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Miniaturization of Rat-race coupler with Harmonic suppression technique

N .Sai venkat[1],V.Ravi sekharareddy[2], A.Ravindra[3],Y.Sreekanth[4]
[2]Assistant Professor, [1,3,4]Student, Department of Electronics and Communication,
Lakireddy Balireddy College of Engineering, Mylavaram, India

***Abstract*:**
In this work, a compact RRC using a T-shaped line configuration, in place of all 90° conventional transmission line sections is presented to achieve broadband suppression of harmonics. A lossless transmission line model is derived for the design. As the design is not composed of any complicated structures, via holes and lumped elements, it is simple to implement and easy to fabricate.

Keywords:

RRC,T-shaped line configuration, harmonics, lumped elements, lossless transmission line

I. Introduction

Hybrid directional coupler, recognized as rat-race coupler (RRC), is one of the fundamental components used in microwave integrated circuits (MICs), such as mixers, amplifiers, multipliers, modulators, demodulators, antenna feed networks etc. Besides simplicity, it has broader bandwidth as compared to 90° branch-line coupler, and the isolation between the input ports may be independent of the output termination impedances. However, the conventional coupler consumes significant amount of circuit area especially at low frequencies, due to the required large 540° electrical length transmission line, usually in circular or rectangular shape. In addition, the conventional coupler has spurious pass-bands at harmonics of the fundamental frequency, which affects the circuit performance when used in wireless applications. RAT-RACE coupler is a four port network with a 180phase shift between the two output ports and can also be operated in phase at the outputs. It functions widely in the microwave balanced mixer and amplifier [1]. Several methods are proposed to reduce the physical size of a rat-race coupler,such as by use of artificial transmission lines (ATLs) [2] and[3], metamaterial transmission line [4], using λ/8 or λ/6 sections to replace λ/4 traditional sections [5], adding open-circuited stubs [6], [12] double C-section folded line structure [7],three equal arms of arbitrary electrical length [8], adding defected ground structure (DGS) [9], and compensated spiral compact microstrip resonator cells (C-SCMRCs) [10] and substituting transmission lines by periodic stepped-impedance units cells [11]. However, [2]–[8] do not discuss about the harmonic suppression. Consequently, harmonic suppression is discussed in [9]–[12]. In [9], the DGSs introduce a transmission zero at the upper stop band. In [10], the harmonic suppression is achieved by multiple transmission zeros generated by the C-SCMRCs. In [11], the first harmonic of the coupler is adjusted away from the fundamental resonance by adjusting the impedance ratio of the stepped-impedance unit cells. However, there are some shortcomings in [9]–[12], such as the absence of accurate circuit models which add complicities to the design [9], significant dependence on EM simulations [10], and degraded return loss bandwidth [11], [12].

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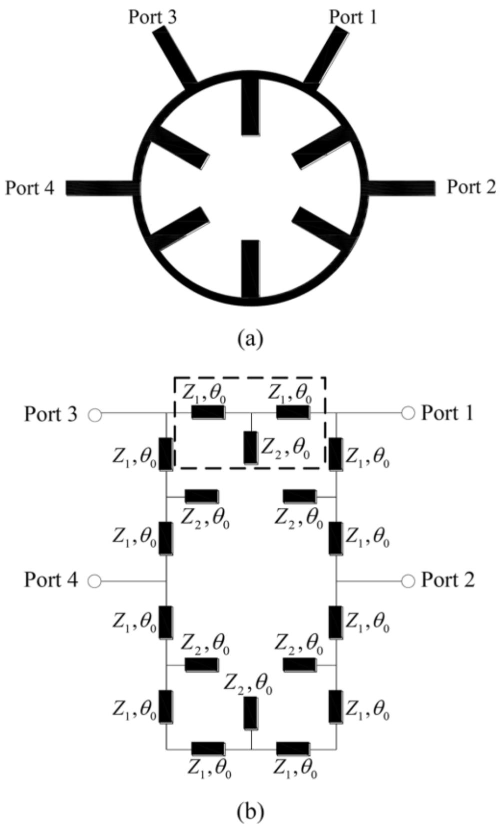
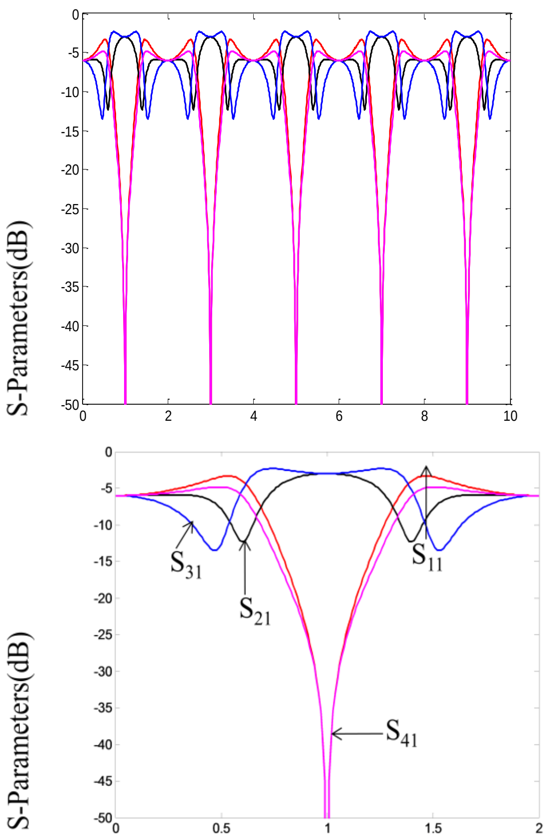


