Progress In Electromagnetics Research Letters, Vol. 38, 35–44, 2013

A NOVEL MINIATURIZED BRANCH-LINE COUPLER WITH EQUIVALENT TRANSMISSION LINES

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Abstract—In this paper, a novel miniaturized branch-line coupler (BLC) operating at 1.675 GHz is proposed. Partially meandered lines and dual transmission lines equivalent technology are used as the coupler's shunt arms, producing significant reduction by more than 68% compared with the conventional coupler. Moreover, the coupler can equally divide the input signal with 90° phase of difference while maintaining the initial power from the source with a simple structure. The simulated and measured results are in good agreement, thereby verifying the design concept.

1. INTRODUCTION

The branch-line coupler (BLC) is a fundamental component in planar microwave-integrated circuit that has many applications in devices such as phase shifters, vector modulators, amplifiers, and mixers. The compact size and high-performance of this element are highly demanded in many communication systems.

The conventional branch-line coupler is composed of four quarter-wavelength transmission sections at designed frequency, which result in a large occupied area especially at low frequencies. However, nowadays, portable devices require compact and cost-efficient components. Therefore, high performance, compact size and low cost are often the stringent requirements that should be driven forward in order to fulfill the demand of modern microwave communication systems.

Recently, several methods have been vastly investigated for size reduction in different studies. The lumped-element technique described in [1, 2] provides significant size reduction. However, the design of lumped-element circuits must be rather pragmatic and

Received 13 January 2013, Accepted 27 February 2013, Scheduled 4 March 2013
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needs precise inductor models based on careful measurements of test elements [3, 4]. The combination of shunt lumped capacitors with short high-impedance transmission lines is another option in shrinking the coupler's size [5, 6]. Additionally, Ring and Line Rat-race hybrid couplers as an alternative to produce compact designs have been proposed in [7].

2. COUPLER STRUCTURE

2.1. The Even-Odd Mode Analysis of the Conventional BLC

The geometry of the branch-line coupler is shown in Fig. 1. The equivalent model of the branch line coupler are shown in Fig. 2. In the analysis of the branch-line coupler, we consider the scattering matrix of the coupler. In order to find them, we use even-odd mode analysis. The *ABCD* matrixes are used to find the overall transmission and

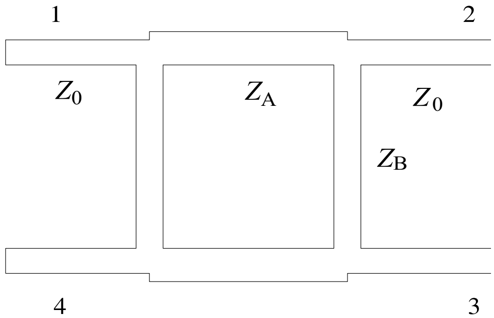


Figure 1. Geometry of the conventional coupler structure.

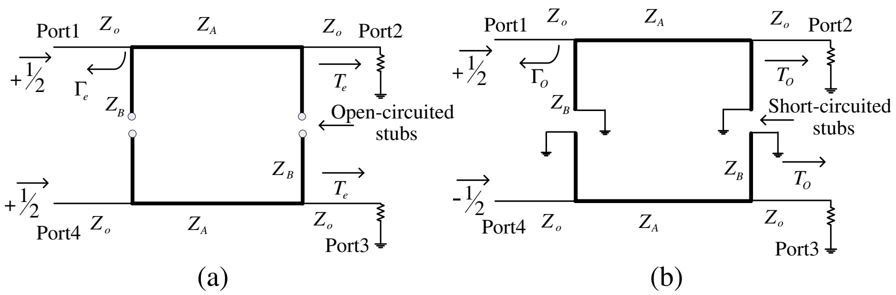


Figure 2. Equivalent model of the branch line coupler: (a) even mode, (b) odd mode.

reflection characteristics of the network. With $Y_A = 1/Z_A = \sqrt{2}$ and $Y_B = 1/Z_B = 1$, we have the $ABCD$ matrix of even and odd mode [10, 11].

