A Simple Coupled-Line Wilkinson Power Divider for Arbitrary Complex Input and Output Terminated Impedances

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Abstract **─** A simple and analytical design methodology for a novel coupled-line power divider with arbitrary complex terminated impedances is proposed in this paper. Because of the usage of a single-section coupled line, the additional odd-mode characteristic impedance increases the design degree of freedom and makes the isolation structure still use a single resistor when terminated impedances are extended from real values (such as 50 Ohm) to arbitrary complex values. To design this generalized coupled-line power divider, the electrical parameters including electrical lengths and characteristic impedances can be redesigned by the provided closed-form mathematical expressions when complex terminated impedances are known. The validity of this given design methodology has been confirmed by simulation and measurement of two typical microstrip examples.

Index Terms **─** Arbitrary complex terminated impedances, coupled line and power divider.

I. INTRODUCTION

Conventional Wilkinson power dividers [1] can be applied to split the input signal into two ones with the same amplitude and phase. Also, these power dividers can be used to combine two of the same signals into a single one as combiners. Many efforts have been made to enhance its performance, such as ultra-wideband power divider [2], dual-band and optional isolation power dividers using parallel strip line and open stubs [3,4], compact coupled-line and stepped-impedance transmission lines dual-band Wilkinson power dividers [5-10] and multi-way dual-band planar power dividers[11-14].

Obviously, typical hybrid Wilkinson power dividers are terminated with a constant real-value resistances. To extend the terminated impedances, three-port equal power dividers terminated in different impedances are proposed by Ahn in [15]. As a more generalized case, a novel CAD algorithm for the design of multi-section power dividers terminated in complex frequency-dependent impedances has been developed by Rosloniec in [16]. However, the given power dividers in [15] are only suitable for different terminated resistances, while the rigorous closed-form design equations are not provided in [16]. Moreover, the coupled-line section is not considered in the design of the power dividers in [15] and [16]. In addition, to reduce the circuit size and provide more freedom of design parameters, the coupled-line sections are used in the design of power dividers in [17]; but three terminated impedances of the coupled-line power dividers in [17] are equal to the same constant resistance. The dual-band power divider two-section cascaded coupled-line structure in [18], but has small frequency-ratio limitation, in succession, frequency-ratio limitation of the dual-band divider is improved in [19]. It is necessary to point out that these coupled-line power dividers in [18] and [19] are special cases of structures in [9]. Although, several Wilkinson power dividers with harmonics suppression or for multi-frequency applications are researched in [20-22], the

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complex input and output terminated impedances are not considered.

In this paper, a novel coupled-line power divider with arbitrary complex terminated impedances is proposed, since the complex terminated or equivalent impedances are common in antennas and power amplifiers. Different from the previous coupled-line power divider in [17], these terminated impedances in this paper are extended from real values (such as 50 Ohm) to arbitrary complex values. By using even-mode and odd-mode analysis, a simple and analytical design equations are obtained. Once the complex terminated impedances are known, the even-mode (and odd-mode) characteristic impedances and electrical lengths can be determined uniquely. The design parameters of typical examples for complex impedances are presented. Finally, the given design approach is validated by two fabricated microstrip power dividers with different complex terminated impedances.

II. THE PROPOSED CIRCUIT AND DESIGN APPROACH

The circuit configuration of the proposed coupled-line Wilkinson power divider for complex terminated impedances is shown in Fig. 1. The input-port impedance is $Z_S = R_S + jX_S$ and the matched output-port impedance is $Z_L = R_L + jX_L$. Although, two terminated impedances are complex, the isolation structure only includes a single resistor with the defined parameter R_W. This is because a coupled-line section is used as main impedance matching circuit. The even-mode and odd-mode characteristic impedances are defined as Z_e and Z_o, respectively. Due to match two complex impedances, the electrical length θ of the coupled-line section will not always be 90 degrees, which is determined by given terminated impedances.

When even-mode analysis is considered, the circuit configuration shown in Fig. 1 can be simplified as the equivalent circuit shown in Fig. 2 (a). The input-port impedance Z_S is doubled, while the odd-mode characteristic impedance Z_o and the isolation resistor R_W are neglected. This kind of impedance transformer has been analyzed in [23-25]. Now, we can reconsider the circuit shown in Fig. 2 (a) when different parameters definition is used. The design equations can be written as:

$$Z_e = \sqrt{2R_S R_L + \frac{(4X_S^2 R_L - 2X_L^2 R_S)}{2R_S - R_L}}, \qquad (1)$$

$$\theta = \text{atan}[\frac{Z_e(2R_S - R_L)}{2R_S X_L - 2R_L X_S}]. \qquad (2)$$

Note, that even-mode characteristic impedance Z_e should be real positive values. This limits the applicable scope of complex terminated impedances. However, the value of the electrical length θ can be real negative; we can obtain the final available values according to the equation $\theta' = \theta + n\pi, (n = 0, \pm 1, \pm 2, ...)$.

