

## **DUAL-BAND EQUAL/UNEQUAL WILKINSON POWER DIVIDERS BASED ON COUPLED-LINE SECTION WITH SHORT-CIRCUITED STUB**

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**Abstract**—This paper presents dual-band equal/unequal Wilkinson power dividers based on a coupled-line section with short-circuited stub (called as the “coupled-line section” for short), which consists of a pair of parallel coupled lines and a short-circuited stub. With the analyses of the phase shift and equivalent characteristic impedance, the coupled-line section is used to replace the quarter-wavelength branch line in the conventional equal/unequal Wilkinson power divider to obtain excellent dual-band operation. The closed-form equations and design procedures of dual-band Wilkinson power divider are given, where one degree of design freedom is obtained and design flexibility is shown. As two examples, a dual-band equal Wilkinson power divider with the frequency ratio of 1.8 : 1 and an unequal one with the high power dividing ratio of 7 : 1 and frequency ratio of 1.8 : 1 are designed, fabricated and measured. The measurements are in good agreement with the simulations. It is shown that the proposed power dividers have simple topologies, and can be easily fabricated with small frequency ratios and high power dividing ratios.

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## 1. INTRODUCTION

Power dividers are fundamental components in many microwave circuits such as antenna arrays, power amplifiers, mixers and phase shifters [1]. Among various kinds of power dividers, the Wilkinson power divider is mostly used because of its simple structure and easiness to design. Based on the power dividing ratio, the Wilkinson power divider can be classified as the equal power divider and the unequal power divider [1]. Many efforts have been made on the equal Wilkinson power dividers with size miniaturization and harmonics suppression [2–4], and similarly on the unequal ones with high dividing ratio [5, 6]. However, these equal/unequal Wilkinson power dividers operate only in single-band applications.

Recently, some topologies of dual-band equal/unequal Wilkinson power dividers have been reported in applications of dual-band wireless communication systems [7–29]. For dual-band equal power divider, a simplified two-section transformer [7] was introduced to obtain dual-band operation with the drawback of poor output return loss and port isolation [8]. In [9–11], the two-section transformers together with lumped  $LC$  elements have been developed to improve the performances of the power divider in [8], but the lumped elements may result in parasitic effects especially at high frequency. Subsequently, several implementations with distributed elements have been proposed by using transmission-line sections with stubs [12–15], port extensions [16, 17], artificial transmission lines [18], and coupled lines [19–21]. And for dual-band unequal power divider, some designs, corresponding to the dual-band equal topologies [9–15, 21], have been presented in [21–29]. However, due to parasitic effects and difficulties of fabricating high impedances, these dual-band unequal power dividers are mainly concerned about low power dividing ratios (not more than 4 : 1). Therefore, it is interesting to find a new structure not only for the dual-band equal Wilkinson power dividers, but also for the dual-band unequal ones (especially with power dividing ratio higher than 4 : 1).

In this paper, a coupled-line section with short-circuited stub (we simply call it as the “coupled-line section”) is introduced to design dual-band equal/unequal Wilkinson power dividers. Based on analyzing the phase shift and equivalent characteristic impedance with the even-odd mode analysis, the coupled-line section is used to replace the quarter-wavelength branch line in the conventional equal Wilkinson power divider to obtain dual-band operation. Moreover, it can exhibit high (low) equivalent characteristic impedance with the same phase shift, thus it can be applied to the design of dual-band unequal power

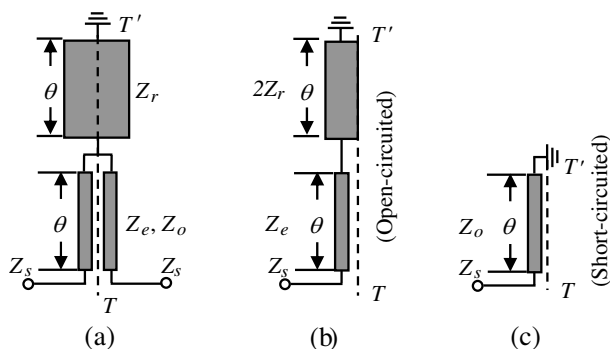
divider with high power dividing ratio. The design procedures of dual-band Wilkinson power divider are derived with one degree of design freedom which makes the design more flexible. As design examples, a dual-band equal Wilkinson power divider with the frequency ratio of 1.8 : 1 is designed first, and then another unequal one with the high power dividing ratio of 7 : 1 and frequency ratio of 1.8 : 1 is designed in the same way. Both the proposed dual-band equal/ unequal power dividers have simple topologies without extra lumped elements except the isolation resistor.

The idea of using the coupled-line section to design dual-band unequal power divider was first presented in [30] by the authors. However, some problems regarding the implementation of the power divider, such as design procedures, the maximum range of operating frequency ratio, the freedom value of the even-mode characteristic impedance, practical effects of fabrication tolerance and the measurement results, are not fully discussed. These problems will be investigated thoroughly in this paper.

