Novel Compact Dual-Band Branch-Line Couplers with Half Elliptical-Ring Impedance Stub Lines

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Abstract—Novel compact dual-band branch-line couplers are presented. By using a half elliptical-ring impedance stub as a basic unit, dual-band branch-line couplers are obtained. Since a couple of half elliptical-ring impedance stubs can be folded inward to its enclosed area without overlap, the branch-line coupler can be miniaturized. In order to verify the effectiveness of the half elliptical-ring impedance stub, two different branch-line couplers operating at 2.4/5.8 GHz are designed, fabricated and tested. Measured results agree well with simulated ones. Compared with the stepped-impedance-stub branch-line couplers, sizes of the proposed couplers are reduced by 43% and 30%, respectively.

1. INTRODUCTION

Couplers are widely used in the design of microwave devices such as power amplifiers, mixers and modulators. The rat-race and branch-line couplers are the most fundamental and commonly used devices in the microwave integrated circuits. The branch-line coupler is a 3 dB directional coupler with a 90° phase difference in the outputs of the through and coupled arms, which is often used for the feeding network of the circularly polarized antenna. However, based on a simple quarter-wavelength transmission line section, the conventional branch-line coupler is large in size and operates only at single frequency band. Therefore, its applications to multiband and compact systems are limited.

Previously, some designs for dual-band branch-line couplers have been proposed [1–4]. By using four additional quarter wavelength branches, a dual-band microstrip line coupler has been achieved [1]. By adding two additional cross branches [2] and an additional branch [3] to the conventional branch-line coupler, dual-band performance is obtained. The dual-band branch-line coupler can also be designed by adding four stubs to the conventional coupler [4]. Varieties of miniaturized techniques also have been proposed for reducing sizes of the branch-line coupler circuits [5–11]. The widely used method is meandering transmission lines [5] or coupled lines [6]. Nevertheless, parasitic coupling between transmission-line sections increases in these cases. In [7], the shunt open-stub of length smaller than a quarter wavelength is proposed to design miniaturized branch-line couplers. In addition, artificial transmission lines (ATLs) are used [8]. Asymmetrical T-structures [9] and new symmetric equivalent circuits [10] are employed to miniaturize branch-line couplers. But the couplers in [5–10] operate only at single frequency band. Recently, compact dualband branch-line couplers with stepped-impedance-stub are proposed [11]. Because the stepped-impedance-stub is too long to fold inward to couplers, sizes of the couplers in [11] are still large. Therefore, design of compact branch-line couplers is still a challenging task.

In this paper, novel compact dual-band branch-line couplers based on half elliptical-ring impedance stubs are proposed. The half elliptical-ring impedance stub can be folded inward to couplers, which is favorable for miniaturizing the branch-line couplers. Detailed design process is also given in this paper. To verify effectiveness of this idea, two different branch-line couplers operating at 2.4/5.8 GHz

are designed, and their areas are only 57% and 70% of the corresponding stepped-impedance-stub branchline couplers. Simulated and measured results show remarkable dual-band performance.

This paper is organized as follows. The design principle is presented in Section 2. Detailed simulated and measured results are shown in Section 3. Conclusion is drawn in Section 4.

2. DESIGN PRINCIPLE

In [11], the stepped-impedance-stub branch line is introduced for size reduction and dual-band operations. The stepped-impedance-stub branch line is shown in Fig. 1(a). A stepped-impedance-stub of (Z_1, θ_1) and (Z_2, θ_2) is tapped to the center of a conventional line $(Z_3, 2\theta_3)$. The $ABCD$ matrix formulation is utilized to obtain the design equations. By multiplying the $ABCD$ matrices of these three cascading sections, the $ABCD$ matrix of the stepped-impedance-stub branch line is expressed as

$$
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{T1} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{T2} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{T1}
$$

$$
= \begin{bmatrix} \cos\theta_3 & jZ_3\sin\theta_3 \\ (j/Z_3)\sin\theta_3 & \cos\theta_3 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1/Z_e & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_3 & jZ_3\sin\theta_3 \\ (j/Z_3)\sin\theta_3 & \cos\theta_3 \end{bmatrix} \tag{1}
$$

where T1, T2 represent the transmission matrices for (Z_3, θ_3) and (Z_e, θ_e) in Fig. 1(a) respectively. And Z_e is expressed as

$$
Z_e = jZ_2\frac{Z_2\tan\theta_2 - Z_1\cot\theta_1}{Z_2 + Z_1\tan\theta_2\cot\theta_1} \tag{2}
$$

