Coupled Line 180° Hybrids with Modified Trans-directional Couplers

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Abstract— A novel coupled line 180° hybrid comprises of two modified trans-directional (TRD) couplers and one half-wave transmission line is proposed. The two identical TRD couplers are perpendicular connected to each other at two end points with one directly and the other through a $\lambda/2$ line section. The proposed hybrid can be easily realized on a single-layer substrate by using general printed circuit board (PCB) technology with a low cost. Modified TRD couplers with arbitrary coupling are presented in the paper to construct the hybrid with simple structure, easy fabrication, and wide range of coupling values. Theoretical analysis of the modified TRD coupler and detailed design procedures of the hybrid is given. To validate the structure, experimental circuit with a 3 dB coupling value was also designed and fabricated. Simulation results are compared with the measurements, and a good agreement is observed.

1. INTRODUCTION

Hybrid couplers are essential component used extensively in various microwave circuits, such as balanced amplifiers, balanced mixers, phase shifters, and feed networks in antenna arrays. Consider the phase differences between the two output ports, hybrid couplers can be classified into two categories: 9° and 180°. For 90° hybrids, parallel couple-line and branch-line couplers are well known examples [1]. For certain applications, namely, mixers and phase shifters, the 180° hybrids are preferred since the isolation between the two input ports may be independent of the value of two balanced-impedance loads [2]. Regarding the signal split ratio, the most commonly used is the equal power split hybrid.

The rat race is a widely used 180° hybrid [3]. It consists of a $3\lambda/2$ perimeter microstrip ring at the operating frequency with four ports connected along the ring. Numerous publications have been reported for the improvements of this type of hybrid mainly dealing with size reduction [4, 5], simultaneous size reduction and suppression of the harmonic response [6], increasing the bandwidth [7, 8], dual band operation [9], and arbitrary power divisions [10].

In [11], an alternative realization of a 180° hybrid is proposed based on a cascade connection of the two identical parallel coupled line couplers. Figure 1 shows the electrical schematic of such a coupled line hybrid. The parallel coupled lines are connected at two end points with one directly and the other through a $\lambda/2$ line section. It features the characteristics of simple structure, easy fabrication, and wide range of coupling values. However, the coupling levels of the parallel coupled line couplers are smaller due to fabrication constraints on the spacing of the coupled lines. Thus, it is hard to realize a tight coupling 180° hybrid on a substrate with arbitrary height and permittivity.

Based on the structure, coupled line 180° hybrids with non-TEM directional couplers [12] and Near-TEM Lange couplers [13] are presented. However, single frequency of equal power division or symmetrical over-coupling is not possible if non-TEM directional couplers are used, since the even and odd mode velocities of the coupled lines are different. Though the near-TEM Lange couplers tends to compensate for the unequal even and odd mode phase velocities, the closed narrow lines and the necessary bonding wires across the lines are difficult to fabricate using PCB technology.

In the paper, modified TRD couplers with arbitrary coupling are presented to construct the coupled line 180° hybrid. An experimental microstrip prototype with a 3-dB coupling has been fabricated on a PCB substrate (ε = 3.5, h = 1.5) with a low cost. The consistency with the simulated and measured results validates the proposed circuit structure.

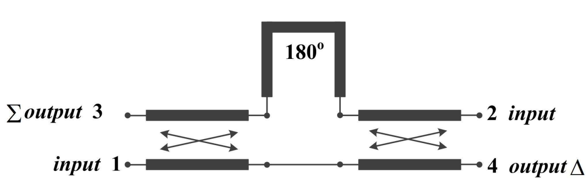


Figure 1: Electrical schematic of the coupled line 180° hybrid.

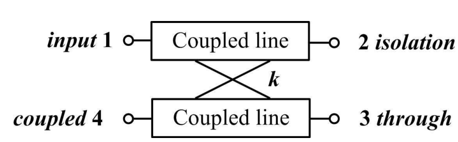


Figure 2: Schematic of the TRD coupler.

2. PROPOSED MODIFIED TRD COUPLER

From the port numbers of Figure 1, three types of directional couplers can be described according to the relative location of the isolation port to the input port. If port 3 is the isolation port, then co-directional coupler can be formed, while if port 4 is the isolation port, contra-directional coupler is constituted. The isolation port of port 2 is corresponding to the TRD coupler.

