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A Planar Out-of-Phase Power Divider with Unequal Power Dividing Ratio

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Abstract—A planar power divider with unequal power division and out-of-phase feature is presented. Firstly, the principle of the proposed power divider containing transmission lines with the same characteristic impedance is analyzed. The power dividing ratio can be adjusted by only the electrical lengths of the transmission lines. Design equations of the proposed circuit are derived. Secondly, the method to reduce the size of the power divider is discussed. For illustration, a 2 : 1 prototype operating at 1.5 GHz is designed, fabricated and measured. The measured results show that S_{21}, S_{31}, and S_{11} are about −1.84, −4.96 and −28.4 dB at 1.5 GHz, respectively, that the isolation S_{23} is better than −20 dB from 1.44 to 1.56 GHz and that the phase difference between two output ports is about 180.54° at the center frequency.

1. INTRODUCTION

Power dividers (PDs) with out-of-phase feature are very important in balanced circuit designs such as balanced mixers, which rely on balanced signal to improve the performance. Different techniques and configurations are used to design the out-of-phase power dividers. Asymmetrical coplanar stripline is used to design an equal Wilkinson power divider with 180° phase difference between two output ports [1]. Microstrip to slot-line transitions is adopted to design Wilkinson power divider with out-of-phase characteristics [2–4]. As the balanced transmission line has an inherent out-of-phase characteristic between the two strip lines, parallel-strip lines (PSLs) and double-sided parallel-strip lines (DSPSLs) are introduced to design single- or dual-band Gysel power divider with out-of-phase characteristics [5–9]. As the techniques discussed above use un-planar structures, the corresponding power dividers are very difficult to integrate with other microstrip circuits. In [10], a planar out-of-phase Gysel power divider with wide operating bandwidth is discussed. The whole electrical length of the circuit is about 3π. But only equal dividing ratio is discussed, and the circuit occupies a larger area. A 180° planar Gysel power divider with high power dividing ratio based on parallel coupled lines with two short circuited ends is presented in [11]. However, the configuration cannot be used to design power divider with equal or lower unequal power dividing ratio as it is very difficult for physical realization.

In this paper, a planar out-of-phase power divider with unequal power division is proposed. The power dividing ratio can be obtained by only adjusting the electrical lengthes of transmission lines. The design equations of the proposed circuit are derived. The way to miniaturize the size of the circuit is also introduced. For demonstration, a miniaturized 1.5 GHz prototype with power dividing ratio of 2 : 1 is designed, fabricated and measured. The measured results are in good agreements with the simulated ones.

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2. THEORY ANALYSIS OF PROPOSED PD

The topology of power divider with unequal power dividing ratio discussed in [12] is shown in Fig. 1(a). The power dividing ratio can be realized by choosing proper electrical length of ϕ. With the assumption that power dividing ratio is $K^2\,(K^2 = P_2/P_3 > 1)$, $\phi < 90^\circ$ and system impedance $Z_0 = 50\,\Omega$, the corresponding design equations can be written as

$$\psi = \frac{\pi}{2} \tag{1a}$$

$$Z_m = \sqrt{2}Z_0 \tag{1b}$$

$$\phi = \cos^{-1}(1/K) \tag{1c}$$

$$R_1 = 2Z_0 \tag{1d}$$

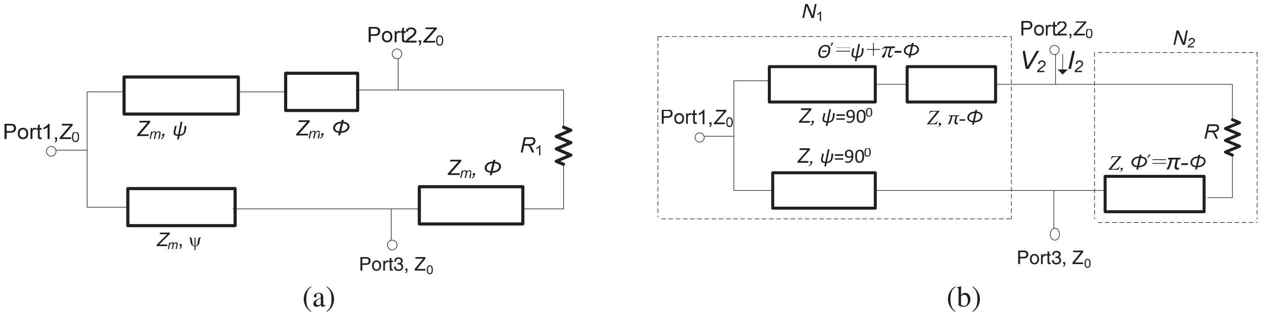


Figure 1. Topoloy of power divider. (a) Traditional power divider, (b) proposed power divider.

