A Compact Gysel Power Divider With Unequal Power-Dividing Ratio Using One Resistor

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***Abstract*—A novel compact Gysel power divider is proposed and investigated in this paper. The proposed power divider consists of two transmission lines, a pair of coupled lines, and only one grounded resistor for unequal power-dividing ratio. Comparing to the conventional Gysel power divider, the new power divider saves its space by eliminating the 180° electrical length transmission line and reduces complicity by using one grounded resistor. The flexibility in choosing the value of the resistor provides favorable freedom in circuit realization. In addition, analytic design formulas of the proposed power divider, for both equal and unequal ratio cases, are given. For the equal radio case, two grounded resistors are required. Two prototype power dividers are simulated, fabricated, and measured. Both prototypes operate at 2 GHz, but with different power divisions, one for power division ratio $k = 1$ and the other for $k = 2$. There are good correlation between the measured results and those of the theoretically designed, justifying the circuit configuration and the design theory.**

***Index Terms*—Arbitrary power division, coupled line, high power-handling capability, power divider.**

I. Introduction

THE POWER divider is an important component in modern communication systems and has been widely used in feeding networks of antenna arrays, power amplifiers, and mixers. The Wilkinson power divider [1] has been extensively studied [2]–[5] and used for its simplicity in structure, low insertion loss, and good isolation. However, since the resistor between the output ports is not grounded, the heat dissipation is a major issue for high-power applications. The Gysel power divider [6] overcomes the high power-handling problem by introducing two short-ended resistors that can transfer the heat to the ground plane effectively. For this specialty, much attention has recently been paid to the Gysel power divider. In [7], a modified Gysel power divider has been proposed with arbitrary real terminated impedances to achieve unequal or equal power divisions. Replacing the 180° transmission line in a conventional Gysel power divider by a phase inverter, a broadband Gysel power divider has been proposed in [8] to achieve more than 80% bandwidth. An electromagnetic-bandgap (EBG) structure has been utilized in [9] to reduce the size of a conventional Gysel power divider. In [10], a general method has been developed for analyzing an asymmetrical multi-sectional power divider with arbitrary power division and impedance matching at all ports. Dual-band Gysel power dividers have also been proposed using extra open and short stubs [11], or coupled lines [12] to achieve a compact size.

In this paper, a novel Gysel power divider with an arbitrary power division ratio is proposed. The configuration of the power divider consists of two sections of transmission lines and a pair of coupled lines with one or two grounded resistors. Theoretically, this new power divider only needs one resistor when the power division is unequal. However, when the power division ratio equals to one (the equal power division case) or close to one, the power divider requires two grounded resistors with a large, but realizable coupling coefficient for the coupled lines. Simple and explicit design equations are derived for both equal and unequal power division cases. In addition, selection for the value of the resistor is very flexible to meet the same microwave performance requirement, which gives more freedom to the design of a proposed power divider.

This paper is organized as follows. In Section II, the configuration of the proposed power divider and its design theory are introduced. Explicit design formulas are derived based on the even- and odd-mode analysis. Realizable characteristic impedances of the transmission line are then discussed with the change of the resistor in different power division ratios. In Section III, two prototype power dividers are simulated, fabricated, and measured with equal and unequal power division. The measured results show that the proposed Gysel power divider can achieve theoretical matching and isolation properties very well.

II. Theory

Fig. 1 shows the schematic diagram of the proposed power divider. The isolation part is formed by a pair of coupled lines with each end connected with a grounded resistor (R_1, R_2). With the grounded resistors, like a conventional Gysel power divider, the proposed power divider is also capable of handling high power,

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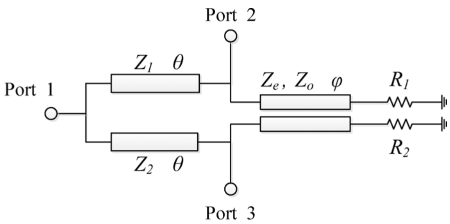

Fig. 1. Schematic diagram of the proposed power divider.

but with a simpler structure and smaller size. Defining the power dividing ratio at the two output ports as $k^2(=P_2/P_3)$. Basically, the proposed power divider must satisfy the following equations at the center frequency:

$$S_{11}=S_{22}=S_{33}=S_{23}=0 \tag{1a}$$

and

$$S_{21}=kS_{31}. \tag{1b}$$

To analyze the proposed circuit, the port impedance is set to be Z_L at each port, and all the transmission lines are ideal.

