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A MINIATURIZED BRANCH-LINE COUPLER WITH WIDEBAND HARMONICS SUPPRESSION

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Abstract—This paper presents a miniaturized branch-line coupler with suppression of wideband harmonics based on a unit of transmission-line section with triple-stub. This fundamental unit produces three transmission zeros and exhibits wide stopband response due to the triple stubs. It is used to replace a quarter-wavelength line in conventional branch-line coupler, leading to size reduction and wideband harmonics suppression. The closed-form equations are given for the coupler design. As an example, a branch-line coupler operating at 1.0 GHz is designed, fabricated and measured. Measurements agree well with simulations, and show that the proposed branch-line coupler occupies 56% size of a conventional one and achieves wideband harmonics suppression (better than 17 dB) from 1.8 GHz to 6.4 GHz. The 2nd, 3rd, 4th, 5th, and 6th harmonics are suppressed better than 34 dB, 19 dB, 30 dB, 17 dB, and 32 dB, respectively. With the theoretical analyses and practical results, it is shown that the proposed one has the advantages of simple structure, convenient analysis and wideband harmonics suppression.

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1. INTRODUCTION

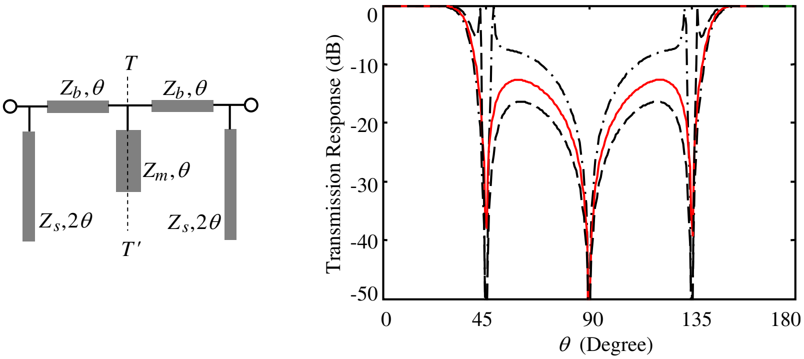
Branch-line coupler is one of the most fundamental components in microwave circuits, which has wide applications in balanced mixers, image rejection mixers, balanced amplifiers, power combiners, and power dividers [1]. The conventional branch-line couplers usually consist of four quarter-wavelength transmission lines. This kind of couplers occupies a large circuit area at low frequencies, and operates at a fundamental frequency and its odd harmonics. In the design of modern wireless and communications systems, the couplers are usually needed to be miniaturized and suppress the undesired harmonics. Some efforts have been made for this purpose in recent years [2–8]. In [2, 3], the branch-line couplers using defected ground structure (DGS) and complementary spilt ring resonators (CSRRs) are proposed, respectively. Unfortunately, these structures need additional etching technique in fabricated process in addition to relatively limited abilities of miniaturizing the circuit and suppressing the harmonics. In [4], compensated spiral compact microstrip resonant cells (SCMRCs) are introduced to design a branch-line coupler, which has 24% size of a conventional one and suppresses the 2nd and 3rd harmonics. The slow-wave branch-line couplers in [5, 6] occupy less than 30% sizes compared with a conventional one and have the 2nd harmonic suppressed. The branch-line coupler using planar artificial transmission lines is proposed in [7], which has ultra-wide band harmonic suppression and the size is reduced to 27% of a conventional one. Although the coupler sizes presented in [4–7] are reduced extremely, these couplers are needed to establish exact equivalent circuit models to analyze and optimize the complex unit structures, which will increase the design procedures and difficulties. In [8], a simple unit of transmission-line section with shunted stubs is proposed to design branch-line couplers, which achieve about 60% sizes of a conventional one and up to 5th harmonics suppression. Due to the simple topology and analysis, it can also be applied for designing rat-race coupler [8] and power divider [9]. However, this unit cell produces only one transmission zero in the stopband, which is not suitable for sharp-rejection and wideband harmonics suppression.