For the even mode:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_E = \begin{bmatrix} 1 & 0 \\ jY_B & 1 \end{bmatrix} \begin{bmatrix} 0 & jZ_A \\ jY_A & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_B & 1 \end{bmatrix} = \begin{bmatrix} -Y_B Z_A & jZ_A \\ j(Y_A - Y_B^2 Z_A) & -Y_B Z_A \end{bmatrix} \tag{1}$$

$$\Gamma_e(S_{11}) = \frac{A+B-C-D}{A+B+C+D} = 0 \tag{2}$$

$$T_e(S_{21}) = \frac{2}{A+B+C+D} = -\frac{(1+j)}{\sqrt{2}} \tag{3}$$

For the odd mode:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_O = \begin{bmatrix} 1 & 0 \\ -jY_B & 1 \end{bmatrix} \begin{bmatrix} 0 & jZ_A \\ jY_A & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -jY_B & 1 \end{bmatrix} = \begin{bmatrix} Y_B Z_A & jZ_A \\ j(Y_A - Y_B^2 Z_A) & Y_B Z_A \end{bmatrix} \tag{4}$$

$$\Gamma_o(S_{11}) = \frac{A+B-C-D}{A+B+C+D} = 0 \tag{5}$$

$$T_o(S_{21}) = \frac{2}{A+B+C+D} = \frac{(1-j)}{\sqrt{2}} \tag{6}$$

where Z_A and Z_B represent the characteristic impedances of the conventional branch lines; Γ_e and T_e represent reflection coefficient and transmission coefficient in the even mode; Γ_o and T_o represent reflection coefficient and transmission coefficient in the odd mode.

If we consider the matching condition: the scattering matrix of the conventional branch-line coupler is:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} = -1/\sqrt{2} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \tag{7}$$

It can be seen from the matrix above that scattering matrix of branch-line coupler that the power entering port1is evenly divided between ports 2 and 3 with a 90° phase shift between these output ports. No power is coupled to port 4 (isolated port). Therefore, the isolation and directivity of that matched coupler, which will be mentioned in following part, is very high (for perfect case infinity), at center frequency.

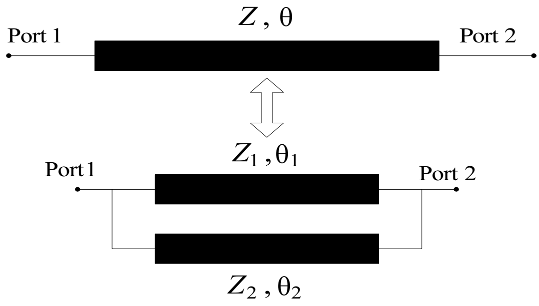


Figure 3. Equivalent circuit of single transmission line with dual transmission lines.

2.2. The Proposed BLC with Dual Transmission Lines

Figure 3 shows the equivalent circuit of a single transmission line with dual transmission lines. In this paper, to reduce the BLC's size, the usual quarter wavelength lines in conventional BLC are replaced by the proposed compact model of dual transmission lines [8]. With dual transmission lines, the single transmission line will be shorter. The equivalent equations of a single transmission line with dual transmission lines depicted by using admittance matrices [9] can be expressed as:

$$[Y_{\sin gle}] = \begin{bmatrix} -j\cot\theta Y & jY/\sin\theta \\ jY/\sin\theta & -j\cot\theta Y \end{bmatrix} \tag{8}$$

$$[Y_{double}] = \begin{bmatrix} -j\cot\theta_1 Y_1 - j\cot\theta_2 Y_2 & jY_1/\sin\theta_1 + jY_2/\sin\theta_2 \\ jY_1/\sin\theta_1 + jY_2/\sin\theta_2 & -j\cot\theta_1 Y_1 - j\cot\theta_2 Y_2 \end{bmatrix} \tag{9}$$