A. Even-Mode Analysis

In even- and odd-mode analysis, we utilize the method described in [2]. When port 1 is excited, for an ideal case in which the input power will be transmitted to port 2 and port 3 completely with a power-dividing ratio of k^2 ($k\geq 1$), there will be no current flowing into the two resistors. Thus, the original circuit can be reduced to the circuit shown in Fig. 2(a), where the resistors are short circuited and the port voltages at ports 2 and 3 are related by

$$V_{2e}=kV_{3e} \tag{2a}$$

with the matching condition of

$$V_{1e}=(I_{2e}+I_{3e})\,Z_L \tag{2b}$$

where the source impedance of Z_L at port 1 is used. Using the $ABCD$ matrices of transmission lines (Z_1,θ) and (Z_2,θ), the following equations can be found:

$$\begin{bmatrix}V_{1e}\\ I_{2e}\end{bmatrix}=\begin{bmatrix}\cos\theta & jZ_1\sin\theta\\ \frac{j\sin\theta}{Z_1} & \cos\theta\end{bmatrix}\begin{bmatrix}V_{2e}\\ I'_{2e}+I''_{2e}\end{bmatrix} \tag{3a}$$

$$\begin{bmatrix}V_{1e}\\ I_{3e}\end{bmatrix}=\begin{bmatrix}\cos\theta & jZ_2\sin\theta\\ \frac{j\sin\theta}{Z_2} & \cos\theta\end{bmatrix}\begin{bmatrix}V_{3e}\\ I'_{3e}+I''_{3e}\end{bmatrix} \tag{3b}$$

where

$$I'_{2e}=\frac{V_{2e}}{Z_L} \tag{4a}$$

$$I'_{3e}=\frac{V_{3e}}{Z_L}. \tag{4b}$$

It is known that a pair of short-ended coupled lines is an all-stop circuit with an ideal isolation when its electrical length $\varphi=n\pi/2$, $n=1,2,3,\ldots$ [13]. For simplicity, $\varphi=\pi/2$ is chosen. In this case, the input impedance of the coupled line

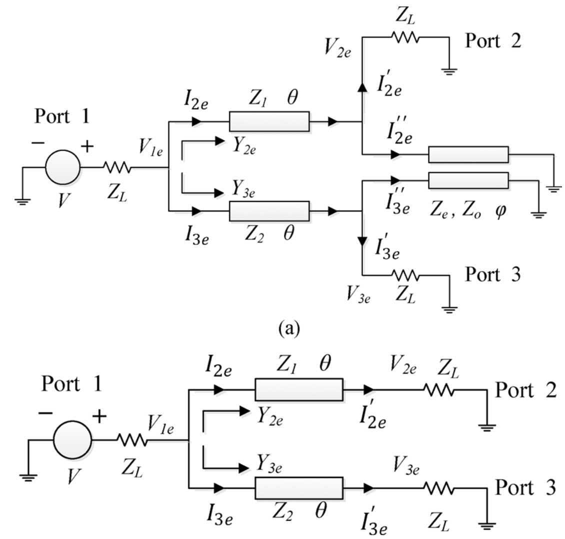

Fig. 2. (a) Even-mode circuit and (b) simplified even-mode circuit of the proposed power divider.

becomes infinite, which makes it open circuited. Thus, $I''_{2e}=I''_{3e}=0$, and the even-mode circuit can be simplified to the circuit shown in Fig. 2(b). By substituting (3) and (4) into (2), the characteristic impedances of the two transmission lines can be found as

$$Z_1=\frac{\sqrt{k^2+1}}{k}Z_L \tag{5a}$$

$$Z_2=\sqrt{k^2+1}Z_L \tag{5b}$$

with the assumption that

$$\theta=n\pi+\frac{\pi}{2},\qquad n=1,2,3,\ldots. \tag{5c}$$

For simplicity, $\theta=\pi/2$ is chosen in this study.

