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Complex Impedance-Transformation Out-of-Phase Power Divider with High Power-Handling Capability

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Abstract—A novel 180° out-of-phase power divider with complex-source to complex-load impedance transformation and high power-handling capability is proposed in this paper. It is composed of three double-sided parallel-strip lines (DSPSLs), a conduct plane in the middle as common ground, and two resistors for heat sinking and high isolation. Based on the rigorous odd- and even-mode analytical methods, closed-form design equations about electrical parameters are obtained. To demonstrate our design theory, a practical three-layer out-of-phase power divider is designed, simulated and measured. The measured results show that the return losses $|S_{ii}|$ (i = 1, 2, and 3) are all larger than 17 dB. The insertion loss $|S_{21}|(|S_{31}|)$ is 3.6 dB (3.7 dB). The isolation $|S_{23}|$ is -24 dB, and the output phase difference is $-177°$ at the operating frequency. Good agreements between the simulated and measured results verify our design theory.

1. INTRODUCTION

Dealing with complex impedance is always a key problem in the design of active circuits and active systems because the input impedances of power amplifiers (PA) [1], antennas [2] and other transceiver systems are not always real. Adopting basic passive circuits with the function of transformation from complex-source to complex-load impedance will greatly reduce the sizes of whole circuits because the extra parts of complex impedance transformation will be avoided, and the design complexity will be greatly decreased in the meanwhile.

The passive components with complex impedance transformation have been widely discussed in recent papers such as impedance transformers [3], power divider [4], and balun [5, 6]. For example, multi-frequency impedance transformers for frequency-dependent complex loads with multi-frequency inverters, which consist of a transmission line and two-side multi-frequency susceptances, are proposed in [3]. A 3-dB power divider terminated in equal complex impedances, which is composed of two identical 90° transmission-line sections and an isolation circuit, is presented [4]. The isolation network is the key to realize the complex termination impedances, and three methods of adding transmission-line sections, open stubs, and short stubs are adopted in this paper. An asymmetrical coupled-line circuit with three pairs of coupled lines and two tapped transmission-line stubs are designed to realize a planar microstrip coupled-line balun [5]. Three reactances are added to the Marchand balun to form a novel type of Marchand balun [6], which has the function of transformation between arbitrary complex impedances. The passive circuits discussed in [3–6] have a common point where they all handle the problems of complex impedance transformation.

However, the 180° out-of-phase power divider [7] with complex impedances transformation, which is very useful in the balanced mixers, push-pull circuits, is still blank. Therefore, this paper mainly discusses 180° out-of-phase power divider with inherent complex-source to complex-load impedance

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transformation. The DSPSL is a balanced transmission line, hence the phase difference between the two output ports is 180° and frequency-independent over a broad band. By using the rigorous odd-even mode analysis, closed-form equations about the circuit parameters are obtained in Section 2. An experimental out-of-phase power divider operating at 1.8 GHz is designed, simulated, and measured in Section 3.

2. CIRCUIT STRUCTURE AND DESIGN THEORY

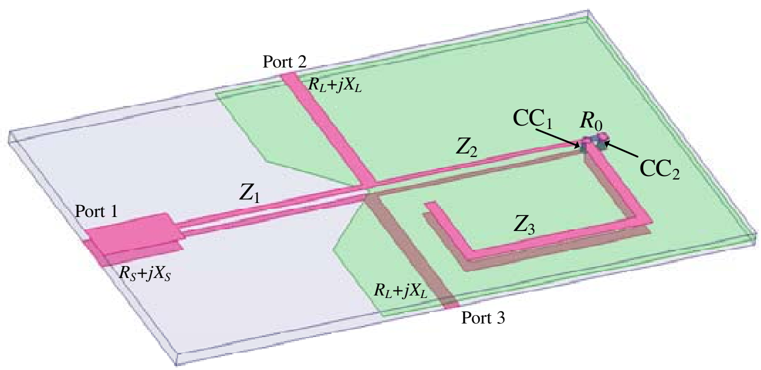

Figure 1. The circuit configuration of the proposed out-of-phase power divider.