## 2. STRUCTURE AND THEORY

### 2.1. Coupled-line Section with Short-circuited Stub

Figure 1(a) depicts the structure of the coupled-line section, which consists of a pair of parallel coupled lines with a short-circuited stub terminated at one side of the coupled lines, while input and output ports at the other. This coupled-line section can be analyzed by the even-odd mode analysis because it is symmetrical with respect to the plane  $T-T'$ . When an even-mode excitation is applied, the symmetrical



**Figure 1.** (a) Structure of the coupled-line section with short-circuited stub; (b) Equivalent circuit of even-mode excitation; (c) Equivalent circuit of odd-mode excitation.

plane  $T-T'$  is a magnetic wall (or open-circuited), as illustrated in Fig. 1(b). Similarly, under an odd-mode excitation, the symmetrical plane  $T-T'$  is an electric wall (or short-circuited), and the equivalent circuit is illustrated in Fig. 1(c). Therefore, the even- and odd-mode input impedances can be calculated as:

$$Z_{ine} = j \tan \theta \frac{Z_e + 2Z_r}{1 - \frac{2Z_r}{Z_e} \tan^2 \theta} \quad (1)$$

$$Z_{ino} = jZ_o \tan \theta \quad (2)$$

where  $Z_e$  and  $Z_o$  are the even- and odd-mode characteristic impedances of the coupled lines, respectively.  $Z_r$  is the characteristic impedance of the short-circuited stub. The electrical lengths of all the transmission lines are  $\theta$ .

The phase shift  $|\phi|$  and equivalent characteristic impedance  $Z_c$  of the coupled-line section can be written as follows:

$$\begin{aligned} |\phi| &= \left| \cos^{-1} \left( \frac{Z_{ine} + Z_{ino}}{Z_{ine} - Z_{ino}} \right) \right| \\ &= \left| \cos^{-1} \left( \frac{Z_e(Z_e + Z_o) + 2Z_r(Z_e - Z_o \tan^2 \theta)}{Z_e(Z_e - Z_o) + 2Z_r(Z_e + Z_o \tan^2 \theta)} \right) \right| \end{aligned} \quad (3)$$

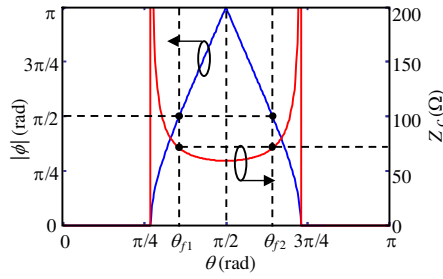
$$Z_c = \sqrt{Z_{ine}Z_{ino}} = \sqrt{\frac{Z_e Z_o (Z_e + 2Z_r)}{2Z_r}} \sqrt{\frac{1}{1 - \frac{Z_e}{2Z_r} \cot^2 \theta}} \quad (4)$$

With (3) and (4), the phase shift  $|\phi|$  and equivalent characteristic impedance  $Z_c$  varying with electrical length  $\theta$  ( $0 \leq \theta \leq \pi$ ) are displayed in Fig. 2, where  $Z_e$ ,  $Z_o$  and  $Z_r$  are chosen to be  $55 \Omega$ ,  $34.5 \Omega$  and  $26.67 \Omega$ . As seen from Fig. 2,  $|\phi|$  and  $Z_c$  are symmetrical about  $\theta = \pi/2$ . Meanwhile, the values of  $|\phi|$  and  $Z_c$  at  $\theta_{f1}$  stay the same as those at  $\theta_{f2}$ . This property shows that the coupled-line section can be used to replace a transmission line in microwave components for dual-band operation.

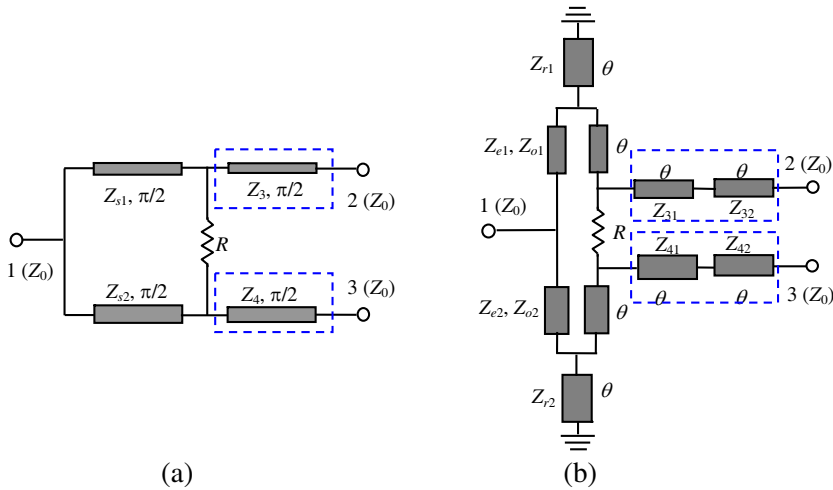
## 2.2. Conventional Wilkinson Power Divider