B. Odd-Mode Analysis

To analyze the circuit when port 2 and port 3 are excited, the method described in [2] is utilized. Assume that the magnitude of the source voltages excited at port 2 and 3 are $2V_s$ and $-2kV_s$, respectively. When ports 2 and 3 are matched, the voltage at port 2 and port 3 should be V_s and $-kV_s$, respectively. Thus, applying the principles of superposition and reciprocity and (1b), the voltage at port 1 will be

$$V_1=S_{21}V_s+S_{31}\cdot(-kV_s)=(S_{21}-kS_{31})V_s=0 \tag{6}$$

which means that port 1 is short circuited. The odd-mode circuit can then be simplified to the one illustrated in Fig. 3. Since port 2 and port 3 should be matched and $\theta=\pi/2$, the currents flowing through the coupled lines can be expressed as

$$I_{2o}=\frac{V_s}{Z_L} \tag{7a}$$

$$I_{3o}=-\,k\cdot\frac{V_s}{Z_L}. \tag{7b}$$

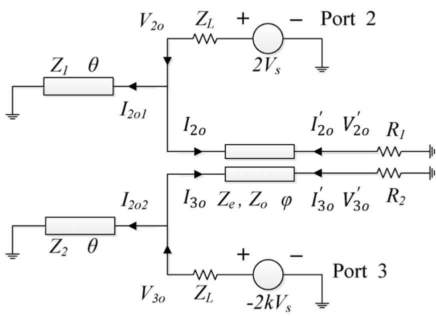

Fig. 3. Odd-mode circuit of the proposed power divider.

It is known that the voltage and the current relation at the four ports of the coupled lines is [13]

$$\begin{bmatrix} V_{2o} \\ V_{3o} \\ V'_{3o} \\ V'_{2o} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{12} & Z_{11} & Z_{14} & Z_{13} \\ Z_{13} & Z_{14} & Z_{11} & Z_{12} \\ Z_{14} & Z_{13} & Z_{12} & Z_{11} \end{bmatrix} \begin{bmatrix} I_{2o} \\ I_{3o} \\ I'_{3o} \\ I'_{2o} \end{bmatrix} \tag{8}$$

where

$$Z_{11} = -j\frac{Z_{0e}+Z_{0o}}{2}cot\varphi = 0 \tag{9a}$$
$$Z_{12} = -j\frac{Z_{0e}-Z_{0o}}{2}cot\varphi = 0 \tag{9b}$$
$$Z_{13} = -j\frac{Z_{0e}-Z_{0o}}{2}csc\varphi = -j\frac{Z_{0e}-Z_{0o}}{2} \tag{9c}$$
$$Z_{14} = -j\frac{Z_{0e}+Z_{0o}}{2}csc\varphi = -j\frac{Z_{0e}+Z_{0o}}{2}. \tag{9d}$$

By substituting

$$V_{2o} = V_s \tag{10a}$$
$$V_{3o} = -kV_s \tag{10b}$$
$$V'_{2o} = -R_1 I'_{2o} \tag{10c}$$
$$V'_{3o} = -R_2 I'_{3o} \tag{10d}$$

and (7) into (8), one can find that

$$R_1 = \frac{Z_e Z_o\left[(Z_e+Z_o) - k(Z_e-Z_o)\right]}{\left[(Z_e+Z_o)+k(Z_e-Z_o)\right]Z_L} \tag{11a}$$
$$R_2 = \frac{Z_e Z_o\left[k(Z_e+Z_o) - (Z_e-Z_o)\right]}{\left[k(Z_e+Z_o)+(Z_e-Z_o)\right]Z_L}. \tag{11b}$$

