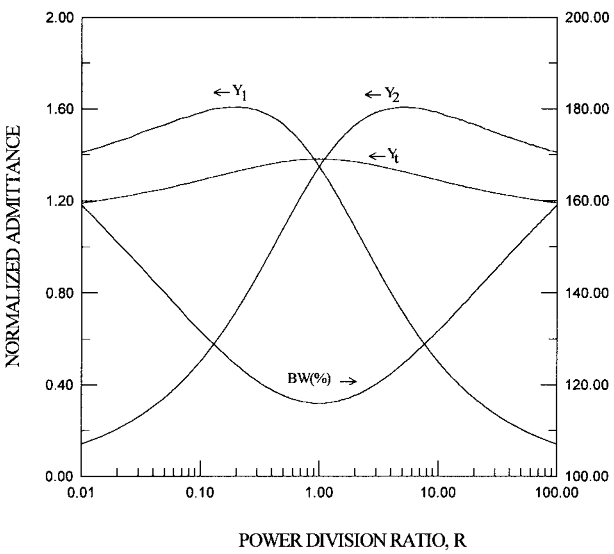

Fig. 6. Normalized admittance Y_1, Y_2, Y_t, and bandwidth (%) versus power-division ratio R for 15-dB return loss and equiripple response (three return-loss dips).

$$\frac{\big(Y_t^2-1\big)(Y_1+Y_2)(2Y_t+Y_1+Y_2)-Y_t^2+Y_t^4}{Y_2Y_t^2\sqrt{R+1}} = 8hZ\big(a^2-x_0^2\big)^2\Big/\sqrt{a^2-x_0^2}. \tag{15c}$$

These equations can also be solved numerically. The numerical result of the equal (3-dB) power division ($Y_1 = Y_2$) is shown in Fig. 5, which indicates that the 116% (124%) bandwidth for return loss better than 15 dB (10 dB) can be achieved. Fig. 6 shows the plot of admittance Y_1, Y_2, Y_t, and bandwidth (%) versus power-division ratio R for 15-dB return loss. It is observed that, in Figs. 5 and 6, the admittance Y_1, Y_2, and Y_t satisfy the relation $Y_t^2 = \sqrt{Y_1^2+Y_2^2}$. This relation can be easily derived by letting $|S_{11}| = 0$ or $S|_{22}| = 0$ (i.e., $|B-C| = 0$) at the center frequency. The bandwidth of the design by optimum equiripple function is a little bit narrower than that of the four dips equiripple design.

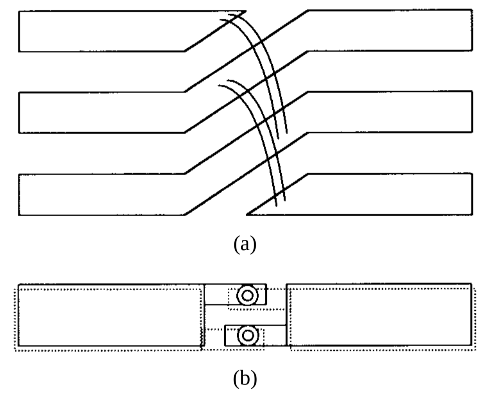

Fig. 7. Circuit configuration of ideal phase inverter. (a) Realized with FCPW. (b) Realized with broadside line.

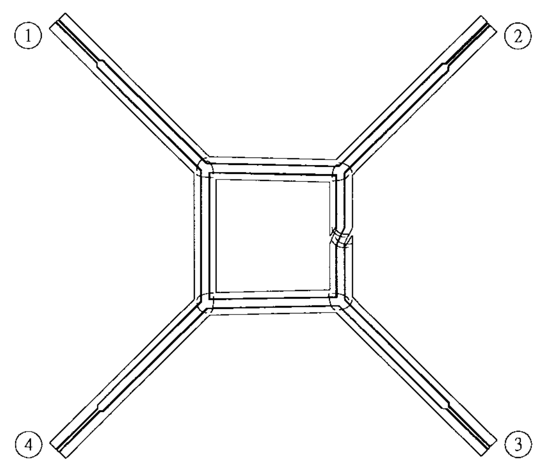

Fig. 8. Circuit layout of the FCPW ring coupler.

III. Experimental Results

The theory of the proposed rat-race ring coupler is based on an ideal phase inverter, as shown in Fig. 1. As we mentioned previously, the FCPW and broadside line are good candidates to realize this ideal phase inverter. Fig. 7 shows the circuit layout of the ideal phase inverter realized in these two types of lines.

