Miniaturized Rat Race Coupler with Microstrip-to-CPW Broadside-Coupled Structure and Stepped-Impedance Sections

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***Abstract* — Miniaturization of microstrip rat race coupler is implemented by incorporating a broadside-coupled structure and stepped-impedance line sections into the design. The former is used to replace the 3λ/4-section and the latter is to substitute the λ/4-line in the conventional circuit. No lumped-element is required in the circuit. One of the experimental circuits occupies only 18.3% of the area of a traditional 6λ/4-rat race. It is believed that it has the best size reduction in comparison with those in open literature. In addition to a wideband characteristic, total inband power loss is better than 3.2%. Measurement results are shown to validate the design and theoretical prediction.**

***Index Terms* — 3-dB coupler, broadside-coupled, miniaturization, rat race, wideband.**

I. Introduction

Recent development in wireless and mobile communication systems has created a need of RF circuits with high performance and compact size. The rat race coupler is one of the most popular passive devices widely used in the RF modules, e.g. balanced amplifiers and mixers. Its circuit size can be very large when operation frequency is low, since it is comprised of one 3λ/4- and three λ/4-line sections [1].

Many methods for miniaturizing the rat race couplers have been proposed [2-12]. In [2], 5λ/4- and 7λ/6-ring couplers have only 69.4% and 60%, respectively, of the area of a conventional 6λ/4-ring. In [3], microstrip lines loaded with periodic open stubs are adopted to design branch-line and rat race couplers. The stubs serve as capacitive loads of the main transmission line to create the slow-wave effect. The circuit area is 32% ~ 46% of the conventional design. A similar approach in [4] shows a ring with a 0.75λ-circumference.

Obviously, the 3λ/4-section of the traditional design is the first choice for the miniaturization. Based on the fact that a λ/4-coupled line section with diametrically opposing ends short-circuited can approximate a phase-reversing network over a wide frequency range [5-7], the circuit circumference can be reduced to 1λ and its normalized area size is only $(4/6)^2$ = 44.4%. There are also several designs offering even better size reduction. In [8], the folded structure can save ring area up to 75%. Artificial lumped-element left-handed transmission lines are devised in [9] to take over the role of the 270° section. If the areas used by the lumped-elements are excluded, the design saves 50% of the circumference; it corresponds to an area reduction of 75%. In the design of [10], each λ/4-section is replaced by a λ/8-line with additional lumped capacitors on both ends. At the same time, the 3λ/4-line is replaced by a π-network of which the shunt inductances almost cancel and the lumped capacitances added to the λ/8-lines. As a result, more than 80% of the area can be saved. To the best of our knowledge, this design has hitherto offered the best size reduction for rat race hybrids implemented in planar or quasi-planar forms.

It is worth mentioning that miniaturization of distributive circuits usually accompanies wide operation bandwidth. The effective bandwidth of the reverse-phase hybrid ring coupler in [6] can be increased by 28% with a return loss of 20 dB. The uniplanar crossover hybrid-ring coupler in [7] has a bandwidth of more than one octave from 2 to 4 GHz with ±0.4 dB power dividing balance and ±1° phase balance. The hybrid in [9] shows 58% and 49% bandwidth enhancements at 2 GHz in the 180°-out-of-phase and in-phase operations, respectively.

In [11], we present a miniaturized rat race coupler having 21.4% area of a 6λ/4-ring rat race. The design utilizes the 7λ/6 configuration in [2] incorporating with the stepped-impedance line sections for substituting the 4λ/6- and the three λ/6-sections. Alternatively, in this paper, based on the traditional design, we propose a broadside-coupled structure of λ/4 in length to replace the 3λ/4-counterpart. The coupled structure consists of a CPW (coplanar waveguide) and a microstrip sharing the same ground plane. Also, the active CPW conductor and the microstrip use the same portion in vertical direction so that no extra area is required. It leads the circuit not only to a compact size but also to a wide bandwidth. Then the circuit area is further reduced by using the stepped-impedance sections, like that presented in [11-12]. As a result, total size reduction is better than 81%. In the following, Section II introduces the broadside-coupled structure and its equivalence to the 3λ/4-line. In Section III, simulated and measured results of two fabricated circuits are demonstrated and their results discussed. Section IV draws the conclusion.