Since the stepped-impedance-stub branch line is equivalent to a quarter-wavelength transmission line at two operating frequencies f_1 and f_2, where f_1 and f_2 are center frequencies of the first and second bands, respectively, the corresponding matrix is given by

$$
\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{90°} = \begin{bmatrix} 0 & \pm j/J \\ \pm jJ & 0 \end{bmatrix}_{f_1, f_2} \tag{3}
$$

where J is the characteristic admittance of the $90°$ line. By equating the $ABCD$ matrices (1) with (3), and setting $A = D = 0$ we obtain

$$
Z_3\tan 2\theta_3 = \frac{2Z_2(Z_1\cot\theta_1 - Z_2\tan\theta_2)}{Z_2 + Z_1\tan\theta_2\cot\theta_1} \tag{4a}
$$

$$
Z_3\sin 2\theta_3 + \frac{Z_3^2\sin^2\theta_3(Z_2 + Z_1\tan\theta_2\cot\theta_1)}{Z_2(Z_2\tan\theta_2 - Z_1\cot\theta_1)} = \pm\frac{1}{J} \tag{4b}
$$

For the second operating frequency, we also have

$$
Z_3\tan(2r\theta_3) = \frac{2Z_2(Z_1\cot(r\theta_1) - Z_2\tan(r\theta_2))}{Z_2 + Z_1\tan(r\theta_2)\cot(r\theta_1)} \tag{5a}
$$

$$
Z_3\sin(2r\theta_3) + \frac{Z_2^3\sin^2(r\theta_3)(Z_2 + Z_1\tan(r\theta_2)\cot(r\theta_1))}{Z_2(Z_2\tan(r\theta_2) - Z_1\cot(r\theta_1))} = \pm\frac{1}{J} \tag{5b}
$$

where $r = f_2/f_1$.

For the stepped-impedance-stub branch line, the length of (Z_e, θ_e) corresponds to the frequency ratio, which is always too long to fold inward to the enclosed area of couplers, occupying too much space. If a couple of stepped-impedance-stub lines can be folded inward to the enclosed area of the coupler, the size can be reduced. The half elliptical-ring impedance stub, which is shown in Fig. 1(c), is proposed. Compared with the stepped-impedance-stub (Z_e, θ_e), the proposed half elliptical-ring impedance stub turns space of the length direction into that of the width direction, so a couple of stubs can be folded inward to the enclosed area of couplers without overlap. By employing the half elliptical-ring impedance stub to substitute for the stepped-impedance-stub (Z_e, θ_e), the branchline coupler is miniaturized. As shown in Fig. 1(b), the half elliptical-ring (Part A) consists of two concentric ellipses, which are subtracted and cut by an angle of $2*\theta$. Moreover, the half elliptical-ring is equivalent to (Z_1', θ_1'). Hence, combination of the half elliptical-ring (Z_1', θ_1') with the transmission line (Z_2', θ_2') is
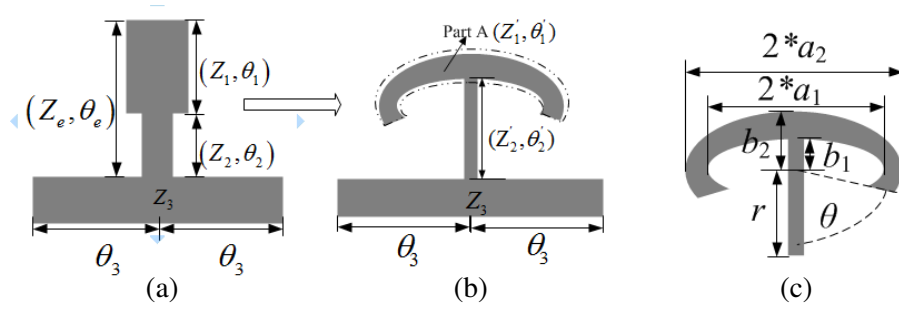
Figure 1. (a) Configuration of the dual-band stepped-impedance-stub branch line in [11]. (b) Configuration of proposed half elliptical-ring impedance stub branch line. (c) Detailed parameters of half elliptical-ring impedance stub.