Here, we choose an FCPW to realize our circuits because of the avoidance of the via hole. The line impedance calculation is based on a sequence of conformal mappings [12]. The substrate to realize the circuits is 25-mil Al_2O_3 alumina ($\varepsilon_r = 9.8$). Fig. 8 shows the circuit layout of the coupler. Three novel rat-race ring couplers are fabricated using an FCPW with system impedance of 50 Ω. The design parameters and circuit dimensions are listed in Table I. The length of the bonding wires used to form the phase inverter is about 20–30 mil and the diameter of the bonding wires is 1 mil. The effects of the bonding wires at crossover can be compensated by shortening the length of the ring arm by 9 mil for circuits I and

TABLE I
DESIGN PARAMETERS AND CIRCUIT DIMENSIONS OF THREE NOVEL RAT-RACE RING COUPLERS (THE $\lambda/4$ LINE LENGTH IS 255 mil FOR 5 GHz)

Circuit	Normalized admittance	Strip width (mil)	Slot width (mil)	Finite ground width (mil)
I	$Y_1 = Y_2 = 1.4$	15	1.5	10
	$Y_t = 1.56$	16	1.5	11
II	$Y_1 = Y_2 = Y_t = \sqrt{2}$	15	1.5	12
III	$Y_1 = Y_2 = 1/\sqrt{2}$	3	3.3	3
	$Y_t = 1$	4.2	1.9	15

