Reduced Rat Race Couplers

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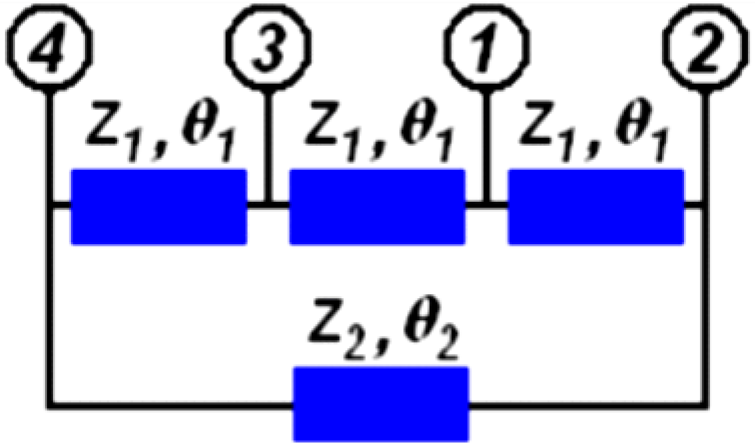
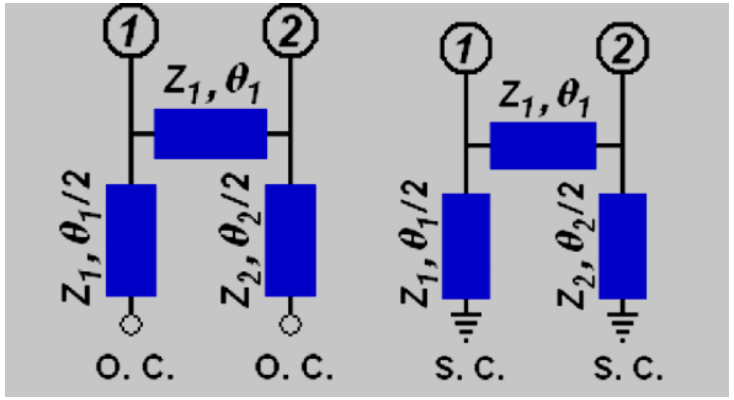
Abstract and Overview

- The 180 ° rat-race coupler is one of the most fundamental components in microwave frequency range. It is often used in various circuit applications such as mixers, multipliers, amplifiers, beam formers, etc.
- The conventional ring coupler had an electrical length of 1.5 λ at the operating frequency and, hence, occupied a large circuit area.
- One efficient approach of miniaturization is to increase effective electrical length by using a slow wave effect. Slow wave effects are realized usually by increasing effective series inductance or shunt capacitance of the transmission line.
- A slotted ground plane is used to increase series inductance, shunt open stubs and artificial transmission lines were used to increase shunt capacitance. Another way of increasing capacitance is to use a spiral compact microstrip resonant cell.
- It is shown that an infinite number of solutions exist for coupler design at a given frequency. For all the solutions, characteristic impedances are less than the conventional $Z0\sqrt{2}$. In some cases, coupler electrical lengths are less than 1.5 λ.
- Due to the lower Z values, the slow wave effect can be used for more effective miniaturization than a 1.5-λ coupler under the same fabrication limit of a high impedance line.
- Bandwidth variations of these unconventional couplers are also investigated.

Design

- A signal applied to port 1 will be evenly split into two in-phase components at ports 2 and 3, and port 4 will be isolated.
- If the input is applied to port 4, it will be equally split into two components with a 180 ° phase difference at ports 2 and 3, and port 1 will be isolated.
- When operated as a combiner, with input signals applied at ports 2 and 3, the sum of the inputs will be formed at port 1, while the difference will be formed at port 4.
- The design is simplified using even and odd mode analysis.





