International Journal of Microwave and Wireless Technologies

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Research Paper

Cite this article: Tan Z, Lu Q-Y, Chen J-X (2019). A novel balanced-to-balanced power divider based on three-line coupled structure. *International Journal of Microwave and Wireless Technologies* **11**, 139–142. https://doi.org/10.1017/S1759078718001708

Received: 23 August 2018
Revised: 29 November 2018
Accepted: 7 December 2018
First published online: 14 January 2019

Key words:
Balanced-to-balanced power divider (PD); three-line coupled structure; common-mode (CM) suppression

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A novel balanced-to-balanced power divider based on three-line coupled structure

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Abstract

This paper presents a novel balanced-to-balanced power divider (PD) based on a simple and compact three-line coupled structure for the first time. By bisecting the proposed symmetrical structure, the differential mode (DM) and the common mode (CM) equivalent circuits can be obtained for analysis. The DM equivalent circuit exhibits a three-line in-phase power dividing response, and then a resistor is added between the two outputs for achieving good isolation. Meanwhile, the CM equivalent circuit shows a three-line all-stop response so that the CM suppression in this design does not need to be considered. Accordingly, the detailed design procedure of the DM PD is given. For demonstration, a prototype centered at 1.95 GHz is designed, fabricated, and measured. The simulated and measured results with good agreement are presented, showing low DM loss and wideband CM suppression.

Introduction

With the fast development of the modern high-speed wireless communication system, the balanced circuits or components are ever-increasingly utilized due to their high immunity to the environmental noise and interference [1, 2]. Accordingly, various balanced-to-balanced power dividers (PDs) have been designed, which provide differential-mode (DM) power division and common-mode (CM) suppression in the frequency band of interest. They are easily integrated with balanced antennas as feeding networks and other balanced components. In previous research [3–7], the balanced-to-balanced PDs are developed by using microstrip line and substrate integrated waveguide. In [4, 5], the microstrip PDs with equal and arbitrary dividing ratio are presented, showing good DM power allocation and high isolation as well as high CM suppression. However, the sizes of both designs are bulky, namely $0.5\lambda_g \times 0.75\lambda_g$ (λ_g is the guided wavelength), since the 180° phase delay line is required. In [6, 7], the classic Wilkinson topology is adopted for designing the balanced-to-balanced PDs with good performance, such as wide DM bandwidth and compact size. But the two PDs with incomplete ground structure cannot be directly assembled at the bottom of the metallic cavity.

In this paper, a novel balanced-to-balanced PD is proposed by using a multilayer three-line coupled structure. It is skillfully designed so that the DM equivalent circuit exhibits a three-line dividing network while the CM equivalent circuit is an all-stop structure. Accordingly, the theoretical analysis and design procedure for the DM are given in detail without considering the CM suppression. To verify the proposed idea, a balanced-to-balanced PD is designed

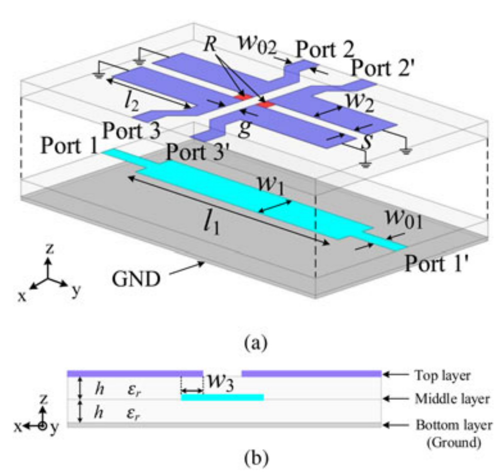

Fig. 1. Layout of the proposed balanced-to-balanced PD. (a) 3-D view. (b) Cross view.

https://doi.org/10.1017/S1759078718001708 Published online by Cambridge University Press

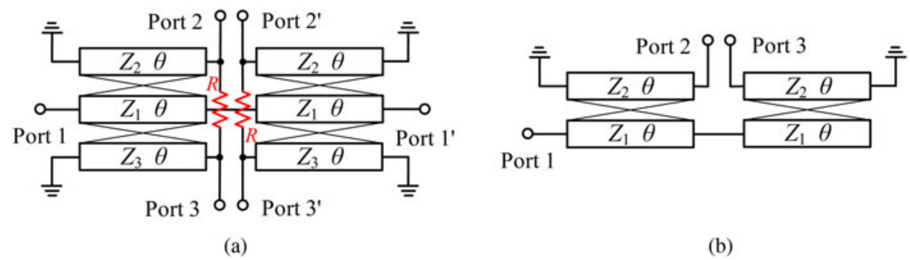

Fig. 2. Transmission-line model. (a) Proposed balanced-to-balanced PD. (b) Marchand balun.