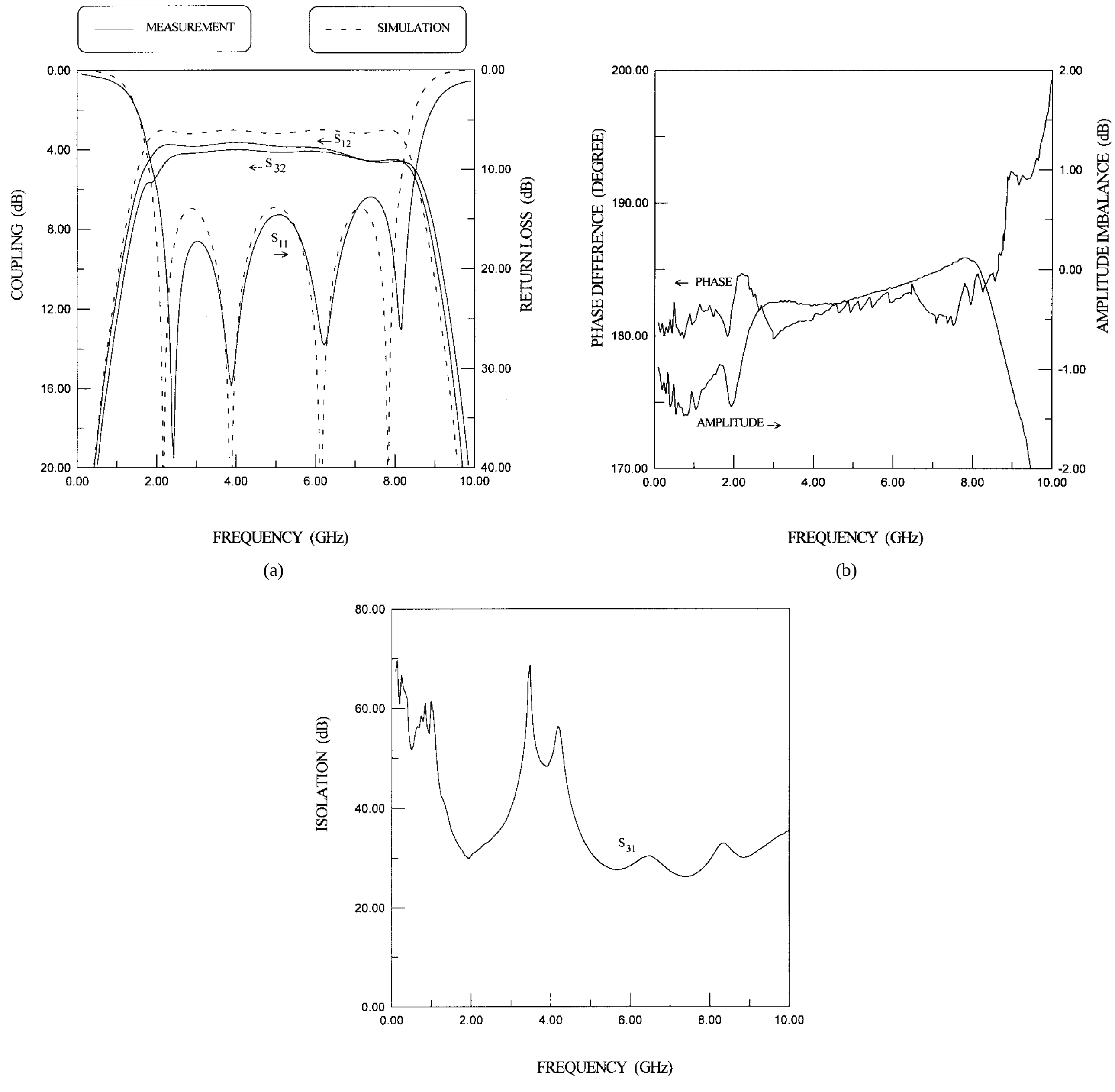

Fig. 9. Measured and simulated frequency response of equiripple (four return-loss dips) rat-race ring coupler. (a) Return loss and coupling. (b) Phase difference and amplitude imbalance. (c) Isolation.

II and 4 mil for circuit III, respectively. Circuit I is designed to satisfy a 13.8-dB return loss corresponding to four dips equiripple function. Circuit II is designed to satisfy a 13.8-dB return loss corresponding to three dips optimum equiripple function. Circuit III is a conventional rat-race ring with an ideal 70.7-Ω FCPW phase inverter.

