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Design and Implantation of a Wideband Microstrip 90° Hybrid Using Quasi-Π-Shaped Structure Loading

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Abstract

This paper presents the design and implantation of a wideband microstrip branched hybrid coupling. The wideband performance of the hybrid means that it possesses equal coupling and difference of phases throughout the operating frequency band, from 3.5 GHz to 6.5 GHz. The compactness of the proposed design is depending on the replacement of branched transmission lines instead of conventional transmission lines. Small and easy to fabricate microstrip layout topology for the hybrid have been designed and constructed relying on a low cost dielectric material, the well-known FR4. In addition, the proposed hybrid can be easily fabricated on the printed circuit board without any lumped element. The proposed hybrid exhibits couplings and phase errors within -3.5 ± 0.75 dB and 4° over a 70% bandwidth with a center frequency of 5 GHz.

Keywords: Coupler, compact, planar, wideband, hybrid

INTRODUCTION

The compact branch-line coupler, which is popular as a hybrid in microwave circuits, is an important circuit in microwave integrated circuits and can be used as a power divider/combiner or a part of a mixer [1]. The conventional branch-line coupler is composed of four quarter-wavelength transmission lines as shown in Figure 2 [2]. However, adopting the quarter-wavelength transmission line to design the coupler takes too much space; therefore, larger circuit area may result in higher cost. In addition, the broadband branch-line coupler takes two times more space than the normal type.

Numerous methods have been proposed to reduce circuit size [3]–[14]. A number of proposed methods are as follows: Based on a methodology, the asymmetrical T-structure can be exactly synthesized and then applied to implement compact planar couplers [3]. The dual transmission lines can be replaced with conventional quarter-wavelength transmission lines for a compact microstrip branch-line coupler and can be easily fabricated on the printed circuit board without lumped element [6]. A compact slow-wave microstrip branch-line coupler not only effectively reduces the occupied area, but also has high second harmonic suppression performance [9]. A class of the novel compact-size branch-line couplers using the quasi-lumped elements approach with symmetrical or nonsymmetrical T-shaped structures is proposed in [11]. Nevertheless, using the lumped element in the circuit design requires an empirical model, such as an inductor model. Based on another methodology, discontinuous microstrip lines whose size is significantly reduced relative to the standard design can be used to implement a compact planar coupler [3]. Highly miniaturized branch-line coupler can be fabricated using a novel π-type multiple coupled microstrip line structure [7]. A conventional quarter wavelength microstrip can be equivalent to a π-equivalent shunt-stub-based artificial transmission lines realized by a series high-impedance microstrip with two sets of branch type shunt stubs. The circuit configuration of the shunt-stub- based artificial transmission lines is beneficial to miniaturize the circuit size using the folding technique [5]. Further minimization of the branch-line hybrid coupler can be achieved by using the interdigitated capacitors which are shunt with the transmission lines [4].

In [3], [4], [8], [10], [11], [14] microstrip lines are employed to design the compact branch-line coupler. However, only a few studies provide detailed discussion on design procedures or formulations. In this paper, a new method for designing the microstrip branch-line couplers with predetermined compact size and bandwidth has been proposed and implemented. Utilizing the proposed multiple shunted open stubs shown in Figure 2(e), which can be realized with either high or low impedance, can easily miniaturize four quarter-wavelength transmission lines of the conventional branch-line couplers or that can be used in conventional broadband branch-line couplers which are shown in Figure 1. The fabricated couplers not only occupy small space, but also reveal good circuit performances compared with that of the conventional branch-line type, and it can be used as an element of broadband Butler Matrix networks to feed an array antenna. Good agreements between the results of the conventional and proposed branch-line coupler are observed. (The related results of the conventional type are not included.)

In Section II, we will provide the transformed equation, which can synthesize the equivalent quarter-wavelength transmission line. The theoretical prediction and simulated results are provided in Section III. Finally, our conclusions are given in Section IV.

DESIGN PROCEDURE

The branch-line coupler (as shown in Figure 1(a)) is popular as a hybrid in microwave circuits especially in planar circuits, while has narrow-band characteristics. To archive the wide band performance, cascaded branch line, broadband branch-line coupler is a better choice (as shown in Figure 1(b)) as a quadrature hybrid circuit. However, it requires a larger circuit area but it has a wider bandwidth. The loaded line such as T-equivalent or π-equivalent structure is a popular method to reduce the size of transmission-line circuits such as branch-line and ring hybrids, which is important for planar integrated circuits. The results using a loaded line without any complexity show good performance with regard to size reduction [14].