Figure 1 shows the physical configuration of the proposed 180° out-of-phase power divider with equal-magnitude signals at two output ports. This complex impedance-transformation out-of-phase power divider has the source impedance R_S+jX_S at port 1 and load impedance R_L+jX_L at ports 2 and 3 as shown in Figure 1. It consists of three double-sided parallel-strip lines Z_i with electrical lengths θ_i (i =1, 2, and 3), a conducted plane, two grounded resistors R_0 and two copper cylinders (CC_1 and CC_2). The conducted plane is inserted in the middle of the substrate as the common ground and converts the DSPSLs (Z_2 and Z_3) into symmetrical back-to-back microstrip lines. When the RF signal is excited at port 1, the phase difference between two output ports is 180° and frequency independent because the DSPSL is a balanced transmission line. Two grounded resistors R_0, which are used to realize the excellent performance of isolation and output port matching, are connected by the CC_1 and CC_2 on both sides. The copper cylinder (CC_2) on the right side of the resistors R_0 is connected to the middle ground directly; however the copper cylinder (CC_1) on the other side is not connected to the middle ground and can be called through ground via (TGV) [8]. This special via can be used to short the resistors when the odd-mode is excited and can be ignored under the even mode.

To see the structure of the proposed circuit clearly, the bottom, middle, and top layers are illustrated in Figure 2. The sizes of the transmission lines on the bottom and top layers are the same, and there is a hole in the middle layer to realize the TGV.

2.1. Odd-Mode Analysis

Under the odd-mode excitation, the middle conducted-plane can be regarded as infinite ground. Signals along the transmission lines on the top and bottom layers have equal amplitudes and opposite phases. The complex impedance of port 1 and DSPSL Z_1 are split to be half of the initial values. All the transmission lines can be regarded as microstrip lines under the odd mode. Two isolation resistors R_0 and transmission line Z_3 are shorted and have no effect on the proposed 180° out-of-phase power divider since the copper cylinder (CC_1) is connected to the virtual ground [8]. The odd-mode equivalent circuit is illustrated in Figure 3(a), and θ_2 can be chosen 90° to simplify the calculated process. Thus, the

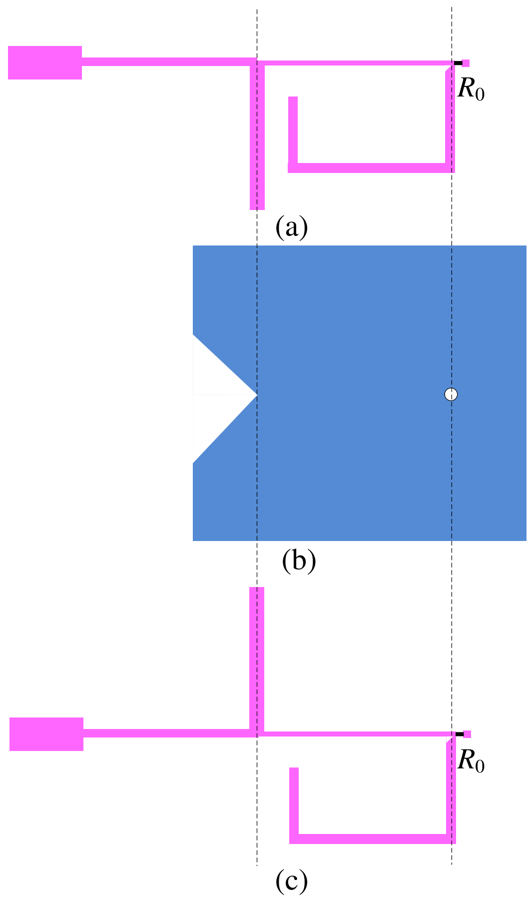

Figure 2. (a) The bottom layer, (b) the middle layer, (c) the top layer of out-of-phase power divider.