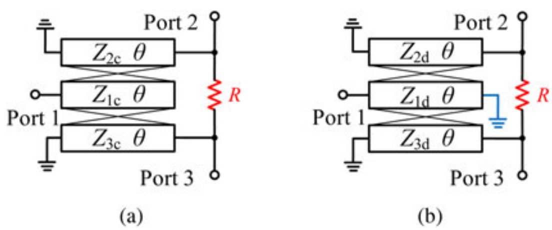

Fig. 3. Equivalent circuits of transmission-line model. (a) CM. (b) DM.

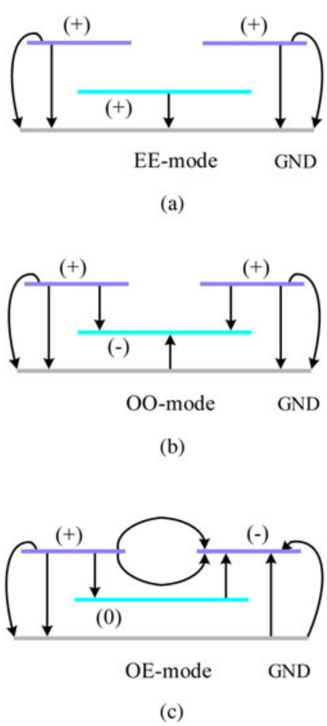

Fig. 4. Sketches of the electric-field lines for the fundamental modes existing in a three-line coupled structure. (a) EE-mode, (b) OO-mode. (c) OE-mode.

and fabricated, and the simulated and measured results are presented, showing good agreement.

Three-line coupled structure analysis

Figure 1 shows the layout of the proposed multilayer balanced-to-balanced PD with bi-symmetric structure, which is designed by using two layers of RO4003C substrates (permittivity $\varepsilon_r = 3.38$, the loss tangent $\tan\delta = 0.0027$, and the thickness $h = 0.508$ mm). A $\lambda_g/2$ microstrip line in the middle layer is fed by a pair of ports (i.e. port 1 and port 1′), which is used as the balanced input. The top layer involves four $\lambda_g/4$ microstrip lines with one short-circuited end, while two pairs of ports (i.e. ports 2 and 2′, 3 and 3′) are used as two in-phase balanced outputs. The red portion represents the loaded lumped resistor R, which is used to realizing good isolation between the two balanced outputs.

Figure 2(a) shows the transmission-line model of the proposed PD. The resistor R for isolating the balanced output ports has no effect on signal transmission from input to outputs. As a result, the balanced-to-balanced PD can be treated as a pair of back-to-back Marchand baluns (shown in Fig. 2(b)) [8]. Accordingly, the design method of the traditional Marchand balun can be referred in the PD design, and the coupling strength between the transmission lines is the key parameter to the bandwidth of the PD [9]. Therefore, the strong multi-layer coupling scheme is adopted, as shown in Fig. 1.

Figures 3(a) and 3(b) show the CM and DM equivalent circuits of the transmission-line model, respectively. It is obvious that the CM equivalent circuit is an all-stop structure [10] so that the CM suppression in this design does not need to be considered. And then the DM equivalent circuit is analyzed to achieve the desired power division. The three-line coupled structure in Fig. 3(b) can be fully analyzed using the fundamental modes of operation, i.e. even–even (EE), odd–odd (OO), and odd–even (OE) modes [11], as shown in Fig. 4.