Figure 3(a) shows the conventional equal (unequal) Wilkinson power divider.  $Z_{s1}$  and  $Z_{s2}$  are the two quarter-wavelength branch lines. It should be noted that  $Z_3$  and  $Z_4$  are the quarter-wavelength transformers, which are used only in unequal power divider design. All the impedances can be calculated as follows [1]:

$$Z_{s1} = Z_0 \sqrt{k(1 + k^2)} \quad (5)$$



**Figure 2.** Phase shift ( $|\phi|$ ) and equivalent characteristic impedance ( $Z_c$ ) versus electrical length ( $\theta$ ).



**Figure 3.** (a) Schematic of the conventional equal (unequal) Wilkinson power divider; (b) Structure of the proposed dual-band equal (unequal) Wilkinson power divider.

$$Z_{s2} = Z_0 \sqrt{\frac{1+k^2}{k^3}} \quad (6)$$

$$Z_3 = Z_0 \sqrt{k} \quad (7)$$

$$Z_4 = \frac{Z_0}{\sqrt{k}} \quad (8)$$

$$R = Z_0 \frac{k^2 + 1}{k} \quad (9)$$

where  $k^2$  is the power dividing ratio of port 3 and port 2, and  $Z_0$  is the port impedance.

### 2.3. Design Procedures of the Dual-band Wilkinson Power Divider

The proposed structure of the dual-band equal (unequal) Wilkinson power divider is given Fig. 3(b). The coupled-line section ( $Z_e$ ,  $Z_o$  and  $Z_s$ ) is used to replace the quarter-wavelength branch line  $Z_s$  in the conventional equal (unequal) Wilkinson power divider (Here, we use  $Z_s$ ,  $Z_e$ ,  $Z_o$  and  $Z_r$  to represent  $Z_{s1}$  ( $Z_{s2}$ ),  $Z_{e1}$  ( $Z_{e2}$ ),  $Z_{o1}$  ( $Z_{o2}$ ) and  $Z_{r1}$  ( $Z_{r2}$ ) respectively for convenience). For this purpose, both the phase shift and equivalent characteristic impedance of the coupled-line section should be equal to those of the branch line at the operating frequencies. First, a phase shift  $|\phi|$  of  $\pi/2$  should be achieved, or  $\cos \phi = 0$ , which leads to:

$$Z_e(Z_e + Z_o) + 2Z_r(Z_e - Z_o \tan^2 \theta) = 0 \quad (10)$$

or

$$\tan^2 \theta = \frac{Z_e}{Z_o} \left( \frac{Z_e}{2Z_r} + \frac{Z_o}{2Z_r} + 1 \right) \quad (11)$$

Meanwhile, the corresponding equivalent characteristic impedance  $Z_c$  should be equal to  $Z_s$ . Using (4) in this way,  $Z_r$  can be calculated as:

$$Z_r = \frac{Z_e (Z_e Z_o \tan^2 \theta + Z_s^2)}{2(Z_s^2 - Z_e Z_o) \tan^2 \theta} \quad (12)$$

By comparing (11) and (12), we can simply have:

$$Z_o = Z_s / |\tan \theta| \quad (13)$$

From (12) and (13), two possible solutions of the electrical length  $\theta_{f1}$  and  $\theta_{f2}$  ( $\theta_{f2} = \pi - \theta_{f1}$ ) can be obtained, which correspond to the two operating frequencies  $f_1$  and  $f_2$  respectively. A general relationship between the electrical length  $\theta_{f1}$  and the operating frequencies  $f_1$  and  $f_2$  was given in [13]:

$$\theta_{f1} = \pi / (1 + f_2 / f_1) \quad (14)$$

Based on the above analyses, the design procedures can then be described as follows:

- a) Choose two operating frequencies  $f_1$  and  $f_2$ , and calculate the corresponding electrical length  $\theta_{f1}$  using (14);
- b) Calculate the odd-mode characteristic impedance  $Z_o$  ( $Z_{o1}$  or  $Z_{o2}$ ) using (13);
- c) Choose an appropriate value of the even-mode characteristic impedance  $Z_e$  ( $Z_{e1}$  or  $Z_{e2}$ ), and then calculate the characteristic impedance of the short-circuited stub  $Z_r$  ( $Z_{r1}$  or  $Z_{r2}$ ) using (12).

