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Miniaturized dual-band coupler using three-branch-line structure and dual transmission lines

Lamin Zhan[a)], **Zuwei Li**[b)], **Wenguang Li**[c)], **and Xiang Zhang**[d)]

School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, Hubei, People's Republic of China

a) *guoanwu00@163.com*

b) *lizuwei00@163.com*

c) *753001044@qq.com*

d) *00keyer@gmail.com*

Abstract: This letter presents a compact dual-band branch-line coupler. Explicit design formulas of the three-branch-line coupler (3-BLC) are derived and useful design curves are given. The equivalent dual transmission lines structure is used to decrease the dimension, and also the partial branch lines are folded to further miniaturize the design. The proposed dual-band (2.45 and 5.8 GHz) coupler has a compact size with 57.6% size reduction compared with the conventional circuit. The measured and simulated results are in good agreement with each other.

Keywords: dual-band coupler, compact size, three-branch-line structure, dual transmission lines

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Owing to the rapid development of wireless communications, microwave components that can operate at multiple frequency bands are playing a more important role in the wireless communications systems [1]. For example, wireless local area network (WLAN) systems work on multiple standards such as IEEE802.11b/g (2.4–2.5 GHz) and IEEE802.11a (5–5.9 GHz), so dual-band microwave components can provide compact solutions for these systems. In recent years, many different methods for designing dual-band couplers have been reported. The T-shaped equivalent circuit proposed in [2], π-shaped proposed in [3], are widely used to design dual-band branch-line couplers. Moreover, some other approaches were reported to design for dual-band operation [4, 5, 6, 7, 8]. The 3-BLC proposed in [1] can provide dual-band operation with enhanced bandwidth. However, these proposed couplers suffer from relatively large size or narrow bandwidth which limits its application. Several papers [9, 10] gave solutions to reduce the size of the dual-band branch-line coupler.

In this paper, a dual-band coupler based on 3-BLC and equivalent dual transmission lines structure is designed to get compact size.

2 Dual-band branch-line coupler design and analysis

Fig. 1(a) shows the schematic diagram of a conventional *3-BLC* and this work is different from that of [1]. To simplify the formulation, we kept $\theta_1 = \theta_2 = 2\theta_0 = \pi$ at f_0 ($f_0 = (f_1 + f_2)/2$), and this structure possesses symmetrical frequency characteristics.

2.1 Three-branch-line coupler design

The coupler can be decomposed into four single-port networks. According to the vertical and horizontal dotted line in Fig. 1(a), the following input admittances can be derived using even and odd mode analysis method.

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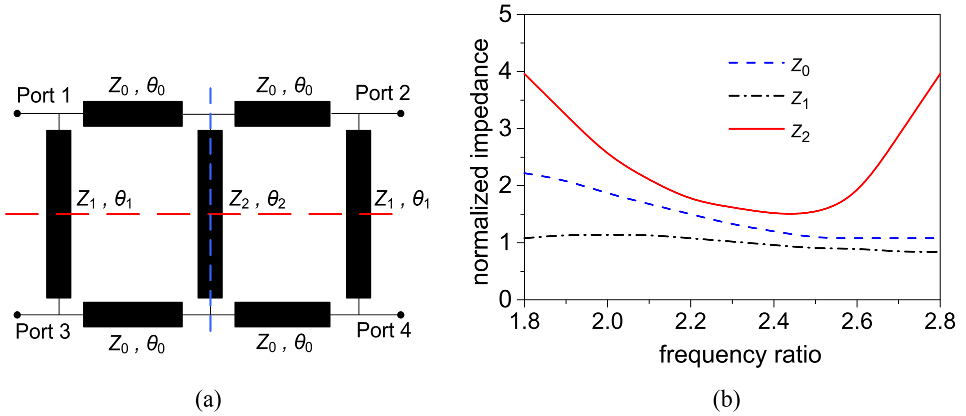