Fig. 4(a) shows the circuit when only port 2 is excited. The isolation condition between port 2 and port 3 is $S_{32}=0$, which leads to

$$V''_{3o} = 0. \tag{12}$$

Thus, the circuit can be simplified to the one shown in Fig. 4(b). Note that the transmission line of Z_2 is short circuited at its right end, thus it is open circuited at its left end since $\theta = \pi/2$. Therefore, it can be removed in Fig. 4(b). Since port 2 is assumed to be matched to Z_L, the admittance looking into the circuit should satisfy that

$$Y_o = Y_{o1} + Y_{o2} = \frac{1}{Z_L} \tag{13}$$

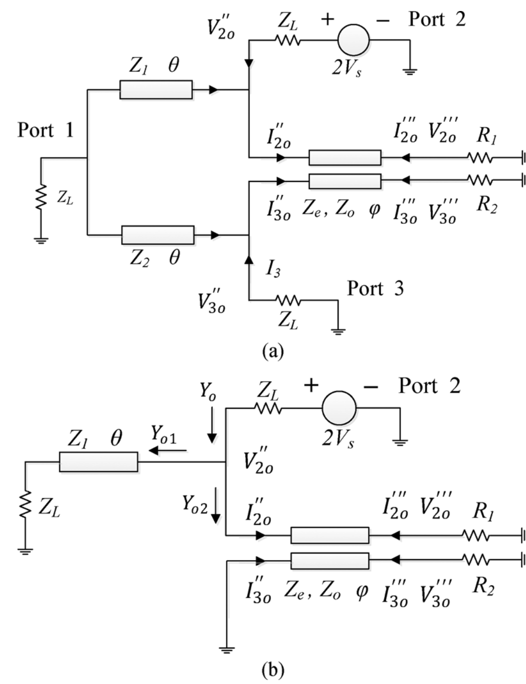

Fig. 4. (a) Equivalent circuit and (b) simplified circuit of the proposed power divider when port 2 is excited.

thus,

$$V''_{2o} = V_s \tag{14a}$$

and

$$Y_{o1} = \frac{Z_L}{Z_1^2} \quad Y_{o2} = \frac{I''_{2o}}{V''_{2o}}. \tag{14b}$$

With condition (14), (13) can be rewritten as

$$V_s = \left(k^2+1\right) Z_L I''_{2o} \tag{15}$$

where relation (5a) is used in deriving (15).

Considering equations in (9) and the definition of the Z matrix for a pair of coupled lines that

$$\begin{bmatrix} V''_{2o} \\ 0 \\ V'''_{3o} \\ V'''_{2o} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{12} & Z_{11} & Z_{14} & Z_{13} \\ Z_{13} & Z_{14} & Z_{11} & Z_{12} \\ Z_{14} & Z_{13} & Z_{12} & Z_{11} \end{bmatrix} \begin{bmatrix} I''_{2o} \\ I''_{3o} \\ I'''_{3o} \\ I'''_{2o} \end{bmatrix} \tag{16}$$

and the voltage–current conditions at the ports of the coupled lines

$$V'''_{2o} = -R_1 I'''_{2o} \quad V'''_{3o} = -R_2 I'''_{3o}. \tag{17}$$

By substituting (15) and (17) into (16), its solution can be found as

$$\left[R_2(Z_e-Z_o)^2 + R_1(Z_e+Z_o)^2\right]\left(k^2+1\right)Z_L = 4Z_e^2 Z_o^2. \tag{18}$$

From relations (11) and (18), two special cases are worthy of being investigated closely.