used to replace the stepped-impedance-stub (Z_e, θ_e). Besides, the parameters (Z_1', θ_1') and (Z_2', θ_2') is equivalent to (Z_1, θ_1) and (Z_2, θ_2) in Eqs. (4)–(5). Consequently, the $ABCD$ matrix of the half elliptical-ring impedance stub is equivalent to matrix T2 in Eq. (1). With these equivalents, the novel compact dual-band branch-line couplers based on half elliptical-ring impedance stubs are designed by using the same method used in [11].

3. EXPERIMENTAL RESULTS

To verify the design concept, two different branch-line couplers are designed, fabricated and tested. Simulated and measured results show desired dual-band performance.

3.1. Single-Section Dual-Band Branch-Line Coupler

A single-section dual-band branch-line coupler is designed, which is printed on an Arlon AD255A substrate with a relative dielectric constant of 2.55 and thickness of 1 mm. Configuration of the branch-line coupler with half elliptical-ring impedance stub branch lines is shown in Fig. 2 (a). Fig. 2(b) shows a photograph of the single-section branch-line coupler. Some of its dimensions are as follows: $w = 2.8$ mm, $w_1 = 5$ mm, $w_2 = 6.6$ mm, $L = 22$ mm. Parameter values of Part 1 and Part 2 shown in Fig. 2(a) are given in Table 1.

**Table 1.** Values in part 1 and part 2 (Unit: mm).

Parameters	a_1	a_2	b_1	b_2	θ	r_1
Part 1	5.5	8.5	2.9	4	35°	6
Part 2	6.5	7.5	1.6	5.5	70°	9

Simulated S parameters of the proposed branch-line coupler are shown in Fig. 3(a). The measured results are also given in Fig. 3(b) for comparison. Fig. 3(c) shows its phase difference. As shown, the simulated insertion losses of the through and coupled ports are 2.9 dB and 3.3 dB with a phase difference of 90° at 2.36 GHz, and 3.5 dB and 3.15 dB with a phase difference of −91.7° at 5.78 GHz, respectively. The phase balance bandwidths with $\angle S_{12}$–$\angle S_{13}$ within ±90°±5° are 19.6% from 2.16 to 2.63 GHz and 9.3% from 5.56 to 6.1 GHz. With the magnitude variation less than ±0.5 dB, the bandwidths are 16.7% from 2.14 to 2.53 GHz and 3.8% from 5.74 to 5.96 GHz. As shown in Fig. 3, the measured results agree well with the simulated ones.

Comparison of the proposed coupler with the stepped-impedance-stub branch-line coupler is shown in Table 2. Bandwidths of the proposed single-section coupler are comparable with that of the single-section stepped-impedance-stub branch-line coupler. By folding a couple of half elliptical-ring impedance stubs inward to the enclosed area of the branch-line coupler, a size reduction of 43% with a lower relative dielectric constant of 2.55 is obtained for the proposed coupler.

Table 2. Bandwidths comparison of the proposed coupler with the stepped-impendence-stub branch-line coupler.