Additionally, for the dual-band unequal power divider, the quarter-wavelength transformers  $Z_3$  and  $Z_4$  should be replaced by the two-section transformer ( $Z_{31}$  and  $Z_{32}$ ) and ( $Z_{41}$  and  $Z_{42}$ ), respectively [7]. The characteristic impedances can be summarized as follows [22–29]:

$$Z_{31} = Z_0 \sqrt{\frac{k}{2(\tan \theta_{f1})^2(1-k)} + \sqrt{\left(\frac{k}{2(\tan \theta_{f1})^2(1-k)}\right)^2 + k^3}} \quad (15)$$

$$Z_{32} = \frac{kZ_0^2}{Z_{31}} \quad (16)$$

$$Z_{41} = \frac{Z_{32}}{k} \quad (17)$$

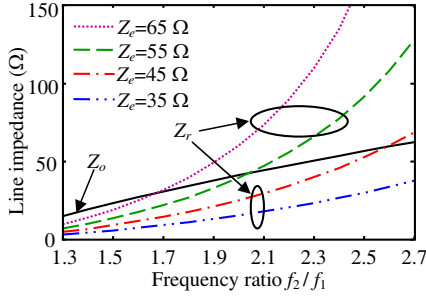
$$Z_{42} = \frac{Z_{31}}{k} \quad (18)$$

### 3. DUAL-BAND EQUAL WILKINSON POWER DIVIDER

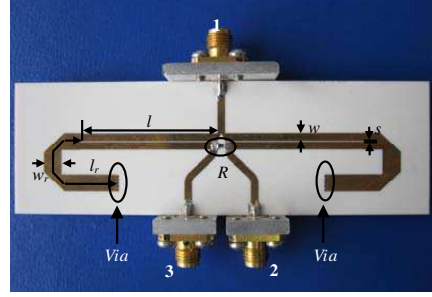
#### 3.1. Design

For the equal Wilkinson power divider ( $k^2 = 1$ ), both the two quarter-wavelength branch lines  $Z_{s1}$  and  $Z_{s2}$  are  $70.7\Omega$ , and the isolation resistor  $R = 100\Omega$ . When designed for dual-band operation,  $Z_{s1}$  and  $Z_{s2}$  are replaced by the same coupled-line section ( $Z_{e1} = Z_{e2} = Z_e$ ,  $Z_{o1} = Z_{o2} = Z_o$  and  $Z_{r1} = Z_{r2} = Z_r$ ). And the design curves of line impedances varying with the frequency ratio are plotted in Fig. 4. As shown,  $Z_o$  simply increases with the frequency ratio, while  $Z_r$  increases with the frequency ratio as well as  $Z_e$ . In a special case of  $Z_e = Z_o$ , the coupled-line section degrades into two branch lines with center-tapped short-circuited stub, which has been applied for the dual-band power divider design [13]. When the frequency ratio gets smaller, the impedance of the center-tapped short-circuited stub will be very low, which leads to a wide junction between the branch lines and the stub. Thus, the performance of the power divider in [13] will deteriorate for the wide junction.

However, in this design,  $Z_e$  is a freedom value and can be chosen larger than  $Z_o$  to obtain a large  $Z_r$ . Thus, the proposed dual-band equal divider is fit for small frequency ratio cases better. The maximum frequency ratio range is  $1.4 \leq f_2/f_1 \leq 2.4$ . As an example, a dual-band equal Wilkinson power divider with a frequency ratio of  $1.8 : 1$  is designed. The corresponding  $\theta_{f1}$  and  $Z_o$  can be calculated easily as  $0.357\pi$  and  $34.05\Omega$  respectively. When it comes to choosing an appropriate value of  $Z_e$ , two guidelines should be obeyed as follows:



**Figure 4.** Line impedances ( $Z_o$  and  $Z_r$ ) versus frequency ratio ( $f_2/f_1$ ) at different  $Z_e$ .



**Figure 5.** Photograph of the fabricated dual-band equal Wilkinson power divider.

- Increasing  $Z_e$  will lead to a growing  $Z_r$ . Therefore,  $Z_e$  should be as large as possible;
- As the difference between  $Z_e$  and  $Z_o$  broadening, the line width and line separation of coupled lines will get narrower, which certainly increases the difficulties of fabrication.

Based on these guidelines,  $Z_e$  is chosen to be  $55\ \Omega$ , which represents the best compromise between the realized value of  $Z_r$  and fabrication difficulties. Thus,  $Z_r$  is calculated as  $26.67\ \Omega$ . With these impedances of  $Z_o$ ,  $Z_e$  and  $Z_r$ , we can find out from Fig. 2 that both of the phase shifts  $|\phi|$  are equal to  $\pi/2$  at  $\theta_{f1} = 0.357\pi$  and  $\theta_{f2} = \pi - \theta_{f1} = 0.643\pi$ , and the corresponding equivalent characteristic impedances  $Z_c$  are found to be  $70.7\ \Omega$ .

