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Miniaturization of Trans-Directional Coupled Line Couplers Using Series Inductors

Hong Mei Liu[1], Shao Jun Fang[1, *], Zhong Bao Wang[1], and Yun Zhou[2]

Abstract—A miniaturized trans-directional (TRD) coupled line coupler comprises series inductors and capacitor loaded coupled lines is proposed in the paper. Series inductors are added to the periodically loaded coupled lines for further miniaturization of volume. A novel equivalent circuit is presented and theoretically analyzed. Test circuits for the miniaturized and conventional 3-dB TRD couplers were designed to operate at 1.6 GHz and fabricated using printed circuit board (PCB) technology. Samples have been measured, and comparisons in terms of volume, schematic simulation results and measurement results between the miniaturized and conventional 3-dB TRD couplers have been made to validate the proposed structure. Results show that the proposed miniaturized TRD coupler achieves a size reduction of 47.6% compared to the conventional TRD coupler with similar performances.

1. INTRODUCTION

Directional couplers [1–4] are passive components widely used for power splitting and combining. They are often incorporated in a variety of microwave and millimeter-wave circuits, such as balanced amplifiers [5], antenna feed networks [6, 7], and filters [8]. From the port numbers in 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 [9–11]. Since the TRD couplers are similar to co-directional couplers when constructed with branch lines, they are seldom realized [12].

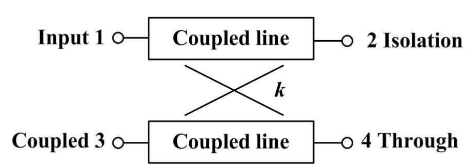

Figure 1. Schematic of the trans-directional coupler.

When coupled-line directional couplers are used in Butler matrices, problems of circuit complexity and parasitic effects are caused by crossover circuits [13]. To solve this problem, Shie et al. proposed a 3-dB microstrip TRD coupler implemented by periodically capacitor-loaded coupled lines [9]. The TRD couplers can achieve tight coupling and shorter electrical lengths with coupled microstrip circuits, and allow decoupling the direct current path between input and output ports. Therefore, it can make connections with active circuits easier, eliminating some off-chip biasing circuits. However, the structure

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* Corresponding author: Shao Jun Fang (fangshj@dlmu.edu.cn).
[1] School of Information Science and Technology, Dalian Maritime University, Dalian, Liaoning 116026, China. [2] School of Physics and Electronic Technology, Liaoning Normal University, Dalian, Liaoning 116026, China.

proposed in [9] can only realize a TRD coupler with electrical length range of 60° to 90°, which is still large in modern integrated circuits, especially at low frequencies.

In the paper, a miniaturized TRD coupled-line coupler is proposed to further reduce the volume, especially at low frequencies. Series inductors are added to the periodically loaded coupled lines for miniaturizing the volume and improving the directivity of the TRD coupler [14, 15]. The formulation and implementation are discussed and demonstrated. For experimental validation, a conventional and a miniaturized 3-dB TRD couplers are designed and fabricated using F4B ($\varepsilon_r = 3.5$, $h = 1.5$ mm) substrate.

2. MINIATURIZATION TECHNIQUE

The novel equivalent circuit of the miniaturized TRD coupler is proposed, as illustrated in Figure 2. It consists of periodically capacitor- and inductor-loaded coupled lines. Capacitors are in parallel with the coupled line cell, and inductors with equal values are series with the coupled line cell.

Figure 2(a) shows the equivalent circuit of a transmission line periodically loaded with normalized shunt susceptance b and series reactance x. Let θ' be the electrical length of each unit cell and Z'_0 be the characteristic impedance of the transmission line. According to [16], the $ABCD$ matrix of one cell is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} m_1 - x \cdot m_2 & jZ'_0\left(m_3 + 2x \cdot m_1 - x^2 \cdot m_2\right) \\ \dfrac{jm_2}{Z'_0} & m_1 - x \cdot m_2 \end{bmatrix} \tag{1}$$

with

$$m_1 = \cos\theta' - \frac{b}{2}\sin\theta' \tag{2}$$

$$m_2 = \sin\theta' + \frac{b}{2} + \frac{b}{2}\cos\theta' \tag{3}$$

$$m_3 = \sin\theta' - \frac{b}{2} + \frac{b}{2}\cos\theta' \tag{4}$$

According to Equation (1), we have

$$\cos\theta = m_1 - x \cdot m_2 \tag{5}$$

$$Z_B^{\pm} = \pm Z'_0\sqrt{\frac{m_3 + 2x \cdot m_1 - x^2 \cdot m_2}{m_2}} \tag{6}$$