It should be noted that the power divider shown in Fig. 1(a) has in-phase characteristics between two output ports, and it can be converted to equal Wilkinson power divider when $K^2 = 1$.

The planar structure of the proposed power divider with out-of-phase characteristics is shown in Fig. 1(b). It basically consists of four sections of transmission lines with the uniform characteristic impedance of Z and an isolation resistor of R. At the center frequency, the electrical lengthes of transmission lines are equal to 90° and $\pi - \phi$, respectively. It is assumed that the input power is divided and transmitted solely to two output loads at the designated power dividing ratio of K^2. The even and odd mode equivalent circuits of the proposed power divider are shown in Fig. 2. When the input port is excited, there is no current flowing through the isolation resistor, and the original circuit can therefore be equivalent to the network, as shown in Fig. 2(a). By applying transmission line theory, the input

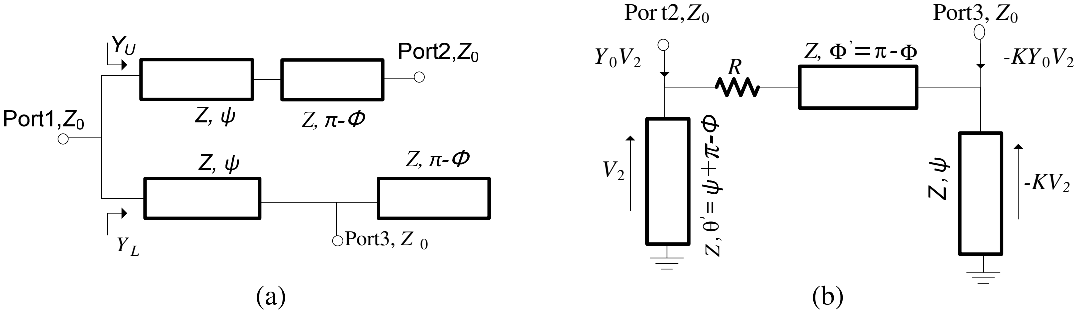


Figure 2. Even and odd mode equivalent circuit of proposed power divider. (a) Even mode, (b) odd mode.

admittances of the upper and lower branches (Y_U and Y_L) can be expressed as

$$Y_U = Y\frac{Y_0 + jY\text{ctg}\phi}{Y + jY_0\text{ctg}\phi} \tag{2}$$

$$Y_L = Y\frac{jY\text{ctg}\phi}{Y + jY_0\text{ctg}\phi} \tag{3}$$

where $Y = 1/Z$ and $Y_0 = 1/Z_0$.

Under the input matched condition, we have

$$Y_0 = Y_U + Y_L \tag{4}$$

By substituting Eqs. (2), (3) into Eq. (4), we can get

$$Z=\sqrt{2}Z_0 \tag{5}$$

As the input admittances (Y_U and Y_L) have the same voltage node, the power dividing ratio of K^2 can also be described as

$$K^2 = \frac{Re(Y_U)}{Re(Y_L)} \tag{6}$$

By substituting Eqs. (2), (3) into Eq. (6), we can get

$$K^2 = \frac{1}{\cos^2\phi} \tag{7}$$

It can be observed that the power dividing ratio is only determined by the electrical length of ϕ.

By applying the transmission matrix concept into Fig. 1(b), the $ABCD$ parameters of these two networks at the center frequency may be expressed as

$$\begin{bmatrix} A_{N1} & B_{N1} \\ C_{N1} & D_{N1} \end{bmatrix} = \begin{bmatrix} -\cos\phi & -2Z_0\cos\phi - j\sqrt{2}Z_0\sin\phi \\ \dfrac{-j\sin\phi}{\sqrt{2}Z_0} & -\cos\phi - j\sqrt{2}\sin\phi \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} A_{N2} & B_{N2} \\ C_{N2} & D_{N2} \end{bmatrix} = \begin{bmatrix} \cos\phi + \dfrac{jR\sin\phi}{\sqrt{2}Z_0} & R\cos\phi + j\sqrt{2}Z_0\sin\phi \\ \dfrac{j\sin\phi}{\sqrt{2}Z_0} & \cos\phi \end{bmatrix} \tag{9}$$