In this paper, a miniaturized branch-line coupler with wideband harmonics suppression is proposed. Its fundamental unit, consisting of a transmission line with a center-tapped open-stub and an end-tapped open-stub at each end, exhibits sharp-rejection characteristic and wide stopband. It is used to replace a quarter-wavelength transmission line in conventional branch-line coupler, leading to the size reduction and wideband harmonics suppression. The closed-form equations for branch-line coupler design are given. A sample branch-line coupler operating at 1.0 GHz is designed, fabricated and measured. The measurement results show that the proposed one has several advantages, such as simple structure, convenient analysis and wideband harmonics suppression.

2. STRUCTURE AND THEORY

2.1. The Unit Structure

Figure 1(a) shows the fundamental unit of transmission-line section with triple-stub, which consists of a transmission line (Z_b, 2θ) with a center-tapped open-stub (Z_m, θ) and an end-tapped open-stub (Z_s, 2θ) at each end. Fig. 1(b) shows the transmission responses of the proposed unit. As shown, there are three transmission zeros at $\theta = 45°$, $90°$, $135°$ in the stop band due to the tapped open-stubs. The transmission zeros at $\theta = 45°$ and $135°$ lead to sharp rejection for stopband. It is also seen from Fig. 1(b) that the transmission response has a flat passband and wide stopband as the impedance of the center-tapped open-stub (Z_m) at a half of the transmission line (Z_b). Therefore, Z_m is fixed at $Z_b/2$ in the design. Actually, this unit is a special case of the bandstop filters proposed in [10] and shows a wide stopband with sharp-rejection as the same as the filters in [11, 12]. Here, it is used to design a branch-line coupler with wideband harmonics suppression.



(a) (b)

Figure 1. (a) The proposed unit of transmission line with triple-stub; (b) Transmission responses with different Z_m with $Z_b = 60.35\,\Omega$ and $Z_s = 85.34\,\Omega$ (dash and dot line: $Z_m = 50\,\Omega$; solid line: $Z_m = Z_b/2 = 30.175\,\Omega$; dash line: $Z_m = 20\,\Omega$).

2.2. Network Equivalence

In the first passband ($\theta < 45°$), the proposed unit is equivalent to a conventional transmission line (Z_c, θ_c) as shown in Fig. 2(c), and thus it will lead to a compact size. Based on even-odd mode method, the analysis procedure can be derived as follows:

When an even-mode excitation is applied, the symmetrical plane T-T' shown in Fig. 1(a) is a magnetic wall (or open-circuited), and the even-mode equivalent circuit is shown in Fig. 2(a). Therefore, the even-mode input impedance is calculated as

$$Z_{ine} = -j\frac{Z_b Z_s}{Z_b + Z_s}\cot 2\theta \tag{1}$$

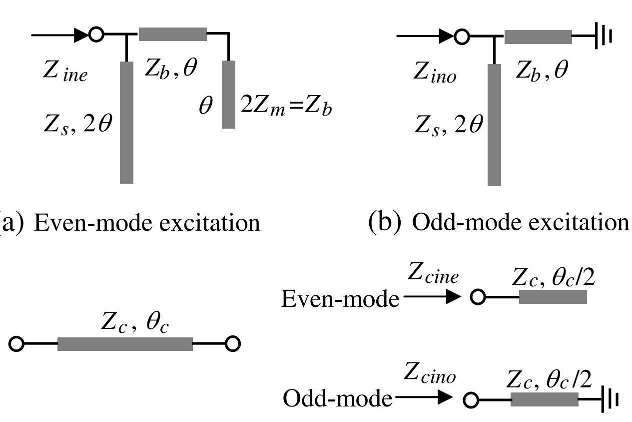
Similarly, under an odd-mode excitation, the symmetrical plane T-T' is an electric wall (or short-circuited), and the odd-mode equivalent circuit is shown in Fig. 2(b). Then, the odd-mode input impedance is derived as

$$Z_{ino} = j\frac{Z_b Z_s \tan\theta \cot 2\theta}{Z_s \cot 2\theta - Z_b \tan\theta} \tag{2}$$