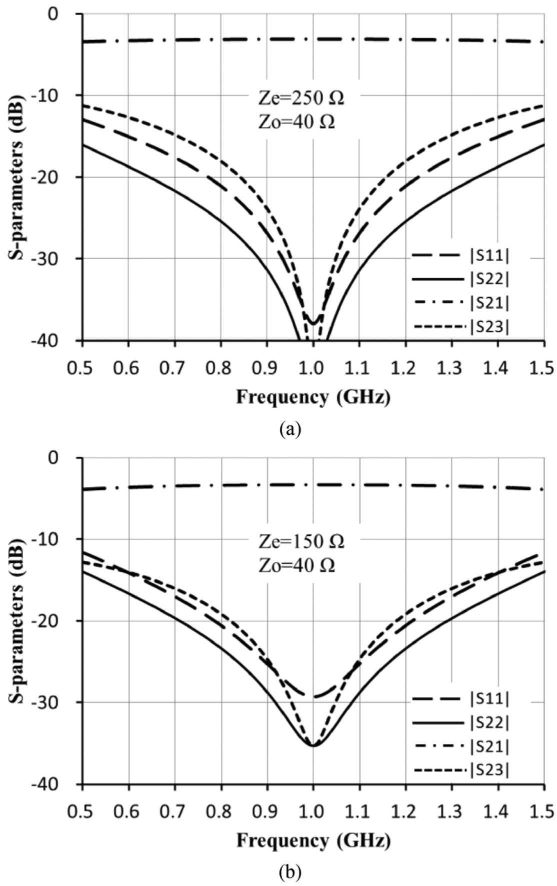

Fig. 5. S-parameters of an ideal circuit of the proposed power divider with $k = 1$ under two different ratios of Z_e/Z_O. (a) $Z_e = 250\ \Omega$ and $Z_O = 40\ \Omega$. (b) $Z_e = 150\ \Omega$ and $Z_O = 40\ \Omega$.

Case 1) When $k = 1$: In this case, by substituting $k = 1$ into (11) and (18), one possible solution can be found that

$$R_1 = R_2 = \frac{Z_o^2}{Z_L} \tag{19}$$

in conjunction with

$$\frac{Z_o^2}{Z_e^2} = 0. \tag{20}$$

Obviously, this is a singular case and an exact realization to (20) is impossible. However, if the ratio of Z_e/Z_o is large enough, an approximate solution that is good enough to meet the requirement can always be found. Fig. 5 shows an ideal response of the proposed power divider with equal power division ($k = 1$) under two different ratios of Z_e/Z_o, namely, 6.25 and 3.75, which incur extra insertion losses of 0.1 and 0.3 dB, respectively. It can be observed that the smaller the ratio, the larger the insertion loss is introduced due to the decreasing of isolation.

Case 2) When $k \neq 1$: By substituting (11) into (18), one can find that

$$Z_e = \frac{k+1}{k-1} \quad Z_o\,(k \neq 1)\,. \tag{21}$$

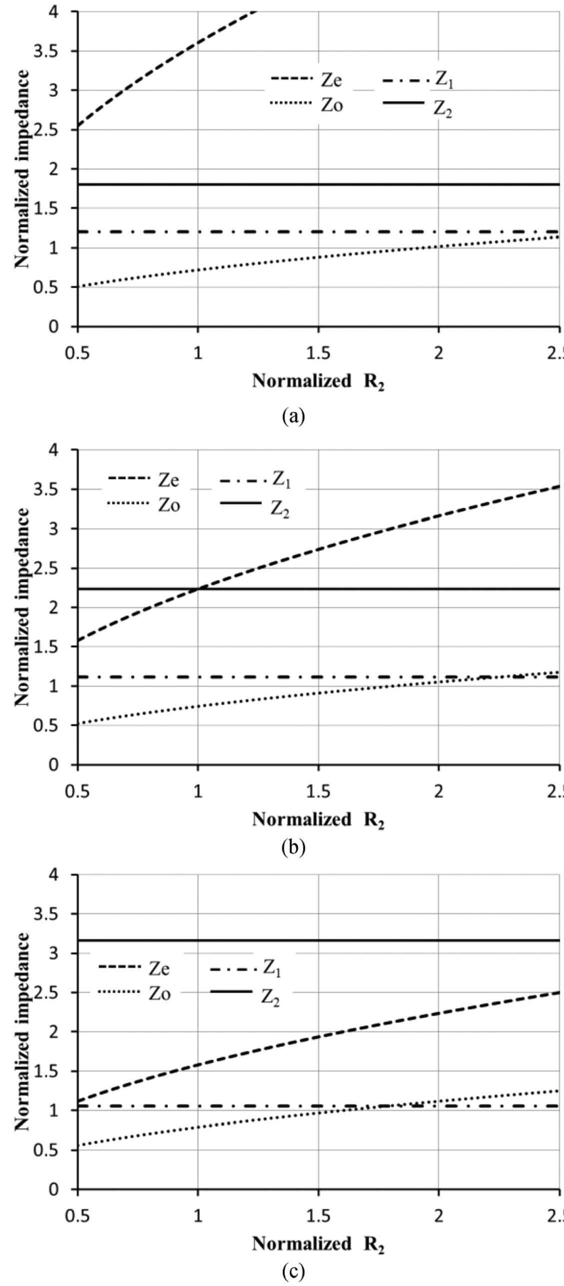

Fig. 6. Normalized impedance of Z_e, Z_o, Z_1, and Z_2 versus normalized R_2 with different k: (a) $k = 1.5$, (b) $k = 2$, and (c) $k = 3$.