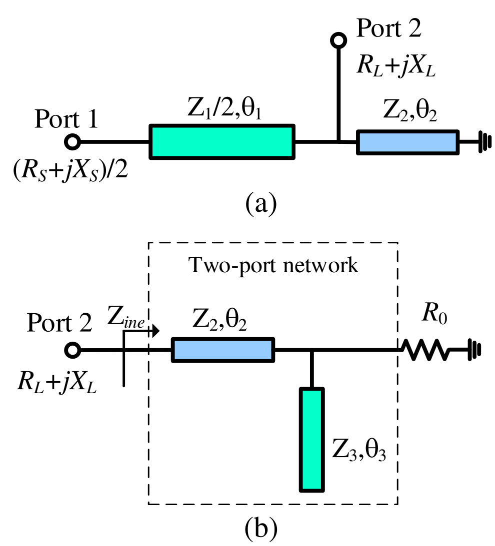

Figure 3. (a) Odd-mode, (b) even-mode equivalent circuits of the proposed out-of-phase power divider.

impedance Z_1 and its electrical length θ_1 can be calculated using the theory in [9, 10]:

$$Z_1 = \sqrt{\frac{2R_L(R_S^2 + X_S^2) - 4R_S(R_L^2 + X_L^2)}{R_S - 2R_L}}, \tag{1}$$

$$\theta_1 = \tan^{-1}\left(\frac{Z_1(R_S - 2R_L)}{2R_S X_L - 2R_L X_S}\right). \tag{2}$$

2.2. Even-Mode Analysis

In the even mode, the signals along the transmission lines on the top and bottom layers have equal amplitudes and phases. The voltages on two strips of the input port and DSPSL Z_1 are the same, thus there is no current flowing through them, and they can be ignored. The copper cylinder (CC_1) has no effect on the isolation resistors R_0 and the transmission lines (Z_2, and Z_3) [8]. The even-mode equivalent circuit is illustrated in Figure 3(b).

Mathematically, the $ABCD$ matrix of the two-port network in Figure 3(b) is:

$$\begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} = \begin{bmatrix} 0 & jZ_2 \\ \dfrac{j}{Z_2} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j\tan\theta_3}{Z_3} & 1 \end{bmatrix} = \begin{bmatrix} -\dfrac{Z_2}{Z_3}\tan\theta_3 & jZ_2 \\ \dfrac{j}{Z_2} & 0 \end{bmatrix} \tag{3}$$

The input impedance Z_{ine} of the even-mode equivalent circuit can be expressed as

$$Z_{ine} = \frac{A_e R_0 + B_e}{C_e R_0 + D_e} \tag{4}$$

The conjugate matching condition at the port 2 becomes:

$$Z_L + jX_L = \overline{Z_{ine}} \tag{5}$$

After substituting Equations (3) and (4) into Equation (5) and separating the real and imaginary parts, R_0 and Z_3 can be achieved as:

$$R_0 = \frac{Z_2^2}{R_L} \tag{6}$$

$$Z_3 = -\frac{R_0 X_L Z_2^2}{R_0 R_L^2 + R_0 X_L^2 - R_L Z_2^2}\tan\theta_3 \tag{7}$$

2.3. The Discussion of the Electrical Parameters

To discuss the circuit parameters conveniently, the complex source impedance R_S+jX_S can be chosen as $(120+j60)\Omega$, and the load impedance R_L+jX_L is chosen as $(90+j40)\,\Omega$ in this paper.

Based on the investigations about the theory of out-of-phase power divider, it can be seen that the characteristic impedance and electrical length of the transmission line Z_1 are only decided by the complex-source and complex-load impedances according to Equations (1) and (2).

