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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 exhibits 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

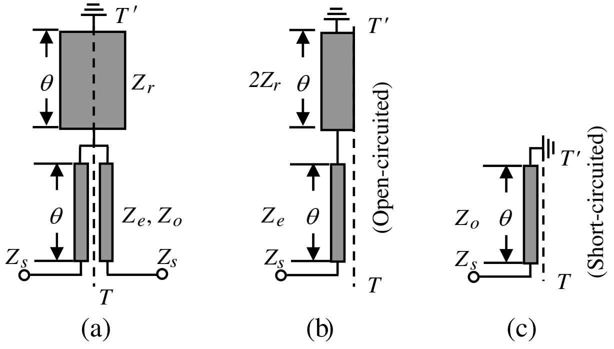


Figure 1. (a) Structure of the coupled-line section with short-circuited stub; (b) Equivalent circuit of even-mode excitation; (c) Equivalent circuit of odd-mode excitation.

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:

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

$$Z_{ino} = jZ_o \tan\theta \tag{2}$$

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 θ.

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

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

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

With (3) and (4), the phase shift $|\phi|$ and equivalent characteristic impedance Z_c varying with electrical length θ ($0 \le \theta \le \pi$) 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 θ_{f1} stay the same as those at θ_{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]:

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

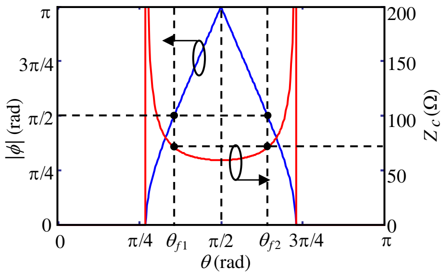


Figure 2. Phase shift ($|\phi|$) and equivalent characteristic impedance (Z_c) versus electrical length (θ).

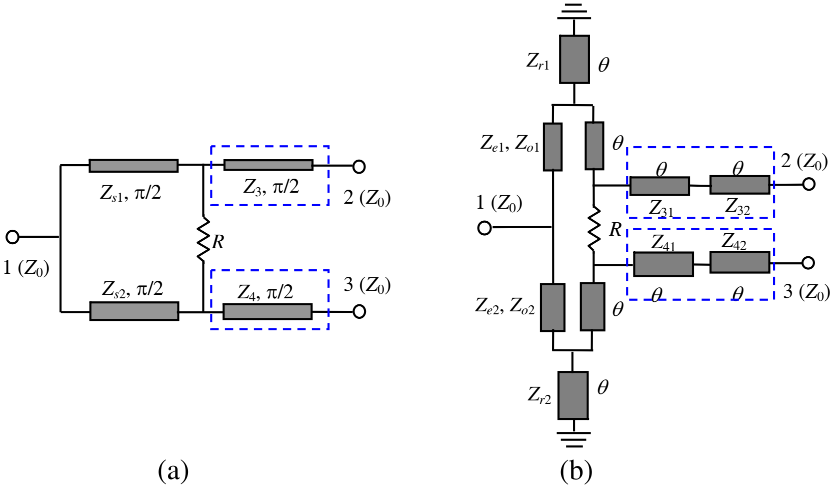


Figure 3. (a) Schematic of the conventional equal (unequal) Wilkinson power divider; (b) Structure of the proposed dual-band equal (unequal) Wilkinson power divider.

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

$$Z_3 = Z_0\sqrt{k} \tag{7}$$

$$Z_4 = \frac{Z_0}{\sqrt{k}} \tag{8}$$

$$R = Z_0\frac{k^2+1}{k} \tag{9}$$

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:

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

or

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

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:

$$Z_r = \frac{Z_e\left(Z_eZ_o\tan^2\theta + Z_s^2\right)}{2\left(Z_s^2 - Z_eZ_o\right)\tan^2\theta} \tag{12}$$

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

$$Z_o = Z_s/|\tan\theta| \tag{13}$$

From (12) and (13), two possible solutions of the electrical length θ_{f1} and θ_{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 θ_{f1} and the operating frequencies f_1 and f_2 was given in [13]:

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

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 θ_{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]:

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

$$Z_{32} = \frac{kZ_0^2}{Z_{31}} \tag{16}$$

$$Z_{41} = \frac{Z_{32}}{k} \tag{17}$$

$$Z_{42} = \frac{Z_{31}}{k} \tag{18}$$

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 θ_{f1} and Z_o can be calculated easily as 0.357π and $34.05\,\Omega$ respectively. When it comes to choosing an appropriate value of Z_e, two guidelines should be obeyed as follows:

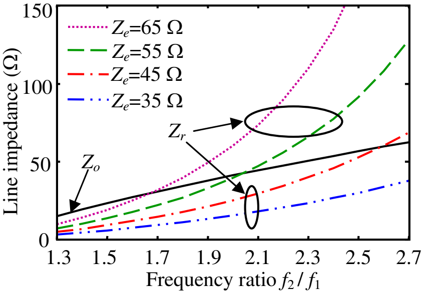


Figure 4. Line impedances (Z_o and Z_r) versus frequency ratio (f_2/f_1) at different Z_e.

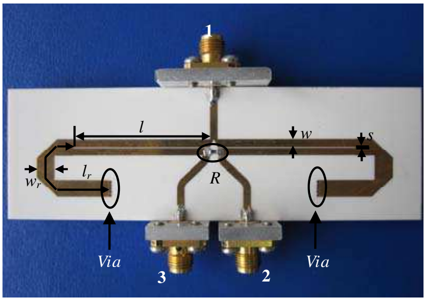


Figure 5. Photograph of the fabricated dual-band equal Wilkinson power divider.

a) Increasing Z_e will lead to a growing Z_r. Therefore, Z_e should be as large as possible;

b) 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 $70.7\,\Omega$.

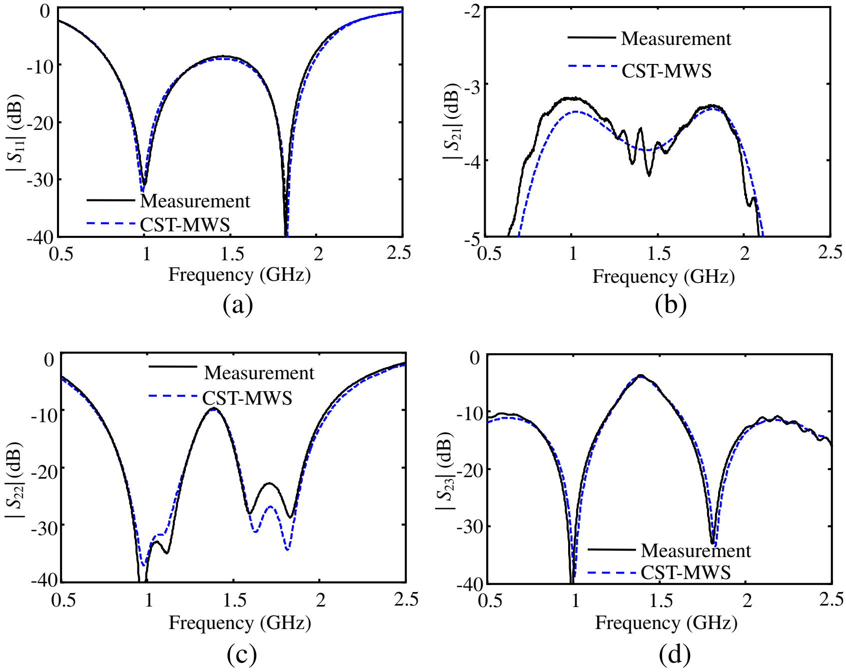
3.2. Results

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 ($\varepsilon_r = 3.55$, $h = 0.813$ 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 $f_1 = 1.0$ GHz, the measured $|S_{11}| = -30.9$ dB, $|S_{21}| = -3.21$ dB, $|S_{22}| = -38.57$ dB, and $|S_{23}| =$