Substituting (21) into (11), it is interesting to find that the only solution for R_1 and R_2 is

$$R_1 = 0 \quad R_2 = \frac{(k+1)^2 Z_o^2}{(k^2+1)\,Z_L} \tag{22}$$

which states that when $k \neq 1$, only one resistor is needed. For the convenience of realization, the value of k is suggested to be larger than 1.5. In addition, [14] proposes a method that can achieve the ratio of Z_e/Z_o around 8–9, which means the corresponding k of 1.25 can be realized on a single-layer printed circuit board (PCB).

For a k value that is very close to 1, e.g., 1.1, an exact solution requires an impractical coupling for the coupled line. However, an approximate solution can be found similar to the case

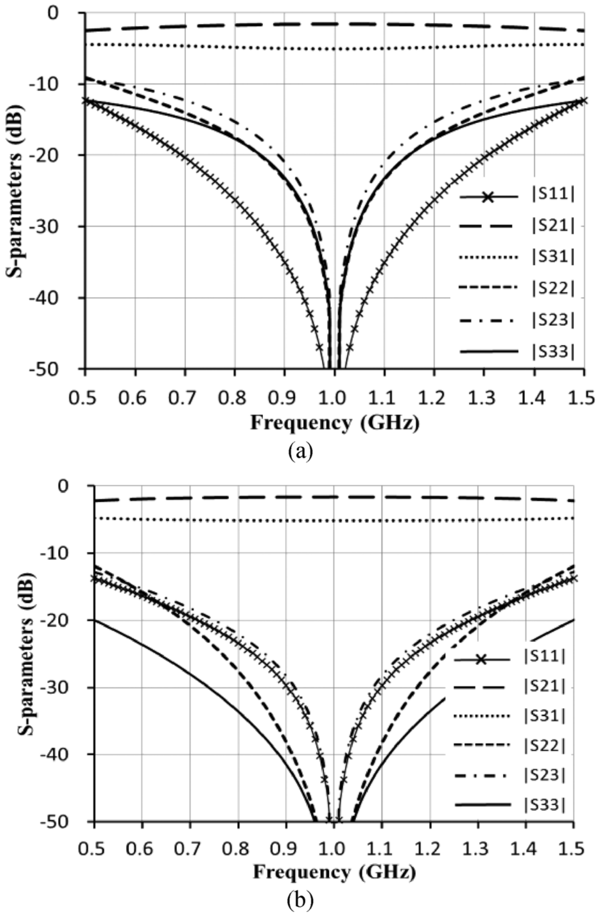

Fig. 7. Ideal response of the proposed power divider with different values of the resistor when $k = 1.5$. (a) $R_2 = 25\ \Omega$. (b) $R_2 = 100\ \Omega$.

of $k = 1$, utilizing (5) and (19) with two resistors. The value of the resistor R_2 can be set according to a convenient choice of Z_o. Changing the value of R_2 will result in the changing of Z_e and Z_o, but Z_1 and Z_2 will remain the same. Fig. 6 shows the normalized impedance of Z_e, Z_o, Z_1, and Z_2 versus the normalized R_2. It can be seen that setting the value of the resistor is very flexible. Choosing a larger value of R_2 will result in larger values of Z_e and Z_o. However, the choice of R_2 will affect the bandwidth of the power divider. Fig. 7 shows the performance of the ideal circuits of the proposed power divider with different R_2 when $k = 1.5$. It can be seen that the bandwidth of matching and isolation level of -20 dB changes significantly with the changing of the resistor.

III. Design Examples

To prove the concept, two prototype power dividers are designed, fabricated, and tested. The prototype circuits are build on a double-sided Duroid substrate with a dielectric constant of 2.33 and a thickness of 1.575 mm. Two circuits operate at 2 GHz, one is with $k = 1$ and the other is with $k = 2$. The electromagnetic (EM) simulation was done by Agilent EMPro [15] and the prototypes were measured by Agilent E5071A.

