Miniaturization Design for Planar Hybrid Ring Couplers

（Invited Paper）

Yi-Chyun Chiou, Cheng-Hsiu Tsai, Juo-Shiuan Wu, and Jen-Tsai Kuo*
Department of Communication Engineering, National Chiao Tung University
1001 Tahsueh Rd., Hsinchu, 300 Taiwan
E-mail: * jtkuo@mail.nctu.edu.tw

Abstract - **Miniaturization of a microstrip rat race coupler is implemented by three approaches. First, a new rat race hybrid design is devised for circuit miniaturization based on the periodic stepped-impedance ring structure. The circuit has a normalized area of 21.5%. In the second approach, miniaturization is carried out by incorporating a broadside-coupled structure and stepped-impedance sections into the design. The former is used to replace the 3λ/4-section and the latter is to substitute each λ/4-section in the regular 6λ/4 circuits. As a result, one of the circuits occupies only 18% of the area of a traditional rat race. Finally, a general synthesis is performed to design reduced-length rat race rings. Incorporating the stepped-impedance configuration, the normalized circuit area is 13.12% of a 6λ/4-ring. All the designs are validated by comparing measured four-port parameters with the simulated results.**

I. INTRODUCTION

Recent development of 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 balanced amplifiers and mixers. The size of such a coupler is unacceptably large when operation frequency is low, since it is comprised of one 3λ/4- and three λ/4-line sections [1].

Many miniaturization methods for the rat race couplers have been proposed [2-11]. In [2], each λ/4-section is replaced by a λ/8-line with increased characteristic impedance and 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. Consequently, more than 80% of the area can be saved. In [3], 5λ/4- and 7λ/6-ring couplers have only 69.4% and 60%, respectively, of the area of a conventional 6λ/4-ring. In [4], the folded structure can save ring area up to 75%. In [5], microstrip lines periodically loaded with open stubs are adopted to design branch-line and rat race couplers. The stub serves as capacitive load of the main transmission line to create slow-wave effect. The normalized area of the circuit is 32% ~ 46%. A similar approach in [6] shows a ring with a 0.75λ-circumference.

Obviously, the 3λ/4-section of the traditional design is the first target for circuit 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 [7-9], the circuit circumference can be reduced to 1λ and its normalized area is only $(4/6)^2$ = 44.4%. There are also several designs offering even better size reduction. Artificial lumped-element left-handed transmission lines are devised in [10] to take over the role of the 270° section. If the lumped-elements are excluded, the design saves 50% of the circumference; it corresponds to an area reduction of 75%. It is worth mentioning that miniaturization of distributive circuits usually accompanies wide operation bandwidth. The uniplanar crossover hybrid-ring coupler in [8] 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 effective bandwidth of the reverse-phase hybrid ring coupler in [9] can be increased by 28% with a return loss of 20 dB. The hybrid in [10] shows 58% and 49% bandwidth enhancements at 2 GHz in the 180°-out-of-phase and in-phase operations, respectively.

In this paper, three approaches for miniaturizing the rat race coupler are reported [12-14]. First, a miniaturized rat race having 21.4% area of a 6λ/4-ring rat race is presented [12]. The design utilizes the 7λ/6 configuration in [3] incorporated with the stepped-impedance line sections for substituting the 4λ/6- and the three λ/6-sections. In the second [13], based on the traditional design, a broadside-coupled structure of λ/4 long is used to replace the 3λ/4-counterpart. The broadside-coupled structure consists of a coplanar waveguide (CPW) and a microstrip sharing the same ground plane. 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 in [11]. As a result, a size reduction factor of better than 82% can be achieved. Finally, a generalized synthesis is performed to develop miniaturized hybrid rings [14]. The four arms are allowed to have different characteristic impedances and electric lengths at the design frequency. Experimental results are presented along with the simulation to validate the designs.