### 3.2. Results

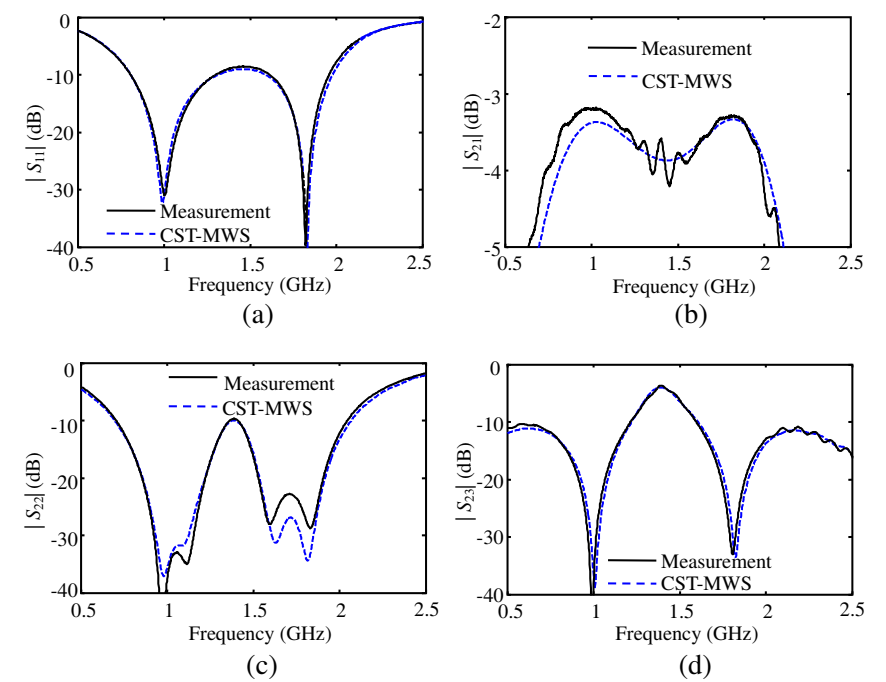
A dual-band equal Wilkinson power divider is designed to operate at 1.0 and 1.8 GHz. The proposed power divider is fabricated on a substrate RO4003C ( $\epsilon_r = 3.55$ ,  $h = 0.813\text{ mm}$ ), as shown in Fig. 5. It should be noted that when the coupled lines are implemented with the microstrip technology, the difference between the even- and odd-mode electrical lengths should be considered because of the dispersion property. However, in our design, the short-circuited stub only affects the even-mode, but has no influence on the odd-mode, as shown in Fig. 1. Thus, the length of the short-circuited stub can be tuned to decrease the difference, which has been similarly discussed in [31, 32]. The design parameters are listed in Table 1. Fig. 6 gives the simulated and measured  $S$ -parameters, which show good agreement between them. At the design frequency  $f_1 = 1.0\text{ GHz}$ , the measured  $|S_{11}| = -30.9\text{ dB}$ ,  $|S_{21}| = -3.21\text{ dB}$ ,  $|S_{22}| = -38.57\text{ dB}$ , and  $|S_{23}| =$



−38.09 dB. And at  $f_2 = 1.8$  GHz, the measured  $|S_{11}| = -27.1$  dB,  $|S_{21}| = -3.29$  dB,  $|S_{22}| = -26.79$  dB, and  $|S_{23}| = -32.03$  dB. The measured bandwidths of −20 dB  $|S_{23}|$  are 0.91–1.07 GHz and 1.74–1.88 GHz, respectively. Over these two operating bandwidths, the measured return losses of all ports are better than 15 dB.

**Table 1.** Design parameters of the dual-band equal Wilkinson power divider ( $k^2 = 1$ ,  $R = 100\ \Omega$  and  $Z_0 = 50\ \Omega$ ).

Design frequencies (GHz)	Coupled-line section ( $\Omega$ )	Physical dimensions (mm)
$f_1 = 1.0, f_2 = 1.8$ ( $\theta_{f_1} = 0.357\pi$ )	$Z_e = 55, Z_o = 34.05$	$w = 2.01, l = 32.48,$ $s = 0.24$
	$Z_r = 30.11$	$w_r = 4.43, l_r = 29.19$



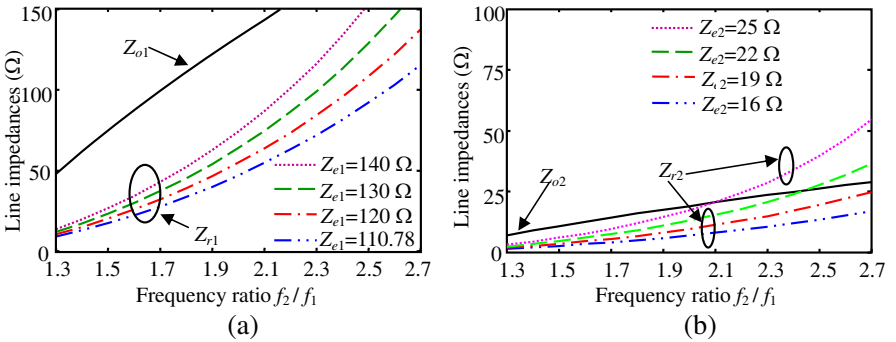
**Figure 6.**  $S$ -parameters of the dual-band equal Wilkinson power divider.