Fig. 1. 3-BLC: (a) Schematic of the conventional 3-BLC (b) Normalized impedance Z_0, Z_1, and Z_2 against frequency ratio

$$Y_{oo}(\theta) = -j\frac{\cot\theta}{Z_1} - j\frac{\cot\theta}{Z_0} \tag{1}$$

$$Y_{eo}(\theta) = -j\frac{\cot\theta}{Z_1} + \frac{Z_0 - 2Z_2\tan^2\theta}{Z_0(j2Z_2\tan\theta + jZ_0\tan\theta)} \tag{2}$$

$$Y_{ee}(\theta) = j\frac{\tan\theta}{Z_1} - \frac{Z_0 + 2Z_2}{Z_0(j2Z_2\cot\theta - jZ_0\tan\theta)} \tag{3}$$

$$Y_{oe}(\theta) = -j\frac{\cot\theta}{Z_0} + j\frac{\tan\theta}{Z_1} \tag{4}$$

The S-parameters of the coupler are directly related to the input admittances. Furthermore, a dual-band 90° coupler needs to satisfy $S_{11} = S_{12} = 0$ and $S_{13} = \pm jS_{14}$ at centre frequencies f_1 and f_2. The former conditions lead to $\Gamma_{ee} = -\Gamma_{eo}$ and $\Gamma_{oe} = -\Gamma_{oo}$ while the latter leads to $\Gamma_{oo} = \pm j\Gamma_{eo}$. Γ_{ee}, Γ_{eo}, Γ_{oe} and Γ_{oo} are reflection coefficients corresponding to the four single-port networks. Using (1)–(4), the following relations are established where the frequency ratio $\delta = f_2/f_1$.

$$Y_{ee}(\theta)Y_{oe}(\theta) = Y_{ee}(\delta\theta)Y_{oe}(\delta\theta) = 1 \tag{5}$$

$$Y_{eo}(\theta)Y_{oo}(\theta) = Y_{eo}(\delta\theta)Y_{oo}(\delta\theta) = 1 \tag{6}$$

$$\frac{1 - Y_{oo}(\theta)}{1 + Y_{oo}(\theta)} \times \frac{1 + Y_{oe}(\theta)}{1 - Y_{oe}(\theta)} = \pm\frac{1 - Y_{oo}(\delta\theta)}{1 + Y_{oo}(\delta\theta)} \times \frac{1 + Y_{oe}(\delta\theta)}{1 - Y_{oe}(\delta\theta)} = \pm j \tag{7}$$

To satisfy (5)–(7), it is found that $\theta = \pi/(\delta + 1)$. The set of (5)–(7) can be solved numerically to find the values of Z_0, Z_1 and Z_2 as shown in Fig. 1(b) when the port impedance is set to 50 Ω. The range of the frequency ratio is limited by the value of Z_2 which should be feasible to fabricate. Compared with [1], rigorous analysis and results are given in this work in which the design mainly relies on the results of optimization.

2.2 Compact structure

The quarter-wavelength transmission line can be replaced by dual transmission lines [11], as shown in Fig. 2(a). The equivalent equations using admittance matrices can be expressed as follows.

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$$\begin{bmatrix} 0 & jY \\ jY & 0 \end{bmatrix}_{\frac{\lambda}{4}} = \begin{bmatrix} -jY_3 \cot\theta_3 & jY_3 \csc\theta_3 \\ jY_3 \csc\theta_3 & -jY_3 \cot\theta_3 \end{bmatrix} + \begin{bmatrix} -jY_4 \cot\theta_4 & jY_4 \csc\theta_4 \\ jY_4 \csc\theta_4 & -jY_4 \cot\theta_4 \end{bmatrix} \tag{8}$$

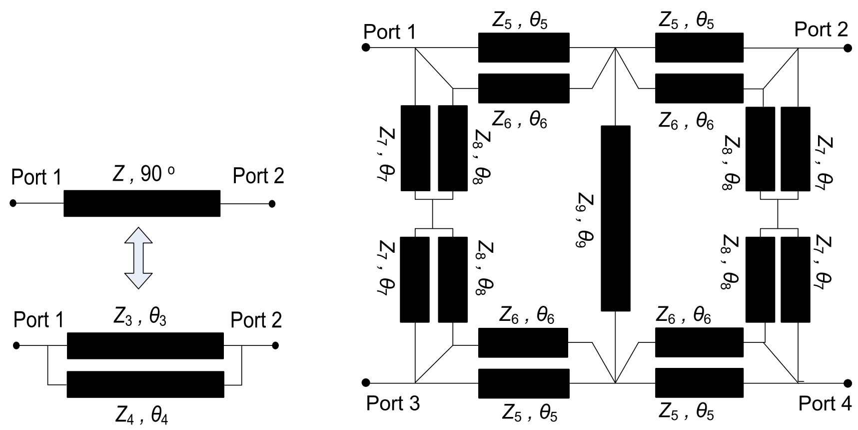
The following results can be derived from equation (8):

$$Y_3 = \frac{Y}{\csc\theta_3 - \cot\theta_3 \sec\theta_4}, \quad Y_4 = \frac{Y}{\csc\theta_4 - \cot\theta_4 \sec\theta_3} \tag{9}$$