Other parameters such as R_0 and Z_3 can be calculated by using Equations (6) and (7) when characteristic impedance Z_2 varies in the range from $20\,\Omega$ to $130\,\Omega$, and electrical length θ_3 is equal to $100°$, $120°$, $140°$, and $160°$, respectively. The curves of calculated parameters (R_0 and Z_3) are plotted in Figure 4. It can be observed that characteristic impedance Z_3 and resistance R_0 increase as the impedance Z_2 increases. When impedance Z_2 is chosen an arbitrary value from $20\,\Omega$ to $130\,\Omega$, the impedance Z_3 increases along with the decrease of electrical length θ_3; however the resistance R_0 keeps unchanged. The variation trend can also been seen from Equations (6) and (7).

It should be noted that the range of characteristic impedances (Z_2 and Z_3) are from $20\,\Omega$ to $130\,\Omega$, and characteristic impedance Z_1 can be chosen from $20\,\Omega$ to $260\,\Omega$ in the practical fabrication.

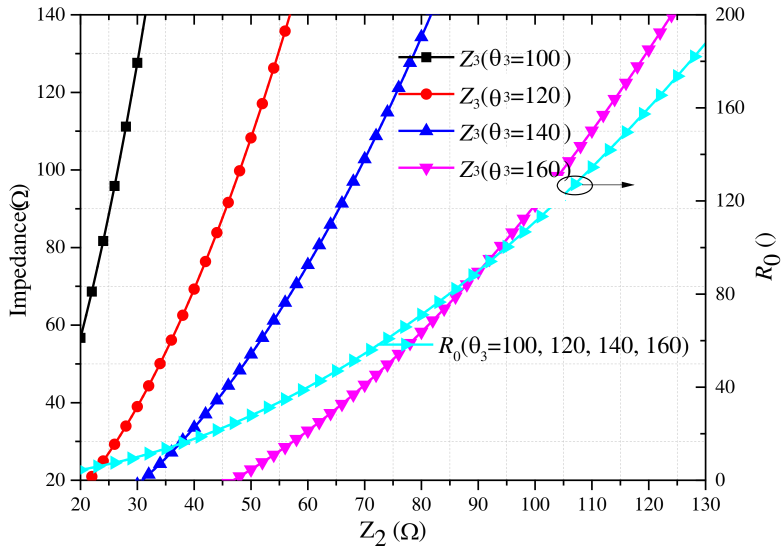

Figure 4. Calculated circuit parameters Z_3 and R_0 VS Z_2 when θ_3 =100°, 120°, 140° and 160°, respectively.

3. SIMULATED AND MEASURED RESULTS

The analytical solutions and parameter analysis have been discussed minutely in Section 2. A three-layer out-of-phase power divider with complex input port impedance $(120+j60)\,\Omega$ and complex output port impedance $(90+j40)\,\Omega$ is fabricated on two Rogers 4350B substrates with a dielectric constant of 3.48 and a thickness of 0.762 mm. Two substrates are bonded together, and the whole thickness including the copper is about 1.6 mm.

In order to be measured by the Vector Network Analyzer directly, three transmission-line transformers are adopted because the source and load impedances are complex. The impedance ZT_1, which is between port 1 and the out-of-phase power divider, is $92.582\,\Omega$, and its electrical length is 65.1601°. The impedance ZT_2, which is between port 2 (3) and the out-of-phase power divider, is $80.6226\,\Omega$, and its corresponding electrical length is 58.1939°. Other parameters of the designed out-of-phase power divider are adopted or calculated as follows: $Z_1 = 153.6229\,\Omega$, $\theta_1 = 82.5824°$, $Z_2 = 80\,\Omega$, $\theta_2 = 90°$, $Z_3 = 58.2352\,\Omega$, $\theta_3 = 160°$, and $R_0 = 71.1111\,\Omega$. The practical resistor can be chosen $68\,\Omega$ with footprint 0806.