The even- and odd-mode circuits of the equivalent conventional transmission line are shown in Fig. 2(c), and the corresponding input impedances are written as

$$Z_{cine} = -jZ_c \cot(\theta_c/2) \tag{3}$$

$$Z_{cino} = jZ_c \tan(\theta_c/2) \tag{4}$$



(c)

Figure 2. (a) and (b) Even- and odd-mode equivalent circuit of the proposed unit. (c) Conventional transmission line and its even- and odd-mode equivalent circuits.

Then, by letting $Z_{ine} = Z_{cine}$ and $Z_{ino} = Z_{cino}$, we have

$$Z_b = \frac{Z_c(\tan 2\theta + \cot\theta)}{\tan(\theta_c/2) + \cot(\theta_c/2)} \tag{5}$$

$$Z_s = \frac{Z_c Z_b \tan 2\theta}{Z_b \tan(\theta_c/2) - Z_c \tan 2\theta} \tag{6}$$

As shown in (5) and (6), for a given transmission line with impedance of Z_c and electrical length of θ_c, the impedance Z_b and Z_s are determined only by the variable θ.

3. BRANCH-LINE COUPLER DESIGN

In this design, the equivalent conventional transmission line (Z_c, θ_c) is represented as the quarter-wavelength main and branch line in conventional 3 dB branch-line coupler respectively, leading to $Z_{c1} = 35.35\,\Omega$, $Z_{c2} = 50\,\Omega$, and $\theta_{c1} = \theta_{c2} = 90°$. Then, based on the above analysis, the proposed unit can be used to replace a quarter-wavelength line to design a miniaturized and harmonics suppressed branch-line coupler. By using (5) and (6), the impedances of Z_{b1} (Z_{b2}) and Z_{s1} (Z_{s2}) corresponding to the quarter-wavelength line Z_{c1} (Z_{c2}) as functions of electrical length θ are plotted in Fig. 3. As shown, Z_{b1} (Z_{b2}) and Z_{s1} (Z_{s2}) can be selected appropriate values as θ less than 45°, which leads to a miniaturized structure. Fig. 4 shows the schematic of the proposed branch-line coupler. It is noticed that the open stub Z_o represents Z_{s1} in parallel with Z_{s2}. To suppress the 2nd and higher harmonics, the operating electrical length θ is chosen as 22.5°. Therefore, the 2nd, 4th and 6th harmonics are at the transmission zeros of the fundamental units, and can be

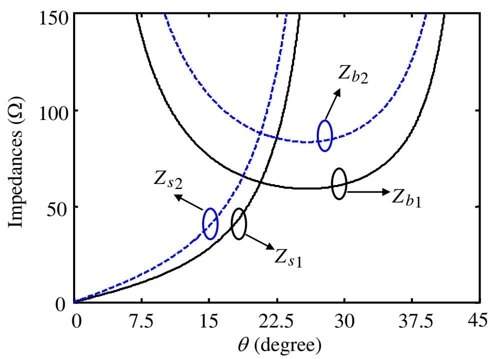


Figure 3. Calculated Z_{b1} (Z_{b2}) and Z_{s1} (Z_{s2}) as functions of θ corresponding to Z_{c1} (Z_{c2}).

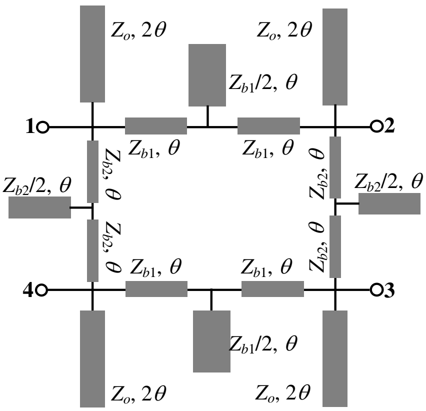


Figure 4. The schematic of the proposed branch-line coupler.

