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DESIGN OF A COMPACT TRI-BAND POWER DIVIDER WITH UNEQUAL OUTPUTS

Hai Jin Zhou*, Hua Feng Wu, Guo Zhong Lei, and Yun Zhu Ma

Xi'an Electronic Engineering Research Institute, P. O. Box 132, Xi'an, Shaanxi 710100, China

Abstract—In this paper, we present a new design of a compact tri-band unequal power divider, which is composed of a circular-coupling power divider and a triple-band resonator. The unequal power dividing characteristic is realized by two circular shaped microstrip lines coupled through a circular shaped slot. The triple-band resonator, which comprises a conventional half-wavelength resonator, a short stub and an open stub, deals with the triple-bandpass performance. The proposed tri-band power divider with 1 : 1.6 output power ratios working at 3.4 GHz, 4.2 GHz, and 5.25 GHz is simulated and fabricated, and good agreements between the simulated and measured results are observed.

1. INTRODUCTION

Power dividers are one of the most important components in various RF subsystems. They are widely used in antenna arrays, power amplifiers, vector modulators, etc.. The simplest power divider is the Wilkinson divider [1], which presents a match at all ports and high isolation between output ports by using quarter-wavelength impedance transformers and isolation resistors. Another classical structure is Gysel power divider [2, 3]. This structure can be used in some high-power-combining applications due to its external resistors are grounded with a direct path for heat sinking. Recently, new types wideband power dividers utilizing broadside coupling via multilayer microstrip/slot transitions of elliptical or tapered slot have been proposed [4, 5]. These dividers are mostly non-coplanar and suitable to be applied in some fields, such as the six-port junction [6–8] and non-coplanar couplers [9].

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* Corresponding author: Hai Jin Zhou (zhjhere@163.com).

With the rapid development of wireless communication technology and radar system, there has been increased interest in multi-band design of power dividers for dual-band [10, 11] or tri-band [12] operations. In [10], the dual-band power divider consists of two branches acting as impedance transformers, which are formed by two sections of transmission lines with different characteristic impedance and a parallel connection of a resistor, a capacitor, and an inductor. By tuning the parameters of the transformers, the presented power divider can operate at two arbitrary frequencies. Another compact dual-band power divider is proposed in [11]. An all-pass coupled lines section is utilized to realize the necessary impedance transformation at two selected frequencies. In [12], a compact tri-band power divider which is based on a tri-band resonator and the interdigital coupled-line structure is researched.

However, all the multi-band power dividers mentioned above are designed for equal outputs. As to unequal power divider, dual-band dividers are widely discussed [13, 14] while tri-band dividers are seldom researched. In [13], a dual-band Gysel power divider with unequal outputs is presented. To obtain the unequal property, branch lines with different characteristic impedance attached to a short-circuit terminated stub and an open-circuit terminated stub are utilized. The proposed structure can support large power dividing ratio with wide frequency ratio rang. In [14], a dual-band unequal Wilkinson power divider with arbitrary power division and arbitrary terminal impedances through recombinant structures and dual-frequency transformers is presented. But, the difficulty with the high distribution ratio multiband Wilkinson divider is the realization of high characteristic impedance transmission lines.

In this paper, we present a new design of a compact tri-band unequal power divider, which exhibits a bandpass characteristic at WiMAX (3.4 GHz), C-band satellite communication system (4.2 GHz) and WLAN (5.25 GHz) with 1 : 1.6 output power ratios. In order to find the initial dimension of the proposed divider, odd- and even-mode method is applied. Final dimensions are obtained by the full-wave electromagnetic analysis software Ansoft HFSS (V12.0). The prototype is fabricated and measured. Good agreements between the simulated and measured results verify the validity of the proposed design.

2. DESIGN OF THE UNEQUAL TRI-BAND POWER DIVIDER

The configuration of the proposed compact power divider, which is capable of proving a tri-band operation with unequal outputs, is shown in Figure 1. It is observed in Figure 1(d) that the structure is composed of two parts. One is a circular-coupling power divider and the other is a triple-band resonator. The unequal power dividing characteristic is realized by the circular coupler which consists of two circular shaped microstrip lines coupled through a circular shaped slot. The triple-band resonator, which comprises a conventional half-wavelength resonator, a short stub and an open stub, deals with the triple-bandpass performance. The resonator was introduced and applied in the design of a tri-band filter in [15]. The transmission lines in the structure are folded for a reduced size of the resonator. Thus, the proposed divider will be discussed by two parts as follows.