In [14], a realization of the TRD coupler is reported with the coupling level limited to less than 4.8 dB. However, the coupling values of the two couplers are 7.67 dB [11] for constructing the 3-dB 180° hybrid. Thus, the structure is needed to be modified for large range of coupling. Though TRD couplers for weak coupling are presented [15], the equations are complicated and the realizations are complex with the inductance (L) added to the four ports of the TRD coupler.

Figure 3 shows the schematic of the modified TRD coupler. It consists of three cells of capacitor-loaded coupled lines. The parameters of cell_1 are the same with cell_3. The even (odd) mode characteristic impedances of the cell_2 are equal with $\text{cell}_{1,3}$, except the shunt capacitors.

A convenient method for analyzing the proposed TRD coupler involves the derivation of an ABCD matrix for each of the constituent cell. The circuit is decomposed into three cells, described by $M_{1(e,o)}$, $M_{2(e,o)}$ and $M_{3(e,o)}$. The $ABCD$ matrices of the three cells are

$$M_{1(e,o)} = \begin{bmatrix} a_{1(e,o)} & b_{1(e,o)} \\ c_{1(e,o)} & d_{1(e,o)} \end{bmatrix} \tag{1}$$

$$M_{2(e,o)} = \begin{bmatrix} a_{2(e,o)} & b_{2(e,o)} \\ c_{2(e,o)} & d_{2(e,o)} \end{bmatrix} \tag{2}$$

$$M_{3(e,o)} = M_{1(e,o)} \tag{3}$$

where

$$a_{1,2(e,o)} = d_{1,2(e,o)} = \cos\theta_1 - \frac{b_{1,2(e,o)}}{2}\sin\theta_1 \tag{4}$$

$$b_{1,2(e,o)} = jZ_{1(e,o)}\left(\sin\theta_1 - \frac{b_{1,2(e,o)}}{2} + \frac{b_{1,2(e,o)}}{2}\cos\theta_1\right) \tag{5}$$

$$c_{1,2(e,o)} = \frac{j}{Z_{1(e,o)}}\left(\sin\theta_1 + \frac{b_{1,2(e,o)}}{2} + \frac{b_{1,2(e,o)}}{2}\cos\theta_1\right) \tag{6}$$

$$b_{1,2(e)} = 0 \tag{7}$$

$$b_{1,2(o)} = 2\omega C_{1,2} Z_{1o} \tag{8}$$

$$\omega = 2\pi f \tag{9}$$

The equivalent $ABCD$ matrix of the TRD coupler is

$$M_{\text{all}(e,o)} = \begin{bmatrix} \cos\theta_{e,o} & jZ_{0(e,o)}\sin\theta_{e,o} \\ \frac{jZ_{0(e,o)}}{\sin\theta_{e,o}} & \cos\theta_{e,o} \end{bmatrix} \tag{10}$$

where

$$Z_{0e} = Z_0\sqrt{\frac{1+k}{1-k}} \tag{11}$$

$$Z_{0o} = Z_0\sqrt{\frac{1-k}{1+k}} \tag{12}$$

In the above equations, f is the frequency, θ_1 is the electrical length of each cell, and $Z_{1(e,o)}$ are the even and odd mode characteristic impedance of the coupled lines. $\theta_{(e,o)}$ and $Z_{0(e,o)}$ are the electrical length and equivalent characteristic impedance of the even and odd mode transmission line. Z_0 is the equivalent port impedance (50 Ω) and k is the coupling coefficient of the coupler. Matrix multiplication gives the equation listed as follows.

$$M_{\text{all}(e,o)} = M_{1(e,o)} \cdot M_{2(e,o)} \cdot M_{3(e,o)} \tag{13}$$

Then we have

$$Z_{1e} = Z_{0e} \tag{14}$$

$$b_{2o} = \frac{2\left[m_1 \cdot \cos\theta_1 - (m_2 + m_3) \cdot \sin\theta_1 - \cos\theta_o\right]}{m_1 \cdot \sin\theta_1 + m_2 \cdot (1 + \cos\theta_1) + m_3 \cdot (\cos\theta_1 - 1)} \tag{15}$$

