IMPROVEMENTS TO THE DESIGN OF THE 0-180^0 RAT RACE COUPLER AND ITS APPLICATION TO THE DESIGN OF BALANCED MIXERS WITH HIGH LO TO RF ISOLATION

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ABSTRACT

An improved rat-race coupler is described which, in the ideal case, has a pair of ports with infinite isolation between them at all frequencies. This improved rat-race coupler is useful in such applications as the design of balanced mixers with high LO to RF isolation.

INTRODUCTION

The conventional rat-race coupler provides a 3dB power split with the two outputs having 180^0 phase difference at band centre only. The rat-race coupler is often used in balanced mixers, but its performance is the limiting factor in determining the LO to RF isolation of the mixer over broad bandwidths. An improved rat-race coupler is described which, in the ideal case, has a pair of ports with frequency-independent infinite isolation between them.

Figure 1(a) shows a conventional rat-race coupler. At band centre, i.e. when the electrical length of the ring is 1.5λ, a signal incident at port 1 will split equally between ports 2 and 4 but the two outputs will be 180^0 out of phase with respect to each other, and there will be no output from port 3. The conventional rat-race coupler is a narrowband device with the isolation being better than 25dB only over a 20% bandwidth and the phase split being within 180+/-10^0 over a 32% bandwidth.

The bandwidth can be enhanced if the phase difference between the clockwise and counter-clockwise waves travelling between ports 1 and 3 is as close as possible to 180^0. March's [1] method of achieving this is shown in Fig 1(b). The 3λ/4 uncoupled transmission line is replaced by a pair of λ/4 coupled transmission lines with alternate ends shorted to ground. Figure 2 shows the equivalent circuit of the coupled line section. At band centre the coupled line section is equivalent to a single uncoupled transmission line of characteristic admittance $(Y_{oo}-Y_{oe})/2$ in cascade with an ideal 1:-1 transformer. Obviously, the characteristic impedance of the equivalent λ/4 uncoupled transmission line must be identical to that of the original 3λ/4 transmission line i.e.

$$(Y_{oo} - Y_{oe})/2 = Y_o/\sqrt{2} \qquad (1)$$

March also imposed the additional requirement that

$$\sqrt{2}Z_0 = \sqrt{Z_{oe}Z_{oo}} \qquad (2)$$

It should be noted that there is no necessity for imposing this additional requirement as can be seen from Fig.2. Furthermore, it also leads to extreme values of impedance since Z_{oe}=170.7Ω and Z_{oo}=29.3Ω in a 50Ω system. March's additional requirement results in a unique solution for the value of Z_{oe}, and hence of Z_{oo}, whereas an infinity of values of Z_{oe} can be used such that the higher the value of Z_{oe} the broader the bandwidth of the coupler, with Z_{oo} determined from equation (1).

IMPROVED RAT-RACE COUPLER

It is obvious from Figure 2 that if quarter-wave shunt short-circuit stubs of characteristic impedance Z_{oe} are connected to the ring at ports 1 and 2, as shown in Figure 1(c), with Z_{oe} and Z_{oo} chosen as before to satisfy just equation (1), then an exact 180^0 phase difference will exist at all frequencies at port 3 between the waves travelling clockwise and anti-clockwise around the ring. This has two very important consequences. Firstly, infinite isolation will exist between ports 1 and 3 at all frequencies irrespective of the value chosen for Z_{oe}. Secondly, if port 1 is the input port then an exact 180^0 phase difference exists between the outputs from ports 2 and 4 at all frequencies, again regardless of the value chosen for Z_{oe}. Once again, the higher the value of Z_{oe}, the broader the bandwidth over which flat coupling and a good VSWR is achieved. This improved rat-race coupler has certain similarities with the conventional 3dB single-section quadrature coupler since both devices have one port perfectly isolated at all frequencies, both devices have a frequency-independent phase relationship between their coupled outputs (90^0 for the quadrature coupler and 180^0 for this improved rat-race coupler), and both devices offer nominal 3dB coupling over an octave bandwidth. The only major difference is that the 3dB quadrature coupler is perfectly matched at all ports at all frequencies whilst this improved rat-race coupler is perfectly matched only at band-centre, although the VSWR is better than 2:1 at all ports over an octave bandwidth.