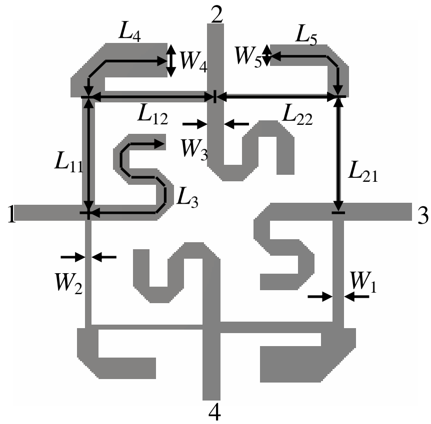


Figure 5. Topology of the proposed branch-line coupler.

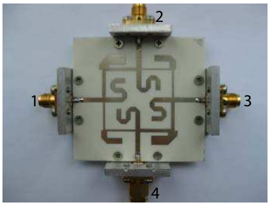


Figure 6. Photograph of the fabricated 3 dB branch-line coupler.

suppressed deeply. Meanwhile, the 3rd and 5th harmonics are also suppressed. All the impedances can be calculated as $Z_{b1} = 60.35\,\Omega$, $Z_{m1} = Z_{b1}/2 = 30.175\,\Omega$, $Z_{b2} = 85.36\,\Omega$, $Z_{m2} = Z_{b2}/2 = 42.68\,\Omega$, and $Z_o = Z_{s1}Z_{s2}/(Z_{s1} + Z_{s2}) = 49.99\,\Omega$. For further miniaturization, the topology of the proposed branch-line coupler is arranged carefully as shown in Fig. 5. As seen, four end-tapped open-stubs (Z_o, 2θ) are placed within the rectangular area, and all the open-stubs are also meandered.

4. RESULTS AND DISCUSSION

The proposed branch-line coupler is designed operating at 1.0 GHz, and fabricated on substrate RO4003C ($\varepsilon_r = 3.55$) with thickness of 0.813 mm. All the design parameters shown in Fig. 5 are listed in Table 1. The line widths and line lengths can be calculated by using