$$Z'_{0o} = \frac{Z_{0o}}{\sqrt{\frac{p_1 \cdot (2\sin\theta_1 + b_{1o}\cos\theta_1 - b_{1o}) - p_2 + p_3}{p_1 \cdot (2\sin\theta_1 + b_{1o}\cos\theta_1 + b_{1o}) - p_4 + p_5}}} \tag{16}$$

where

$$m_1 = \cos 2\theta_1 - b_{1o} \cdot \sin 2\theta_1 - \frac{b_{1o}^2 \cdot (\cos 2\theta_1 - 1)}{4} \tag{17}$$

$$m_2 = \left(\cos\theta_1 - \frac{b_{1o} \cdot \sin\theta_1}{2}\right) \cdot \left[\sin\theta_1 + \frac{b_{1o}\,(\cos\theta_1 - 1)}{2}\right] \tag{18}$$

$$m_3 = \left(\cos\theta_1 - \frac{b_{1o} \cdot \sin\theta_1}{2}\right) \cdot \left[\sin\theta_1 + \frac{b_{1o}\,(\cos\theta_1 + 1)}{2}\right] \tag{19}$$

$$p_1 = \left(\cos\theta_1 - \frac{b_{1o} \cdot \sin\theta_1}{2}\right) \cdot \left(\cos\theta_1 - \frac{b_{2o} \cdot \sin\theta_1}{2}\right) \tag{20}$$

$$p_2 = \left[\sin\theta_1 + \frac{b_{1o} \cdot (\cos\theta_1 - 1)}{2}\right]^2 \cdot \left[\sin\theta_1 + \frac{b_{2o} \cdot (\cos\theta_1 + 1)}{2}\right] \tag{21}$$

$$p_3 = \left[\cos\theta_1 - \frac{b_{1o} \cdot \sin\theta_1}{2}\right]^2 \cdot \left[\sin\theta_1 + \frac{b_{2o} \cdot (\cos\theta_1 - 1)}{2}\right] \tag{22}$$

$$p_4 = \left[\sin\theta_1 + \frac{b_{1o} \cdot (\cos\theta_1 + 1)}{2}\right]^2 \cdot \left[\sin\theta_1 + \frac{b_{2o} \cdot (\cos\theta_1 - 1)}{2}\right] \tag{23}$$

$$p_5 = \left[\cos\theta_1 - \frac{b_{1o} \cdot \sin\theta_1}{2}\right]^2 \cdot \left[\sin\theta_1 + \frac{b_{2o} \cdot (\cos\theta_1 + 1)}{2}\right] \tag{24}$$

For simplification, the phase coupling of the transmission lines is ignored, $\theta_e = \pi/2$, $\theta_o = 3\pi/2$, and $\theta_1 = \pi/6$. For certain coupling value, $Z_{0(e,o)}$ are calculated using Equations (11) and (12), and functional dependency of Z_{1o} to the value of b_{1o} can be plotted according to Equation (16). Thus, proper values of Z_{1o} can be chosen, and all the other parameters of the TRD coupler are obtained.

3. 180° HYBRID DESIGN

As a first step in the design of a 3-dB 180° hybrid, the 7.67-dB TRD coupler operating at 3 GHz is designed. From Equations (11) and (12), for 7.67 dB coupling, $Z_{0e} = 77.6\,\Omega$ and $Z_{0o} = 32.2\,\Omega$.

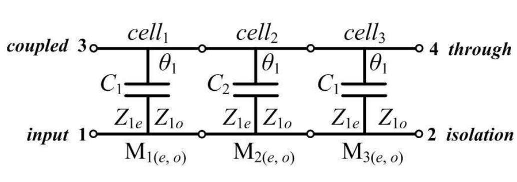


Figure 3: Schematic of the proposed TRD coupler.

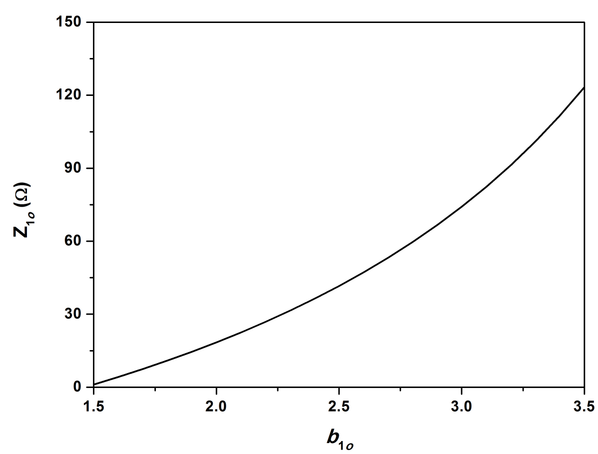


Figure 4: Z_{1o} curve as a function of b_{1o}.