PD design

To achieve good matching at the input and outputs, there must be [12]

$$Z_0 = \sqrt{Z_{1oo}Z_{1ee}} = \sqrt{Z_{2oo}Z_{2ee}} = Z_{2oe} \tag{1}$$

where Z_{ee}, Z_{oo}, and Z_{oe} are EE-, OO-, and OE-mode impedance, respectively. In this case, the coupling factor (F) from the center line to each of the side lines can be accurately calculated by using Z_{oo} and Z_{ee}:

$$F = \frac{Z_{2ee} - Z_{2oo}}{\sqrt{(Z_{1ee} + Z_{1oo})(Z_{2ee} + Z_{2oo})}} \tag{2}$$

For a PD with equal power division, i.e. power division ratio 1:1, F is equal to$\sqrt{1/2}$. As shown in Fig. 1(a), the lengths of the coupled structure are $l_1 = \lambda_g/2$ (λ_g is the effective wavelength calculated at the center frequency $f_0 = 1.95$ GHz) and $l_2 = \lambda_g/4$. The value of R is selected to achieve perfect matching for the two output ports at the centered frequency when the power division ratio

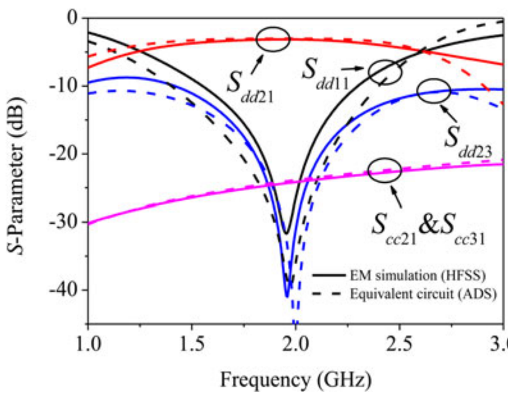

Fig. 5. The extracted *S* parameters of equivalent circuit (ADS) and EM simulation (HFSS).

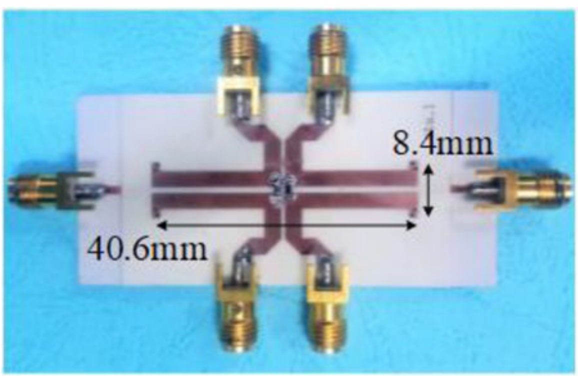

Fig. 6. Photograph of the fabricated PD.

is 1:1, thus it can be calculated from [13] as $R = 2Z_{2oe}^2/Z_0 = 100\,\Omega$.

After optimization using Ansoft HFSS, the structure parameters of the proposed balanced-to-balanced PD are as follows: $l_1 = 40$ mm, $l_2 = 20$ mm, $w_1 = 3.3$ mm, $w_2 = 2.5$ mm, $w_3 = 1.15$ mm, $w_{01} = 1.1$ mm, $w_{02} = 2.6$ mm, $s = 1$ mm, $g = 0.6$ mm, and the overall size of the PD is 40.6 mm × 8.4 mm, corresponding to the electrical size is $0.44\lambda_g \times 0.09\lambda_g$. Figure 5 shows the comparison results of the equivalent circuit and EM simulation of the PD. The fabricated balanced-to-balanced PD is shown in Fig. 6.

Result and discussion

Figure 7 shows the simulated and measured DM results of the proposed balanced-to-balanced PD centered at f_0. The simulated and measured results exhibit good agreement. As shown in Fig. 7(a), the measured DM return loss S_{dd11} shows fractional bandwidth (FBW) of 16% better than 15 dB over the frequency range from 1.75 to 2.1 GHz, and the best DM isolation S_{dd23} between the two balanced output ports is 34 dB. Figure 7(b) shows that the measured DM phase difference between the two output ports is from −0.4 to 0.36° over the frequency range. It can be seen from Fig. 8 that the CM suppression is better than 20 dB over the frequency range, achieving FBW of 100%. Meanwhile, the differential-to-CM results are better than 40 dB for the whole measured frequency band.