	ε_r	$\angle S_{12}-\angle S_{13}$ ($\pm 90°\pm 5°$)	$|S_{12}|-|S_{13}|$ (± 0.5 dB)	Size (mm × mm)
The coupler in [11]	3.38	21%/4%	11%/5%	70 × 70
The proposed coupler	2.55	19.6%/9.3%	13.4%/3.5%	70 × 40

(a) (b)
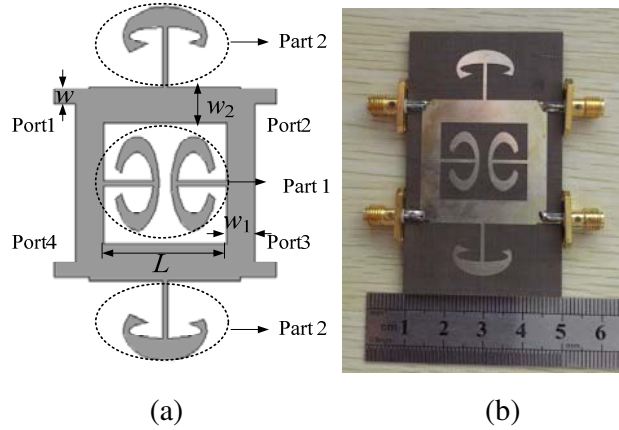
Figure 2. (a) Configuration of the proposed single-section branch-line coupler. (b) Photograph of the proposed single-section branch-line coupler.

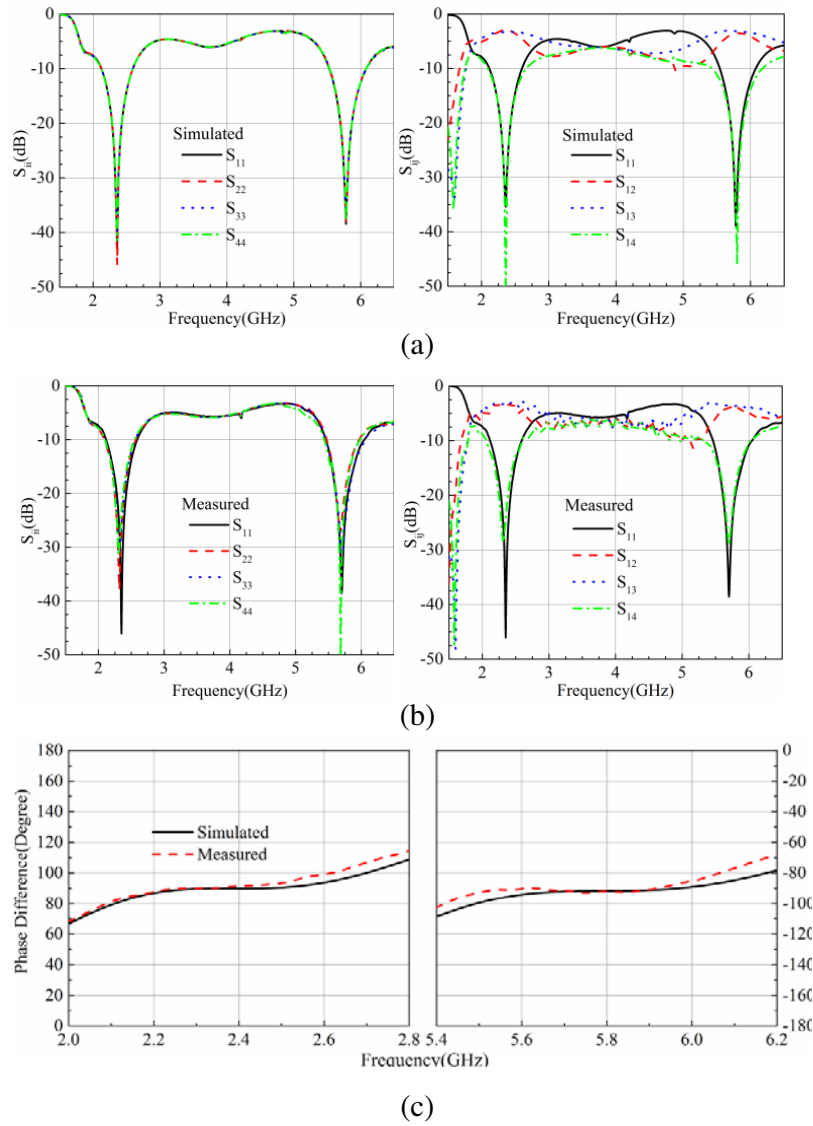### 3.2. Two-Section Dual-Band Branch-Line Coupler