Moreover, assuming that $\theta_3 \leq \frac{\pi}{2} \leq \theta_4$, $\theta_3 + \theta_4 = \pi$, the results are simplified.

$$Y_3 = Y_4 = \frac{Y \sin\theta_3}{2} \tag{10}$$

The proposed dual-band coupler is shown in Fig. 2(b). The design procedure can be summarized. First of all, decide the operation frequencies and calculate the frequency ratio. Next, choose the optimum values of Z_0, Z_1 and Z_2 using Fig. 2. Finally, substitute dual transmission lines for the quarter-wavelength transmission line and calculate the characteristic impedance and electrical length shown in Fig. 3 using equations (9), (10).



(a) (b)

Fig. 2. Compact structure: (a) Equivalent dual transmission lines structure (b) Prototype of the proposed coupler

3 Implemention and measurement

For experimental verification purpose, a dual-band coupler that operates at 2.45 and 5.8 GHz was designed and fabricated. The coupler was built on a TLY-5 substrate with a dielectric constant of 2.2 and thickness of 0.78 mm. Specifically, for further miniaturization, the vertical branch lines are folded inside which is shown in Fig. 3. The fabricated circuit is approximately by $0.24\lambda_g \times 0.18\lambda_g$ (21.4 mm × 16.4 mm). λ_g is the guided wavelength at the first centre frequency.

According to Fig. 1(b), the impedances Z_0, Z_1, and Z_2 can be chosen as 58 Ω, 50 Ω, and 80 Ω. By choosing $\theta_5 = 55°$, $\theta_6 = 125°$, $\theta_7 = 90°$, $\theta_8 = 90°$, $\theta_9 = 180°$, the impedances Z_5, Z_6, Z_7, Z_8 and Z_9 can be calculated as $Z_5 = Z_6 = 141.6\,\Omega$, $Z_7 = Z_8 = 100\,\Omega$, $Z_9 = 80\,\Omega$, respectively. After optimization using ANSYS HFSS, the final impedances are $Z_5 = Z_6 = 137\,\Omega$, $Z_7 = Z_8 = 100.7\,\Omega$, $Z_9 = 89\,\Omega$ and their electrical lengths are $\theta_5 = 61°$, $\theta_6 = 131°$, $\theta_7 = 96°$, $\theta_8 = 96°$, $\theta_9 = 191°$.

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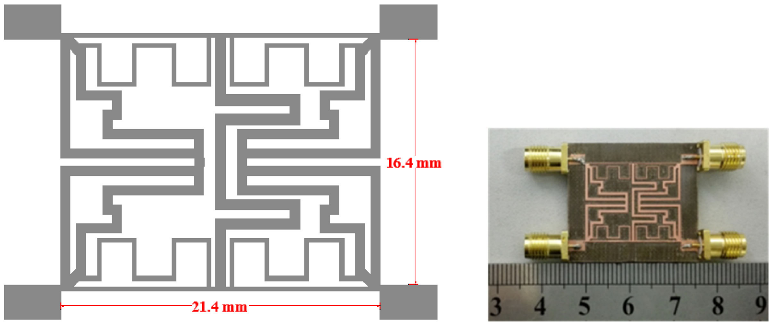

(a) (b)

Fig. 3. Experiment design: (a) Schematic of the design coupler (b) Photographs of manufacture

