Miniaturized Rat Race Coupler With Suppression of Spurious Passband

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***Abstract*—A new hybrid ring coupler design is devised for circuit miniaturization based on the periodic stepped-impedance ring resonator structure. The circuit has an area of 21.5% of a conventional rat race coupler and no passband up to the sixth harmonic of the design frequency. The designs are validated by comparing measured four-port parameters with the simulated results.**

***Index Terms*—Directional coupler, miniaturization, rat race, ring hybrid, stepped-impedance.**

I. INTRODUCTION

THE rat race coupler is a basic circuit for equal power division in microwave balanced mixers and balanced amplifiers. The circuit size is large if only distributed elements are used when the operation frequency is low. Shrinking the circuit area by using lumped elements to reduce the length of transmission lines is possible, but inductors typically have a low Q [1], [2], which will impact the coupler performance.

Many good ideas have been contrived to realize miniaturized couplers in distributed form. Probably the most intuitive way to achieve the size reduction is to fold the line sections [3]. As compared with the conventional configuration, four- to five-fold reduction in footprint can be obtained. The defected ground structure (DGS) in [4] cannot only miniaturize the circuit but also suppress the spurious passband at the third harmonic. Phase inverters of $\lambda/4$ long [5], [6] can be employed to substitute for the $3\lambda/4$ section which occupies half of the circuit size, where λ represents the guided wavelength. In [7], transmission lines periodically loaded with open circuit stubs, so-called artificial lines, are used to construct reduced-sized compact branch-line and rat race couplers. For the best case, the circuit area is only 32% of that of the conventional counterpart. The miniaturized ring hybrid in [8] is designed based on a similar approach. In [9], designs of $5\lambda/4$- and $7\lambda/6$-ring 3-dB couplers using fundamental $\lambda/8$ and $\lambda/6$ sections, respectively, are proposed. The ratio of circuit area of the latter to that of the conventional 1.5λ-ring is $(7/9)^2 \approx 60\%$.

Based on the periodic stepped-impedance ring resonator configuration in [10], a $7\lambda/6$-ring coupler is designed in this letter. The circuit miniaturization relies on the fact that electric length of transmission line sections can be scaled up by impedance junctions along the ring circumference. In the following, Section II formulates the analysis, Section III demonstrates the simulated and measured responses, and Section IV draws the conclusion.

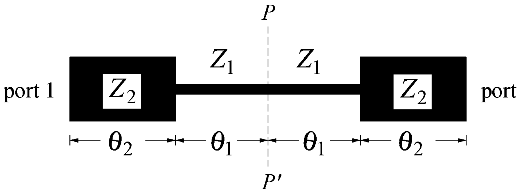

Fig. 1. One of the seven unit cells of the periodic stepped-impedance rat race coupler.

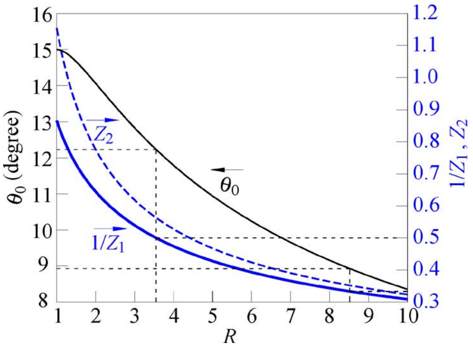

Fig. 2. Z_1, Z_2 and θ_0 as functions of R.

II. ANALYSIS

The $7\lambda/6$-ring [9] consists of one $4\lambda/6$ and three $\lambda/6$ sections having a uniform normalized characteristic impedance $Z_r = 2/\sqrt{3}$. The structure is treated as seven $\lambda/6$ sections and each of them will be implemented by a two-port consisting of a cascade of two low-Z sections with a hi-Z section in between as shown in Fig. 1. The $ABCD$ matrix of the two-port can be readily derived as

$$A = D = \cos 2\theta_1 \cos 2\theta_2 - S \sin 2\theta_1 \sin 2\theta_2 \tag{1a}$$

$$B = jZ_2 \left[\cos 2\theta_1 \sin 2\theta_2 + \sin 2\theta_1 (S \cos 2\theta_2 + d)\right] \tag{1b}$$

$$S = \frac{1}{2}(R + R^{-1}) \tag{1c}$$

$$d = \frac{1}{2}(R - R^{-1}) \tag{1d}$$

where $R = Z_1/Z_2$ is defined as the impedance ratio of the structure. Letting the two-port parameters be identical to those of a $\lambda/6$-section ($\theta = 60^\circ$), we have $A = 1/2$ and $B = j$. There are four variables $(\theta_1, \theta_2, Z_1, Z_2)$ to be solved by these two conditions. From (1a), we have

$$\cos 2(\theta_1 + \theta_2) = \frac{1 + (S - 1)\cos 2(\theta_1 - \theta_2)}{S + 1}. \tag{2}$$