A transmission line and its π-equivalent circuit are shown in Figure 2, and the design equations can be defined as follows [14]:

$$\frac{\tan\theta_P}{Z_P} = \frac{\cos\theta_S - \cos\theta_0}{Z_0 \sin\theta_S} \qquad (1)$$

$$Z_S = \frac{Z_0 \sin\theta_0}{\sin\theta_S} \qquad (2)$$

where $0 \leq \theta_S \leq \theta_0 \leq 90°$.

For demonstration, we select a transmission line of Figure 2(a) with the characteristic impedance Z_0 and electrical length θ_0 as a unit line section, and it can be replaced by a π-equivalent circuit in Figure 2(b). Then each open stub can be replaced by a balanced open stub with equal characteristic impedance Z_P and total electrical length θ_P (i.e. $\theta_P = \theta_P/2 + \theta_P/2$) as shown in Figure 2(c, d). Finally, the approached structure is a balanced π-equivalent structure as shown in Figure 2(e). The simulated results, which are presented in the next section, show acceptable frequency response within the operating band width with regard to size reduction.

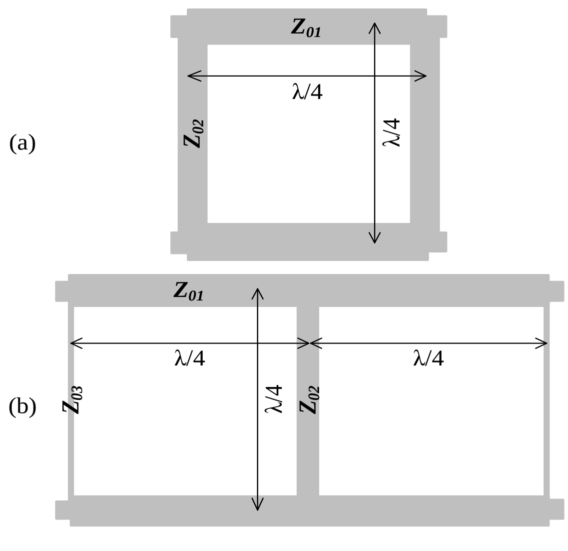

Figure 1. (a) Conventional 90° branch-line coupler, (b) Conventional broadband 90° branch-line coupler (λ is effective wave length).

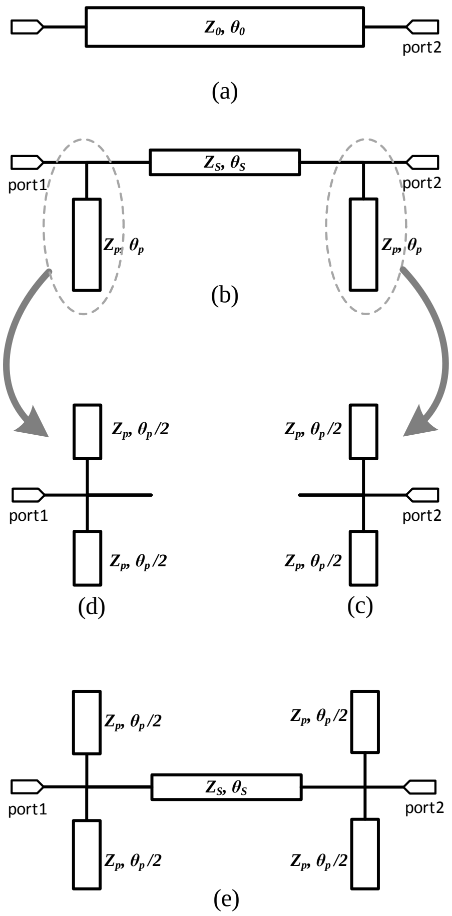

Figure 2. Conventional transmission line and its balanced π-equivalent structure. (a) A conventional transmission line, (b) π-equivalent transmission line of the conventional type, (c, d) balanced equivalent structure of the open stubs, and (e) The balanced π-equivalent structure of the conventional transmission line.

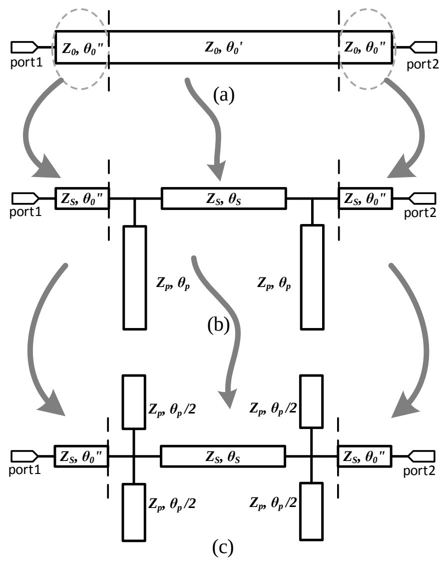

Figure 3. (a) A Conventional transmission line, (b) The proposed quasi-π-equivalent structure and (c) The proposed balanced quasi-π-equivalent structure of the conventional transmission line.