Electrical parameters of the circuit with equal power division are $Z_1 = Z_2 = 70.7\ \Omega$, $Z_e = 235\ \Omega$, $Z_o = 64\ \Omega$, and

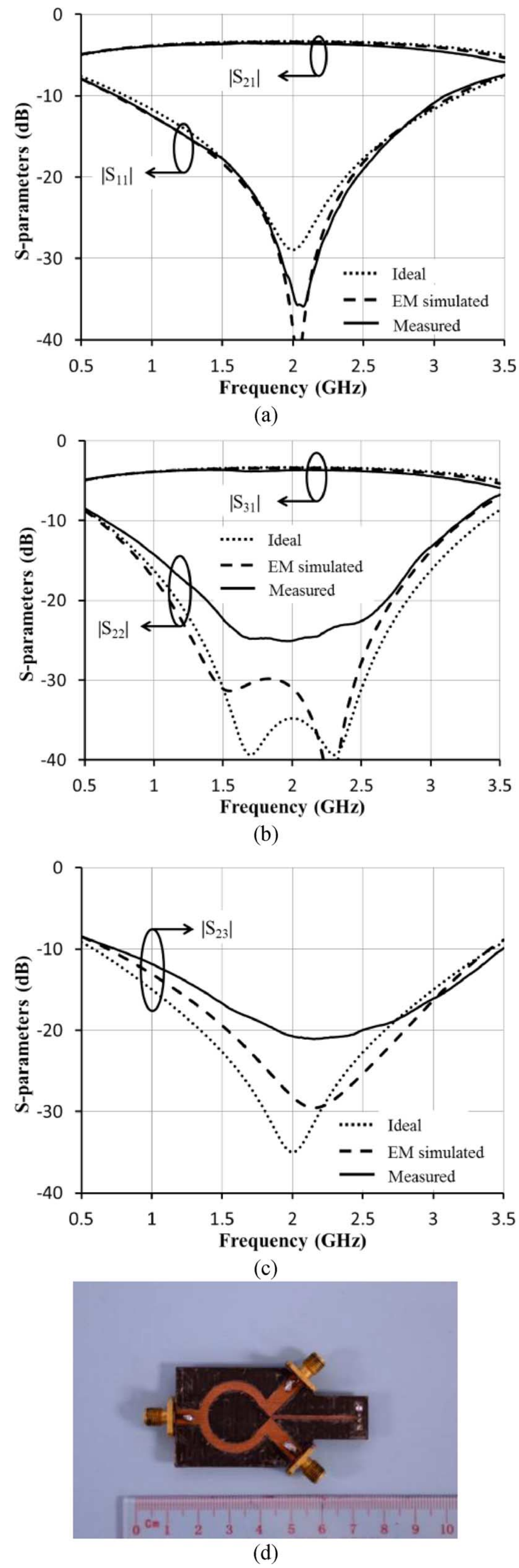

Fig. 8. S-parameters of the prototype power divider with equal power division. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{22}|$ and $|S_{31}|$. (c) $|S_{32}|$. (d) Photograph.

$R_1 = R_2 = 82\ \Omega$. The corresponding dimensions of the fabricated prototype are: the width of transmission lines Z_1 and Z_2 is 2.67 mm; the width and the gap of the coupled line are 0.32 mm