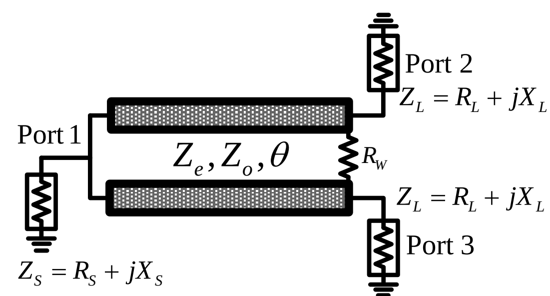


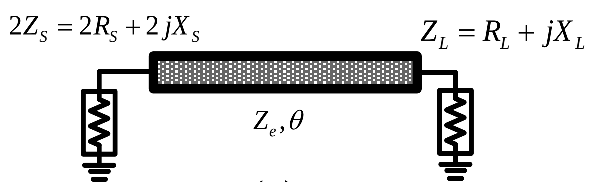
Fig. 1. The circuit configuration of the proposed coupled-line Wilkinson power divider for complex terminated impedances

Next, the odd-mode analysis is considered. The simplified circuit is shown in Fig. 2 (b). Different from the conventional Wilkinson power divider, the odd-mode characteristic impedance Z_o provides a free variable in the design of perfect output-port matching and isolation between them. Therefore, although the terminated impedance Z_L is complex value, the ideal output-port matching and isolation can be easily achieved by modifying Z_o and R_W. The accurate design mathematical expressions are:

$$Z_o = \frac{-(R_L^2 + X_L^2)}{X_L \tan(\theta)}, \qquad (3)$$

$$R_W = \frac{2(R_L^2 + X_L^2)}{R_L}. \qquad (4)$$

According to the above equations (1)-(4), we can calculate the electrical parameters of this coupled-line Wilkinson power divider with complex terminated impedances. As shown in Fig. 2 (a), the even-mode characteristic impedance Z_e and electrical length θ affect the input-port matching and transmission performance. As shown in Fig. 2 (b), the perfect isolation performance is obtained by varying the odd-mode characteristic impedance Z_o and the isolation resistor R_W.



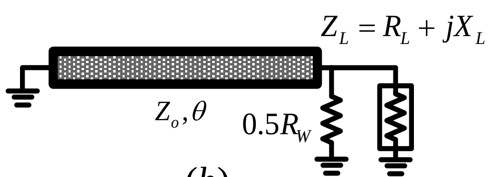
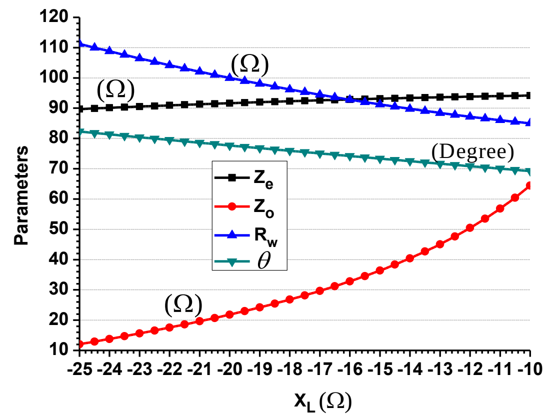
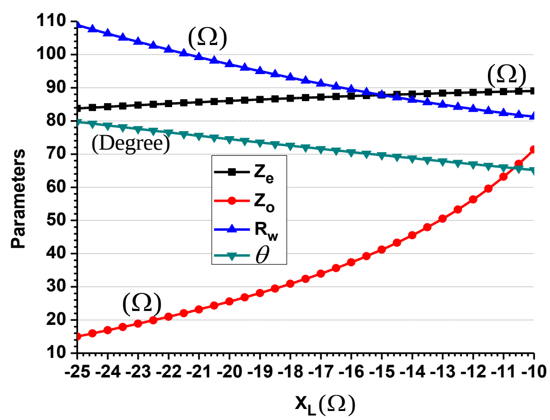


Fig. 2. The equivalent simplified circuits under: (a) even-mode and (b) odd-mode excitations.