$-38.09\,\text{dB}$. And at $f_2 = 1.8\,\text{GHz}$, the measured $|S_{11}| = -27.1\,\text{dB}$, $|S_{21}| = -3.29\,\text{dB}$, $|S_{22}| = -26.79\,\text{dB}$, and $|S_{23}| = -32.03\,\text{dB}$. The measured bandwidths of $-20\,\text{dB}$ $|S_{23}|$ 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 (Ω)	Physical dimensions (mm)
$f_1 = 1.0$, $f_2 = 1.8$ ($\theta_{f1} = 0.357\pi$)	$Z_e = 55$, $Z_o = 34.05$	$w = 2.01$, $l = 32.48$, $s = 0.24$
	$Z_r = 30.11$	$w_r = 4.43$, $l_r = 29.19$



(a) (b)

(c) (d)

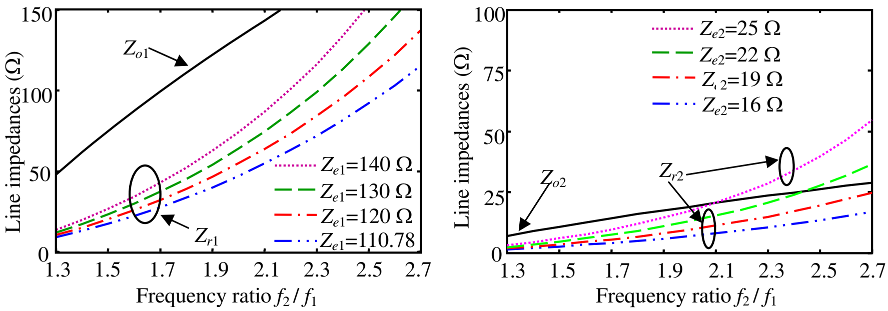
Figure 6. S-parameters of the dual-band equal Wilkinson power divider.

4. DUAL-BAND UNEQUAL WILKINSON POWER DIVIDER

4.1. Design

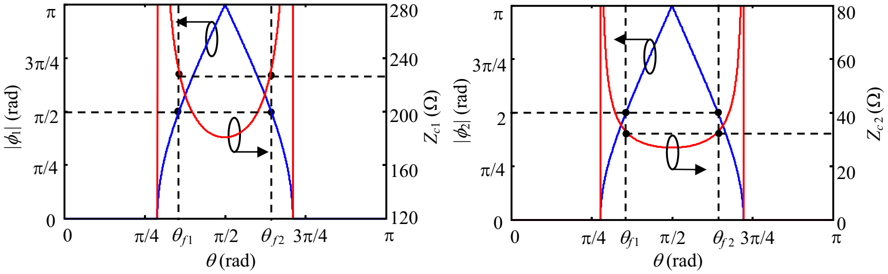
In this paper, an unequal Wilkinson power divider with the power dividing ratio k^2 of 7 is realized. By using (5)–(9), the characteristic impedances are calculated as $Z_{s1} = 230.03\,\Omega$, $Z_{s2} = 32.86\,\Omega$, $Z_3 = 78.25\,\Omega$, $Z_4 = 31.95\,\Omega$, and the isolation resistor $R = 151.19\,\Omega$. 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 θ_{f1} and Z_{o1} (Z_{o2}) can be calculated as 0.357π and $110.78\,\Omega$ ($15.83\,\Omega$), respectively. The guidelines to choose Z_{e1} and Z_{e2} are as follows:



(a) (b)

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}.



(a) (b)

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 Ω), 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 Ω.

With the chosen value of Z_{e1} (Z_{e2}), Z_{r1} (Z_{r2}) can be calculated as 33.45 Ω (6.72 Ω). Fig. 8 demonstrates the phase shift $|\phi_1|$ ($|\phi_2|$) and equivalent characteristic impedance Z_{c1} (Z_{c2}) 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_{c1} (Z_{c2}) are found to be 230.03 Ω (32.86 Ω). 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 Ω, 67.61 Ω, 25.56 Ω and 36.98 Ω by (15)–(18), respectively.