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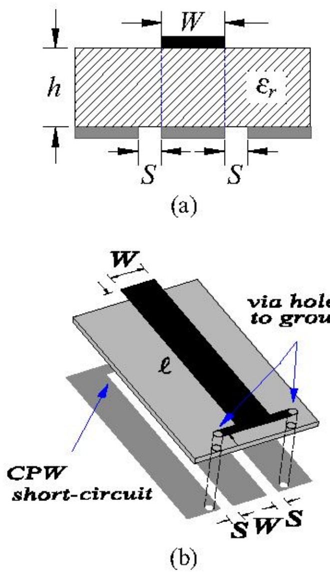

Fig. 1. The microstrip-to-CPW broadside-coupled structure. (a) Cross-section view. (b) Three-dimensional view.

II. The Broadside-Coupled Structure and Its Coupling Characteristics

When a 3λ/4-section is replaced by a symmetric microstrip coupled-line with diametrically opposing ends short-circuited, their characteristic impedances are related by [5]

$$Z_c = \frac{2Z_{oe}Z_{oo}}{Z_{oe} - Z_{oo}} \tag{1}$$

where Z_{oe} and Z_{oo} are the even- and odd-mode characteristic impedances of the coupled-line, and Z_c is that of the 3λ/4-section, i.e. $\sqrt{2}\,Z_o$. The above relation can be obtained by establishing equivalence between their two-port parameters at operation frequency. Usually, the following relation is also invoked [5] to determine the linewidth and space of the coupled-line:

$$Z_c = \sqrt{Z_{oe}Z_{oo}} \tag{2}$$

If Z_o = 50 Ω, solution to (1) and (2) gives Z_{oe} = 171 Ω and Z_{oo} = 29 Ω. Implemented by coupled microstrips, the line space over substrate thickness S/h will be 0.01 and 0.03 for substrates with ε_r = 2.2 and 10.2, respectively. For substrates of $h \approx 1$ mm, such gap sizes are definitely far beyond fabrication resolution of the standard microstrip process.

We use the microstrip-to-CPW broadside-coupled structure shown in Fig. 1 to realize the necessarily high coupling level. The CPW and the microstrip have identical linewidths for ease of design. As shown in Fig. 1(b), the active conductors share the same ground plane and the microstrip short-circuit is implemented by two via holes connected to the ground plane.

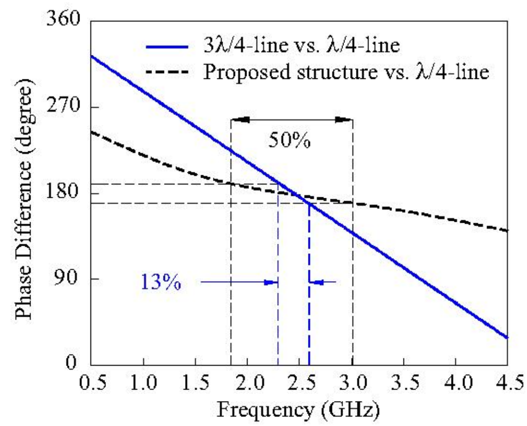

Fig. 2. Comparison of S_{21} phases of the broadside-coupled structure and a 3λ/4-section. Both are referred to that of a λ/4-section. Circuit dimension in Fig. 1(b): W = 1.7 mm, S = 0.66 mm and ℓ = 22.7 mm. Substrate: ε_r = 2.2, thickness = 0.508 mm.