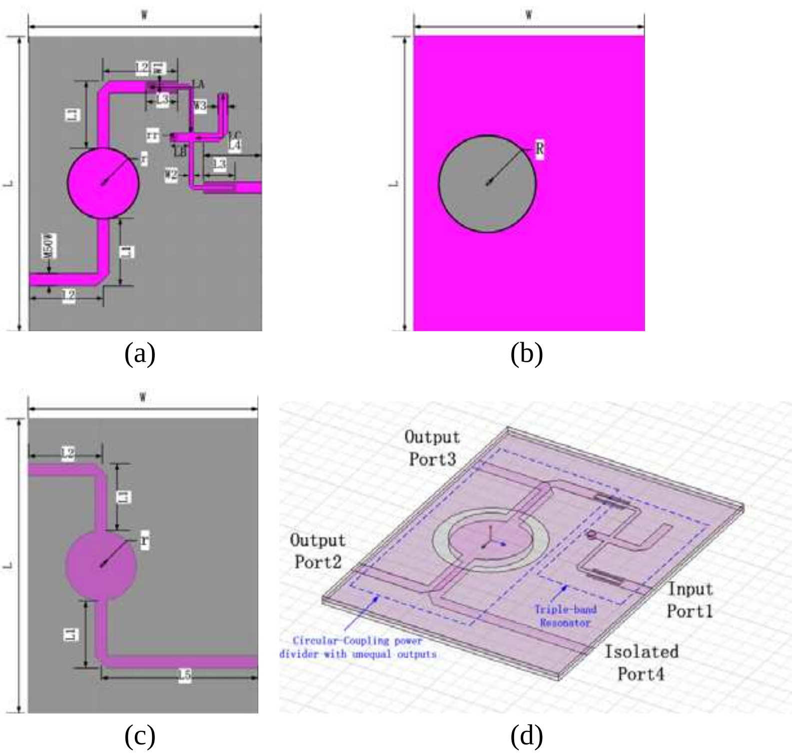


Figure 1. Configuration of the proposed power divider. (a) Top layer. (b) Mid layer. (c) Bottom layer. (d) The whole configuration.

2.1. Analysis of the Circular-coupling Power Divider with Unequal Outputs

The circular-coupling power divider consists of three conductor layers interleaved by two dielectrics. The input and one of the output ports are placed at the top layer while the other output port and the isolated port terminated by matched load are at the bottom layer. All of the ports are microstrip ports. The ground plane, which includes a coupling slot, is located at the mid layer. The microstrip coupled patches and the slot are circular shapes, which are different with the power divider and coupler mentioned in [4, 16]. The matched load terminated in the isolated port is used to absorb any reflected signal from the output ports which may degrade the isolation performance between the two output ports.

Using the odd- and even-mode analysis, we can get the initial dimensions of the element. Assuming that the coupler is required to have $C_{(\mathrm{dB})}$ coupling, the even (Z_{oe}) and odd (Z_{oo}) mode characteristic impedances are calculated using (1) and (2) as follows [16]:

$$Z_{oe} = Z_0 \left(\frac{1 + 10^{C/20}}{1 - 10^{C/20}} \right)^{0.5} \tag{1}$$

$$Z_{oo} = Z_0 \left(\frac{1 - 10^{C/20}}{1 + 10^{C/20}} \right)^{0.5} \tag{2}$$

where Z_0 is the characteristic impedance of the microstrip port.

The proposed divider, which is used for the distribution of input power of two power amplifiers with 50 W and 80 W outputs respectively, is designed to realize the unequal outputs with about 1 : 1.6 power ratios in our application. Thus, the ideal output transmission values of $|S_{21}|$ and $|S_{31}|$ are equal to -4.15 dB and -2.1 dB respectively and $|S_{31}| - |S_{21}| = 2.05$ dB. The coupling coefficient $C_{(\mathrm{dB})}$ here is consequently equal to -2.1 dB. The values of Z_{oe} and Z_{oo}, which can be calculated from (1) and (2), are given as 144 Ω and 17 Ω respectively.

By comparing the calculated even- and odd-mode impedance to the values designed in [16], which deals with 3 dB, 6 dB, 10 dB coupler, we can obtain the initial parameters of the circular shaped microstrip patches and slot analogically. However, the purpose of this step is only help to set the initial value in the simulation and reduce the design time. The final dimensions R and r are obtained by iteratively running the finite-element method design and analysis package Ansoft HFSS (V12.0).