The Z_{1o} curve as a function of b_{1o} with 7.67 dB coupling value is plotted, as illustrated in Figure 4. It can be seen that with the increase of b_{1o}, the value of Z_{1o} increases, and when b_{1o} is more than 3.03, the value of Z_{1o} exceeds 77.6 Ω (more than Z_{1e}). Thus, considering the coupling value of the coupled lines, $Z_{1o} = 66.6\,\Omega$ and $b_{1o} = 2.9$ is chosen. The coupling value of the coupled line is 18 dB. Finally, with Equations (8) and (15), $C_1 = 1.15$ pF and $C_2 = 1.86$ pF.

After optimizing using Ansoft HFSS, the suitable coupling value of 7.5 dB has been obtained with a line width of 1.6 mm, a separation gap of 0.9 mm $C_1 = 1.0$ pF and $C_2 = 1.8$ pF. The length of the coupler was 16 mm.

In the next step, models of the 180° hybrid comprises of the two TRD couplers and a 180° transmission line were constructed, as shown in Figure 5. Optimizations have been carried out to obtain a 3-dB 180° hybrid. The final dimensions are $w_1 = 3.3$ mm, $w_2 = 1.6$ mm, $s_1 = 0.9$ mm, $l_1 = 15.4$ mm, $l_2 = 14.0$ mm, $l_3 = 4.0$ mm, $l_4 = 6.7$ mm, $l_5 = 5.7$ mm, $l_6 = 7.4$ mm, $l_7 = 6.5$ mm, $l_8 = 6.6$ mm, $C_1 = 1.0$ pF and $C_2 = 1.8$ pF.

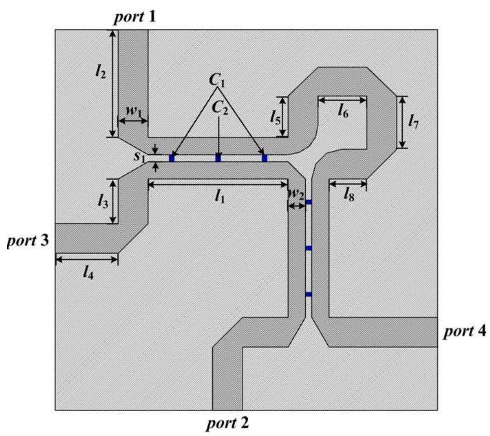


Figure 5: The layout of the proposed 180° hybrid.

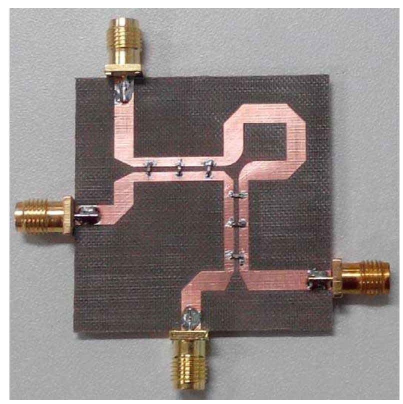
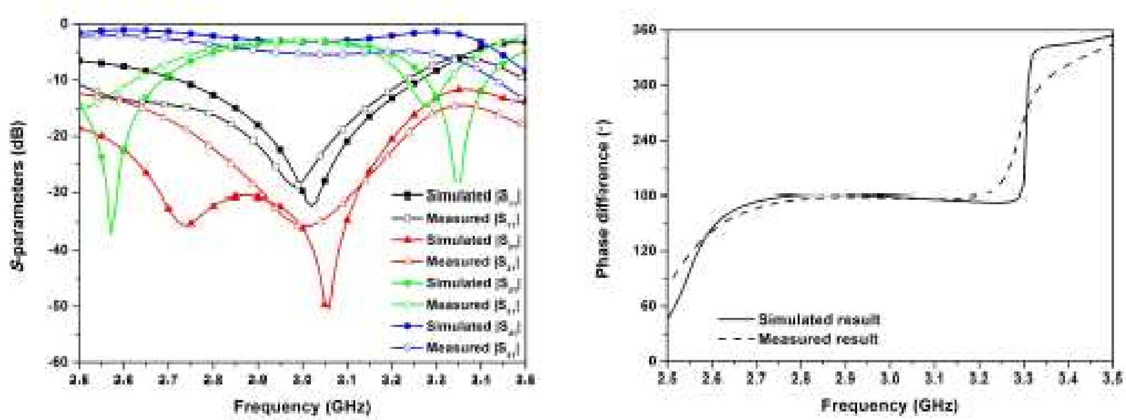