Let $[Y_{single}] = [Y_{double}]$.
Then:

$$\begin{aligned} -j\cot\theta Y &= -j\cot\theta_1 Y_1 - j\cot\theta_2 Y_2 \\ jY/\sin\theta &= jY_1/\sin\theta_1 + jY_2/\sin\theta_2 \end{aligned} \tag{10}$$

The general solutions of (2) and (3) can then be expressed as follows.

$$Y_1 = \frac{Y\sin\theta_1\,(\cos\theta - \cos\theta_2)}{\sin\theta\,(\cos\theta_1 - \cos\theta_2)} \tag{11}$$

$$Y_2 = \frac{Y\sin\theta_2\,(\cos\theta - \cos\theta_1)}{\sin\theta(\cos\theta_2 - \cos\theta_1)} \tag{12}$$

where Y_1, Y_2, θ_1 and θ_2 represent the characteristic admittance and the electric lengths of dual transmission lines, respectively, and Y is the characteristic admittance of the single transmission line.

The following equation can be derived as

$$Z_1 = Z_2 = 2 * Z / \sin\theta_2 \tag{13}$$

where Z_1 and Z_2 represent the characteristic impedances of dual transmission lines, respectively, and Z is the characteristic impedance of the $\lambda/4$ transmission line. So the equivalent circuit of the branch line coupler with dual transmission lines can be depicted in Fig. 4.

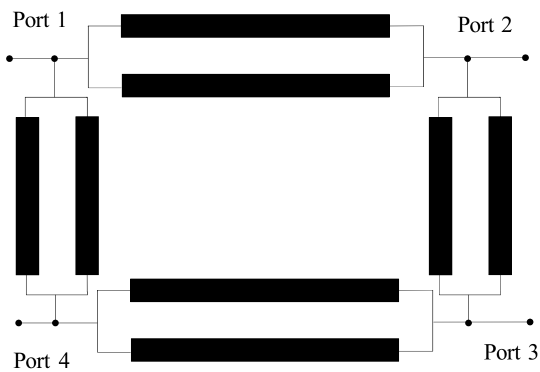


Figure 4. Equivalent circuit of the proposed coupler with dual transmission lines.

2.3. Geometry and Dimension of the Proposed Coupler

For simplified design [9], a $\lambda/4$ transmission line with the characteristic impendence of 50 Ω can be equivalent to a shunt connection of electrical lengths θ_1=120° and θ_2=60° transmission lines, with the corresponding impedance and length being (115 Ω, 40 mm), (115 Ω, 20 mm) for the parallel shunt arms and (80 Ω, 40 mm), (80 Ω, 20 mm) for the series shunt arms at 1675 MHz respectively. Therefore, the size reduction rate is 68% from the conventional BLC to the proposed one. The geometry and dimensions of the proposed structure are shown in Fig. 5 and Table 1. The line widths and line lengths of the proposed BLC were calculated by using ADS/Linecalc tool, the BLC was simulated by Ansoft simulation software, HFSS.

The design procedure of the proposed BLC is given as follows:

(i) Width and length of lines of conventional BLC at central frequency should be calculated by using ADS/Linecalc tool.

(ii) According to Equations (8) and (9), lengths of the equivalent dual transmission lines could be obtained.

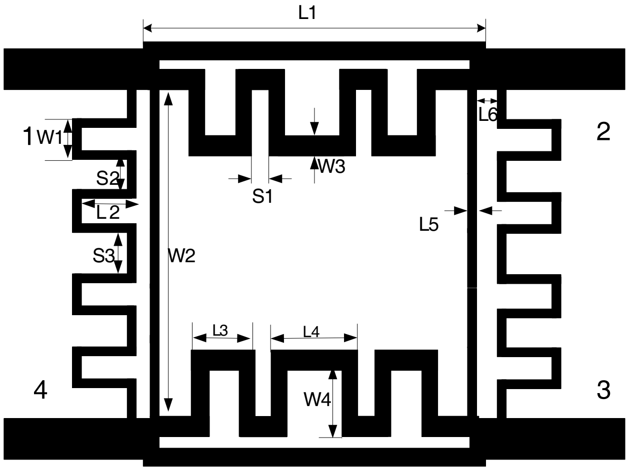


Figure 5. Geometry of the proposed structure.