II. Periodic Stepped-impedance Rat Race Coupler

The $7\lambda/6$-ring [3] 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. Using the transmission line theory in [1], the length and characteristic impedance of low- and hi-Z sections can be readily calculated. Fig. 2 plots values of θ 0 and Z_2 for $1 \le R \le 10$, where $\theta_0 = \theta_1 = \theta_2$ and $R = Z_2/Z_1$, respectively. Suppose that the circuit substrate has $\varepsilon_r = 2.2$ and thickness = 0.508 mm. The upper limit of the realizable line impedance is then 150 Ω, corresponding to a 0.15-mm line width, 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 = 8.9360. The ratio of area of the stepped-impedance ring to that of the conventional ring is $(28\theta_0/540°)^2$ =21.5%, wherethe stepped-impedance configu-ration contributes a shrink factor of $(8.936/15)^2$ or 35.5% to the circuit area.

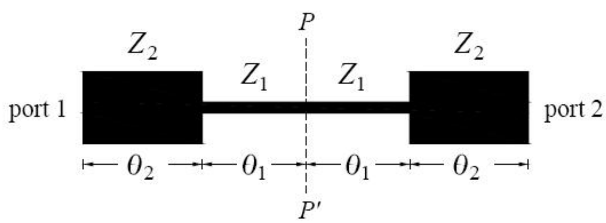


Fig.1. A stepped-impedance section

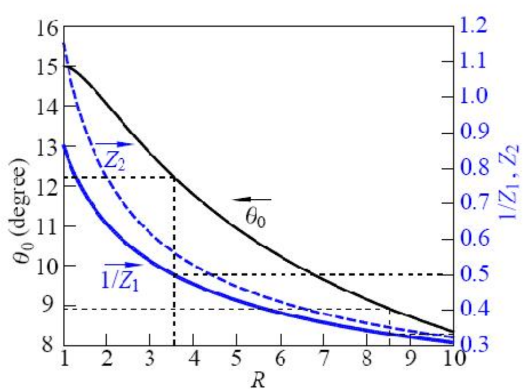


Fig. 2. Z_1, Z_2 and θ_0 as the function of R

Fig. 3 compares simulation and measured responses of the miniaturized rat race coupler with those of a uniform 1.5λ-ring. The simulation is done by the IE3D [15]. $|S_{11}|$ and $|S_{21}|$ are in Fig. 3(a), and $|S_{31}|$ and $|S_{41}|$ in Fig. 3(b). It can be observed from Fig. 3(a) that the bandwidth of return loss at 20-dB level 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 the impedance junctions. For