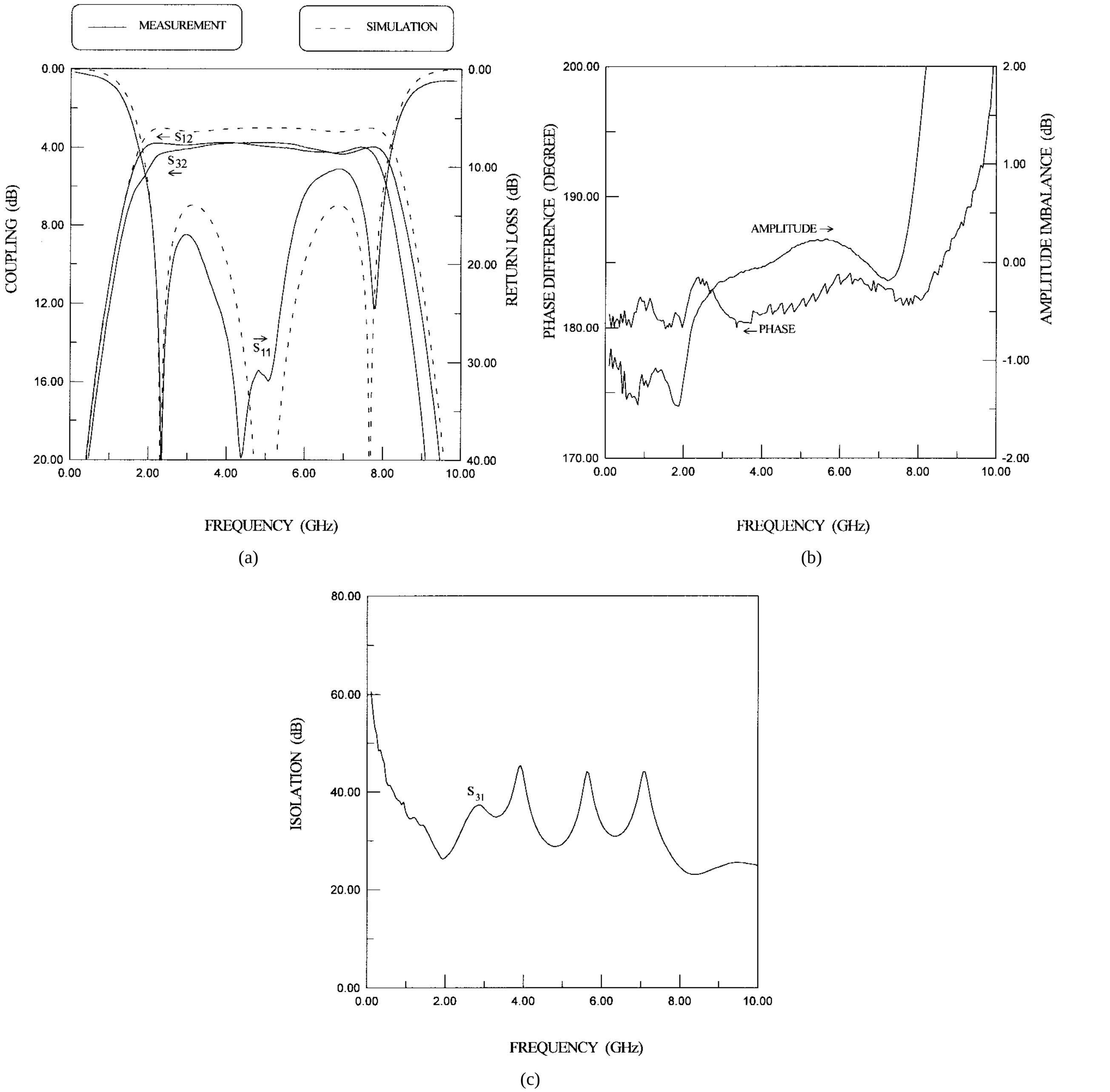

Fig. 10. Measured and simulated frequency response of equiripple (three return-loss dips) rat-race ring coupler. (a) Return loss and coupling. (b) Phase difference and amplitude imbalance. (c) Isolation.

Circuit I has line impedances of $Z_1 = Z_2 = 35.7\ \Omega$ and $Z_t = 32.05\ \Omega$. The CPS, although suitable for the phase inverter, is impossible to realize a line with such a low impedance. The simulated and measured results are shown in Fig. 9. The return-loss data, shown in Fig. 9(a), match very well to the theoretical data. The measured return-loss bump is higher than 13.8 dB at the high frequency end, and the passband is shifted a little bit to higher frequency (the desired passband is 1.93–8.07 GHz and has 123% bandwidth). This is due to the parasitics of four Y junctions, and can be compensated by tuning the line length of Y_t sections. The measured coupling, also shown in Fig. 9(a), is about 4 dB (theoretically, it should be 3 dB), which is due to the line losses of the FCPW. The output amplitude imbalance, shown in Fig. 9(b), is less than 1 dB from 2.16–8.8 GHz. The perfect 180° phase difference between S_{32} and S_{12} in Fig. 9(b) and good isolation in Fig. 9(c) imply good performance of the FCPW phase inverter. The phase error of the difference port is less than 5° from 45 MHz to 8.65 GHz. The sum port phase error and amplitude imbalance are not shown, but the performance is better than that of difference port. The measured isolation is better than 25 dB from 45 MHz to 10 GHz.

Circuit II has line impedances of $Z_1 = Z_2 = Z_t = 35.36\ \Omega$. The simulated and measured results are shown in Fig. 10. The designed passband is 2.05–7.95 GHz (118% bandwidth). The measured return loss and coupling agree well with the simulation. The output amplitude imbalance is less than 1 dB