The fabricated top view of the out-of-phase power divider is shown in Figure 5. The physical circuit parameters are (unit: mm): $WP_1 = 4.58$, $WP_2 = 1.72$, $WT_1 = 1.80$, $LT_1 = 18.11$, $WT_2 = 0.72$, $LT_2 = 16.39$, $W_1 = 0.79$, $L_1 = 23.74$, $W_2 = 0.56$, $L_2 = 26.74$, $W_3 = 1.34$, $L_{31} = 15.16$, $L_{32} = 22.58$, and $L_{33} = 10.37$.

This fabricated out-of-phase power divider is simulated by HFSS and measured by the Vector Network Analyzer E5071C. Figures 6(a)–(c) compare the simulated and measured results.

The return losses of three ports ($|S_{11}|$, $|S_{22}|$, and $|S_{33}|$) are all above 17 dB at both the simulated and measured results at the operating frequency. The measured results of the out-of-phase power divider in Figure 6(a) show that the insertion loss $|S_{21}|(|S_{31}|)$ is 3.6 dB (3.7 dB), indicating that the magnitudes of the output signal are equal. The isolation between two output ports is -24.28 dB, and it can be seen that the two resistors play a key role in the isolation structure. Furthermore, the measured phase difference between port 2 and port 3 is in the range of $-180° \pm 5°$ from 1 GHz to 2.6 GHz in Figure 6(c). It fully demonstrates that this power divider has the function of converting a signal into two-way differential signals, and the performance of out-of phase is frequency independent. The available bandwidth of the power divider is from 1.68 GHz to 2.02 GHz under the conditions of $|S_{ii}| < -10$ dB (i = 1, 2, 3), $|S_{21}|\&|S_{31}| > -4$ dB, $|S_{23}| < -10$ dB. Small performance degradation and frequency shift can be accounted for the errors of fabrication, instrument calibration, measurement, etc.

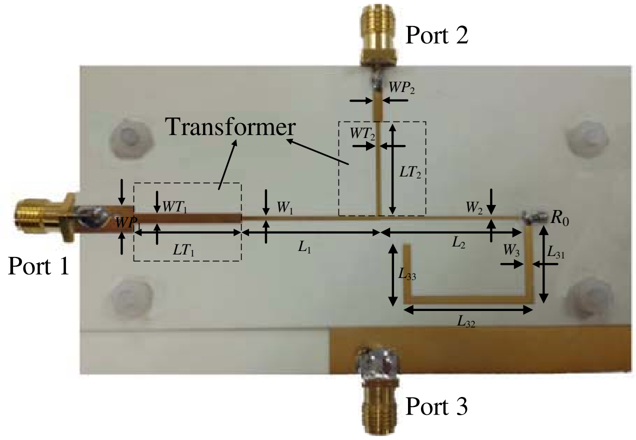

Figure 5. Top view of the fabricated out-of-phase power divider at f_0 =1.8 GHz.