In order to explain the applicable scope of the complex terminated impedances, Fig. 3 shows two types of parameter curves for different terminated impedances. The first case has an input-port impedance of $55 - j45\,(\Omega)$ and an output-port resistance of $40\,(\Omega)$, as shown in Fig. 3 (a). The second case has an input-port impedance of $45 - j40\,(\Omega)$ and an output-port resistance of $38\,(\Omega)$, as shown in Fig. 3 (b). The output-port inductance $X_L\,(\Omega)$ of these two cases changes from -25 to -10. Both for Figs. 3(a) and (b), when output-port inductance X_L increases, the characteristic impedances Z_e and Z_o increase, while the electrical length θ and the resistor R_W decrease. There are three main features for available parameters in Figs. 3 (a) and (b): (1) $Z_e \geq Z_o > 0$, (2) $R_W > 0$ and (3) $\theta > 0$.



(a)



(b)

Fig. 3. The design parameters of typical examples for complex impedances: (a) $Z_S = 55 - j45, R_L = 40$ and (b) $Z_S = 45 - j40, R_L = 38$.

III. EXAMPLES

To verify our proposed idea experimentally, two typical examples are designed, fabricated and measured. The Rogers R04350B substrate with a relative dielectric constant of 3.48 and a thickness of 0.762 mm is used in these examples. The first power divider (A) is terminated in input-port impedance of $55 - j40\,(\Omega)$ and output-port impedance of $40 - j10\,(\Omega)$. The calculated electrical parameters of power divider A are $Z_e = 88.8819\,(\Omega)$, $Z_o = 57.3795\,(\Omega)$, $R_W = 85\,(\Omega)$ and $\theta = 71.3491\,(\text{Deg.})$. The second power divider (B) is terminated in input-port impedance of $75 + j40\,(\Omega)$ and output-port impedance of $50 + j10\,(\Omega)$. The calculated electrical parameters of power divider B are $Z_e = 102.7132\,(\Omega)$, $Z_o = 63.2830\,(\Omega)$, $R_W = 104\,(\Omega)$ and $\theta = 103.6796\,(\text{Deg.})$. In addition, the operating center frequency of the power divider A (B) is 2.1 (2) GHz. The accurate physical dimension values (unit: mm) of the power divider A (B) shown in Fig. 4 are $w_p = 1.72(1.72)$, $w_S = 0.46(0.43)$, $w_L = 0.85(0.65)$, $L_1 = L_2 = 8(8)$ and $L_3 = 17.14(26.14)$. The simulation is based on lossless coupled-line models and ideal resistors. The measurement of the power dividers A and B is accomplished by using Agilent N5230A network analyzer. The three-port extension about 7.5 mm physical-length 50-Ohm transmission line is used to obtain the desired scattering parameters. Figure 5 shows the simulated and measured results of the power dividers A and B. In details, the measured center frequency of the power divider A (B) is about 2.1 (2.01) GHz. When the ports matching and isolation are considered in the constant complex terminated impedances, the measured -20 dB fractional bandwidth of the power divider A is about 16 % (from 1.95 to 2.29 GHz), while the similar fractional bandwidth of the power divider B is also about 16% (from 1.85 to 2.17 GHz).