## 4. DUAL-BAND UNEQUAL WILKINSON POWER DIVIDER

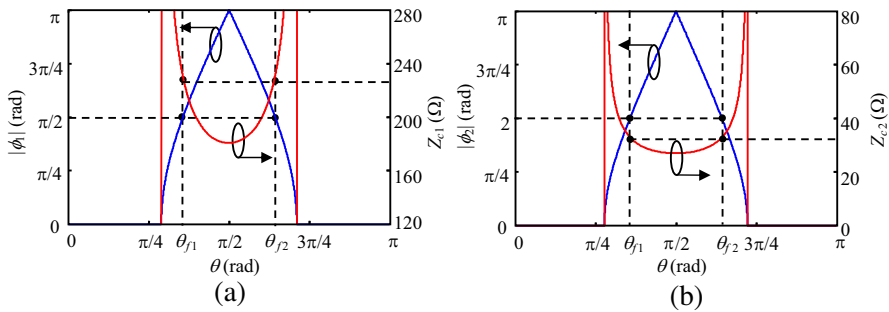
### 4.1. Design

In this paper, an unequal Wilkinson power divider with the power dividing ratio  $k^2$  of 7 is realized. By using (5)–(9), the characteristic impedances are calculated as  $Z_{s1} = 230.03 \Omega$ ,  $Z_{s2} = 32.86 \Omega$ ,  $Z_3 = 78.25 \Omega$ ,  $Z_4 = 31.95 \Omega$ , and the isolation resistor  $R = 151.19 \Omega$ . When designed for dual-band operation, the high and low impedance lines ( $Z_{s1}$  and  $Z_{s2}$ ) are replaced by the coupled-line sections ( $Z_{e1}$ ,  $Z_{o1}$  and  $Z_{r1}$ ) and ( $Z_{e2}$ ,  $Z_{o2}$  and  $Z_{r2}$ ), respectively. The design curves of line impedances varying with frequency ratio are displayed in Fig. 7, which shows that the tendencies of  $Z_{o1}$  ( $Z_{o2}$ ) and  $Z_{r1}$  ( $Z_{r2}$ ) are similar to those in Fig. 4. In a special case of  $Z_{e1} = Z_{o1}$  and  $Z_{e2} = Z_{o2}$ , the dual-band power divider is exactly presented in [26], where the characteristic impedance  $Z_{r2}$  will be extremely low at high dividing ratio. The junction between the low impedance branch lines and the short-circuited stub is very wide, thus resulting in a bad dual-band performance of the power divider.

However, in our design, we can make the value of  $Z_{e2}$  larger than that of  $Z_{o2}$  to obtain a reasonable  $Z_{r2}$ . Due to the fabrication limitation, the design frequency ratio of the proposed dual-band unequal power divider should be less than 2 : 1. As an example, the frequency ratio is chosen to be 1.8 : 1. The corresponding  $\theta_{f1}$  and  $Z_{o1}$  ( $Z_{o2}$ ) can be calculated as  $0.357\pi$  and  $110.78 \Omega$  ( $15.83 \Omega$ ), respectively. The guidelines to choose  $Z_{e1}$  and  $Z_{e2}$  are as follows:



**Figure 7.** (a) Line impedances ( $Z_{o1}$  and  $Z_{r1}$ ) versus frequency ratio ( $f_2/f_1$ ) at different  $Z_{e1}$ ; (b) Line impedances ( $Z_{o2}$  and  $Z_{r2}$ ) versus frequency ratio ( $f_2/f_1$ ) at different  $Z_{e2}$ .



**Figure 8.** Phase shift and equivalent characteristic impedance of (a) the coupled-line section ( $Z_{e1}$ ,  $Z_{o1}$  and  $Z_{r1}$ ) and (b) the coupled-line section ( $Z_{e2}$ ,  $Z_{o2}$  and  $Z_{r2}$ ).