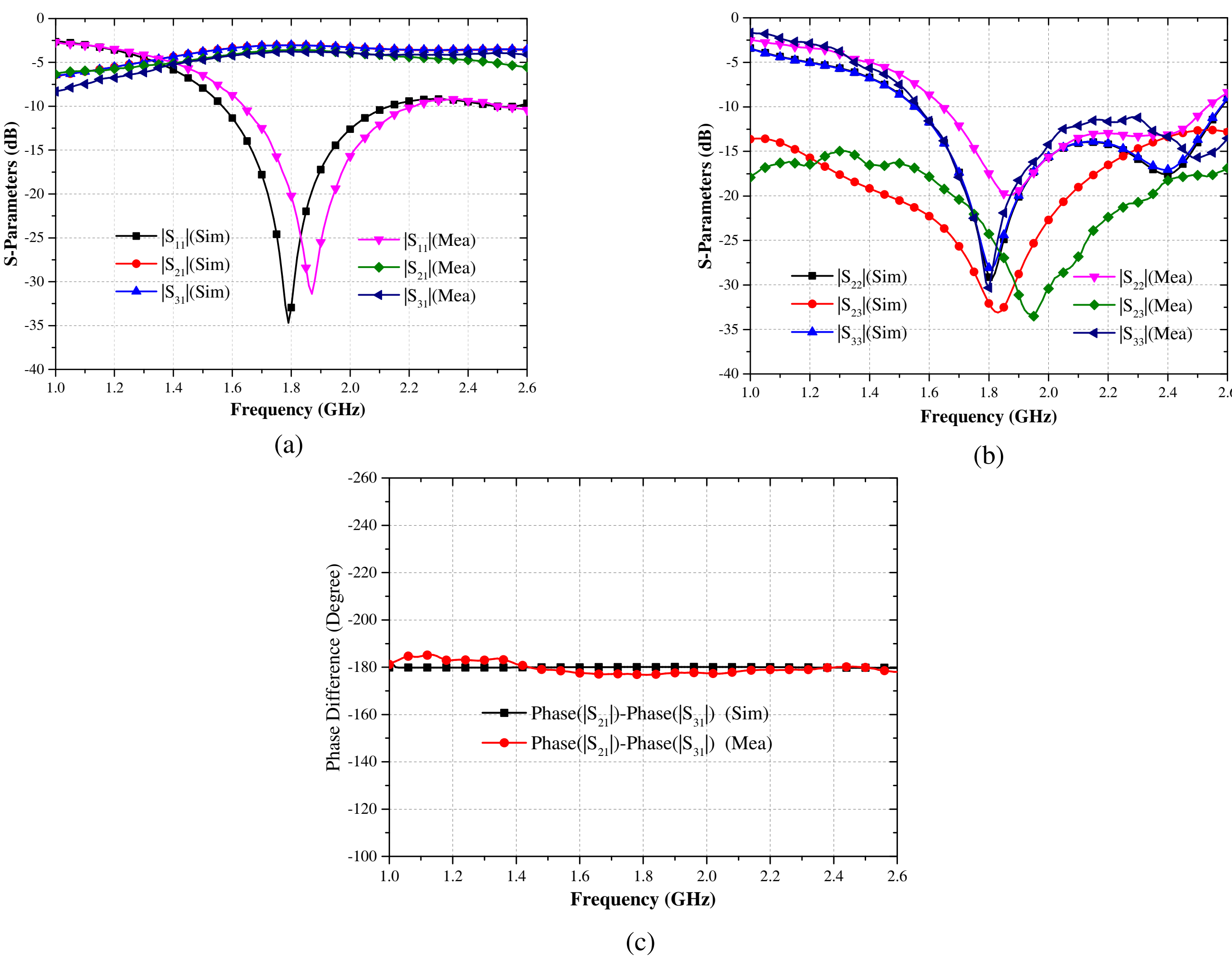

Figure 6. (a) $|S_{11}|$, $|S_{21}|$, $|S_{31}|$, (b) $|S_{22}|$, $|S_{23}|$, $|S_{33}|$, (c) phase difference of the proposed out-of-phase power divider.

4. CONCLUSION

A three-layer out-of-phase power divider with the function of complex-source to complex-load impedance transformation is illustrated and discussed in this paper. This proposed power divider, constructed by three DSPSLs, a conduct plane in the middle as the common ground, and two isolation resistors for heat sinking and high isolation, features complex-impedance transformation, high power capability and excellent 180° phase difference over a broad band. Rigorous odd- and even-mode analysis, closed-form analytical expressions, and the discussion of circuit parameters are given in Section 2. To demonstrate the practical balance performance, perfect isolation and return loss, a practical out-of-phase power divider is designed, fabricated, and measured. Good agreements between the simulated and measured results verify this proposed circuit. It can be fully believed that this novel out-of-phase power divider with complex-impedance transformation will greatly be used in the balanced circuits and systems.

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