If a microwave signal is input from port 2, the following relationships should be satisfied for the perfect isolation and output port matching of the proposed power divider, respectively.

$$B_{N1} + B_{N2} = 0 \tag{10a}$$

$$Z_0 = \frac{V_2}{I_2} = \frac{B_{N1}}{D_{N1} - D_{N2}} \tag{10b}$$

Subsequently, by replacing Eq. (10a) with Eqs. (8) and (9), we have

$$R= 2Z_0 \tag{11}$$

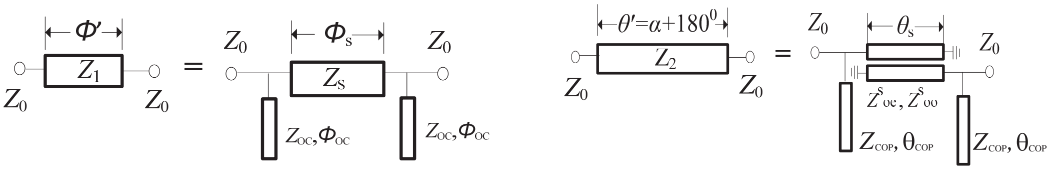
The perfect isolation between two output ports is achieved. Moreover, if we substitute Eqs. (8), (9) into Eq. (10b), it can found that Eq. (10b) is also satisfied, which indicates that both output ports are matched to system impedance.

According to $ABCD$ matrix analysis, the phase angle of the transmission coefficients S_{21} and S_{31} of the proposed circuit at the center frequency are simply determined by using Eq. (12), respectively.

$$\angle S_{21}=\frac{1}{\cos\theta + j\sqrt{2}\sin\theta} = \pi - \tan^{-1}(\sqrt{2}\text{cot}\phi) \tag{12a}$$

$$\angle S_{31}=\frac{1}{-\tan\phi + j\sqrt{2}} = -\tan^{-1}(\sqrt{2}\text{cot}\phi) \tag{12b}$$

The proposed power divider is compared with the topology shown in Fig. 1(a). Only the electrical lengths of transmission lines are modified from ϕ to $\pi - \phi$ ($\phi < 90°$), and the other parameters are kept



(a) (b)

Figure 3. Transmission-line sections and their equivalent circuits. (a) $\phi' < 180°$, (b) $\theta' > 180°$.

unchanged. However, the proposed configuration has out-of-phase characteristics between two output ports while the circuit shown in Fig. 1(a) is an in-phase power divider.

As discussed above, the whole electrical length of the proposed power divider is $3\pi - 2\phi$. In order to further reduce the size of the proposed circuit, the transmission line with electrical length ϕ' shown in Fig. 1(b) at the center frequency (which is less than 180°) can be replaced with a π-type transmission line equivalent circuit as shown in Fig. 3(a). The relationships between the parameters of the transmission line ϕ' and the corresponding equivalent circuit can be expressed as [13]

$$Z_s = Z_1 \frac{\sin\phi'}{\sin\phi_s} \tag{13a}$$

$$Z_{oc}\tan\phi_{oc} = \frac{Z_1\sin\phi'}{\cos\phi_s - \cos\phi'} \tag{13b}$$

Moreover, the transmission line with the electrical length θ' shown in Fig. 1(b) at the center frequency (which is larger than 180°) can be replaced with a short circuited coupled-lines equivalent circuit as shown in Fig. 3(b). The parameters of the corresponding equivalent circuit can be written as

$$Z_{oe}^s = Z_2 \frac{\sin\alpha}{\sin\theta_s}\frac{C}{1-C} \tag{14a}$$

$$Z_{oo}^s = Z_2 \frac{\sin\alpha}{\sin\theta_s}\frac{C}{1+C} \tag{14b}$$

$$Z_{cop}\text{ctg}\theta_{cop} = \frac{Z_2 C\sin\alpha}{\cos\theta_s - C\cos\alpha} \tag{14c}$$

where C is the coupling coefficient of short circuited coupled lines and $\alpha = 90° - \phi$.