FORMULA

Port 1 Transmission parameters

$$A_e = \cos\theta_1 - \frac{Z_1}{Z_2}\frac{\sin\theta_1}{\cot\frac{\theta_2}{2}}$$

$$B_e = jZ_1 \sin\theta_1$$

$$C_e = j\frac{\cos\theta_1}{Z_1\cot\frac{\theta_1}{2}} - j\frac{\sin\theta_1}{Z_2\cot\frac{\theta_1}{2}\cot\frac{\theta_2}{2}} + j\frac{\sin\theta_1}{Z_1} + j\frac{\cos\theta_1}{Z_2\cot\frac{\theta_2}{2}}$$

$$D_e = \cos\theta_1 - \frac{\sin\theta_1}{\cot\frac{\theta_1}{2}}.$$

$$A_o = \cos\theta_1 + \frac{Z_1}{Z_2}\frac{\sin\theta_1}{\tan\frac{\theta_2}{2}}$$

$$B_o = jZ_1 \sin\theta_1$$

$$C_o = -j\frac{\cos\theta_1}{Z_1\tan\frac{\theta_1}{2}} - j\frac{\sin\theta_1}{Z_2\tan\frac{\theta_1}{2}\tan\frac{\theta_2}{2}} + j\frac{\sin\theta_1}{Z_1} - j\frac{\cos\theta_1}{Z_2\tan\frac{\theta_2}{2}}$$

$$D_o = \cos\theta_1 + \frac{\sin\theta_1}{\tan\frac{\theta_1}{2}}.$$

Port 4 Transmission parameters

$$A_e = \cos\theta_1 - \frac{\sin\theta_1}{\cot\frac{\theta_1}{2}}$$

$$B_e = jZ_1 \sin\theta_1$$

$$C_e = j\frac{\cos\theta_1}{Z_2\cot\frac{\theta_2}{2}} - j\frac{\sin\theta_1}{Z_2\cot\frac{\theta_1}{2}\cot\frac{\theta_2}{2}} + j\frac{\sin\theta_1}{Z_1} + j\frac{\cos\theta_1}{Z_1\cot\frac{\theta_1}{2}}$$

$$D_e = \cos\theta_1 - \frac{Z_1}{Z_2}\frac{\sin\theta_1}{\cot\frac{\theta_2}{2}}.$$

$$A_o = \cos\theta_1 + \frac{\sin\theta_1}{\tan\frac{\theta_1}{2}}$$

$$B_o = jZ_1 \sin\theta_1$$

$$C_o = -j\frac{\cos\theta_1}{Z_2\tan\frac{\theta_2}{2}} - j\frac{\sin\theta_1}{Z_2\tan\frac{\theta_1}{2}\tan\frac{\theta_2}{2}} + j\frac{\sin\theta_1}{Z_1} - j\frac{\cos\theta_1}{Z_1\tan\frac{\theta_1}{2}}$$

$$D_o = \cos\theta_1 + \frac{Z_1}{Z_2}\frac{\sin\theta_1}{\tan\frac{\theta_2}{2}}.$$

At operating frequency, matching ($S_{11} = 0$) and isolation ($S_{41} = 0$) conditions for port 1 excitation yield

$$\frac{Z_1}{Z_2} = -\tan\frac{\theta_1}{2}\tan\frac{\theta_2}{2} \tag{5a}$$

$$\sin\theta_1\left(\frac{Z_1}{Z_0} - \frac{Z_0}{Z_1}\right) - Z_0\cos\theta_1\left(\frac{\tan\frac{\theta_1}{2}}{Z_1} + \frac{\tan\frac{\theta_2}{2}}{Z_2}\right) + \frac{Z_0}{Z_2}\frac{\sin\theta_1}{\cot\frac{\theta_1}{2}\cot\frac{\theta_2}{2}} = 0. \tag{5b}$$

Assuming $Z_1 = Z_2 = Z$, we get

$$\theta_2 = 180^0 + \theta_1$$

$$Z = Z_0\sqrt{\left\{3 - \frac{1}{2}\left(\cot^2\frac{\theta_1}{2} + \tan^2\frac{\theta_1}{2}\right)\right\}}.$$

$$S_{31} = 1/X$$
$$S_{21} = 1/X$$
$$S_{34} = 1/X$$
$$S_{24} = -1/X$$

where

$$X = \left[2\cos\theta_1 + j\frac{1}{2}\sin\theta_1\left(\frac{Z}{Z_0} + \frac{2Z_0}{Z}\right) - j\frac{Z_0}{Z}\cos\theta_1\cot\theta_1\right].$$

CALCULATIONS

Calculations

For the given circuit, we have assumed that $\theta_1 = 90^\circ$, $\theta_2 = 270^\circ$. Thus, $\theta_2 = 180^\circ + \theta_1$.