Fig. 1. The proposed rat-race coupler. (a) Layout, and (b) Equivalent transmission line model

In this paper, a miniaturized rat-race coupler with harmonic suppression is proposed, demonstrating the rigorous theoretical analysis, simple design procedure, compact size, and excellent in-band and out-of-band performances. The configuration is exhibited in Fig. 1. First of all, the analysis is conducted to show how a stub-loaded transmission line can be used to equivalently replace a quarter-wavelength transmission line at an effective frequency. Then all the quarter-wavelength transmission lines in a traditional rat-race coupler are replaced by their equivalent stub-loaded transmission lines. Therefore, the overall physical size of the coupler is significantly reduced. In addition, the transmission zero introduced by the stubs suppresses the spurious pass bands. Finally, the proposed coupler is fabricated and a good match is found between the predicted and measured results. Adding stubs is very common in microwave circuit designs. However, to our best knowledge, it is the first time that such a stub-loaded transmission line is studied to replace the quarter-wavelength transmission lines equivalently in the traditional rat-race coupler to realize miniaturization and harmonic suppression.



(a)frequncy(GHz)
(b) frequncy(GHz)

Fig2. Simulated S-Parameters of the (a) Conventional rat-race coupler with harmonics (b) Conventional rat-race coupler at f_0

II. ANALYSIS OF RAT RACE COUPLER

The layout and its equivalent transmission line model of the proposed coupler are shown in Fig. 1, where is the characteristic impedance and is the electrical length of the transmission lines at the design frequency. One stub-loaded transmission line is marked by dashed rectangle in Fig. 1(b) and its *ABCD* matrix can be derived as

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad \text{-----(1)}$$

Where

$$A = D = \cos^2\theta_0 \ - (1+z1/z2)\sin^2\theta_0 \text{-------------------(2)}$$

$$B = jz1(2\sin\theta_0\cos\theta_0 - z1/z2\sin^2\theta_0\tan\theta_0) \text{--------------(3)}$$

$$C = j\sin\theta_0\cos\theta_0((2/z1) + (1/z2)) \text{---------------(4)}$$

In order to match this stub-loaded transmission line to a quarter wavelength transmission line with a characteristic impedance of Z_0 A=D=0, B=J Z_0 , C=J/ Z_0 and . Therefore Z_1andZ_2 can be worked out as