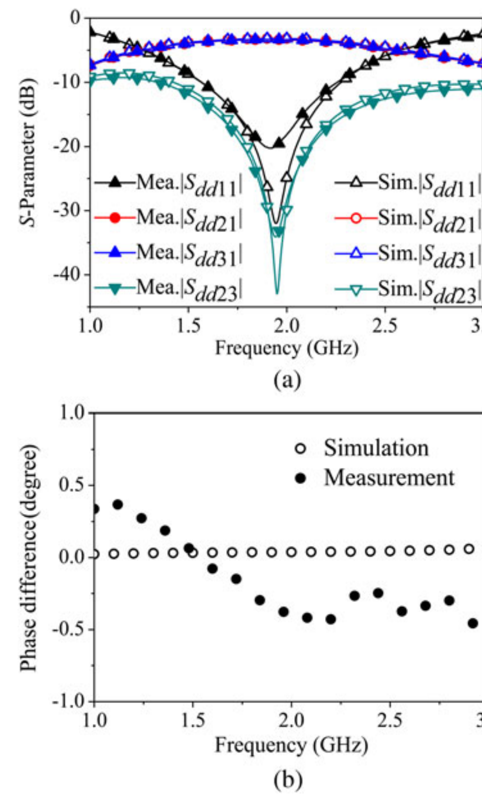

Fig. 7. The simulated and measured DM results. (a) *S*-parameters. (b) Phase differences between two balanced output ports.

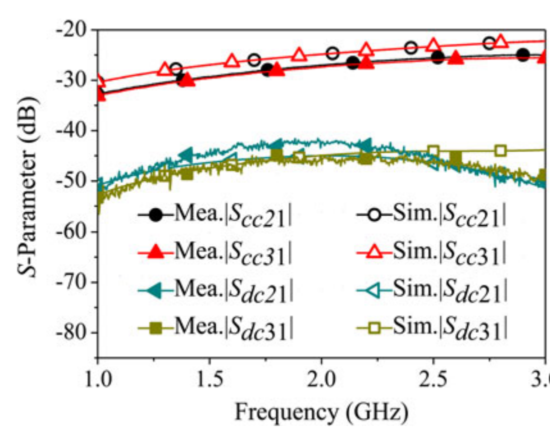

Fig. 8. The simulated and measured CM and differential-to-CM *S*-parameters of the PD.

Table 1 gives the performance comparison of the proposed balanced-to-balanced PD with the previously reported counterparts. It is clear that the proposed PD is very compact due to the back-to-back Marchand balun configuration, as compared with the designs using the Wilkinson topology [4] and Gysel topology [5]. Meanwhile, the proposed PD has wideband CM suppression resulting from the all-stop structure. In addition, the bandwidth of the proposed PD is extended by using the strong multi-layer coupling scheme and it is comparable with that of the designs in [4, 5].

Table 1. Performance comparison with the previous designs.

Ref.	Size (λ_g^2)	f_0 (GHz)	IL (dB)	FBW (>15 dB) (%)	Phase difference (°)	CM suppression FBW (>15 dB) (%)
[4]	$0.4\pi \times 0.4$	5.12	0.4	17	∠2	16
[5]	0.75 × 0.5	2.0	0.2	24	∠0.6	36
This work	0.44 × 0.09	1.95	0.2	16	∠0.4	100

Conclusion

A novel balanced-to-balanced PD has been presented in this paper. The design procedure of the PD can be divided into DM and CM. The three-line coupled structure is used to constitute a simple and compact device. The simulated and measured performances indicate low insertion loss, small phase difference and wideband CM suppression, and the proposed balanced-to-balanced PD can be a valuable candidate for many fully balanced RF front-ends.

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Acknowledgement. This work was supported by the Natural Science Foundation of Jiangsu Province under Grant BK20161281, and by the Industrial Key Technologies Program of Nantong under GY22016015.

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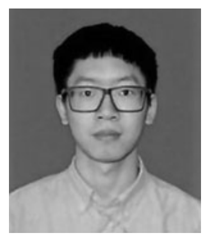

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