Also value of $Z_1 = Z_2 = 71\Omega = Z$.

$Z_0 = 50\Omega$

Thus

$$Z = Z_0\left[\sqrt{3 - \frac{1}{2}\left(\cot^2\frac{\theta_1}{2} + \tan^2\frac{\theta_1}{2}\right)}\right]$$

$$= 50\left[\sqrt{3 - \frac{1}{2}\left(\cot^2\frac{90}{2} + \tan^2\frac{90}{2}\right)}\right]$$

$$= 50\left[\sqrt{3 - \frac{1}{2}(1+1)}\right]$$

$$= 50\left[\sqrt{3-1}\right] = 50\sqrt{2}.$$

$S_{31} = 1/x$

$S_{21} = 1/x$

$S_{34} = 1/x$

$S_{24} = -1/x$

$$X = \left[2\cos 90^\circ + \frac{j}{2}\sin 90^\circ\left(\frac{50\sqrt{2}}{50} + \frac{100}{50\sqrt{2}}\right) - j\frac{50}{50\sqrt{2}}\cos 90 \cot\right.$$

$$= \left[\frac{j}{2}\left(\sqrt{2} + \sqrt{2}\right)\right]$$

$$= j\sqrt{2}$$

Thus,

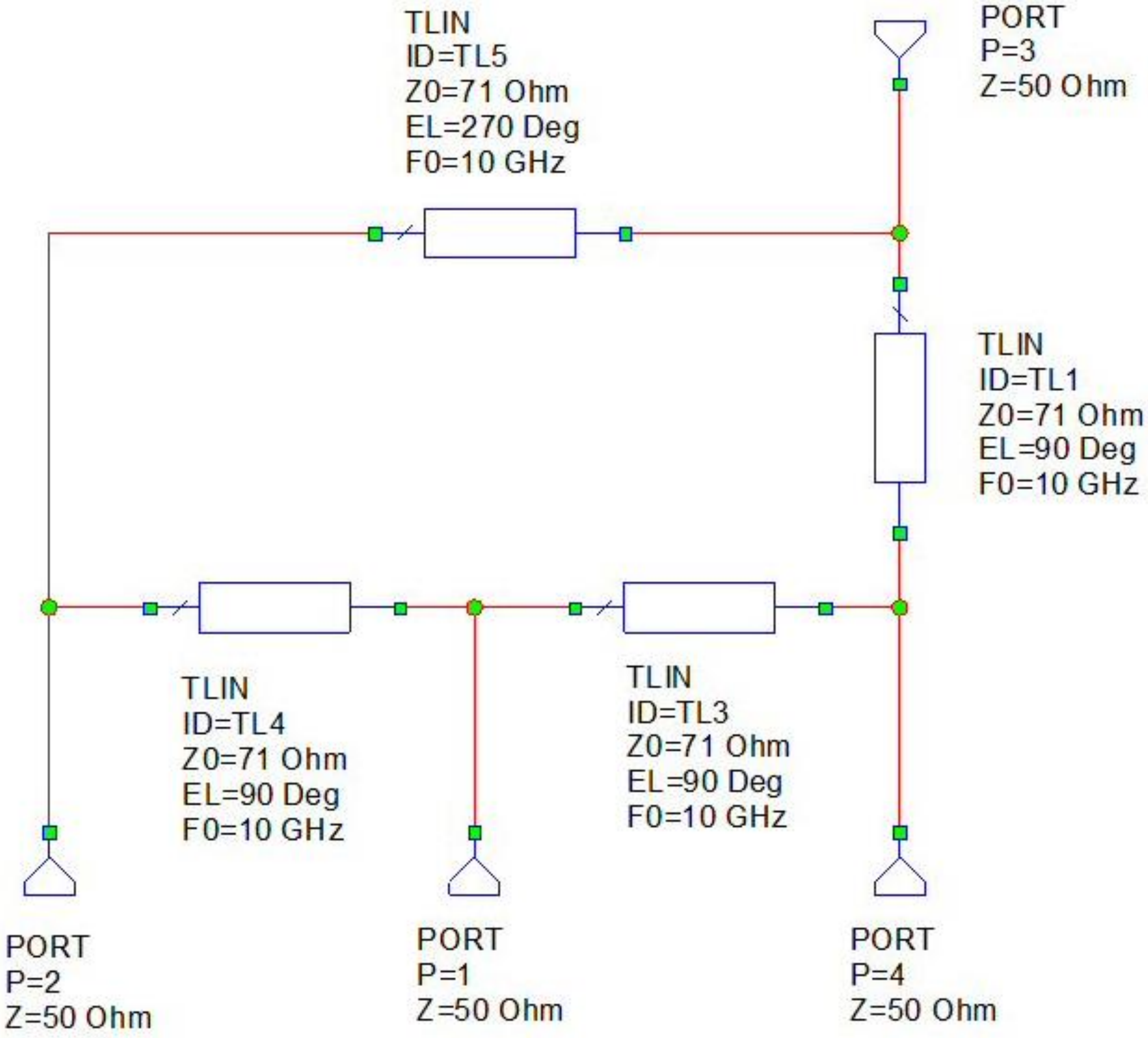
$S_{31} = -j/\sqrt{2}$

$S_{21} = -j/\sqrt{2}$

$S_{34} = -j/\sqrt{2}$

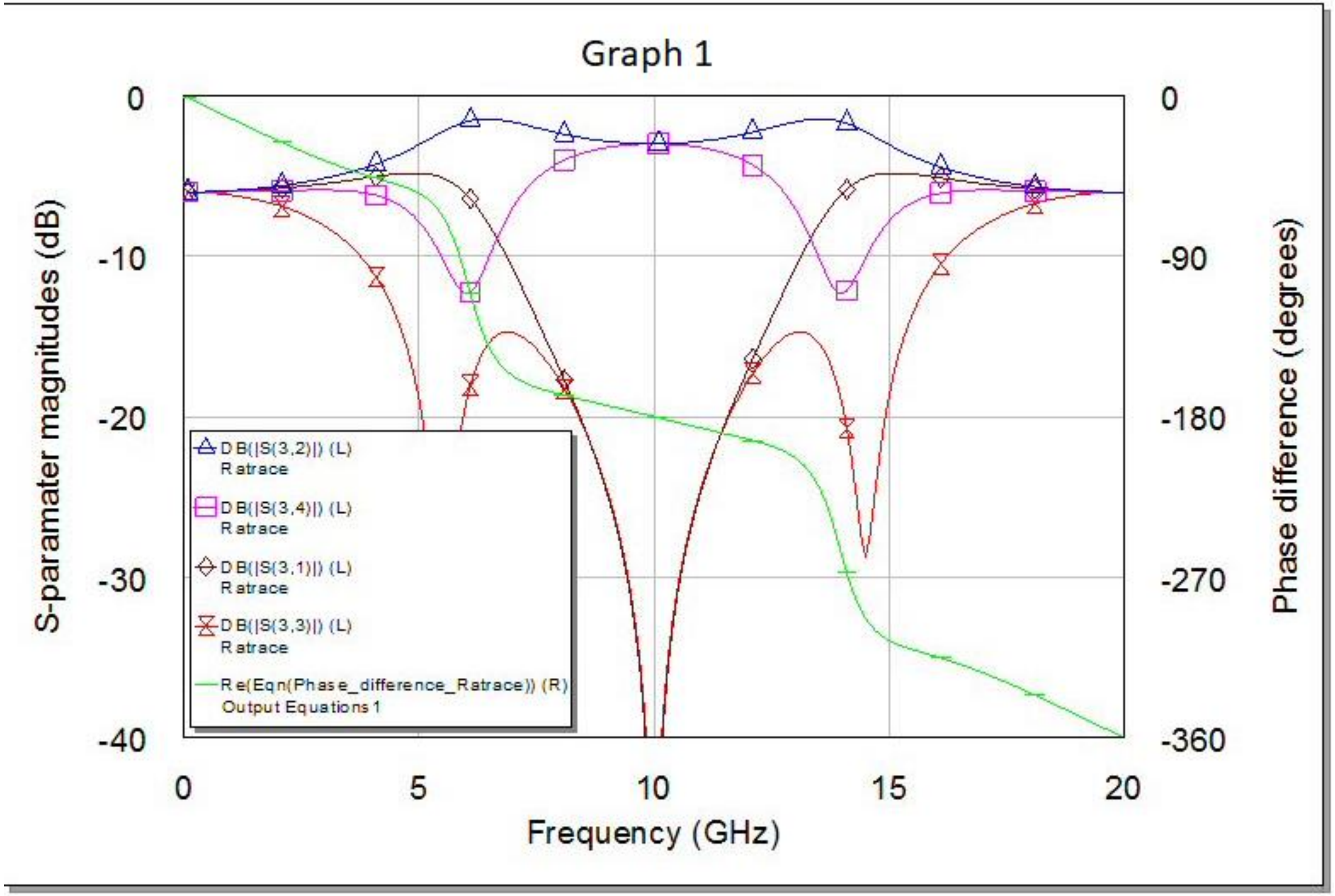
$S_{24} = j/\sqrt{2}$,

Schematic