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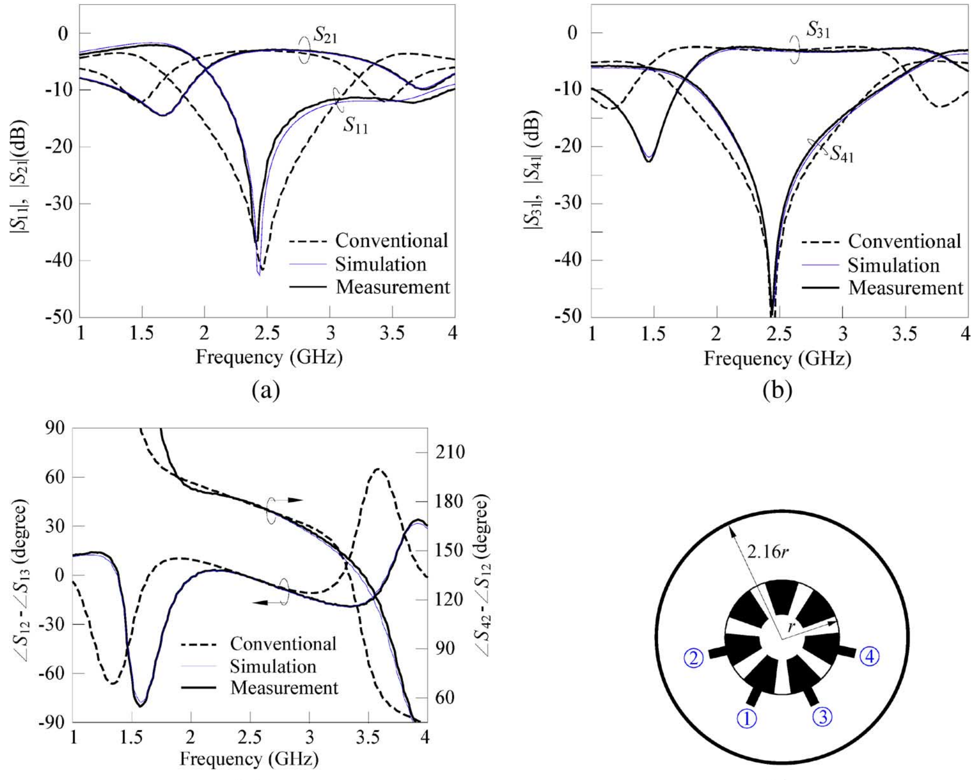

(a) (b)

(c) (d)

Fig. 3. Performance and layout of the rat race coupler designed at f_o = 2.45 GHz. (a) S_{11} and S_{21}. (b) S_{31} and S_{41}. (c) Responses of $\angle S_{41} - \angle S_{21}$ and $\angle S_{31} - \angle S_{21}$. (d) Circuit layout and its comparison with that of a conventional 1.5λ-ring. Inner radius r = 9.875 mm.

To minimize the ring circumference, $\theta_1 + \theta_2$ must be minimized, which is equivalent to maximizing both sides of (2). This results in

$$\theta_1 = \theta_2 = \frac{1}{4}\cos^{-1}\left(\frac{R^2+1}{R^2+2R+1}\right). \quad (3)$$

Obviously, the larger R, the smaller $\theta_1 = \theta_2 \equiv \theta_0$. Next, letting the term on the right hand side of (1b) be j, we have

$$Z_2 = \frac{2}{(1+S)\sin 4\theta_0 + 2d\sin 2\theta_0}. \quad (4)$$

Fig. 2 plots values of θ_0 in (3) and Z_2 in (4) for 1≤ R ≤10. When R =1, $\theta_0 = 15^\circ$, and $4\theta_0 = 60^\circ$. It can be validated that when R =10 the normalized characteristic impedance of the hi-Z section Z_1 = 3.24. Suppose that the circuit substrate has ε_r = 2.2 and thickness = 0.508 mm, and the upper limit of the realizable line impedance is 150 Ω, corresponding to a 0.15-mm linewidth, which is the best resolution of our fabrication process. The curves in Fig. 2 facilitate the solution to the design. Starting with $1/Z_1$ =1/3 of the right vertical axis, we obtain R =8.5 and θ_0 = 8.936°. Here, the lowest realizable low-Z value seems not a problem. Note that the total circumference of proposed circuit is $7\times 4\theta_0 = 28\theta_0$. Thus, the ratio of area of the stepped-impedance ring to that of the conventional ring is $(28\theta_0/540^\circ)^2 = 21.5\%$, where the stepped-impedance architecture contributes a shrink factor of $(8.936/15)^2$ or 35.5% to the circuit area. It is worth mentioning that when a substrate of high ε_r is used, the shrink factor will not be so optimistic. For example, on a substrate of ε_r = 10.2 and thickness = 1.27 mm, the 0.15-mm linewidth corresponds to a line impedance of 100 Ω or Z_1 = 2. The realized θ_0 is 12.23° so that the shrink factor becomes $(12.23/15)^2$ or 66.5%.