Since the rat-race coupler shown in Figure 1(c) is electrically symmetrical with respect to ports 2 and 4 apart from a 1:-1 transformer, the *S* parameters can be determined using an even-odd mode analysis. The result is

$$S_{11} = \frac{3\sqrt{2} + Y_0 Z_{oe} + 2Z_0 Y_{oe} + j\tan\theta}{2Z_{oe}Y_0\tan^2\theta - 3\sqrt{2} - Y_0 Z_{oe} - 2Z_o Y_{oe} - j(2\sqrt{2}Y_0 Z_{oe} + 3)\tan\theta} \quad (3)$$

$$S_{33} = \frac{Y_{oe} + j(Y_0 + \sqrt{2}Y_{oe})\cot\theta}{2\sqrt{2}Y_0 + Y_{oe} + j(2Y_o\tan\theta - (Y_o + \sqrt{2}Y_{oe})\cot\theta)} \quad (4)$$

$$\begin{aligned} S_{13} &= 0 \\ S_{12} &= -S_{14} \\ S_{23} &= S_{34} \end{aligned} \quad (5)$$

Since the device is lossless the coupling performance is given by

$$\begin{aligned} |S_{12}|^2 &= \frac{1}{2}\left(1 - |S_{11}|^2\right) \\ |S_{23}|^2 &= \frac{1}{2}\left(1 - |S_{33}|^2\right) \end{aligned} \quad (6)$$

The expressions for S_{22} and S_{44} are exceptionally cumbersome and so will not be presented. However, one is normally interested in the values of S_{22} and S_{44} in the passband of the device, and accurate approximate values for their magnitudes in this region can be determined as follows. Since the device is lossless

$$|S_{21}|^2 + |S_{22}|^2 + |S_{23}|^2 + |S_{24}|^2 = 1 \quad (7)$$

Now in the passband $|S_{24}|^2 \approx 0$, and making use of equation (6) then

$$|S_{22}|^2 = |S_{44}|^2 \approx \frac{1}{2}\left(|S_{11}|^2 + |S_{33}|^2 \right) \quad (8)$$

Thus the performance is determined entirely by the reflection coefficients of ports 1 and 3.

The computed performance of this improved rat-race coupler is compared with that of the conventional rat-race and March's version in Figures 3(a)-(d). The computation has been undertaken with Z_{oe} set to 100Ω in order to ensure that the device is physically realisable. It can be seen that the price paid for improved isolation and phase-split is a slightly degraded bandwidth for coupling and match but, nevertheless, the device still offers an octave bandwidth capability.

Equation (6) shows that the key to improving the bandwidth is to improve the match, and this can be achieved by connecting a series open-circuit stub to port 1. Numerical analysis shows that the

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optimum characteristic impedance for this stub is 60Ω, and the improved match and coupling performance resulting from its addition to port 1 is shown in Figure 4 (a) and (b). This stub has no effect upon either the isolation or phase-split performance. This additional stub eliminates any bandwidth degradation compared with the March rat-race. Whilst it is difficult to implement a series stub in microstrip, it is more readily realised in CPW.

ACKNOWLEDGEMENT

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REFERENCES

1. S.March,"A Wideband Stripline Hybrid Ring," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-16, p.361, June 1968.