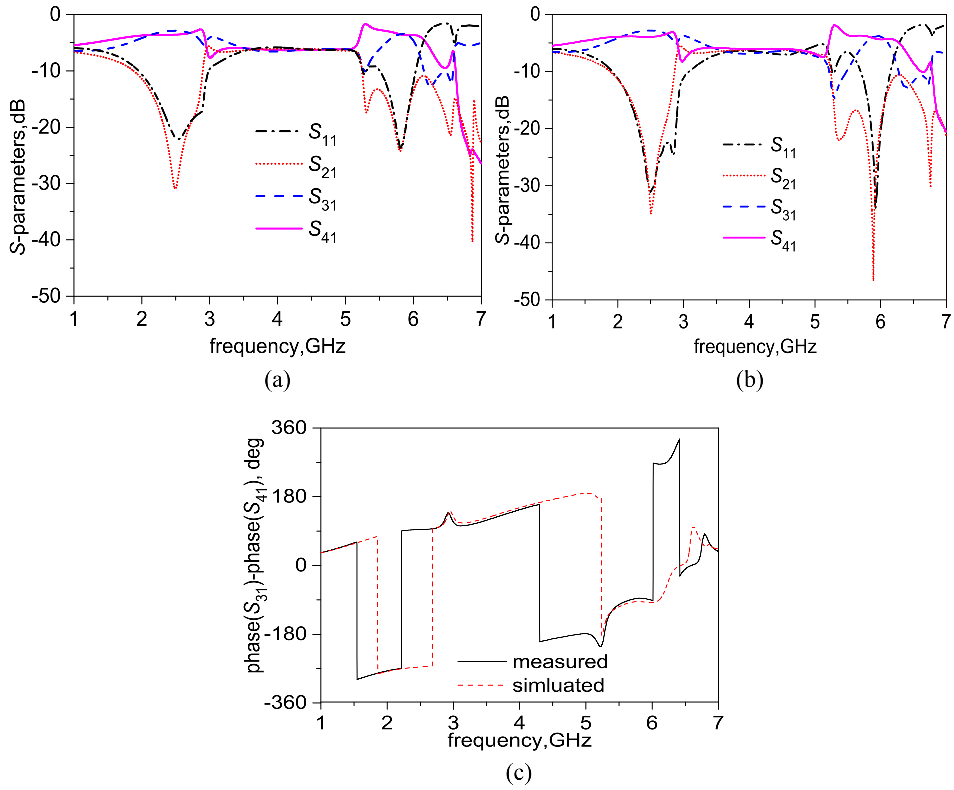

Fig. 4. Simulated and measured results: (a) Simulated S-parameters results (b) Measured S-parameters results (c) Simulated and measured phase response results

Fig. 4 shows the simulation and measurement results in which the measured centre frequencies of the two operating bands were found to be approximately 2.48 and 5.88 GHz. The measured minimum of return loss and port isolation are below −30 dB. For comparison, the bandwidth are defined by the overlapping frequency range of $|S_{11}| < -15\,\text{dB}$, $|S_{21}| < -15\,\text{dB}$, $||S_{31}| - |S_{41}|| < 1\,\text{dB}$, and $|\angle S_{31} - \angle S_{41} \pm 90°/270°| < 5°$. The simulated results of the conventional 3-BLC using Advanced Design System (ADS) are contained in Table I for comparison. The measured performance of the proposed dual-band coupler and other published works are summarized in Table I, while its size, bandwidth and are more superior. Specifically, it shows a 57.6% size reduction, as compared with the conventional

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3-BLC. Theoretically, the proposed coupler has the same bandwidth in the two bands, which is similar to the conventional 3-BLC shown in Table I. However, the unnecessary coupling between the microstrip lines and the impedance discontinuity at the node had bad effects on the bandwidth. These effects are more serious at high frequency. In order to improve the high frequency bandwidth, we can increase the size slightly to expand the gap of the microstrip lines, or chamfer the edges at the node to reduce the influence caused by the discontinuity.

Table I. Comparison with previous works

Ref.	f_1/f_2 (GHz)	Bandwidth (MHz)	Size ($\lambda_g \times \lambda_g$)
[4]	2.45/6.1	<300/<250	0.32 × 0.30
[5]	1.0/2.0	<100/<100	0.33 × 0.17
[9]	2.4/5.8	<200/<200	0.29 × 0.29
[10]	0.93/1.78	<100/<100	0.28 × 0.26
Conventional 3-BLC	2.45/5.80	450/450	0.32 × 0.32
This work	2.48/5.88	420/260	0.24 × 0.18

4 Conclusion

A compact dual-band branch-line coupler based on the 3-BLC and equivalent dual transmission lines structure has been introduced along with a theory of its design. Design procedure and explicit formulas are clearly discussed. For verification purpose, a dual-band couplers used in WLAN systems is fabricated using the proposed structure for 2.45 and 5.8 GHz dual-band operation. Moreover, the dual-band coupler also has been compared with other dual-band couplers proposed in the literature, showing a significant improvement of the size and bandwidth.

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