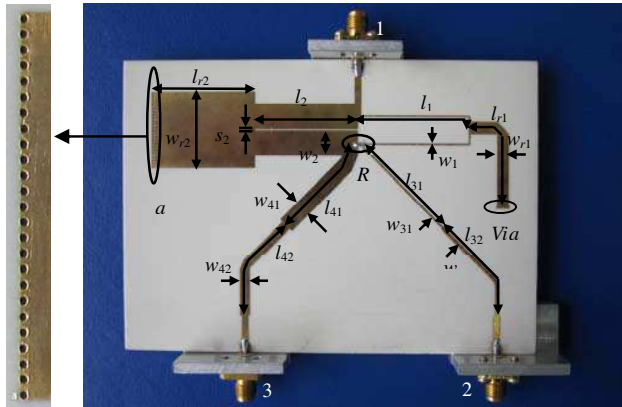
$Z_{e1}$ : If  $Z_{e1}$  is larger than  $Z_{o1}$  ( $110.78 \Omega$ ), it will lead to very narrow line width and line separation of coupled lines. Therefore, a special case of  $Z_{e1} = Z_{o1}$  is adopted when taking account of fabrication easiness and whole size compactness.

$Z_{e2}$ : It is better to choose  $Z_{e2}$  a large value to increase  $Z_{r2}$ . To make fabrication easy,  $Z_{e2}$  is chosen as  $19 \Omega$ .

With the chosen value of  $Z_{e1}$  ( $Z_{e2}$ ),  $Z_{r1}$  ( $Z_{r2}$ ) can be calculated as  $33.45 \Omega$  ( $6.72 \Omega$ ). Fig. 8 demonstrates the phase shift  $|\phi_1|$  ( $|\phi_2|$ ) and equivalent characteristic impedance  $Z_{e1}$  ( $Z_{e2}$ ) varying with electrical length. As shown,  $|\phi_1|$  ( $|\phi_2|$ ) are equal to  $\pi/2$  at  $\theta_{f1} = 0.357\pi$  and  $\theta_{f2} = \pi - \theta_{f1} = 0.643\pi$ , and the corresponding  $Z_{e1}$  ( $Z_{e2}$ ) are found to be  $230.03 \Omega$  ( $32.86 \Omega$ ). Additionally, in view of  $k^2 = 7$  and  $f_2/f_1 = 1.8$ ,  $Z_{31}$ ,  $Z_{32}$ ,  $Z_{41}$  and  $Z_{42}$  can be calculated as  $97.83 \Omega$ ,  $67.61 \Omega$ ,  $25.56 \Omega$  and  $36.98 \Omega$  by (15)–(18), respectively.

## 4.2. Results

A dual-band unequal Wilkinson power divider is designed and fabricated on a substrate RO4003C ( $\epsilon_r = 3.55$ ,  $h = 0.813$  mm), as shown in Fig. 9. All the design parameters are listed in Table 2. To make sure the wide stub  $Z_{r2}$  ( $w_{r2} = 22.16$  mm) good connection to ground, 25 vias are used at the end of the stub. The diameter of each via is 0.5 mm, and the distance between the centers of every two adjacent vias is 0.9 mm. The length of the short-circuited  $Z_{r2}$  should be tuned to compensate the difference between the mode electrical length of the coupled lines ( $Z_{e2}$ ,  $Z_{o2}$ ). Fig. 10 displays the comparison between the measurements and simulations. The measurements agree very well with the simulations except the center frequency with