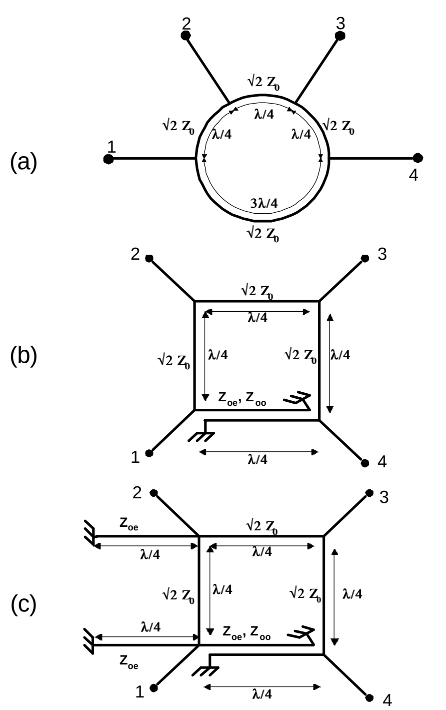


FIGURE 1. (a) Conventional rat-race coupler, (b) March's version of rat-race coupler, (c) rat-race coupler described in this paper.

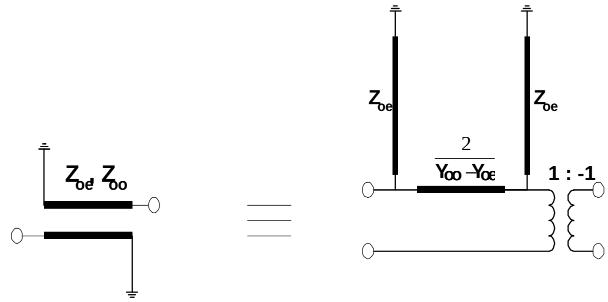
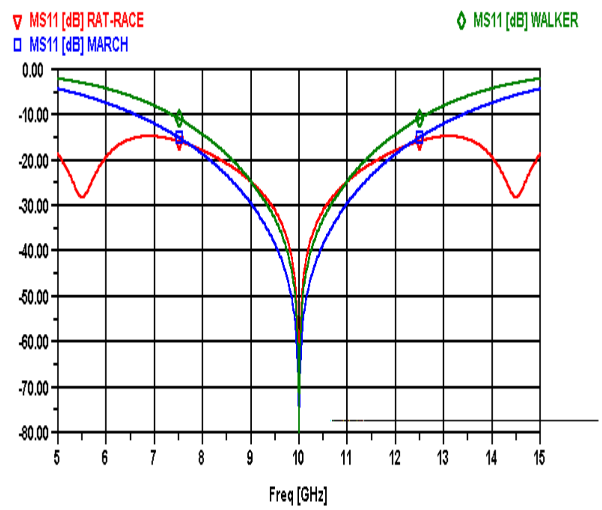
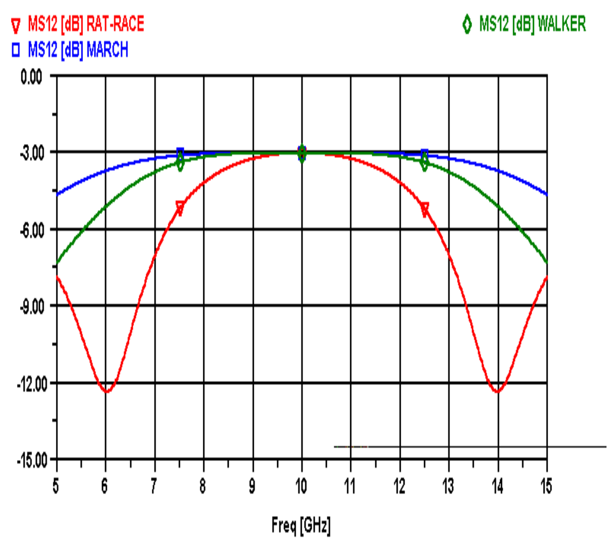