Table 1. Dimensions of the proposed coupler.

Parameters	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$	$W1$
Value (mm)	20	2.8	4.16	5.16	0.52	1	2.2
Parameters	$W2$	$W3$	$W4$	$S1$	$S2$	$S3$	
Value (mm)	18	1.16	4.6	1	1.8	2.8	

(iii) The longer one of the dual transmission lines should be meandered so that it is as long as the shorter one of the dual transmission lines. In this way, the proposed BLC's model could be attained.

(iv) In order to verify the design procedure, the proposed BLC can be simulated by the Ansoft simulation software, HFSS.

The design procedure of the proposed BLC is convenient to implement by readers and engineers.

3. RESULT AND ANALYSIS

The proposed novel miniaturized 3-dB BLC is fabricated on a PTFE ($\varepsilon_r = 2.65$, $h = 1\,\text{mm}$) substrate and has been simulated by Ansoft HFSS software. The photograph of the fabricated BLC is depicted in Fig. 6. The simulated and measured results are plotted in Fig. 7.

The fabricated conventional coupler and the proposed coupler were measured, respectively. The data of the measurements are listed

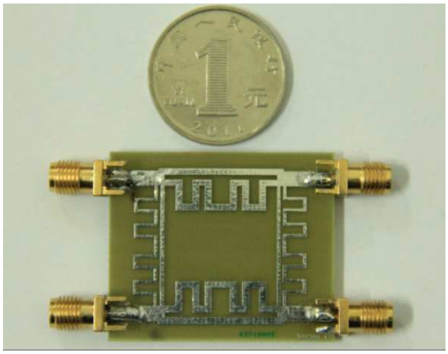
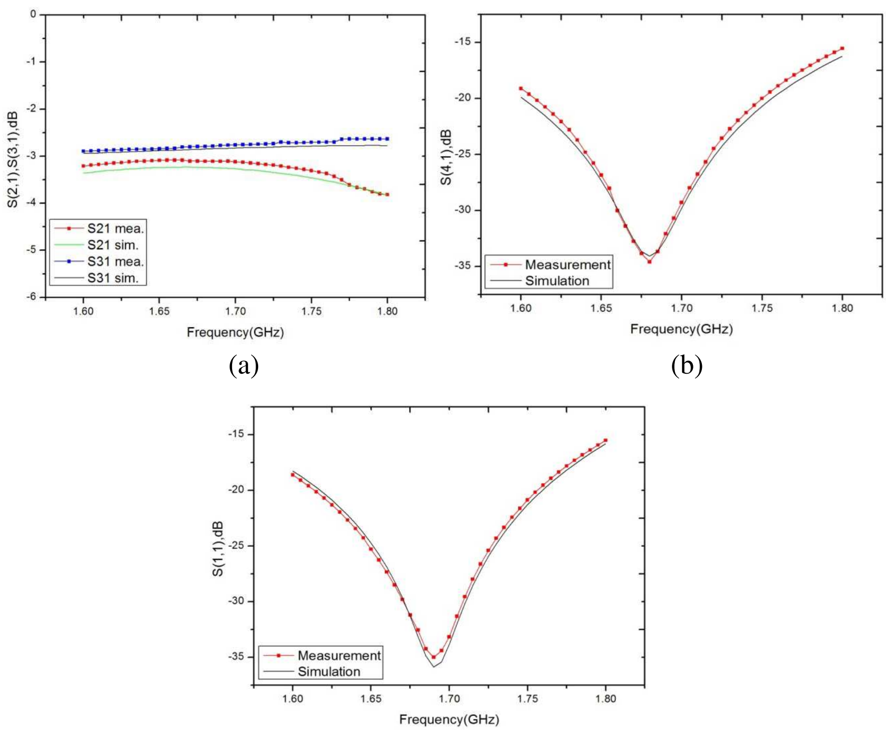


Figure 6. Fabricated proposed miniaturized coupler.