III. SIMULATION AND MEASURED RESULTS

Fig. 3 compares simulation and measured responses of the miniaturized rat race coupler with those of a uniform 1.5λ-ring. It is designed at center frequency f_o = 2.45 GHz, and the linewidths of the low-Z and hi-Z sections are 6.06 mm and 0.15 mm, respectively. The simulation is done by the IE3D [11]. $|S_{11}|$ and $|S_{21}|$ are in Fig. 3(a), and $|S_{31}|$ and $|S_{41}|$ in Fig. 3(b). At f_o = 2.45 GHz, the measured $|S_{11}|$, $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$ are −25 dB, −3.16 dB, −3.12 dB, and −40 dB, respectively. The total power loss is better than 3% or 15 dB. It can be observed from Fig. 3(a) that the bandwidth of return loss at 20 dB of the periodic stepped-impedance ring is only one third of that of the uniform ring. This property attributes to the $7\lambda/6$ implementation, but not from the impedance junctions. For implementing a 1.5λ-ring, a six-section stepped-impedance ring is also designed and fabricated based on the above analysis. The measured results (not shown) indicate that bandwidth of $|S_{11}|$ at a 20-dB level is 90% of that of the conventional ring. In Fig. 3(b), on the other hand, both the stepped-impedance and uniform rings exhibit comparable levels and bandwidths for the isolation $|S_{41}|$. Fig. 3(c) plots the responses of $\angle S_{12} - \angle S_{13}$ and $\angle S_{42} - \angle S_{12}$. At the design frequency, the measured $\angle S_{12} - \angle S_{13}$ and $\angle S_{42} - \angle S_{12}$ are 1.2° and 179°, respectively.

Fig. 3(d) shows the layouts of the fabricated circuit and the conventional 1.5λ-ring. Along the circumference of the stepped-impedance ring, there are impedance junctions whose parasitic

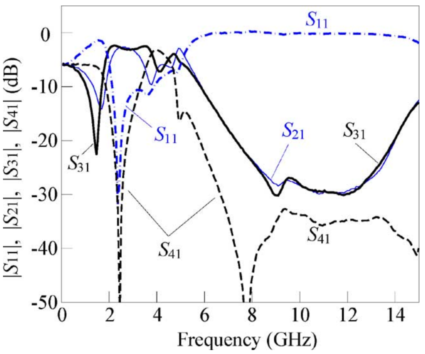

Fig. 4. Broadband performance of the rat race coupler in Fig. 3.

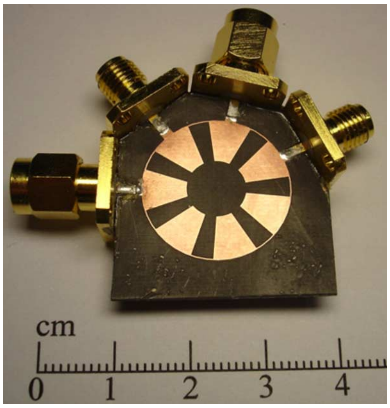

Fig. 5. Photo of the experimental rat race coupler.

effects will alter the frequency dips of S_{11} and S_{41}. Simulation results indicate that $|S_{11}|$ has a dip at 2.5 GHz and $|S_{41}|$ at 2.35 GHz, i.e., $+2\%$ and -4%, respectively, away from the design. To compensate them, the hi-Z and low-Z sections are then cut and increased by 2.8° and 2.7°, respectively.

Fig. 4 depicts the measured S-parameters of the fabricated hybrid ring up to 15 GHz. The circuit presents no spurious S_{21} and S_{31} passbands up to $6f_o$ or 15 GHz. Fig. 5 shows the photo of the experimental rat race coupler.

IV. CONCLUSION

A miniaturized rat race hybrid ring is designed based on the periodic stepped-impedance configuration. Given the impedance ratio, synthesis formulas are derived for designing the whole circuit. For a $7\lambda/6$-ring implementation, the circuit occupies only 21.5% of the area of a conventional 1.5λ-ring. Larger impedance ratio is required for more area reduction, but fine trimming can be inevitable for compensating the parasitics resulted from the strong step discontinuities. The measured results show that the miniaturized coupler presents no spurious passband up to the sixth harmonic of the design frequency.

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