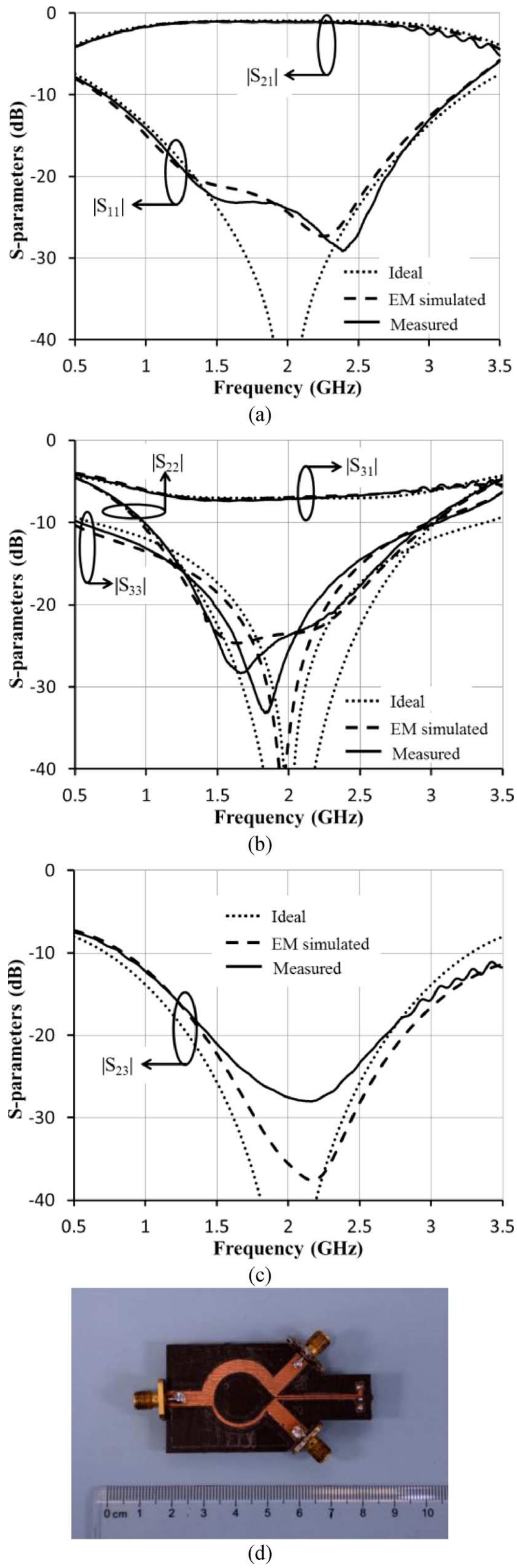

Fig. 9. S-parameters of the prototype power divider with unequal power division. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{22}|$. $|S_{33}|$ and $|S_{31}|$. (c) $|S_{32}|$. (d) Photograph.

and 0.2 mm, respectively. Fig. 8 shows the frequency responses of the prototype power divider, which operates at 2 GHz. The measured $|S_{21}|$ and $|S_{31}|$ are -3.55 and -3.65 dB at the center frequency, respectively. The bandwidths from the measured result, in accordance with that $|S_{11}| \leq -15$ dB; $|S_{22}| \leq -15$ dB; $|S_{33}| \leq -15$ dB; and $|S_{23}| \leq -15$ dB, is about 65%.

Electrical parameters of the circuit with unequal power division ($k = 2$) are $Z_1 = 55.9\ \Omega$, $Z_2 = 111.8\ \Omega$, $Z_e = 212.1\ \Omega$, $Z_o = 70.7\ \Omega$, $R_1 = 0\ \Omega$, and $R_2 = 180\ \Omega$. The corresponding dimensions of the fabricated prototype are width of the transmission lines Z_1 and Z_2 are 4 and 0.96 mm, respectively; the width and the gap of the coupled lines are 0.45 and 0.3 mm, respectively. Fig. 9 shows the frequency responses of the prototype operating at 2 GHz. The measured $|S_{21}|$ and $|S_{31}|$ are -1.07 and -7.1 dB at the center frequency, respectively (the ideal response should be -0.97 and -6.99 dB, respectively). Although S_{33} shift a little to lower frequency, the measured results agree well with the EM simulated ones and the ideal circuit.

IV. Conclusion

In this paper, a novel Gysel power divider with arbitrary power division ratio has been proposed. Taking the advantage of coupled lines, the proposed power divider has a compact and simple structure with much smaller real estate than a conventional Gysel power divider. In addition, the proposed divider only needs one grounded resistor when the power division is unequal. Since there is a wide range of possible resistor value, more freedom can be found in the design of the proposed power divider. Explicit design formulas are derived, which provide a straightforward analytic design procedure. Two prototype power dividers operating at the same frequency, but with a different power division ratio have been designed, fabricated, and measured. The measured results show good agreement with those of the ideal circuit models and those of the EM simulated, which further justifies the proposed new circuit configuration.

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