TLIN
ID=TL5
Z0=71 Ohm
EL=270 Deg
F0=10 GHz
PORT
P=3
Z=50 Ohm
TLIN
ID=TL1
Z0=71 Ohm
EL=90 Deg
F0=10 GHz
TLIN
ID=TL4
Z0=71 Ohm
EL=90 Deg
F0=10 GHz
TLIN
ID=TL3
Z0=71 Ohm
EL=90 Deg
F0=10 GHz
PORT
P=2
Z=50 Ohm
PORT
P=1
Z=50 Ohm
PORT
P=4
Z=50 Ohm

Graphical analysis for schematic

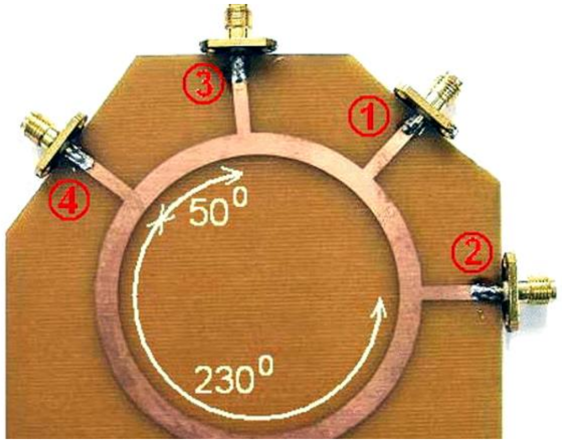


Graphical inference

In the following, coupler bandwidth variations with Z, θ_1, θ_2 are considered. The various coupler upper and lower cutoff frequencies are defined for $\pm$0.5-dB amplitude imbalance, $0 \pm 5^\circ$ and $180 \pm 5^\circ$ phase imbalances between the outputs, respectively, for the sum and difference port excitations and for 20-dB matching and isolation. It is observed that amplitude and phase responses are symmetrical about the operating frequency at $\theta_1 = 90^\circ$ and its odd multiples. The coupler band of operation shifts towards higher frequencies if θ_1 decreases below 90 ° and vice versa. As an example, the transmission line S-parameters for $\theta_1 = 90^\circ$ and 60 ° are shown in Fig. 4. Due to this asymmetry in the S-parameters, upper (f_2) and lower (f_1) cutoff frequencies are not symmetrical about the operating frequency. In bandwidth variation plots, the fractional bandwidths are defined as $2(f_2 - f_1)/(f_2 + f_1)$.

Conclusion

- Design of Unconventional rat-race couplers has been presented.
- Even and odd mode analysis for the coupler is verified.
- Bandwidth variation in terms of matching, isolation, amplitude and phase imbalance has been presented.
- Amplitude and phase imbalance bandwidth are better than conventional coupler.
- Fabricated coupler has 50.7% more area than conventional coupler.



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