where θ is the phase delay of one unit cell due to the Bloch propagation mode and $Z_B^{\pm}$ the Bloch impedance. If both even- and odd-modes of the coupled line are periodically loaded by shunt susceptances b_e and b_o, series reactance x_e and x_o, if the shunt susceptances are realized by capacitors C_e and C_o, and if the series reactance are implemented by inductor L, then the equivalent circuit can be drawn, as shown in Figure 2(b). Note that the phase coupling of the transmission lines is ignored for simplification. Let Z_{0e} and Z_{0o} be the equivalent even- and odd-mode characteristic impedance of

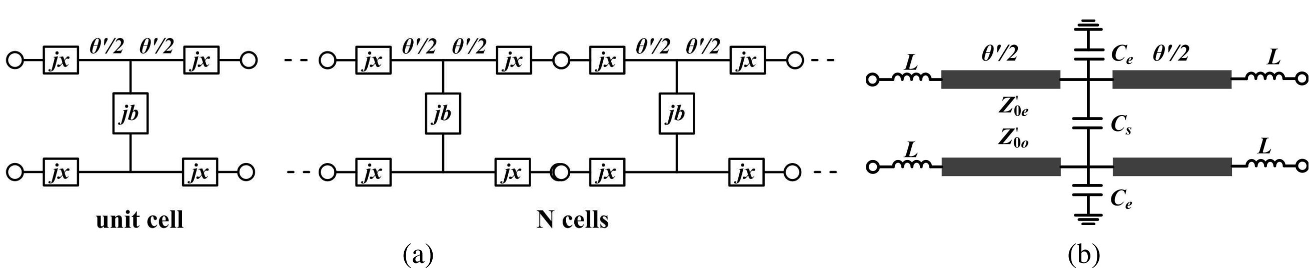


Figure 2. Electrical schematic. (a) Periodically loaded transmission line. (b) Periodically loaded coupled line.

the loaded coupled line, Z'_{0e} and Z'_{0o} be the equivalent even- and odd-mode characteristic impedance of the coupled line only, θ_e and θ_o be the equivalent phase delay of the even- and odd-mode. Substitute Z_{0e}, Z_{0o}, Z'_{0e}, Z'_{0o}, θ_e and θ_o into (5) and (6), we have

$$\cos\frac{\theta_e}{N} = m_{1e} - x_e \cdot m_{2e} \tag{7}$$

$$\cos\frac{\theta_o}{N} = m_{1o} - x_o \cdot m_{2o} \tag{8}$$

$$Z'_{0e} = Z_{0e} \Bigg/ \sqrt{\frac{m_{3e} + 2x \cdot m_{1e} - x^2 \cdot m_{2e}}{m_{2e}}} \tag{9}$$

$$Z'_{0o} = Z_{0o} \Bigg/ \sqrt{\frac{m_{3o} + 2x \cdot m_{1o} - x^2 \cdot m_{2o}}{m_{2o}}} \tag{10}$$

and

$$C_e = b_e / \omega Z'_{0e} \tag{11}$$

$$C_o = b_o / \omega Z'_{0o} \tag{12}$$

$$L = x_e Z'_{0e} / \omega = x_o Z'_{0o} / \omega \tag{13}$$

$$C_s = \frac{C_o - C_e}{2} \tag{14}$$

where N is the number of unit cells, C_s is the total shunt capacitance between the coupled lines. For a uniform symmetric coupler, the following relations are satisfied:

$$Z_0 = \sqrt{Z_{0e} \cdot Z_{0o}} \tag{15}$$

$$k = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \tag{16}$$

where Z_0 is the equivalent port impedance and k the coupling coefficient of the coupler. For a certain coupling value, Z_{0e} and Z_{0o} can be determined from Equations (15) and (16). To operate at TRD mode, the condition $\theta_e = \pi/2$, $\theta_o = 3\pi/2$ should be satisfied. θ' and N are arbitrary selected. It can be found from Equations (7), (9) and (13) that L is a function of b_e. Similarly, according to Equations (8), (10) and (14), L is also a function of b_o. Therefore, curves of L as functions of b_e and b_o can be plotted, and b_e and b_o can be determined with certain value of L. Then, Z'_{0e} and Z'_{0o} can be solved from (9) and (10). Finally, C_e and C_s are calculated from (11), (12) and (14). In the following section, a 3-dB miniaturized TRD coupler is designed. Detailed parameter study is also given.