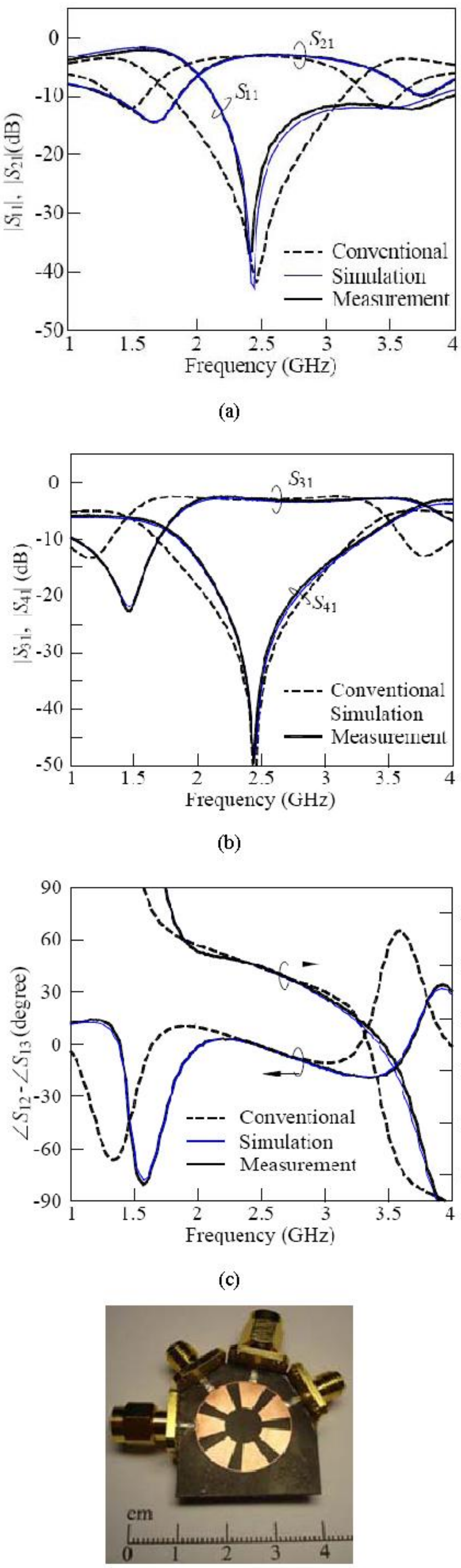


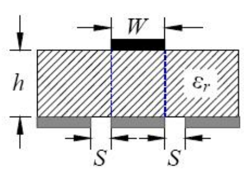
Fig. 3. Performance and layout of the rat race coupler. (a) S_{11} and S_{21}. (b) S_{31} and S_{41}. (c) Responses of $\angle S_{41} - \angle S_{21}$ and $\angle S_{31} - \angle S_{21}$. (d) photograph of the experimental circuit

implementing a 1.5λ-ring, a 6-section stepped-impedance ring is also designed and fabricated based on the above analysis. The measured results 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 magnitudes and bandwidths for the circuit isolation $|S_{41}|$. Fig. 3(c) plots the responses of $\angle S_{41} - \angle S_{21}$ and $\angle S_{31} - \angle S_{21}$. Fig. 3(d) shows the photograph of the experimental circuit.

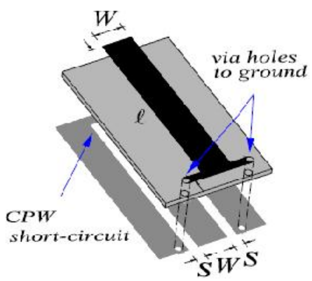
III. Microstrip-to-CPW Broadside-Coupled Structure

When a 3λ/4-section is replaced by a symmetric microstrip coupled-line with diametrically opposing ends short-circuited, their characteristic impedances can be calculated by the formulations in [7].

The microstrip-to-CPW broadside-coupled structure shown in Fig. 4 can be used to realize the necessarily high coupling level. The CPW and the microstrip are assumed to have identical line widths for ease of analysis and design. As shown in Fig. 4(b), the two active conducting strips share the same ground plane and the microstrip short-circuit is implemented by two via holes connected to the ground plane. The equivalence of the structure to a 3λ/4-section can be obtained by comparing the magnitude and phase of S_{21} with port impedances 70.7 Ω. Fig. 5 compares the phases of the broadside-coupled structure and the 3λ/4-section; both are referred to that of a λ/4-section. The circuit substrate has ε_r =2.2 and thickness = 0.508 mm. Simulation is done by the software package IE3D [15]. As shown in Fig. 5, the structure has a bandwidth of 50%, defined by 180° ±10° [9], while the straight λ/4-section has only 13%. Fig. 6 compares the simulated and measured results of the fabricated circuits with the simulated data of the traditional design. Fig. 6(a) plots $|S_{11}|$ and $|S_{21}|$ responses and Fig. 6(b) shows $|S_{31}|$ 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, the measured data indicate that the circuit has 32% more bandwidths than that of the traditional design. In Fig. 6(b), the measured isolations $|S_{41}|$ at the design frequency are