4.2. Results

A dual-band unequal Wilkinson power divider is designed and fabricated on a substrate RO4003C ($\varepsilon_r = 3.55$, $h = 0.813$ 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

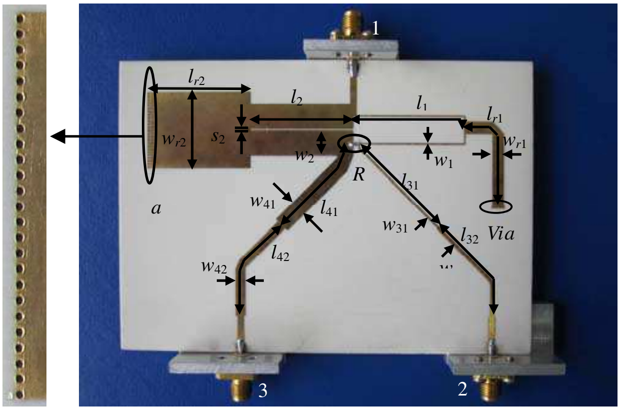


Figure 9. Photograph of the fabricated dual-band unequal Wilkinson power divider.

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 (Ω)	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 (Ω)	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 $\angle S_{21} - \angle S_{31} = -0.7°$. 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 $\angle S_{21} - \angle S_{31} = -0.8°$. The measured bandwidths of -20 dB $|S_{23}|$ are 0.89–1.05 GHz and 1.72–1.85 GHz, respectively. Over these two

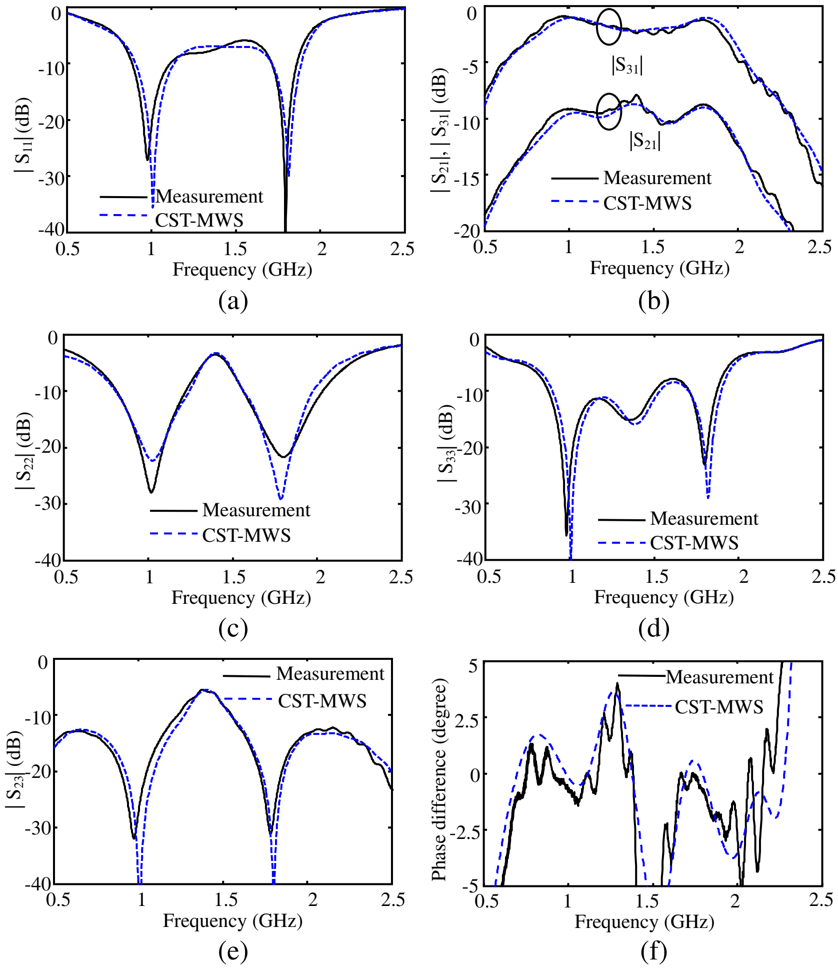


Figure 10. (a)–(e) S-parameters of the dual-band unequal Wilkinson power divider; (f) Phase difference between output port 2 and 3.

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° and 1.2° 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 Ω 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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