3. DESIGN AND COMPARISON

In the first step, a comparison in terms of the realizable length is made between the conventional and the miniaturized TRD coupler. Table 1 shows the parameters of the 3-dB conventional and 3-dB miniaturized TRD couplers with different total electrical length. These parameters are calculated with the equations in [9] and in the paper under the condition that $N = 3$. The designed frequency is 1.6 GHz and L is chosen to be 1.2 nH. Using a less than 200 Ω even-mode characteristic impedance as the criteria, it can be found from Table 1 that the total electrical length of the conventional TRD coupler should be more than 55° and that the total electrical length of the miniaturized TRD coupler is more than 30°.

In the next step, the conventional and miniaturized TRD couplers are compared in terms of schematic simulation results. For the 3-dB miniaturized TRD coupler, the required Z_{0e} and Z_{0o} are 120.7 Ω and 20.71 Ω. The number of the cells, N, is 3, and the total electrical length of the coupled lines is chosen to be 35°. Curves of L as functions of b_e and b_o are given in Figure 3. In the design, L is chosen to be 1.2 nH, thus $b_e = 0.589$ and $b_o = 3.23$. $Z'_{0e} = 176.4\,\Omega$ and $Z'_{0o} = 62.8\,\Omega$ are calculated from Equations (9) and (10). At last, according to Equations (11), (12) and (14), C_e and C_s are evaluated to be 0.332 pF and 2.389 pF, respectively.

Table 1. The parameters of the conventional and miniaturized TRD couplers with different total electrical lengths.

$N\theta'(°)$	Conventional TRD coupler				Miniaturized TRD coupler				
	Z'_{0e} (Ω)	Z'_{0o} (Ω)	C_e (fF)	C_s (fF)	Z'_{0e} (Ω)	Z'_{0o} (Ω)	C_e (fF)	C_s (fF)	L (nH)
90	120.9	77.1	0	2232.8	120.9	77.1	0	2232.8	0
70	156.9	100.1	167.1	2219.4	98.0	36.9	10.1	2071.8	1.2
60	183.4	117.5	233.2	2214.1	112.5	41.4	119.4	2160.3	1.2
55	200.7	128.1	262.1	2211.8	120.5	44.5	166.7	2207.2	1.2
50	221.2	141.1	288.4	2209.7	130.8	47.8	212.8	2252.0	1.2
40	277.1	176.9	333.1	2206.1	158.1	56.9	295.6	2342.8	1.2
35	317.1	202.3	351.5	2204.6	176.4	62.8	332.1	2389.2	1.2
30	370.3	236.3	367.5	2203.3	201.1	71.2	366.1	2435.4	1.2