2.2. Analysis of the Triple-band Resonator

The compact structure of the triple-band resonator, which comprises a half-wavelength resonator, a short stub and an open stub, is shown in Figure 2(a). It is observed that the structure is symmetrical to the T-T' plane. Thus, the odd- and even-mode method can be applied to analyze it. LA denotes the half length of the half-wavelength resonator, and LB, LC denote the lengths of the short stub and the open stub.

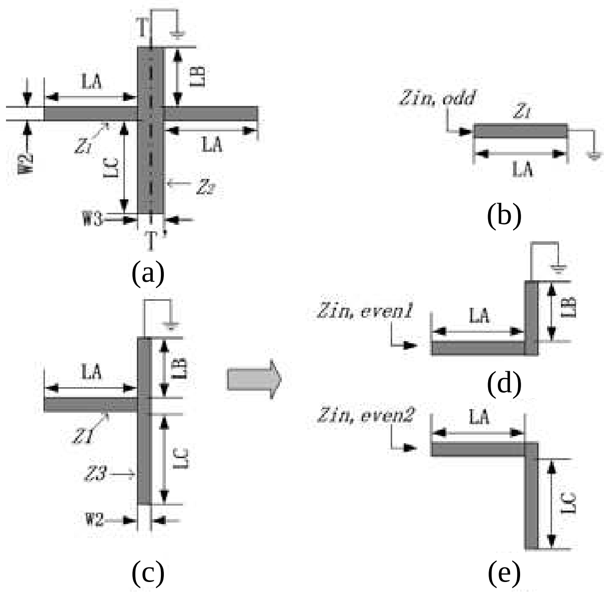


Figure 2. (a) Simplify structure of the triple-mode resonator. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit. (d) Part-I of even-mode equivalent circuit. (e) Part-II of even-mode equivalent circuit.

For odd-mode excitation, the T-T' plane acts as a conducting wall. Figure 2(b) depicts the equivalent circuit. Z_1 is the characteristic impedance of the half-wavelength resonator. Because of the resonance condition of $Y_{in,odd} = 0$, the first odd-mode resonant frequency and $Z_{in,odd}$ can be obtained from (3), (4):

$$f_{odd1} = \frac{c}{4LA\sqrt{\varepsilon_e}} \tag{3}$$

$$Z_{in,odd} = jZ_1 \tan(\beta \cdot LA) \tag{4}$$

where c is the speed of the light in free space, and ε_e denotes the effective dielectric constant of the substrate.

For even-mode excitation, the T-T' plane comes to be a magnetic wall. The equivalent circuit is shown in Figure 2(c), which can be divided into two resonant circuits: a quarter-wavelength resonator and a half-wavelength resonator. When $Z_1 = Z_3$ (Z_3 is the characteristic impedance of the stubs with half width of W_3), the first even-mode resonant frequency of the quarter-wavelength resonator shown in Figure 2(d) and $Z_{in,even1}$ can be described as (5), (6):

$$f_{even1} = \frac{c}{4(LA+LB)\sqrt{\varepsilon_e}} \tag{5}$$

$$Z_{in,even1} = jZ_1 \tan\left(\beta \cdot (LA+LB)\right) \tag{6}$$

The half-wavelength resonator shown in Figure 2(e), which realized by the open stub, produce the second even-mode resonant frequency. The resonant frequency and $Z_{in,even2}$ can be expressed as (7), (8):

$$f_{even2} = \frac{c}{2(LA+LC)\sqrt{\varepsilon_e}} \tag{7}$$

$$Z_{in,even2} = jZ_1 \tan\left(\beta \cdot \left(\frac{LA+LC}{2}\right)\right) \tag{8}$$

From Equations (3), (5), (7), it is obtained that $f_{even1} < f_{odd} < f_{even2}$ when $LB > 0$ and $LC < LA$. Thus, the first resonant frequency is determined by LA and LB, the second resonant frequency is determined by LA, and the third resonant frequency is controlled by LA and LC. Thus, the design procedure of the triple-band resonator is as follows: first, select proper LA to make $f_{odd} = 4.2$ GHz, then adjust the length of short stub (LB) to make $f_{even1} = 3.4$ GHz, finally tune the length of the open stub (LC) to get $f_{even2} = 5.25$ GHz.

3. IMPLEMENTATION AND RESULT

Based on the analysis of the unequal power divider and tri-band resonator, a compact tri-band unequal power divider working at 3.4 GHz, 4.2 GHz, and 5.25 GHz with 1 : 1.6 output power ratios has been designed. The configuration of the proposed element is shown in Figure 1. It is observed that the resonator is interdigital coupled with the input of the unequal power divider. The simulation of the total design was carried out by Ansoft HFSS (V12.0) and the dimensions are determined and shown in Table 1.

