Wideband high-isolation and perfect-balance microstrip rat-race coupler

W.S. Chang, C.H. Liang and C.Y. Chang

A microstrip rat-race coupler with high isolation and perfect balance is presented. By modifying March's rat-race coupler with two additional short-circuited stubs, the isolation and the amplitude/phase balance of the proposed coupler improve significantly. The circuit can be easily fabricated on a single-layer substrate using the conventional printed circuit board process.

Introduction: Microstrip components play an important role in modern microwave applications owing to easy integration into the printed circuit board (PCB). For the rat-race coupler, the size can be reduced and the bandwidth is increased by replacing the $3\lambda/4$ line section with the $\lambda/4$ short-ended coupled-line section [1]. Nonetheless, it requires extremely tight coupled lines which are difficult to implement using the conventional parallel-coupled microstrip lines. In [2] and [3], the vertically installed planar (VIP) structure and the broadside-coupled lines using the microstrip and coplanar waveguide (CPW) technology can achieve tight coupling to realise the rat-race coupler. However, the former requires special constructions, such as vertically installed plates, and may not be suitable for microstrip rat-race couplers. The latter is asymmetric in structure and may not be straightforward to obtain dimensions. In some applications, high isolation and perfect amplitude/phase balance are essential. Several works [4–7] have been reported to deal with these specifications.

In this Letter, a rat-race coupler, which is modified from [1], is proposed. The perfect amplitude/phase balance as well as the high isolation can be achieved theoretically for all frequencies. A microstrip circuit is implemented to verify the theory. Compared to previous studies, the proposed structure is much simpler, and the isolation and the amplitude/phase balance are better.

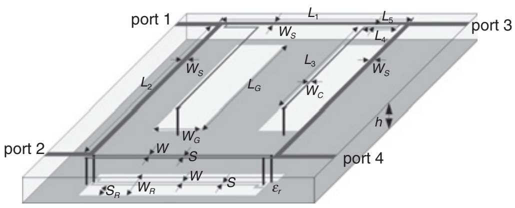

Fig. 1 *Configuration of proposed rat-race coupler*

Circuit design: Fig. 1 depicts the proposed circuit and its microstrip implementation. The coupled-line pair proposed in [8] is adopted to implement the tightly coupled short-ended coupled-line section of the proposed rat-race coupler. Two extra short-circuited stubs with the characteristic impedance equal to the even-mode impedance of the coupled-line section make the equivalent circuit fully symmetric. Thereby, infinite isolation at all frequencies and perfect amplitude/phase balance are obtained for each port excitation as compared to [4]. Applying the even-odd mode analysis, the S-parameters for the proposed rat-race coupler are given as follows:

$$\begin{aligned} p = {} & \cos 2\theta \times (1 + Z_C Y_{0e}) + \sin 2\theta/\tan\theta + jR\sin 2\theta \\ & + j\tan\theta(\cos 2\theta + Z_C Y_{0e}\cos 2\theta + \sin 2\theta/\tan\theta)/R \\ & - (jZ_0 Y_{0e}\cos 2\theta/\tan 2\theta) + (2 + Z_C Y_{0e}) \\ & - jZ_0 Y_{0e}\cos 2\theta/\tan\theta + j(\sin 2\theta - \cos 2\theta/\tan\theta)/R \\ & - \sin 2\theta\tan\theta + Z_C Y_{0e}\cos 2\theta\cos 2\theta \end{aligned}$$

$$\begin{aligned} q = {} & -\tan\theta(\cos 2\theta(1 + Z_C Y_{0e}) + \sin 2\theta/\tan\theta)/R + R\sin 2\theta \\ & + Z_0 Y_{0e}\cos 2\theta/\tan\theta + Z_0 Y_{0e}\cos 2\theta(2 + Z_C Y_{0e})/\tan 2\theta \\ & - \sin 2\theta/R + \cos 2\theta/(R\tan\theta) \end{aligned}$$

$$S = \begin{pmatrix} jq/p & 2/p & 2/p & 0 \\ 2/p & jq/p & 0 & -2/p \\ 2/p & 0 & jq/p & 2/p \\ 0 & -2/p & 2/p & jq/p \end{pmatrix}$$