If the transmission lines of the conventional (broadband) branch-line coupler shown in Figure 2(a) are replaced by balanced π-equivalent structure shown in Figure 2(e) the open stubs on the corners should be merged together, with replacing a fraction of the conventional transmission lines of the couplers by the balanced π-equivalent structure, that can be avoided being the stubs on the corner, see Figure 3. In order to achieve a flatter structure one can replace the rest fraction of each transmission line by the conventional transmission line with the same electrical length, but with the characteristic impedance Z_S instead of Z_0. The simulated results, which are presented in the next section, show acceptability of this approximation.

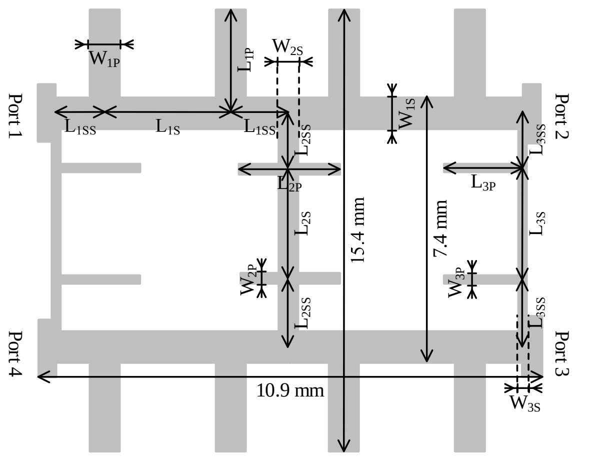

Figure 4. The proposed broadband branch-line coupler with Quasi-π-equivalent structure of the conventional transmission line.

In this work 70% of the transmission lines with characteristic impedance Z_{01} and 80% of the transmission lines with characteristic impedance Z_{02} and Z_{03} of the conventional broadband branch-line coupler (i.e. Figure 2(b)) are replaced by the quasi-π-equivalent structure.

The proposed circuit has been shown in Figure 4 and each conventional transmission line has been replaced by a quasi-π-equivalent structure. Length and width of each intersection transmission line lettered in Figure 4 are as follows:

Table 1. Length and Width of Each Intersection Lettered in Figure 4, (All Values Are in millimeter).

	L_{iSS}	L_{iS}	W_{iS}	L_{iP}	W_{iP}
i=1	0.80	3.4	0.7	4.7	0.8
i=2	1.75	3.2	0.3	3.3	0.2
i=3	1.75	3.2	0.1	2.4	0.1

SIMULATION & EXPERIMENTAL RESULTS

Measurements of the proposed circuit were accomplished using an Agilent™ 8722ES network analyzer and simulation was accomplished using EM simulation software Agilent Advanced Design System, which is an electromagnetic wave simulator which provides an integrated design environment to designers of RF electronic products.

The proposed branch-line coupler is designed on a FR4 substrate with a thickness of 0.8 *mm*, a dielectric constant of 4.4, and a loss tangent of 0.022.

Figure 5 presents the photograph of the developed compact branch-line coupler with quasi-π-equivalent transmission lines and its effective size is 10.9 *mm* × 7.4 *mm* (outer stubs are neglected [14], total size is 10.9 *mm* × 15.4 *mm*). Compared with the conventional structure, the compact branch-line coupler developed in this paper only occupies a 39% circuit size of the conventional one.

The simulation and measured scattering parameters of the proposed branch-line coupler are shown in Figure 6 and phase division is shown in Figure 7. At the designed frequency, 5 GHz, the insertion loss is 3.5±0.1 dB, the isolation is about 20 dB, and the phase difference is 89°. In addition, these figures shows that the performance of the proposed coupler has approximately couplings, phase errors within -3.5 ± 0.75 dB, 4°, return loss and isolation better than 15 dB over a 70% bandwidth (i.e. 4 GHz ~ 6 GHz). Table 2 summarizes the recently published branch-line hybrid couplers with reduced wavelength in transmission line and this work. In addition it shows significant improvement in size reduction with regard to wide band performance.

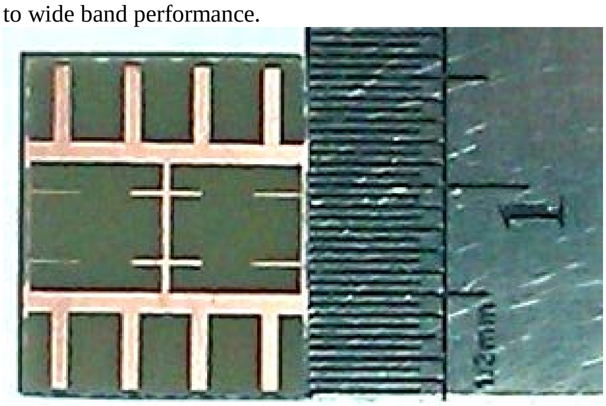

Figure 5. Photograph of the developed broadband branch-line coupler.