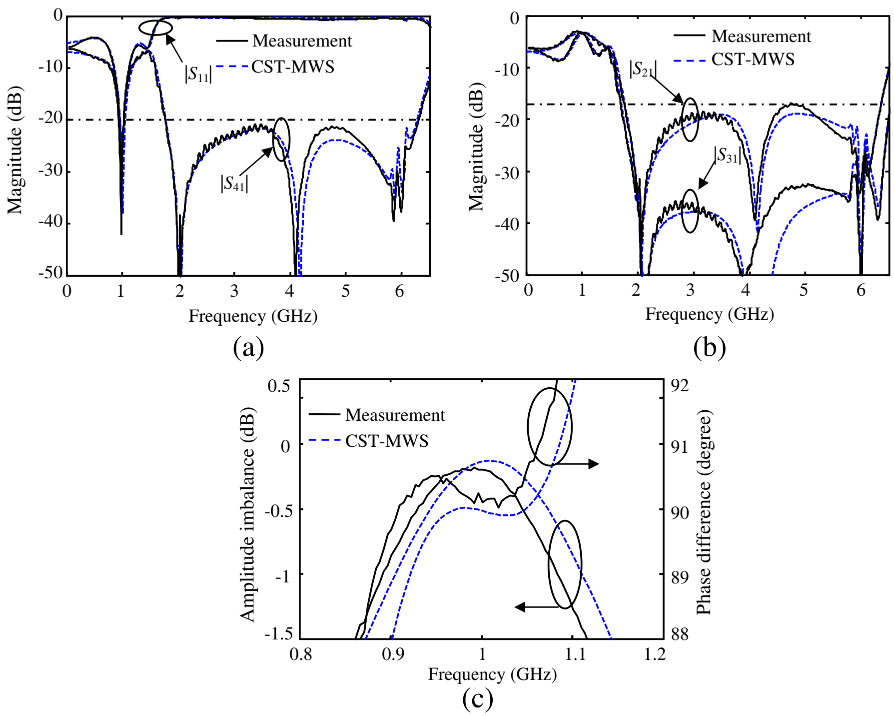


Figure 7. (a) and (b) S-parameters of the proposed branch-line coupler. (c) Amplitude imbalance and phase difference between the output port 2 and port 3.

ADS/Linecalc tool. To account for the junction discontinuity effects, the coupler was simulated by using a full-wave EM simulator (CST-MWS), and all the line lengths have been tuned, as shown in Table 1. Fig. 7 shows the photograph of the proposed branch-line coupler, and the coupler only occupies $31.3 \times 36.3\,\mathrm{mm}^2$ (not including feed lines), which is 56% of a conventional one. Fig. 7 shows the simulated and measured S-parameters of the designed coupler. The measured results agree well with the simulated one. At the design frequency of 1.0 GHz, the measured S_{21} and S_{31} are -3.42 dB and -3.22 dB. The corresponding S_{11} and S_{41} are -25.36 dB and -25.92 dB, respectively. Furthermore, the measurements show that the fractional bandwidth of 20 dB matching and isolation is 9% (0.93 GHz–1.02 GHz), which is 2% narrower than that of a conventional one operating at 1.0 GHz. This is mainly due to the loading stubs, as discussed in [8]. Within the operation band from 0.93 GHz to 1.02 GHz, the measured amplitude imbalance between output port 2 and port 3 is less than 0.5 dB, and phase difference is between 90.02° and 90.51° as shown in Fig. 7(c).

Table 1. Design parameters of the branch-line coupler.

Impedance (Ω)	Electrical length (degree)	Line-width (mm)	Calculated Line-length (mm)	Line-length after tuning (mm)
$Z_{b1} = 60.35$	22.5	$W_1 = 1.30$	L_{11}=L_{12}=11.36	$L_{11} = 12.26$, $L_{12} = 14$
$Z_{b2} = 85.36$	22.5	$W_2 = 0.64$	L_{21}=L_{22}=11.66	$L_{21} = 12.23$, $L_{22} = 13.56$
$Z_o = 49.99$	45	$W_3 = 1.80$	$L_3 = 22.41$	$L_3 = 23.53$
$Z_{m1} = 30.175$	22.5	$W_4 = 3.77$	$L_4 = 10.83$	$L_4 = 11.47$
$Z_{m2} = 42.68$	22.5	$W_5 = 2.30$	$L_5 = 11.08$	$L_5 = 11.10$

Additionally, the 17 dB harmonic suppression bandwidth is 4.6 GHz (from 1.8 GHz to 6.4 GHz). Meanwhile, the 2nd, 3rd, 4th, 5th, and 6th harmonics are suppressed below 34 dB, 19 dB, 30 dB, 17 dB, and 32 dB, respectively.

5. CONCLUSION

A novel miniaturized branch-line coupler with wideband harmonics suppression has been presented based on a unit of transmission-line section with triple-stub. This fundamental unit is equivalent to a quarter-wavelength transmission line in its first passband and has three transmission zeros in the stopband, which lead to size reduction and wideband harmonics suppression for designing branch-line coupler. A design example shows that the proposed one occupies 56% size of a conventional one and achieves the bandwidth from 1.8 GHz to 6.4 GHz with harmonics suppression better than 17 dB. In addition, the unit introduced here can be used to design other microwave components (such as rat-race coupler and power divider) for miniaturization and harmonics suppression.

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