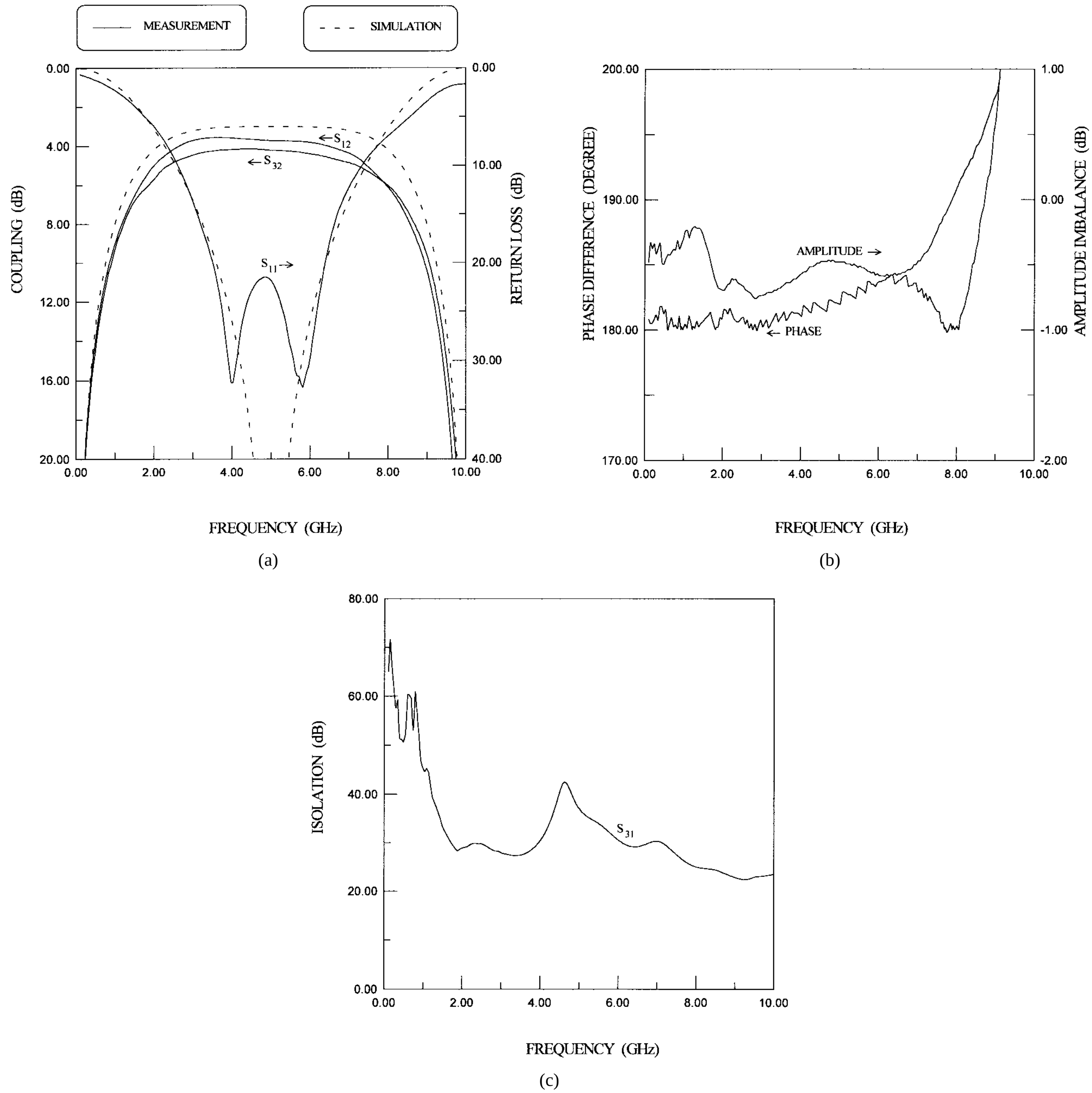

Fig. 11. Measured and simulated frequency response of conventional rat-race ring coupler (Butterworth response). (a) Return loss and coupling. (b) Phase difference and amplitude imbalance. (c) Isolation.

from 2.09 to 7.95 GHz and the phase error of difference port is less than 5° from 45 MHz to 8.6 GHz. The measured isolation is also better than 23 dB from 45 MHz to 10 GHz.

Circuit III has line impedances of $Z_1 = Z_2 = 70.7\ \Omega$ and $Z_t = 50\ \Omega$. The simulated and measured results are shown in Fig. 11. This conventional rat-race ring coupler is fabricated to show that without the unit element at each I/O ports, the bandwidth can only reach 79% (13.8-dB return loss) even with an ideal phase inverter. In Fig. 11, it is actually a Butterworth response of order two. The bandwidth of a Butterworth response is obviously less than that of a Chebyshev response for the same return loss. In Fig. 11(a), the measured return loss has two dips as compared to one dip of the simulation. This is due to the fabricated ring impedance is slightly lower than 70.7 Ω. It can be identified that if the ring impedance is lower than 70.7 Ω (normalized admittance higher than $1/\sqrt{2}$), the return loss will change from Butterworth response to Chebyshev response of order two.

The bonding wires in the phase inverter seem to have little influence on the performance of the couplers. The authors had fabricated a 30 GHz FCPW rat-race ring 3-dB coupler with a Chebyshev response of order two. The measured performance is still very close to theoretical value.

IV. Conclusion

In this paper, the broad-band rat-race ring for Chebyshev characteristics with a bandwidth much better than any previously published magic-T hybrids has been developed.

To achieve the broad bandwidth, both the unit elements of admittance Y_t and the ideal phase inverter are required. The design curves for two types of equiripple response are given. The design curves for different coupling values are also shown. Based on these curves, a broad-band rat-race ring coupler can be easily designed. The FCPW is used to realize the prototype broad-band rat-race ring. The experimental data show very good agreement with the theoretical prediction.

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