$$Z1 = Z0\cot\theta_0/2;$$

$$Z2 = (Z0\tan 2\ \theta_0)/2;$$

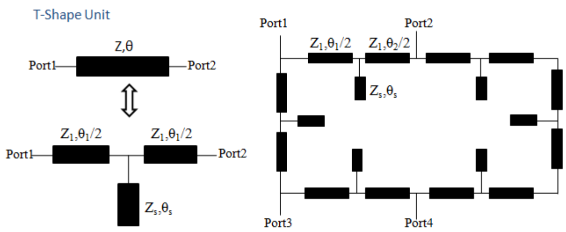


Fig3. Replacing of RRC with proposed RRC

We can notice that when this is the case of a quarter wavelength transmission line. As verified in Fig. 2, when we selected θ_0 to be 35 and 25 , the equivalent responses appear exactly at the electrical lengths equal to 35 and 25 , respectively. So by setting θ_0<35 , the physical size can be reduced accordingly while remaining the performances at the effective frequency. Furthermore, one transmission zero introduced by the stubs appears at θ_0=90 , where the open-circuited stubs act as short circuits. Next a new rat-race coupler is developed using the stub-loaded transmission lines with θ_0=20 , by replacing the quarter-wavelength transmission lines in a traditional rat-race coupler directly. The theoretical magnitudes of the proposed coupler are plotted together with that of the traditional one in Fig. 3. The center frequencies of the couplers are 2.4 GHz. Because the stub-loaded transmission line is matched with its related quarter-wave transmission line completely, the performances of the proposed coupler at the center frequency are exactly ideal as a traditional one, as proved in Fig. 3. The transmission zero appears at 8.64 GHz where the open-circuited stub presents 90 electrical length, and effectively widens the upper-stop band. Based on the above analysis, the design procedure for the proposed rat-race coupler can be summarized as follows: 1) Determining an appropriate θ_0 according to the design requirements; 2) Calculating z1 and z2 using (2a) and (2b), respectively; 3) Finding out the physical dimensions of the stub-loaded transmission lines with values of z1,z2 and ; 4) Placing the stub loaded transmission lines from 3) to substitute the quarter-wavelength transmission lines in a traditional rat-race coupler.

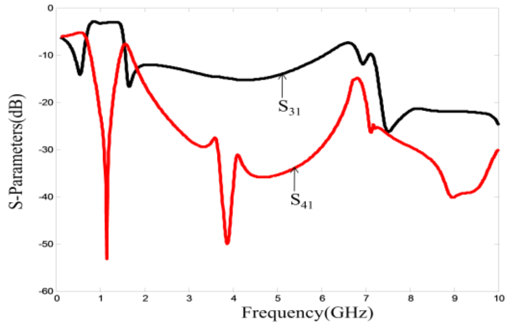


Fig4. Full-wave simulated S-Parameters (S_{31} and S_{41}) of proposed RRC

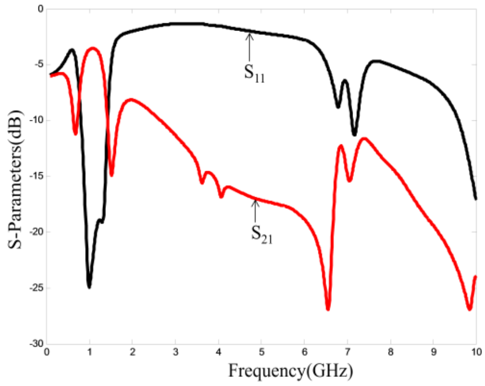


Fig5. Full-wave simulated S-Parameters (S_{11} and S_{21}) of proposed RRC

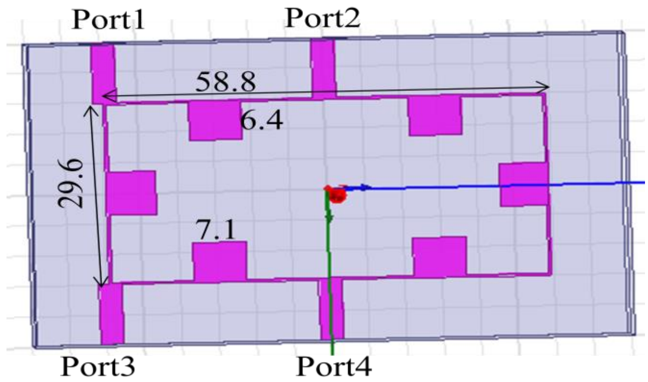


Fig6. proposed full wave simulated harmonic suppressed compact RRC with dimensions(mm)

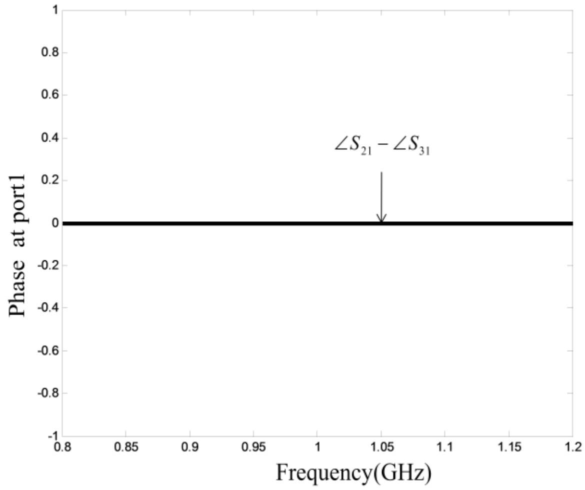


Fig8. Full wave simulated response of proposed RRC for the difference port excitation