A two-section dual-band branch-line coupler operating at 2.2/5.4 GHz is designed, which is also printed on an Arlon AD255A substrate with a relative dielectric constant of 2.55 and a thickness of 1 mm. Figs. 4(a) and 4(b) show the configuration and photograph of the proposed branch-line coupler, respectively. Some of its dimensions are as follows: $w_1 = 1.5$ mm, $w_2 = 5.8$ mm, $L = 27.7$ mm. Parameter values of Part 3 and Part 4 shown in Fig. 4(a) are given in Table 3.

**Table 3.** Values in part 3 and part 4 (Unit: mm).

Parameters	a_1	a_2	b_1	b_2	θ	r_1
Part 3	3.5	8	2.6	3.1	80°	7.8
Part 4	4.5	12.5	1.2	5.6	60°	8.5

Simulated and measured S parameters are shown in Figs. 5(a) and 5(b). Fig. 5(c) shows the phase difference. Detailed simulated results are $|S_{12}| = -3.16$ dB, $|S_{13}| = -3.65$ dB, $\angle S_{12}-\angle S_{13} = 92.3°$ at 2.2 GHz and $|S_{12}| = -3.4$ dB, $|S_{13}| = -3.6$ dB, $\angle S_{12}-\angle S_{13} = 92.5°$ at 5.4 GHz. The dualband phase balance bandwidths are 30.7% from 1.82 to 2.48 GHz at 2.2 GHz, and 17.2% from 4.94 to 5.87 GHz at 5.4 GHz, respectively. The magnitude bandwidths are 20.4% from 1.94 to 2.38 GHz at 2.2 GHz, and 10.7% from 5.14 to 5.72 GHz at 5.4 GHz, respectively.

As shown in Fig. 5, the measured results agree well with the simulated ones. Comparison of the proposed coupler with the stepped-impedance-stub branch-line coupler is also shown in Table 4. As shown, bandwidths of the proposed two-section coupler are comparable with those of the two-section stepped-impedance-stub branch-line coupler. By folding a couple of half elliptical-ring impedance stubs inward to the enclosed areas of the branch-line coupler, a 30% size reduction with a lower relative dielectric constant of 2.55 is also obtained.