For illustration, the proposed power divider and its miniaturized circuit with $K^2 = 4$ operating at 1.5 GHz is designed. The corresponding parameters for the proposed power divider are: $Z = 70.7\,\Omega$, $\psi = 90°$, $\phi = 60°$ ($\phi' = 120°$), $\theta' = 210°$, $R = 100\,\Omega$. Furthermore, for miniaturized circuit, when $\phi_s = 45°$, $\theta_s = 20°$, $C = 0.4$, $\phi_{oc} = 45°$, and $\theta_{cop} = 45°$ are selected, according to Formulas (13) and (14), $Z_s = 86.6\,\Omega$, $Z_{oc} = 50.7\,\Omega$, $Z_{cop} = 23.8\,\Omega$, $Z_{oe}^s = 68.9\,\Omega$ and $Z_{oo}^s = 29.5\,\Omega$ are calculated. The proposed and miniaturized circuits are simulated by ADS software. The frequency response of the proposed power divider with power dividing ratio of $K^2 = 4$ shown in Fig. 1(b) and that of miniaturized power divider using the equivalent circuit are shown in Fig. 4(a) and Fig. 4(b), respectively. It can be observed that the port matching and perfect isolation are achieved for both the proposed power divider and its miniaturized circuit at the center frequency. Moreover, S_{11}, S_{22}, S_{33} and S_{23} of the proposed and miniaturized power dividers are quite different as the transmission-line sections, and their equivalent circuits (which form the miniaturized circuit) shown in Fig. 3 can only be equivalent at the center frequency. The miniaturized circuit has a smaller operating bandwidth than the proposed power divider. In designing the miniaturized circuit with $K^2 = 4$, if a different electrical length of θ_{cop} is chosen (for examples, $\theta_{cop} = 60°$ is selected, and $Z_{cop} = 41.22\,\Omega$ is obtained) and keeping other parameters unchanged, the corresponding input return losses of S_{11} are shown in Fig. 4(c). It can be seen that there is a smaller value of S_{11} above the center frequency, and it will move towards to the center frequency as the electrical length of θ_{cop} with a larger value is selected.