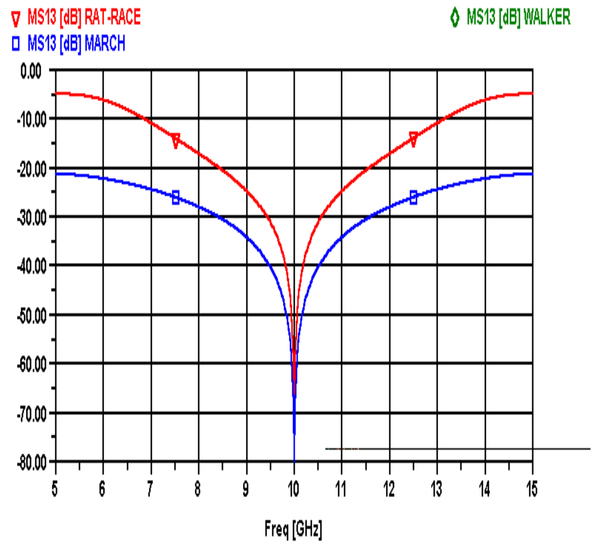
FIGURE 2. Equivalent circuit of coupled line section



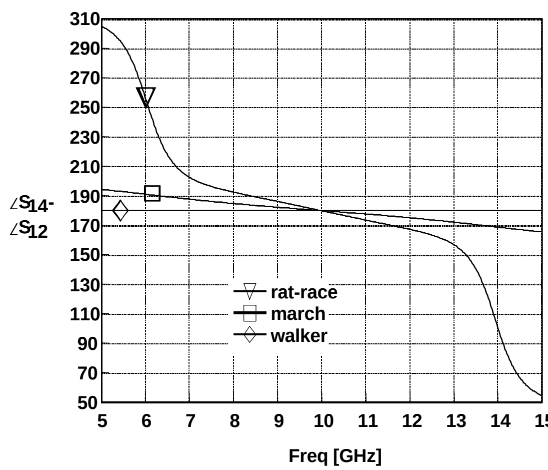
(a)



(b)

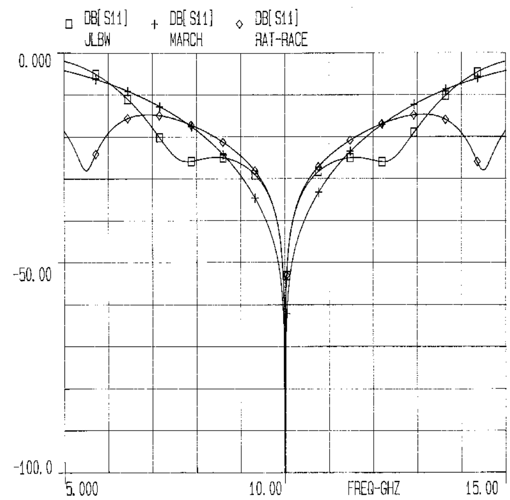


(c)

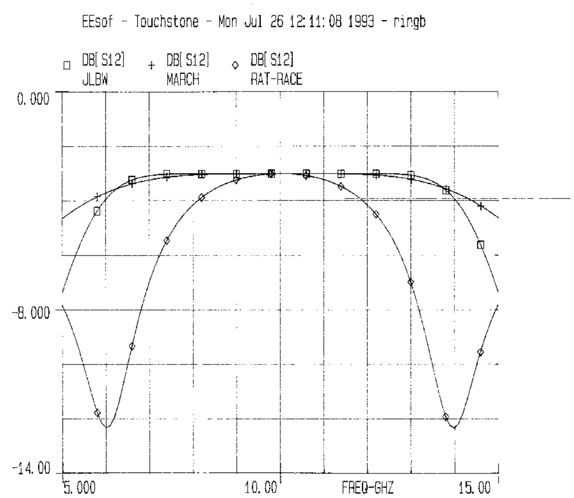


(d)

FIGURE 3(a) - (d). Performance comparison of the three types of rat-race coupler.



(a)



(b)

FIGURE 4. Effect of adding a 60Ω series open-circuit stub to port 1 on S_{11} and S_{12}.