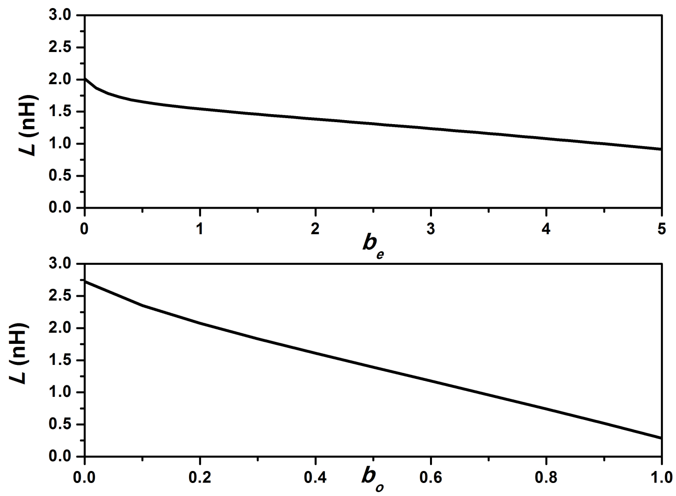
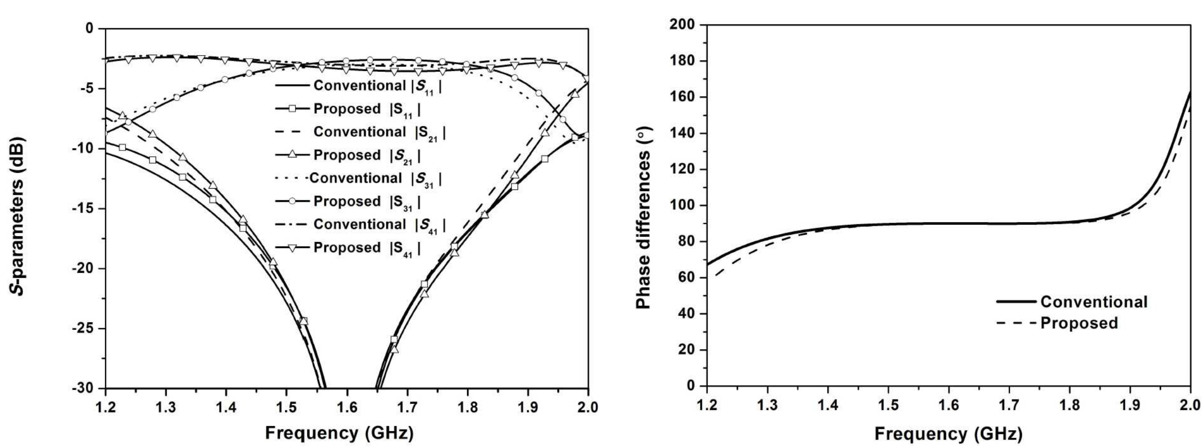


Figure 3. Curves of L as functions of b_e and b_o.



(a) (b)

Figure 4. Schematic simulation results of the conventional and miniaturized TRD coupler.

For comparison, a 3-dB conventional TRD coupler with $N = 3$ was designed according to the procedures in [9]. The total electrical length of the coupled lines is chosen to be 60°. Thus, $Z'_{0e} = 183.4\,\Omega$, $Z'_{0o} = 117.5\,\Omega$, $C_e = 0.233\,\text{pF}$, and $C_s = 2.214\,\text{pF}$. The parameters of the two TRD couplers can also be found in Table 1. Using these parameters, schematic of the conventional and miniaturized TRD couplers is simulated using ADS2009 software and the results are illustrated in Figure 4. It is observed that with the computed parameters, the performances of the miniaturized TRD coupler are nearly the same with that of the conventional TRD coupler.

In the next step, models of the conventional and miniaturized TRD couplers are constructed. Figure 5 shows the layout of the proposed miniaturized TRD coupler. Since the value of the required C_e is too small to be realized by lump element, C_e is implemented by open circular stubs. After optimizing using Ansoft 3-D simulator HFSS, the obtained parameters are: $w = 3.35\,\text{mm}$, $l = 8.4\,\text{mm}$, $w_1 = 0.6\,\text{mm}$, $l_1 = 3.3\,\text{mm}$, $s = 0.6\,\text{mm}$, $d = 3.2\,\text{mm}$, $d_1 = 1\,\text{mm}$, $d_2 = 0.3\,\text{mm}$, $L = 1.2\,\text{nH}$ and $C_s = 2.4\,\text{pF}$.

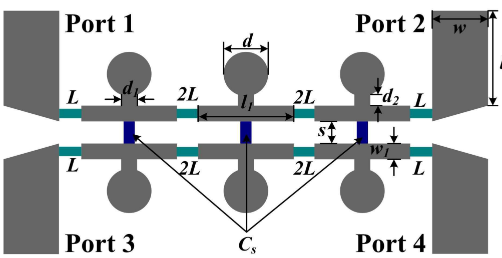


Figure 5. The layout of the proposed miniaturized TRD coupler.

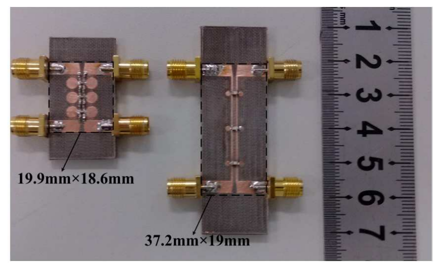


Figure 6. Photograph of the conventional and proposed TRD couplers.

4. FABRICATION AND MEASUREMENT RESULTS

Using the designed parameters, the miniaturized TRD coupler was fabricated, as illustrated in Figure 6. An implementation of the conventional TRD coupler with the optimized parameters is also shown in the figure for comparison.