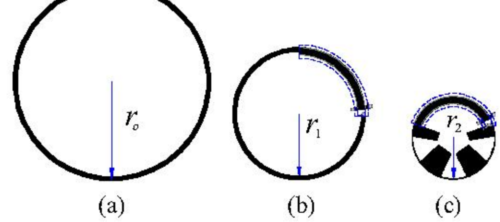

Fig. 3. Layouts of rat races design at f_c = 2.45 GHz. (a) Conventional (6λ/4-ring), r_o = 21.68 mm. (b) 1λ-ring with broadside-coupling, r_1 = 14.45 mm. (c) Further size reduction using stepped-impedance sections, r_2 = 9.27 mm. Substrate: ε_r = 2.2, thickness = 0.508 mm.

The propagation characteristics of the broadside-coupled transmission lines in Fig. 1(a) can be obtained by the spectral domain approach, e.g. [13]. The results will be reported, however, elsewhere due to limited length of this paper. The equivalence of the proposed structure to a 3λ/4-section can be investigated by comparing the magnitude and phase of S_{21} with reference port impedances 70.7 Ω. Fig. 2 compares the phases of the broadside-coupled structure and those of the 3λ/4-section; both are referred to that of a λ/4-section. The circuit has a substrate of ε_r = 2.2 and thickness = 0.508 mm. Simulation data are obtained by the software package IE3D [14]. As shown in Fig. 2, the proposed structure has a bandwidth of 50%, defined by ±10° away from 180° [9], while the traditional counterpart has only 13%.

Fig. 3 compares the layouts of the new couplers with that of the conventional one. In Figs. 3(b) and 3(c), the dashed lines show the conductor edges of the broadside-coupled structure in the ground plane. In Fig. 3(c), the three λ/4-sections are miniaturized by stepped-impedance sections [11]. The low-impedance sections are allocated inside the ring for fully utilizing the space. Design of the stepped-impedance section can be referred to [11-12]. The circuit occupies only 18.3% of area of a traditional 6λ/4-ring by using impedance ratio R = 8.