Figure 3 exhibits the simulated return loss of port1 of the tri-band power divider under different values of LB when LA and LC are fixed. The first resonant frequency decreases when the value of LB increases. The second and third resonant frequencies vary a litter.

Table 1. Values of design parameters in millimeters.

L	W	$L1$	$L2$	$L3$	$L4$	$L5$	$W1$	$W2$
40	31.2	9	10	4.2	7.6	21.2	0.3	0.6
$W3$	$M50W$	LA	LB	LC	r	R	rr	
1.2	1.6	12	2.5	9.8	4.8	6.6	0.45	

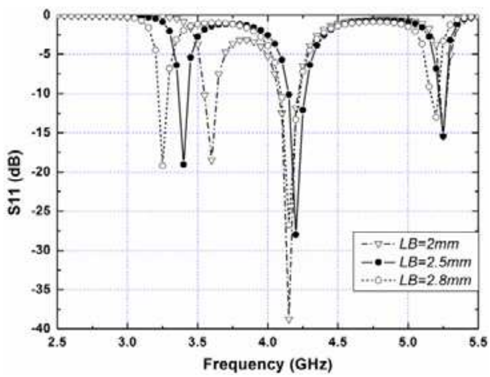


Figure 3. Simulated return loss under different values of LB ($LA = 12\,\text{mm}$, $LC = 9.8\,\text{mm}$).

Figure 4 shows the responses of the third resonant frequency varied with LC when LA and LB are fixed. It is observed that the changing rules of the third frequency responses are almost the same as that of the first one. However, if the value of LA varies while LB and LC are fixed, all of the three frequency responses will be changed. Figure 5 depicts the variation of S_{11} of the divider with different LA.

The proposed power divider was fabricated and tested for the validity of the design. Figure 6 shows the prototype of the divider. A Rogers 5880 substrate featuring a dielectric constant of 2.2 and a loss tangent of 0.0009, 0.508-mm thickness is selected for the divider's development. The total size of the fabricated unequal tri-band power divider is $40\,\text{mm} \times 31.2\,\text{mm}$.

The S-parameter of the proposed divider was measured by Agilent N5244A network analyzer. Figures 7 and 8 depict the measured return loss of input port, transmission coefficients and isolation of two output ports together with those from the electromagnetic simulations. The

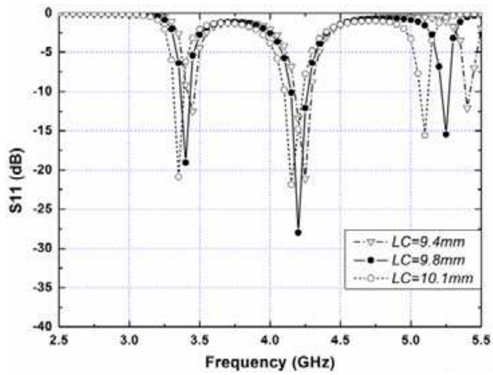


Figure 4. Simulated return loss under different values of LC ($LA = 12\,\text{mm}$, $LB = 2.5\,\text{mm}$).

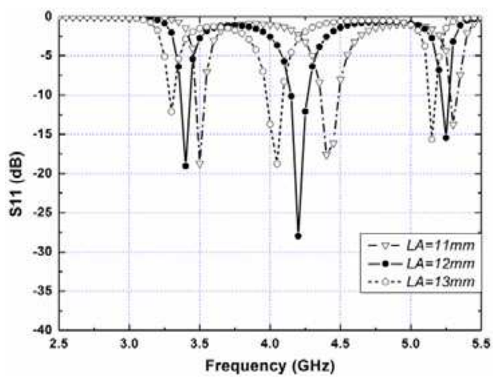
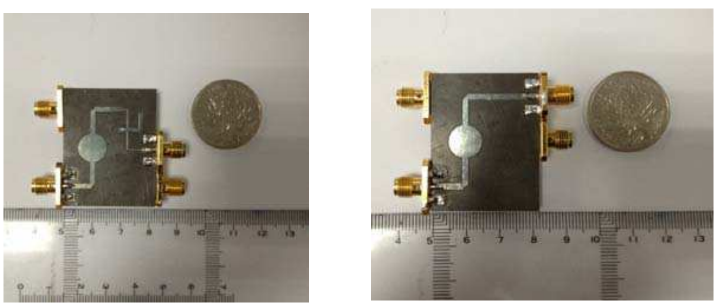


Figure 5. Simulated return loss under different values of LA ($LC = 9.8\,\text{mm}$; $LB = 2.5\,\text{mm}$).

measured and simulated results show reasonable agreements with each other.