The fabricated conventional and proposed miniaturized TRD couplers are both measured using Agilent N5230A vector network analyzer, and the S-parameters of the two TRD couplers are shown in Figure 7. It can be seen that the measured impedance bandwidth ($|S_{11}| < -20\,\text{dB}$) and isolation of the proposed TRD coupler are both better than 20 dB from 1.5 to 1.7 GHz (12.5%), and the best isolation

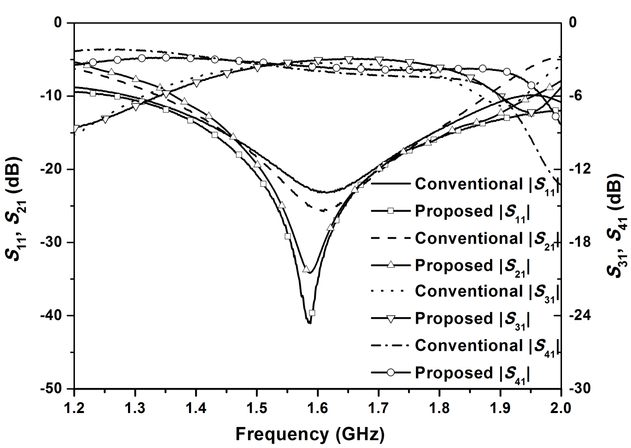


Figure 7. Measured S-parameters of the conventional and proposed TRD couplers.

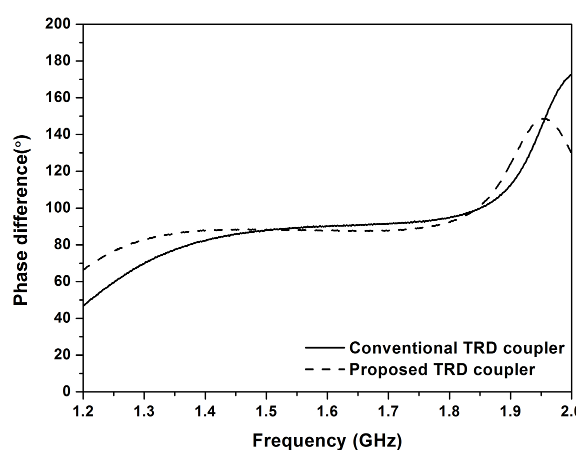


Figure 8. Measured output ports phase difference of the conventional and proposed TRD couplers.

Table 2. Comparison of conventional and proposed TRD couplers.

	Proposed	Conventional
Area (mm^2)	370.14	706.8
Relative size	52.4%	100%
Insertion loss (dB)	3.5 ± 0.5	3.8 ± 0.5
Return loss < 20 dB	1.5–1.7 GHz	1.55–1.68 GHz
Best directivity	37 dB	22 dB
Phase difference	$90^\circ \pm 1^\circ$ (1.5–1.7 GHz)	$90^\circ \pm 5^\circ$ (1.55–1.68 GHz)

is 37 dB at 1.6 GHz. In the bandwidth of $|S_{21}| < -20$ dB, the insertion loss of the proposed TRD coupler is 3.5 ± 0.5 dB. Furthermore, the measured output port phase difference of the proposed TRD coupler is $90^\circ \pm 1^\circ$ in the frequency range of 1.3–1.8 GHz, as shown in Figure 8. Table 2 summarizes the performances of the conventional and proposed miniaturized TRD couplers. It is observed that the proposed TRD coupler achieves 47.6% of size reduction compared to the conventional implementation with the inductors series with the periodically loaded coupled lines. From the schematic simulation results, as illustrated in Figure 4, it can be found that the performances of the two couplers are nearly the same. From the measured results in Figure 7, the proposed TRD coupler obtained a 15 dB improvement in directivity. The discrepancies between simulation and experiment results of the conventional TRD coupler might due to the fabrication error.

5. CONCLUSION

The technique of adding the inductors series with the periodically loaded coupled lines is proposed to effectively miniaturizing the TRD coupler. Comparisons in terms of volume, schematic simulation results and measurement results have been made between the miniaturized and conventional 3-dB TRD couplers operating at 1.6 GHz frequency. Results show that the proposed miniaturized TRD coupler obtained a size reduction of 47.6% compared to the conventional TRD coupler with similar performances. Therefore, the proposed miniaturized TRD coupler is suitable for microwave circuits and systems, especially at low frequencies.

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