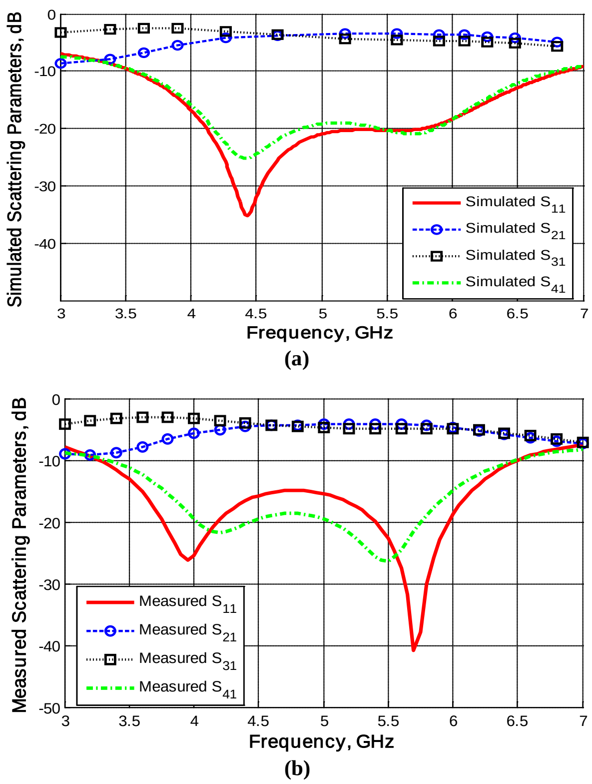

Figure 6. Simulated (a) and measured (b) scattering parameters of the proposed branch-line coupler.

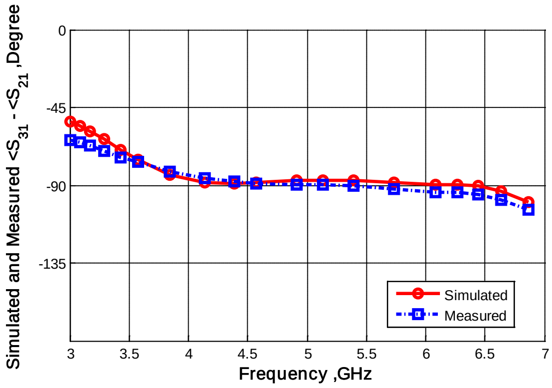

Figure 7. Simulated and measured value of ∠S_{31} - ∠S_{21} of the proposed branch-line coupler.

Table 2. Comparison of Published Compact Branch-Line Couplers and This Work.

Ref.	Phase Error	Substrate	f_0 (GHz)	B.W. (GHz)	Reduction Ratio
[3]	~5	RO4003	0.9	0.3 (0.75~1.05)	0.12
[4]	~2	FR4	0.825	0.15 (0.75~0.9)	0.26
[8]	~4	FR4	2.3	0.6 (2~2.6)	0.54
[10]	>5	RO4003	2.4	0.4 (2.2~2.6)	0.76
[11]	>5	FR4	2.4	0.8 (2~2.8)	0.29
[14]	~5	RO4003	5	2 (4~6)	0.5
This Work	4	FR4	5	3 (3.5~6.5)	0.39

CONCLUSION

In this paper, the conventional broadband branch-line coupler (cascaded branch-line coupler) with seven sections of the quarter-wavelength transmission lines has been miniaturized easily by using the proposed quasi-π-equivalent structure. The corresponding design equations and equivalent structures and their simulated results are presented as well. In order to achieve more size reduction, one can fold the loaded open stubs (L-shaped open stubs) or spilt a fraction of the stubs to two separate stubs with different directions (Y-shaped open stubs at the end point). Table I reveals that using the proposed quasi-π-equivalent structure is an effective approach to miniaturize the circuit size of a branch-line coupler (i.e. the reduction size is 61%) with regard to wideband performance. The proposed branch line coupler exhibits couplings and phase errors within -3.5 ± 0.75 dB and 3° and return loss and isolation better than 15 dB over a 70% bandwidth (i.e. 4 GHz ~ 6 GHz) with a center frequency at 5 GHz. Moreover, these couplers can be fabricated using a standard printed circuit board process, which is easily applicable to the design of microwave integrated circuits, such as broadband Butler Matrix Networks.

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