It is shown in Figure 7 that the measured resonated frequencies of the power divider appeared at 3.415 GHz, 4.165 GHz, 5.245 GHz with return losses of $-22.8\,\text{dB}$, $-24.6\,\text{dB}$, $-13.5\,\text{dB}$, respectively. These measured responses are slightly offset from the designed frequencies 3.4 GHz/4.2 GHz/5.25 GHz due to the tolerance in manufacturing. Figure 9 depicts the return losses of two output ports. It is shown that the S_{22} and S_{33} are below $-14\,\text{dB}$ at three operating frequencies. Besides, the measured power differences $|S_{31}| - |S_{21}|$ between the two outputs are 1.41 dB/2.8 dB/1.78 dB at the three operating frequencies, which show certain deviation from the ideal value 2.05 dB. The deviation may be caused by the disproportion of the coupling coefficients over the operating frequencies and the manufacturing tolerance of the relative position of the two circular patches. Also, it is observed from the curves that some decrease of the transmission coefficients between the design results and ideal values is occurred, which is mainly due to the coupling loss contributed by the interdigital coupler and circular-shaped coupler, as well as the insert loss of dielectric.

The measured isolation coefficients $|S_{23}|$, shown in Figure 8, are all below -15 dB over the three operating frequencies, which means the proposed divider exhibits good isolation characteristics without any resistance components. Figure 10 depicts the measured results of the phase relationship between two outputs. It is shown that the phase difference between the two ports is about 90° over the operating bands.



(a) (b)

Figure 6. The prototype of the proposed power divider. (a) Top view. (b) Bottom view.

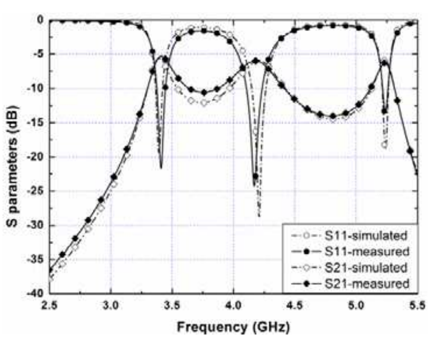


Figure 7. Simulated and measured results of S_{11} and S_{21}.

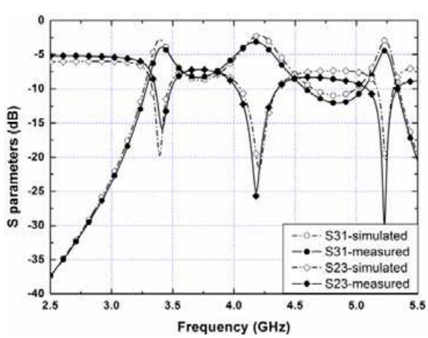


Figure 8. Simulated and measured results of S_{31} and S_{23}.

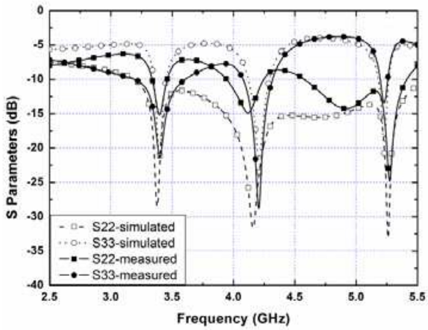


Figure 9. Simulated and measured results of S_{22} and S_{33}.

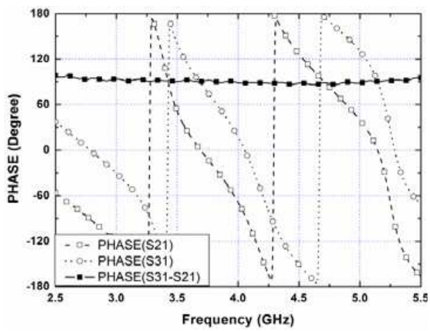


Figure 10. Measured results of the phase relationship between port 2 and port 3.

4. CONCLUSION

A novel compact unequal power divider has been proposed, analyzed, and verified experimentally for tri-band operation at 3.4 GHz, 4.2 GHz and 5.25 GHz. The proposed structure employs a circular-coupling power divider, which deals with unequal outputs, and a triple-band resonator. Final dimensions are obtained by the full-wave electromagnetic analysis software Ansoft HFSS (V12.0). The measured return loss, transmission and isolation coefficients show that the proposed divider exhibits a good performance. Thus, the proposed design can be a promising solution for some multi-band unequal power dividing applications.

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