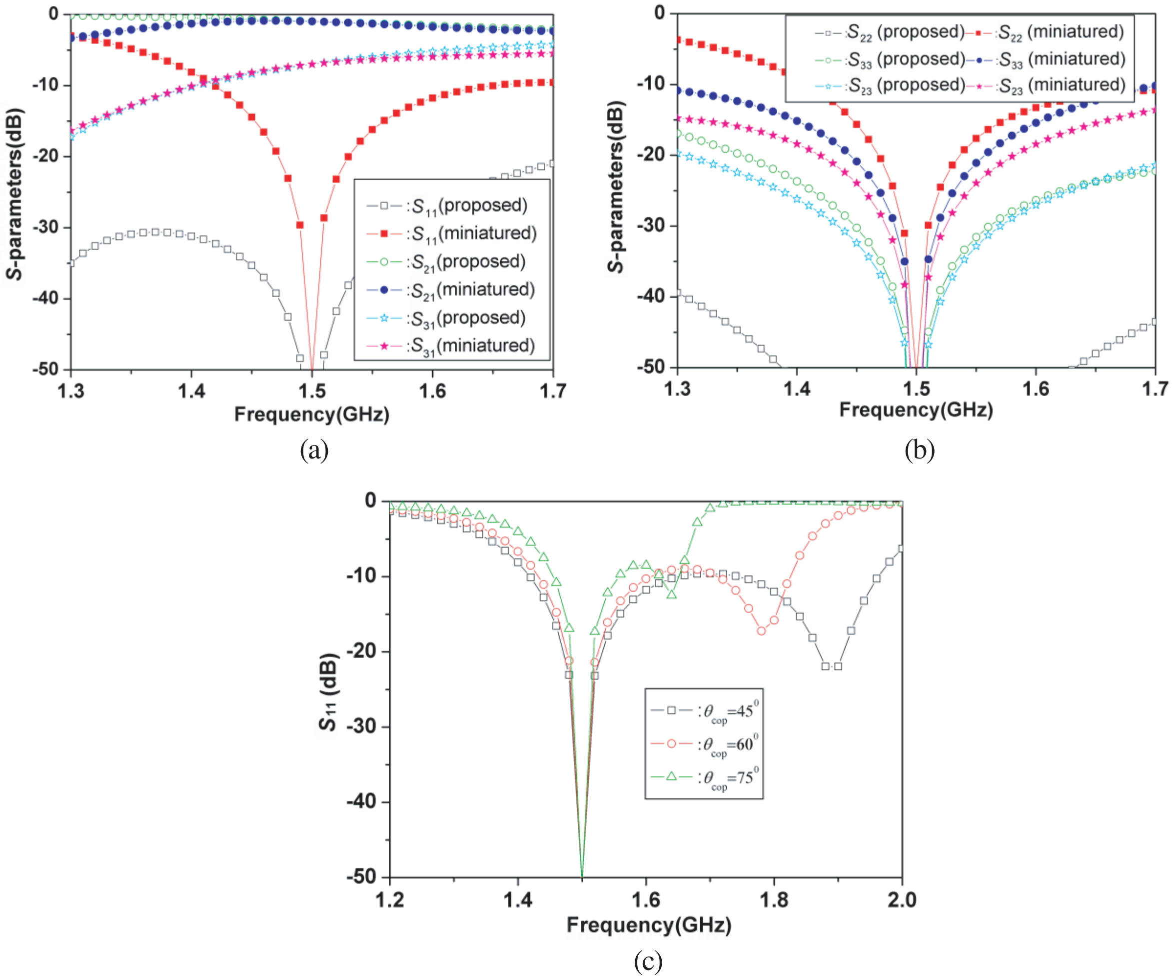


Figure 4. Frequency response of the proposed power divider and its miniaturized circuit with $K^2 = 4$. (a) S_{11}, S_{21} and S_{31}. (b) S_{22}, S_{33} and S_{23}. (c) Input return loss of miniaturized circuit with different θ_{cop}.

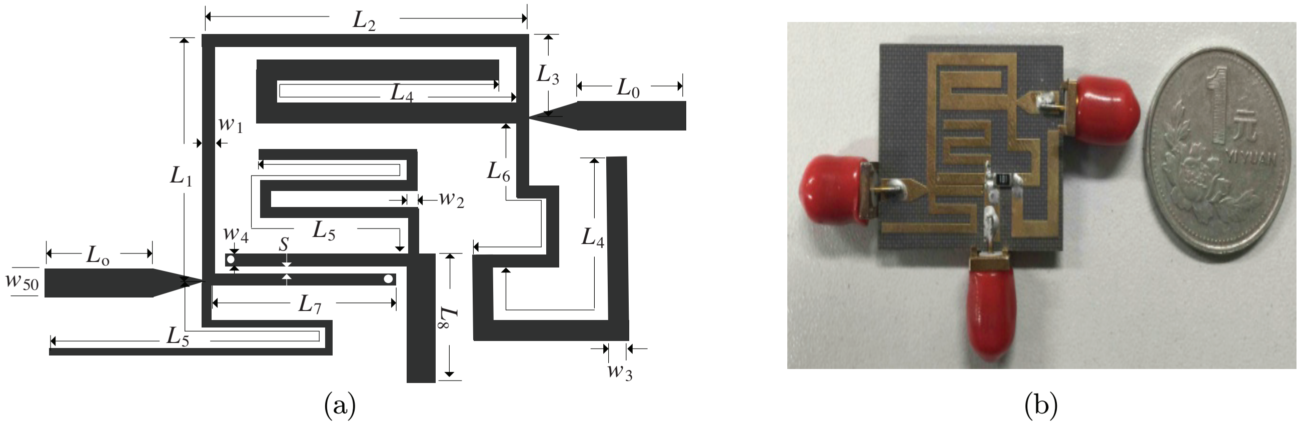
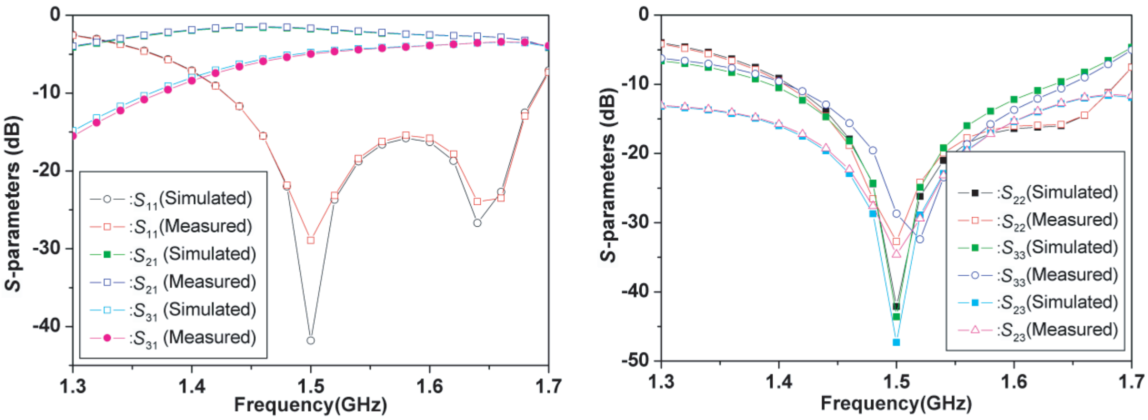


Figure 5. The proposed power divider. (a) Layout. (b) Photograph.