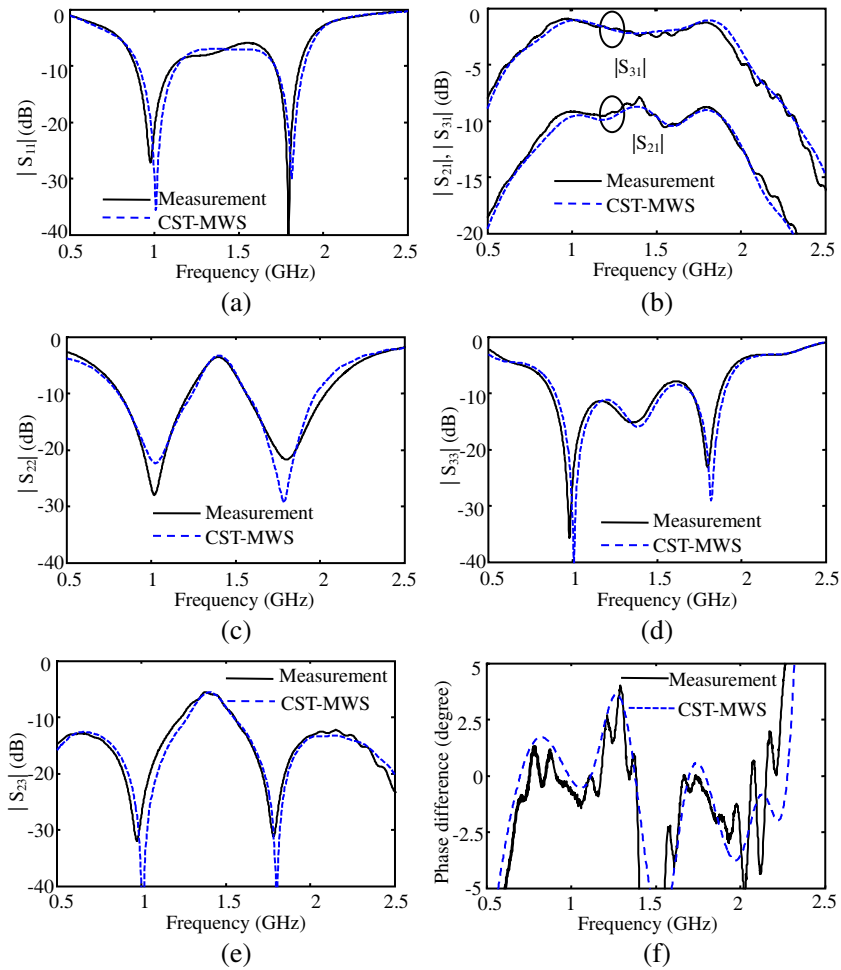


**Figure 9.** Photograph of the fabricated dual-band unequal Wilkinson power divider.

**Table 2.** Design parameters of the dual-band unequal power divider ( $k^2 = 7$ ,  $R = 151 \Omega$  and  $Z_0 = 50 \Omega$ ).

Design frequencies (GHz)	Coupled-line sections ( $\Omega$ )	Physical dimensions (mm)
$f_1 = 1.0, f_2 = 1.8$ ( $\theta_{f1} = 0.357\pi$ )	$Z_{e1} = Z_{o1} = 110.78$	$w_1 = 0.3, l_1 = 33.99$
	$Z_{r1} = 33.45$	$w_{r1} = 3.27, l_{r1} = 31.55$
	$Z_{e2} = 19, Z_{o2} = 15.83$	$w_2 = 7.36, l_2 = 30.50, s_2 = 0.4$
	$Z_{r2} = 6.72$	$w_{r2} = 22.16, l_{r2} = 30.05$
	Two-section transformers ( $\Omega$ )	Physical dimensions (mm)
	$Z_{31} = 97.83$	$w_{31} = 0.46, l_{31} = 33.21$
	$Z_{32} = 67.61$	$w_{32} = 1.05, l_{32} = 32.84$
	$Z_{41} = 25.56$	$w_{41} = 4.68, l_{41} = 31.31$
	$Z_{42} = 36.98$	$w_{42} = 2.84, l_{42} = 31.50$

20 MHz lower, due to fabrication and measurement tolerance. At the design frequency  $f_1 = 1.0$  GHz, the measured  $|S_{21}| = -9.20$  dB,  $|S_{31}| = -1.00$  dB ( $|S_{31}| - |S_{21}| = 8.20$  dB),  $|S_{11}| = -21.47$  dB,  $|S_{22}| = -26.51$  dB,  $|S_{33}| = -25.39$  dB,  $|S_{23}| = -27.41$  dB, and the phase difference  $\angle S_{21} - \angle S_{31} = -0.7^\circ$ . At  $f_2 = 1.8$  GHz, the measured  $|S_{21}| = -8.78$  dB,  $|S_{31}| = -1.26$  dB ( $|S_{31}| - |S_{21}| = 7.52$  dB),  $|S_{11}| = -33.66$  dB,  $|S_{22}| = -21.70$  dB,  $|S_{33}| = -21.14$  dB,  $|S_{23}| = -28.6$  dB, and  $\angle S_{21} - \angle S_{31} = -0.8^\circ$ . The measured bandwidths of  $-20$  dB  $|S_{23}|$  are 0.89–1.05 GHz and 1.72–1.85 GHz, respectively. Over these two



**Figure 10.** (a)–(e)  $S$ -parameters of the dual-band unequal Wilkinson power divider; (f) Phase difference between output port 2 and 3.

operating bandwidths, the measured return losses of all ports are better than 10 dB, and the measured phase differences between output ports 2 and 3 are within  $1.1^\circ$  and  $1.2^\circ$  respectively, as shown in Fig. 10(f).

## 5. CONCLUSION

This paper presents a new class of dual-band Wilkinson power dividers by using coupled-line section with short-circuited stub. This section is used to replace not only the  $70.7\ \Omega$  quarter-wavelength branch lines

in equal Wilkinson power divider to obtain dual-band operation, but also the high (low) impedance branch line in unequal one with high power dividing ratio for dual-band operation. The design procedures are given, showing that the proposed power dividers are very flexible for design and fabrication. Two design examples, have been designed, fabricated and measured. The results show that the proposed power dividers have the advantages of simple topologies, and suitability for small frequency ratios and high power dividing ratios. In addition, the coupled-line section proposed in this paper is applicable to other dual-band components.

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