where Z_0 is the port impedance (i.e. usually 50 Ω), Z_C is the characteristic impedance of the three $\lambda/4$ line sections, $\theta = \pi/4$ at the centre frequency, $R = Z_C/Z_0$, and Y_{0e} and Y_{0o} are the even- and odd-mode admittances of the $\lambda/4$ coupled-line section, respectively. Here, we choose $Z_C = 64\ \Omega$ (i.e. corresponding to a return loss of 20 dB at the centre frequency), $Y_{0e} = 0.00465\ \Omega^{-1}$, and $Y_{0o} = 0.0359\ \Omega^{-1}$. The ground plane is patterned to implement the two short-circuited stubs whose impedances are as high as 215 Ω. The circuit is fabricated on the substrate with a dielectric constant of 3.58, a loss tangent of 0.0021, and a thickness of 0.508 mm. Each via-hole has a diameter of 0.3 mm. The full-wave EM simulation software Sonnet is used to perform the simulation. The rat-race coupler is designed at the centre frequency of 1.5 GHz. Its dimensions are $L_1 = 32.5$, $L_2 = 31.45$, $L_3 = 21.85$, $L_4 = 4.45$, $L_5 = 0.25$, $L_G = 20.15$, $W_S = 0.8$, $W_C = 0.15$, $W_G = 6.75$, $W = 0.3$, $S = 0.2$, $W_R = 4$, $S_R = 1.6$, $h = 0.508$ mm.

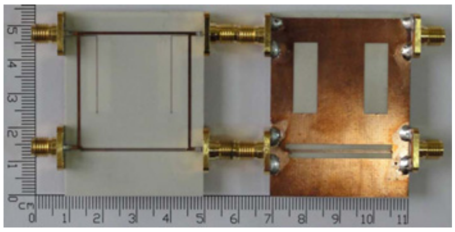

Fig. 2 *Top view (left side) and bottom view (right side) of fabricated rat-race coupler*

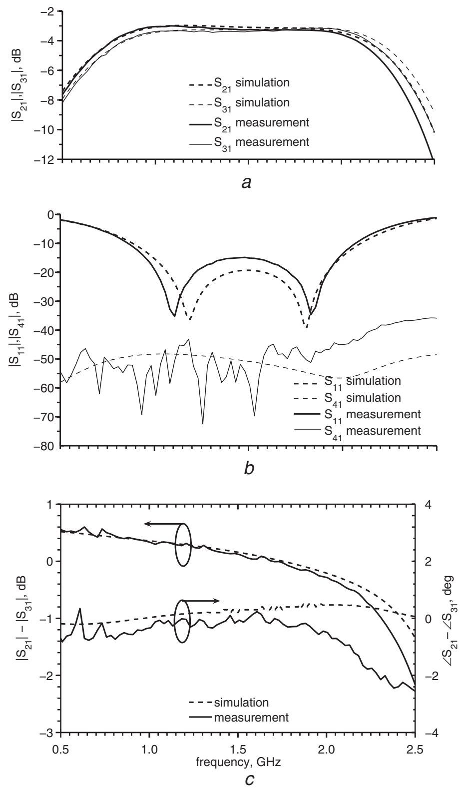

Fig. 3 *In-phase operation (port 1 excitation)*

a Insertion losses S_{21} and S_{31}
b Return loss S_{11} and isolation S_{41}
c Amplitude and phase imbalances

Measurement: Fig. 2 shows the photograph of the fabricated rat-race coupler, which has a size of 32.5 × 35.7 mm. For Σ-port (port 1) excitation as shown in Fig. 3, at the design frequency of 1.5 GHz, the measured $|S_{21}|$ and $|S_{31}|$ are −3.252 and −3.377 dB, respectively. The measured result shows that the return loss and the isolation are better than 15 and 43.2 dB from 0.951 to 1.98 GHz, respectively, corresponding to a fractional bandwidth of 70.215%. Over this frequency range, the measured amplitude imbalance between S_{21} and S_{31} is less than 0.37 dB, and the measured phase difference is between −0.565°and 0.234°. For Δ-port (port 4) excitation as shown in Fig. 4, the measured $|S_{24}|$ and $|S_{34}|$ are −3.4366 and −3.1997 dB at 1.5 GHz, respectively. The measured return loss and isolation are better than 15 and 43.2 dB from 0.949 to 2 GHz, respectively. Across this frequency band, the measured amplitude imbalance between S_{24} and S_{34} is less than 0.4265 dB, and the measured phase difference is between 179.22° and 180.9°.