3. EXPERIMENTAL RESULTS

For verification, a miniaturized microstrip out-of phase power divider with an operating frequency of 1.5 GHz and power dividing ratio of $K^2 = 2$ is designed on a substrate with a dielectric constant of 2.65 and thickness of 1 mm. From the design equations, the calculated parameters are $Z = 70.7\,\Omega$, $\phi = 45°$, $R = 100\,\Omega$, and the corresponding electrical length is $\phi' = 135°$ and $\theta' = 225°$, respectively. In order to reduce the size of the proposed circuit, $\phi_s = 45°$, $\theta_s = 20°$, $C = 0.4$, $\phi_{oc} = 60°$, $\theta_{cop} = 70°$ are selected, according to Formulas (13) and (14), $Z_s = 70.7\,\Omega$, $Z_{oc} = 61.25\,\Omega$, $Z_{cop} = 83.7\,\Omega$, $Z^s_{oe} = 97.4\,\Omega$ and $Z^s_{oo} = 41.75\,\Omega$ are obtained. The dimensions of the miniaturized power divider shown in Fig. 5(a) are as follows (mm): $W_{50} = 2.68$, $W_1 = 1.45$, $W_2 = 1.05$, $W_3 = 1.85$, $W_4 = 1.32$, $S = 0.1$, $L_0 = 5$, $L_1 = 15.5$, $L_2 = 14.5$, $L_3 = 5.95$, $L_4 = 22.35$, $L_5 = 26.84$, $L_6 = 16.95$, $L_7 = 7.5$, $L_8 = 6$. A photograph of fabricated power divider is shown in Fig. 5(b). The simulated and measured scattering parameters are shown in Fig. 6. It can be seen that the measured insertion losses are $S_{21} = -1.84$ dB and $S_{31} = -4.96$ dB, while the measured return losses are $S_{11} = -28.4$ dB, $S_{22} = -32.3$ dB and $S_{33} = -28.7$ dB at the center frequency. The isolation S_{23} is better than -20 dB from 1.44 to 1.56 GHz. Fig. 7 shows the simulated and measured phase differences, and it can be observed that the measured phase difference is $180.54° \pm 5°$ from 1.4 GHz to 1.6 GHz. The measured results show good agreements with the simulated ones. The whole circuit dimension is about $30 \times 24\,\text{mm}^2$ (including $50\,\Omega$ microstrip feeding lines).



(a) (b)

Figure 6. Simulated and measured S-parameters of the miniaturized power divider. (a) S_{11}, S_{21} and S_{31}. (b) S_{22}, S_{33} and S_{23}.

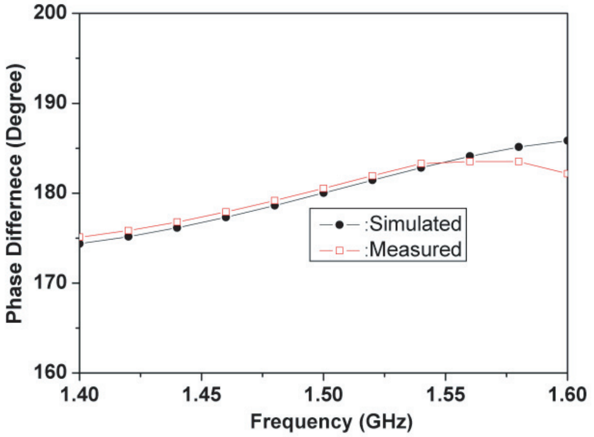


Figure 7. Simulated and measured phase difference of miniaturized power divider.

4. CONCLUSION

A planar out-of-phase power divider with unequal power dividing ratio is presented. A prototype is fabricated and measured. Measured results indicate tha tthe magnitudes of S_{21} and S_{31} are about $-1.84\,\text{dB}$ and $-4.96\,\text{dB}$ at 1.5 GHz, respectively. The phase difference between output ports is about $180.54° \pm 5°$ from 1.4 to 1.6 GHz. The proposed power divider has advantages of compact size, easy fabrication and planar configuration. It can be used in applications with the requirements of power dividing and out-of-phase feature.

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