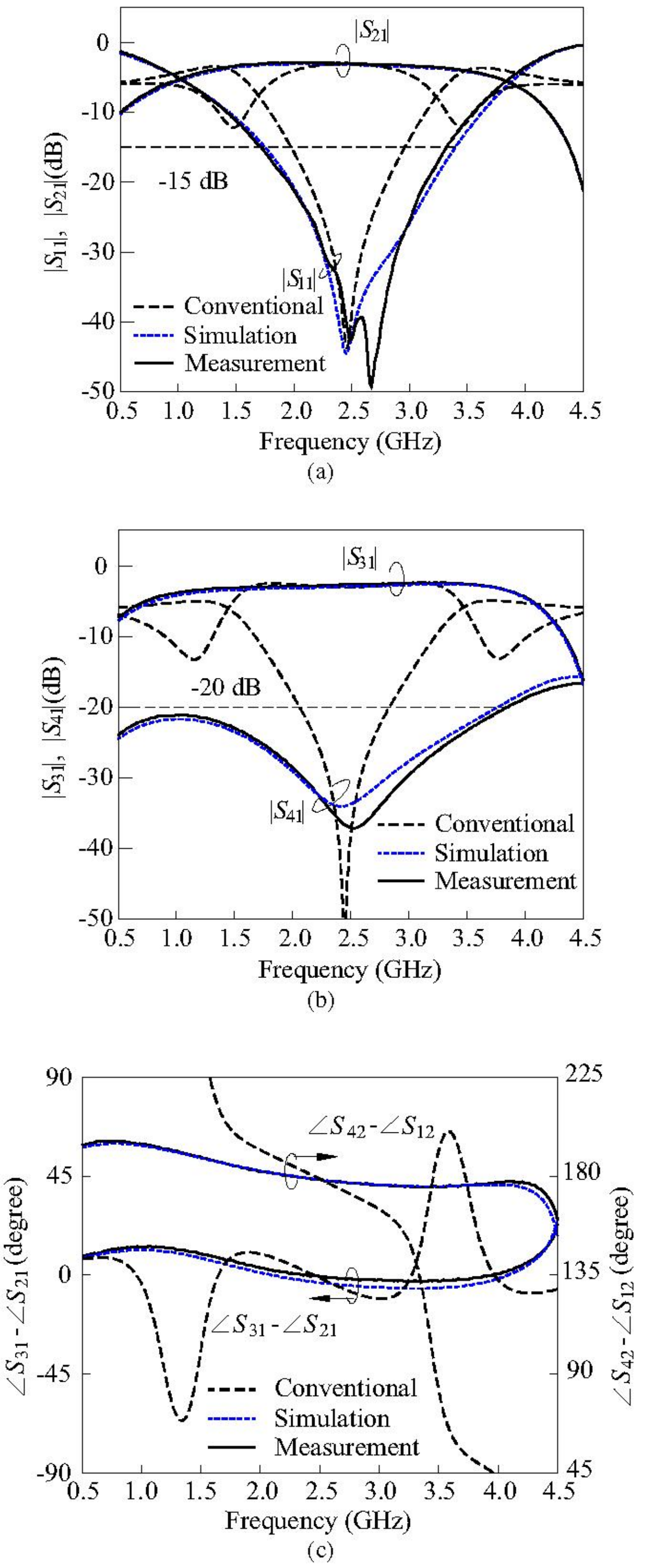

Fig. 4. Simulated and measured responses of the fabricated rat race coupler in Fig. 3(b) in comparison with simulation data of the traditional design. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{31}|$ and $|S_{41}|$. (c) Phase differences $\angle S_{31} - \angle S_{21}$ and $\angle S_{42} - \angle S_{12}$.