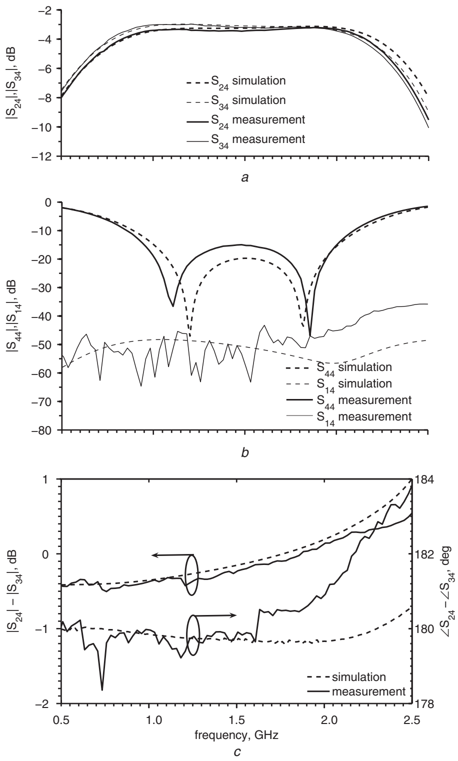

Fig. 4 *Out-of-phase operation (port 4 excitation)*

a Insertion losses S_{24} and S_{34}
b Return loss S_{44} and isolation S_{14}
c Amplitude and phase imbalances

Conclusion: A compact rat-race coupler has been presented using microstrip line on a single-layer PCB substrate. Benefiting from the tightly coupled-line structure and the two high-impedance short-circuited stubs, the proposed rat-race coupler has good amplitude/phase balance and high isolation over a wide bandwidth. The proposed rat-race coupler has a planar structure and is easily realised by the conventional PCB process. Thus, it is very appropriate for microwave applications.

21 January 2012
doi: 10.1049/el.2012.0227
One or more of the Figures in this Letter are available in colour online.

W.S. Chang, C.H. Liang and C.Y. Chang (*Graduate Institute of Communication Engineering, National Chiao-Tung University, Hsinchu, Taiwan*)

E-mail: aa494412338@hotmail.com

References

1 March, S.: 'A wideband stripline hybrid ring', *IEEE Trans. Microw. Theory Tech.*, 1968, **MTT-16**, (6), p. 361
2 Chi, C.H., and Chang, C.Y.: 'A new class of wideband multisection 180° hybrid rings using vertically installed planar couplers', *IEEE Trans. Microw. Theory Tech.*, 2006, **54**, (6), pp. 2478–2486
3 Kuo, J.T., Chiou, Y.C., and Wu, J.S.: 'Miniaturized rat race coupler with microstrip-to-CPW broadside-coupled structure and stepped-impedance sections', *IEEE MTT-S Int. Microw. Symp. Dig.*, June 2007, pp. 169–172
4 Walker, J.L.B.: 'Improvements to the design of the 0–180° rat race coupler and its application to the design of balanced mixers with high LO to RF isolation', *IEEE MTTS Int. Microw. Symp. Dig.*, June 1997, pp. 747–750
5 Piernas, B., Hayashi, H., Nishikawa, K., and Nakagawa, T.: 'Improvement of the design of 180° rat-race hybrid', *Electron. Lett.*, 2000, **36**, (12), pp. 1035–1036
6 He, F.F., Wu, K., Hong, W., Tang, H.J., Zhu, H.B., and Chen, J.X.: 'A planar magic-T using substrate integrated circuits concept', *IEEE Microw. Wirel. Compon. Lett.*, 2008, **18**, (6), pp. 386–388
7 Cruszczynski, S., and Wincza, K.: 'Broadband rat-race couplers with coupled-line section and impedance transformers', *IEEE Microw. Wirel. Compon. Lett.*, 2012, **22**, (1), pp. 22–24
8 Liang, C.H., Chang, W.S., and Chang, C.Y.: 'Enhanced coupling structures for tight couplers and wideband filters', *IEEE Trans. Microw. Theory Tech.*, 2011, **59**, (3), pp. 574–583