(a) Crosssection view



(b) Three-dimensional view

Fig. 4. The microstrip-to-CPW broadside-coupled structure

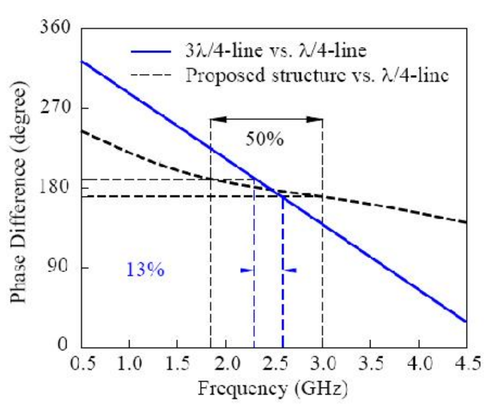
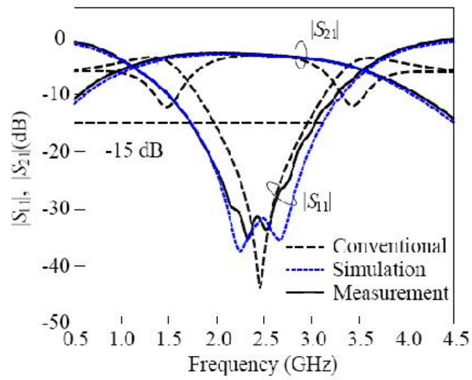
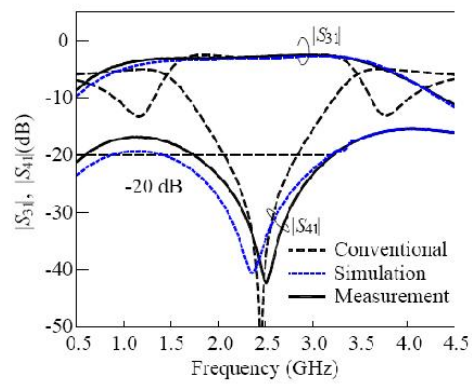


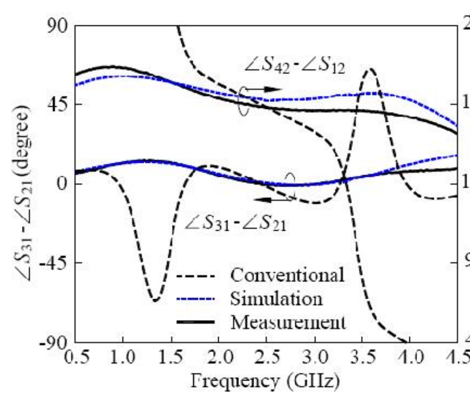
Fig. 5. Comparison of the phases of the proposed structure and the 3λ/4-line (both are referred to that of a λ/4-section line)



(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. 6. Simulated and measured responses of the fabricated rat race coupler in comparison with simulation data of the traditional design

better than 35 dB. For a 20-dB reference, measured isolation has bandwidth enhancements of 84%. Also, detailed measured data show total power loss of the circuit, $P_L = 1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2$, is 3.2% in contrast to 0.8% (simulation) for the conventional ring. Fig. 6(c) plots 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 ±10°-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. 7 shows the photographs of top and bottom views of the fabricated circuit.

Fig. 7. Photos of the fabricated stepped-impedance rat race coupler with the broadside-coupled structure. (a) Top view. (b) Bottom view

IV. Generalized Synthesis of Rat Race Coupler

In [14], a generalized synthesis of rat race coupler is performed. It starts with assuming that the four arms have different characteristic impedances and electric lengths at the design frequency. It can be validated that the two arms on opposite sides have identical characteristic impedances, and the area reduction factor of the final circuit depends on the characteristic impedances adopted for the design. As a result, a hybrid ring with circumference of less then 1λ can be obtained and realized in microstrip form. If the four arms are substituted by stepped-impedance sections, a normalized circuit area of 13.12% can be obtained. The price paid for the circuit area miniaturization is the reduction of circuit bandwidth. For a reference level measured by $|S_{11}|$ = -15 dB at 2.5 GHz, the bandwidth of the conventional ring is 40% and that of the reduced-size ring is only 3.2%.

V. Conclusion

Three design approaches for miniaturizing rat race couplers are demonstrated. The first uses the periodic stepped impedance configuration. Given the impedance ratio, synthesis formulas are derived for designing the whole circuit. For a 7λ/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 is inevitable for compensating the parasitic effects resulted from the strong discontinuities. In the second approach, a λ/4-microstrip-to-CPW broadside-coupler is employed to play the role of the 3λ/4-section in the conventional circuit. This coupler saves more than 82% of the circuit area. 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 third approach performs a generalized synthesis starting from assuming that the four arms have different line parameters. A planar ring hybrid with a normalized area of 13.12% can be realized.

Acknowledgment

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