Figure 6: The photograph of the proposed 180° hybrid.

4. SIMULATED AND MEASURED RESULTS

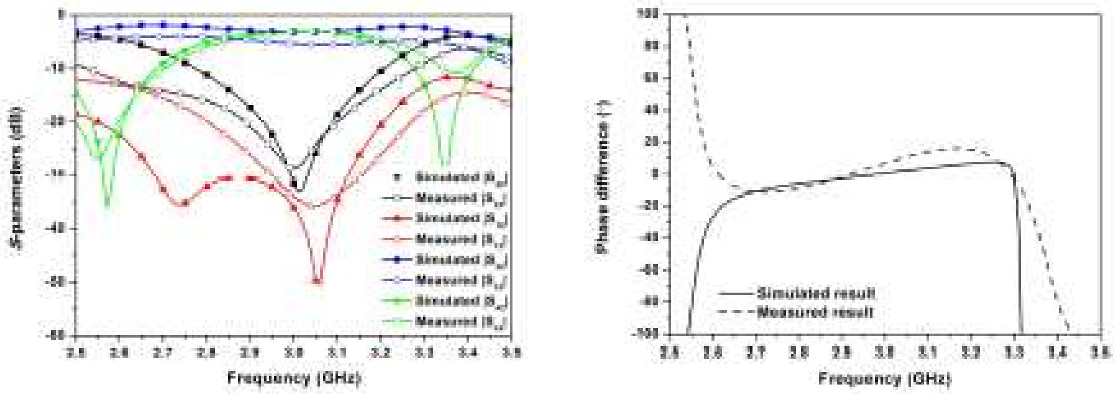
The fabricated sample with optimization dimensions was manufactured on an FB4 substrate with a dielectric constant of 3.5, a loss tangent of 0.003, and a thickness of 1.5 mm. The photograph of the prototype is shown in Figure 6.

Figures 7(a) and (b) display the measured results with the comparison of the simulated results when input at port 1. The amplitude bandwidth defined by 4.1 ± 1.0 dB between ports 3 and 4 is from 2.75 to 3.20 GHz, and their phase bandwidth, defined by $180° \pm 10°$ is in the range of 2.68–3.22 GHz. Meanwhile, the isolation is more than 20 dB throughout the frequency band of



(a) (b)

Figure 7: Measured and simulated results when input at port 1. (a) S-parameters. (b) Phase difference.



(a) (b)

Figure 8: Measured and simulated results when input at port 2. (a) S-parameters. (b) Phase difference.

2.75–3.22 GHz, and the return loss is larger than 15 dB from 2.74 GHz to 3.13 GHz.

Figures 8(a) and (b) show the case of input at port 2 of the hybrid. From 2.70 to 3.10 GHz, the insertion loss is 4.2 ± 1.0 dB and the phase difference is $0^\circ \pm 10^\circ$. The isolation is more than 20 dB in the range of 2.76–3.22 GHz, and a return loss of larger than 15 dB is obtained from 2.88 to 3.13 GHz. The measured results are in good agreement with the simulated results. The slight discrepancies between the simulated and the measured results are believed to be due to the losses introduced by the connectors and the substrate.

5. CONCLUSIONS

A coupled line 180° hybrid comprises of modified TRD couplers and one half-wave transmission line has been presented. To demonstrate the structure, a 3-dB 180° hybrid has been designed and fabricated. Results show that the proposed 180° hybrid has simple structure, and is easy to fabricate on planar PCB circuits with a low cost. Therefore, the proposed 180° hybrid can be a suitable candidate for microwave applications.

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