III. Fabrication and Measurement

A rat-race coupler operating at 1 GHz with θ_0=60, is implemented and fabricated on the substrate with θ_0=60 dielectric constant of 2.2 and thickness of 0.508 mm. With and in the conventional rat-race coupler, and are calculated to be and , respectively. The fabricated rat-race coupler with all physical dimensions is exhibited in Fig. 4. The simulated and measured results are plotted together in Figs. 4–6, which agree with each

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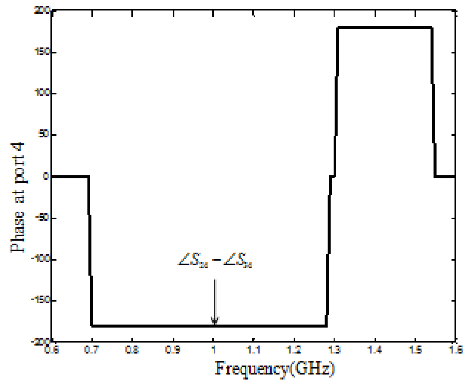

Fig: Full-wave simulated phase response of proposed RRC for the difference port excitatic

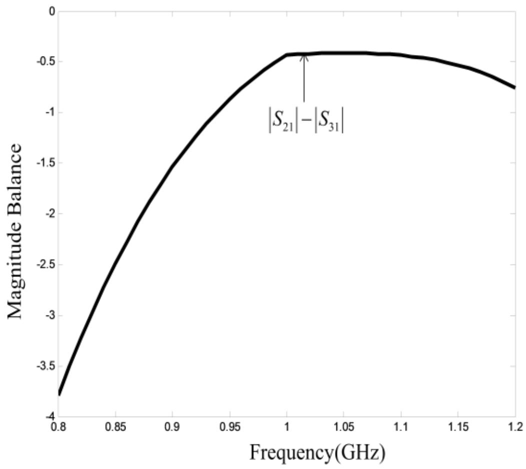

Fig 9. Full wave frequency response of proposed RRC for the difference port excitation

other very well. At the design frequency 1 GHz, the $|s_{21}|$ and $|s_{31}|$ are -3.67db and-3.23db respectively, the isolation at both port 1 and 4 are better than 50 dB, and phase(s_{21}-s_{31}) and phase(s_{24}-s_{34}) are 0^0 and180^0 respectively. As to the bandwidth, return loss better than 20 dB is obtained from 2.2 to 2.86 GHz (24.5%), and isolation better than 50 dB is achieved from 2.15 GHz to 2.8 GHz (27%). In addition, the transmission zero is introduced by the stubs around 9GHz as expected . As a result, the upper stopband is extended up to9 GHz (9 times of the center frequency) with the suppression level better than 10 dB. The effective circuit area of the proposed rat-race coupler is only 45.1% of that of the conventional rat-race coupler. Table I compares the proposed coupler with some previous publications.

TABLE I

Simulated results of proposed & previous RRC

Parameters	Present Work (Full wave simulated)	Previous work
Coupler(Technique)	T-Shape Unit	T-shaped unit
Operating frequency(f0)	1 GHz	2.4GHz
Ring Geometry	Rectangular	Rectangular
Return LossS_{11}(dB)	-24.9dB	-27.4dB
Isolation factorS_{41}	-53dB	-33dB
Insertion Loss(1 to2)S_{21}	-3.67dB	-3.4dB
Insertion Loss(1 to 3)S_{31}	-3.23dB	-3.7dB

IV. CONCLUSION

In this paper, a class of miniaturized rat-race coupler with harmonic suppression has been proposed, demonstrating rigorous theory analysis, simple design procedure, compact size, excellent in-band and out-of-band performance. The analysis of a stub-loaded transmission line has been conducted to equivalently match the related quarter-wavelength transmission line. The closed-form equations have been derived and design procedure has been summarized. Finally, the rat-race coupler with Θ =60^{0}has been fabricated. Consequently, the overall physical size is significantly reduced, and the harmonic is suppressed by the transmission zero introduced by the stubs. Therefore, our design principle has been verified experimentally.

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