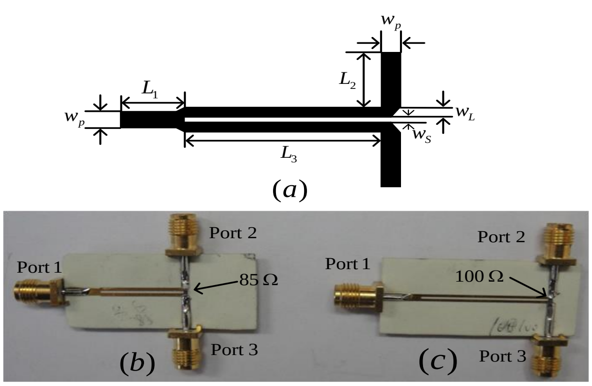
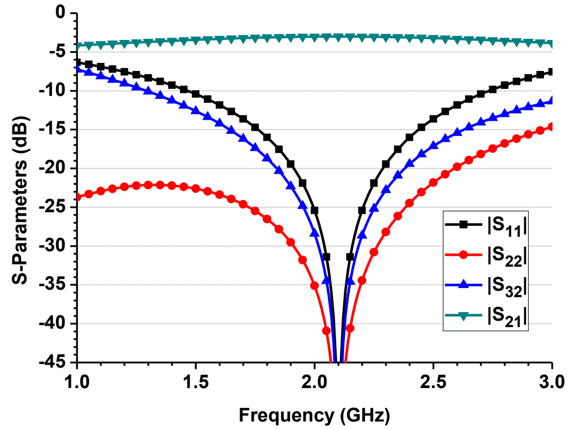
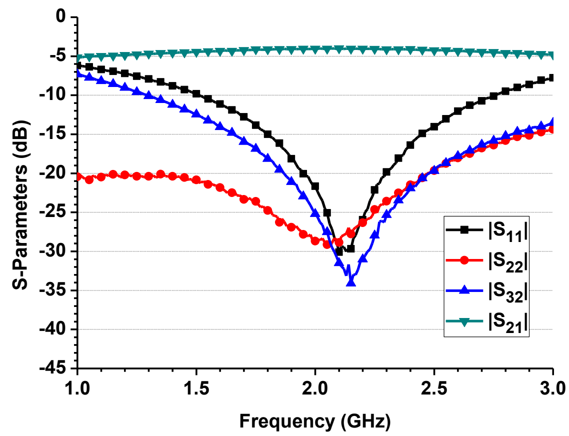


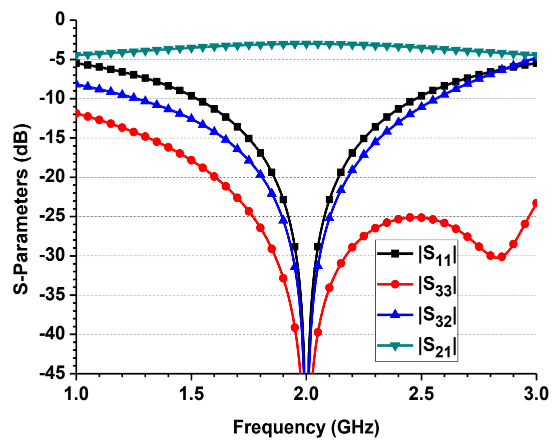
Fig. 4. (a) The physical definition of the proposed power divider; the photograph of the fabricated microstrip power dividers: (b) A and (c) B.



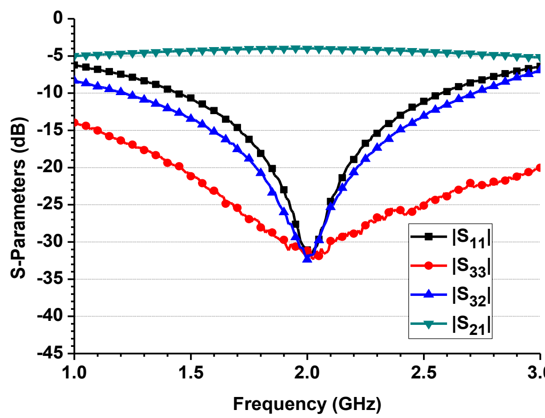
(a1)



(a2)



(b1)



(b2)

Fig. 5. The simulated (a1, b1) and measured (a2, b2) results of the fabricated power divider A (a1, a2) and B (b1, b2).

In general, there is good agreement between the measured and simulated results. Finally, to compare with previous published power dividers, a simple performance comparison is given in Table 1.

Table 1: Performance comparison of this proposed coupled-line power divider with the previous ones

Type	Terminated Impedances	Coupled Line	Design Method	Matching and Isolation
[1]	$Z_0(50\ \Omega)$	No	Simple	Yes
[15]	Arbitrary real	No	Complicated	No
[16]	Complex	No	Complicated	No
[17]	$Z_0(50\ \Omega)$	Yes	Simple	Yes
This work	Arbitrary complex	Yes	Simple and analytical	Yes

IV. CONCLUSION

A novel coupled-line power divider is proposed to satisfy arbitrary complex terminated impedances in this paper. The achieved design approach is analytical and simple. The design parameters of typical examples for complex impedances are illustrated. Furthermore, all the design mathematical expressions are confirmed by the simulation and measurement of two typical examples. Obviously, this proposed power divider not only has small size but also satisfies flexible input and output complex terminated impedances. It is believed that this design approach could be useful in the design of antenna arrays and power amplifiers with complex input impedances.

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