Figure 3. (a) Simulated S parameters of the single-section coupler. (b) Measured S parameters of the single-section coupler. (c) Phase difference $\angle S_{12}$–$\angle S_{13}$.
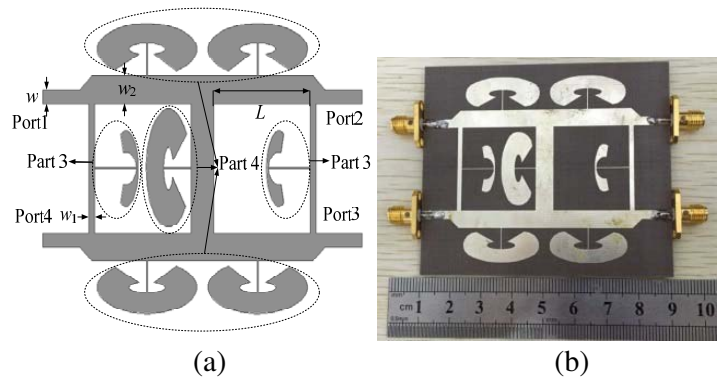
Figure 4. (a) Configuration of the proposed two-section branch-line coupler. (b) Photograph of the proposed two-section branch-line coupler.
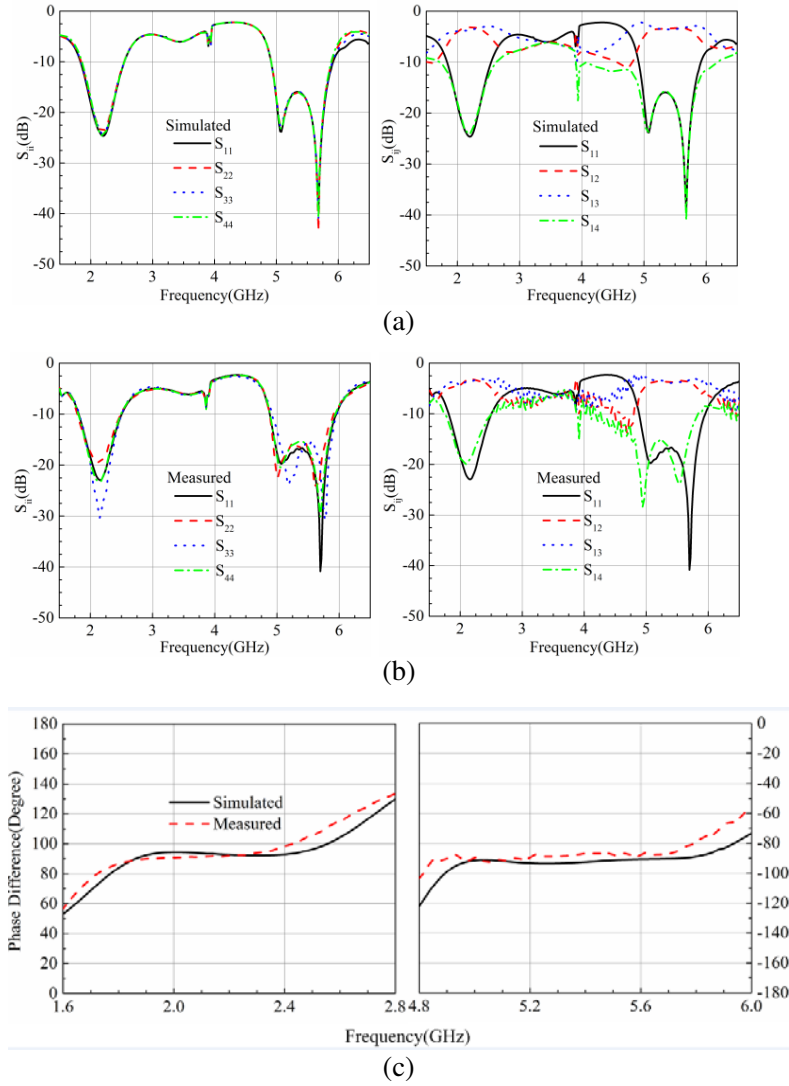
Figure 5. (a) Simulated S parameters of the two-section coupler . (b) Measured S parameters of the two-section coupler. (c) Phase difference $\angle S_{12}-\angle S_{13}$.

Table 4. Bandwidths comparison of the proposed coupler with the stepped-impendence-stub branch-line coupler.

	ε_r	$\angle S_{12}-\angle S_{13}$ ($\pm 90°\pm 5°$)	$|S_{12}|-|S_{13}|$ (± 0.5 dB)	Size (mm $\times$ mm)
The coupler in [11]	3.38	34%/12%	21%/12%	70×115
The proposed coupler	2.55	27%/17.7%	21%/10.3%	70×80

4. CONCLUSION

In this paper, two compact dual-band branch-line couplers based on a half elliptical-ring impedance stub branch line are proposed. Due to the folded feature of the half elliptical-ring impedance stub, the size of these two couplers is obviously reduced. At the same time, these two branch-line couplers are uniplanar and easy to implement. The proposed two branch-line couplers can be used for the feeding network of dual-band circularly polarized antennas.

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