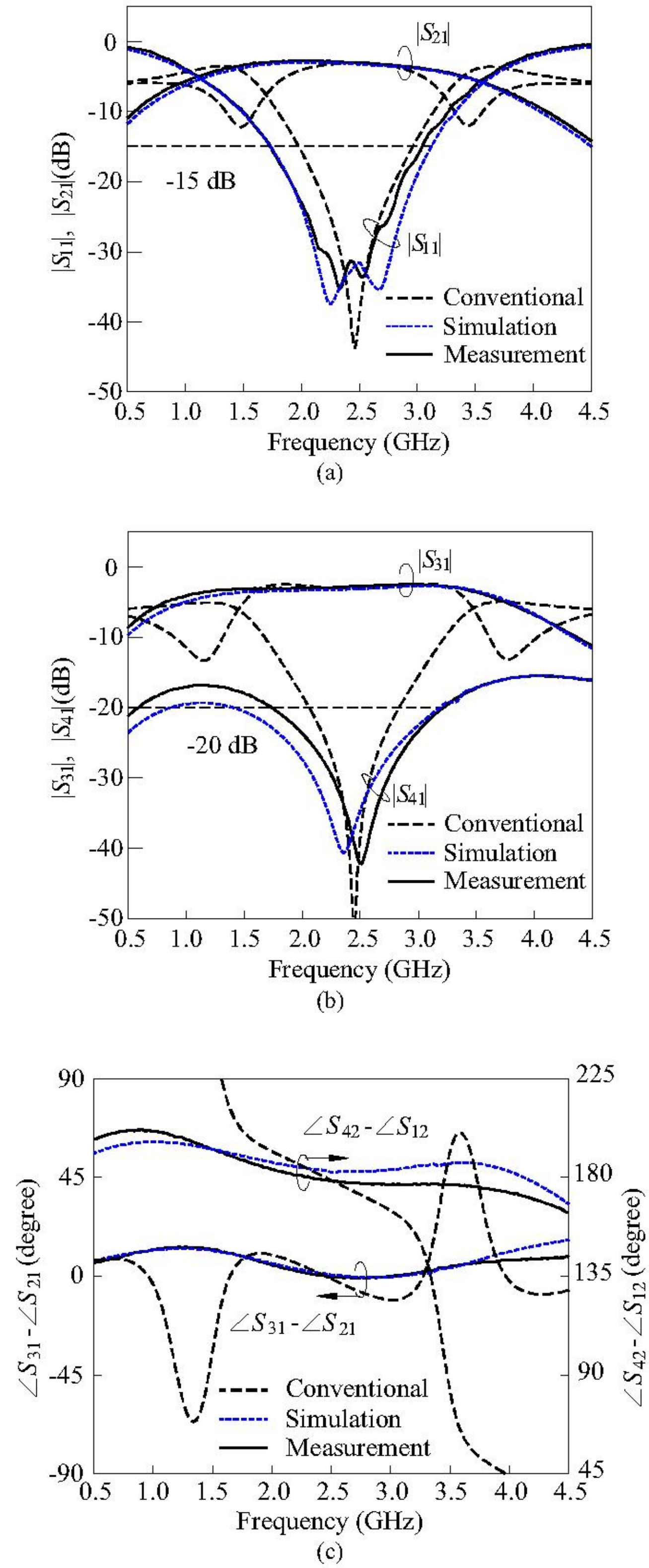

Fig. 5. Simulated and measured responses of the fabricated rat race coupler in Fig. 3(c) in comparison with simulation data of the traditional design. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{31}|$ and $|S_{41}|$. (c) Phase differences $\angle S_{31} - \angle S_{21}$ and $\angle S_{42} - \angle S_{12}$.

(a) (b)

Fig. 6. Photos of the fabricated stepped-impedance rat race coupler with the broadside-coupled structure. (a) Top view. (b) Bottom view.

III. Simulation and Measured Results

Two rat race couplers are designed at center frequency f_c = 2.45 GHz. Figs. 4 and 5 compare the simulated and measured results of the fabricated circuits in Figs. 3(b) and 3(c), respectively, with the simulated data of the traditional design. Figs. 4(a) and 5(a) plot $|S_{11}|$ and $|S_{21}|$ responses and Figs. 4(b) and 5(b) show $|S_{31}|$ and $|S_{41}|$ curves. It can be observed that all measured $|S_{11}|$ results at the design frequency are better than 30 dB. If a 15-dB return loss is referred, measured data indicate that the circuits with and without stepped-impedance sections have 32% and 62%, respectively, more bandwidths than that of the traditional design. In part (b) of both figures, the measured isolations $|S_{41}|$ at the design frequency are better than 35 dB. For a 20-dB reference, measured isolations with and without stepped-impedance sections have bandwidth enhancements of 84% and 320%, respectively. Also, detailed measured data show total power losses of the circuits, $P_L = 1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2$, in Figs. 3(b) and 3(c), are respectively 2.2% and 3.2% in contrast to 0.8% (simulation) for the conventional ring in Fig. 3(a).

Figs. 4(c) and 5(c) plot the responses of phase differences $\angle S_{31} - \angle S_{21}$ and $\angle S_{42} - \angle S_{12}$. One can see that the responses of the proposed circuit have relatively smooth variations in a frequency regime covering from $0.2f_c$ to $1.8f_c$. Their bandwidths for a $\pm 10^o$-deviation are much better than those of the conventional one. Good agreement between the simulation and measured responses for the experiment circuits can be observed. Fig. 6 shows the photographs of top and bottom views of the fabricated circuit in Fig. 3(c).

IV. Conclusion

A new technique for miniaturization of microstrip rat race coupler is presented. A λ/4-microstrip-to-CPW broadside-coupled structure is employed to play the role of the 3λ/4-section in the conventional circuit. This approach saves more than 55% of the circuit area. If stepped-impedance line sections are also implemented to replace the three λ/4-sections, the area reduction is increased to 81.7%. The circuit can have more area reduction when the broadside-coupled structure can be either further realized by the stepped-impedance configuration or incorporated into the 7λ/6- or 5λ/4-design in [2]. Measured results demonstrate that the proposed design not only offers good isolation and but also has a wider bandwidth than the conventional ring hybrid. The price paid for the circuit miniaturization is an extra power loss of 2%.

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