(a) (b)

(c)

Figure 7. Simulation results: (a) magnitude of $S(2,1)$ and $S(3,1)$, (b) magnitude of $S(4,1)$, (c) magnitude of $S(1,1)$.

Table 2. Comparison table between the proposed BLC and the conventional one.

Parameters	Conventional	Miniaturized
Frequency	1.675 GHz	
S_{11}	32.15 dB	−35.1 dB
S_{21}	2.72 dB	−2.8 dB
S_{31}	3.12 dB	−3.15 dB
S_{41}	38.519 dB	−34.1 dB
Phase difference	89.7°	89.3°
Size Width*Length (mm^2)	42mm×38 mm ($1260\,mm^2$)	20mm×20 mm ($400\,mm^2$)
Percentage of Reduction	68%	
Percentage Bandwidth	16.9%	23.2%

in the Table 2. The coupler's S-parameter is analyzed at the operating frequency of 1.675 GHz. The coupling factors versus frequency S_{21} and S_{31} are shown in Fig. 7(a) approaching ideal value 3 dB at a frequency band from 1.6 GHz to 1.8 GHz. What's more, the flatness of S_{21} and S_{31} are both under 0.3 dB at the desired frequency range that determines the coupler's ability to divide the input signal equally at the output port.

The isolation factor S_{41} is shown in Fig. 7(b). It is observed that the isolation factor gets as high as 34.1 dB at the center frequency of 1.675 GHz. Symmetry structures contribute to the same value of coupler's S_{11} (return loss) reflection coefficient. The reflection factor is equal to −35.1 dB at the center frequency of 1.675 GHz as shown in Fig. 7(c).

The phase difference between the coupler's output ports is depicted in Fig. 8. The phase difference is 89.3° at 1.675 GHz. Such value is acceptable for all receivers since 5° error is negligible and indicates good transmission percentage.

Above all, the fabricated coupler only occupies 2 mm×2 mm on the printed circuit board, achieving up to 68% size reduction compared with the conventional coupler which works at the center frequency of 1.675 GHz.

The Table 3 above is a comparison between the proposed BLC in this paper and BLC in reference [6]. It can be seen that the proposed BLC in my paper have advantages on the S_{11}, percentage of Reduction and Phase difference respectively. On the other hand, disadvantage of the proposed BLC is that the percentage bandwidth shrinks evidently.

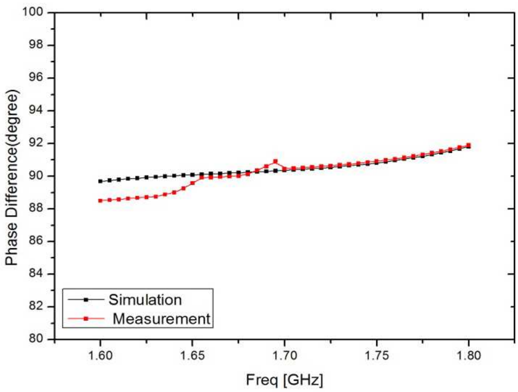


Figure 8. Phase difference between Ports 2 and 3.

Table 3. Comparison table between the proposed BLC and the BLC in reference [6].

Parameters	The BLC in reference [6]	The proposed BLC
S_{11}	-21.7 dB	-35.1 dB
S_{21}	-3.3 dB	-2.8 dB
S_{31}	3.1 dB	-3.15 dB
S_{41}	36.2 dB	-34.1 dB
Phase difference	89°	89.3°
Percentage of reduction	64%	68%
Percentage bandwidth	22.8%	16.9%

4. CONCLUSION

In this paper, a miniaturized BLC operating at 1.675 GHz with an extremely compact simple microstrip structure and low fabrication cost is introduced, and the results are verified by simulation and measurement. It has been shown that the new coupler, with 68% size reduction, works as well as a conventional BLC except for diminished bandwidth. This prototype can be integrated into the design of microwave or millimeter-wave integrated circuits where the compactness of components is crucial.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 61201020).

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