

A Novel Unequal Broadband Out-of-Phase Power Divider Using DSPSLs

Yun Long Lu, Gao-Le Dai, and Kai Li

In this paper, a novel unequal broadband out-of-phase power divider (PD) is presented. Double-sided parallel-strip lines (DSPSLs) are employed to achieve an out-of-phase response. Also, an asymmetric dual-band matching structure with two external isolation resistors is utilized to obtain arbitrary unequal power division, in which the resistors are directly grounded for heat sinking. A through ground via (TGV), connecting the top and bottom sides of the DSPSLs, is used to short the isolation components. Additionally, this property can efficiently improve the broadband matching and isolation bandwidths. To investigate the proposed divider in detail, a set of design equations are derived based on the circuit theory and transmission line theory. The theoretical analysis shows that broadband responses can be obtained as proper frequency ratios are adopted. To verify the proposed concept, a sample divider with a power division of 2:1 is demonstrated. The measured results exhibit a broad bandwidth from 1.19 GHz to 2.19 GHz (59.2%) with a return loss better than 10 dB and port isolation of 18 dB.

Keywords: Power divider, unequal, out-of-phase, external isolation resistor, high power-handling capability.

I. Introduction

Power dividers (PDs) are key components extensively used in microwave and communications systems. Wilkinson [1] and Gysel [2] PDs are the most popular types. Wilkinson PDs have been extensively investigated and widely used in many applications. For instance, equal/unequal single-band [3], [4] and dual-band [5], [6] Wilkinson PDs with various topologies have been developed. They, however, have difficulty diffusing the heat to the outside because their isolation resistors are always located inside of the circuit topologies, resulting in low power-handling capability. Gysel PDs, on the other hand, employ external isolation resistors for heat sinking to obtain high power-handling capability [7]-[11].

Unfortunately, neither the Wilkinson PD nor the Gysel PD is suitable for balanced circuits, such as balanced mixers, multipliers, and push-pull amplifiers, due to their IN-PHASE responses. To meet the demand, several balanced transmission lines, such as microstrip-slot lines [12] and asymmetrical coplanar strip lines (ACPSs) [13] are used to achieve out-of-phase responses. Recently, the double-sided parallel-strip line (DSPSL) became very popular in out-of-phase PD designs [14]-[17]. Herein, the authors employ DSPSLs to design novel high power out-of-phase PDs with equal power division and narrow bandwidth.

Based on our further investigation, in this paper, we present a novel unequal broadband out-of-phase PD using DSPSLs for balanced high-power applications. The proposed divider still utilizes DSPSLs to obtain out-of-phase responses, whereas a newly asymmetric structure is realized for unequal power division. Two external isolation resistors, on the top and bottom sides of the device, are grounded directly for heat sinking so that the PD is very significant in high-power applications. A

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through ground via (TGV), connecting both sides of the DSPSLs, is employed. The special via is realized to make the isolation resistors shorted at the full-frequency band when the excitation is odd mode. Meanwhile, it can be ignored when the excitation is even mode. This property can be used to improve the bandwidth characteristic. To investigate the proposed divider in detail, a set of design equations is derived based on the circuit theory and transmission line theory. Theoretical analysis shows that the proposed PD can operate at two frequencies, f_1 and mf_1 , with a frequency ratio range of $1 < m < 1.6$. Additionally, broadband responses can be obtained as proper frequency ratios are adopted. To demonstrate the proposed idea, an unequal (2:1) out-of-phase PD is designed. The measured results show that a bandwidth of 1,000 MHz (59.2%) with a return loss better than 10 dB and port isolation of 18 dB is obtained. Due to the characteristics of broadband matching/isolation (out-of-phase feature and high power capability), the proposed PD is a perfect candidate for balanced high-power applications.

II. Configuration and Analysis of Proposed PD

Figures 1(a) and (b) show the configuration of the proposed broadband PD. It consists of several asymmetrical DSPSLs, two external isolation resistors, and a mid-inserted conductor plane as well as a TGV. Including the TGV means that a metal via connects the top and bottom sides of the DSPSL through the mid-inserted common conductor plane. The conductor plane is inserted in the mid layer as a common ground, which

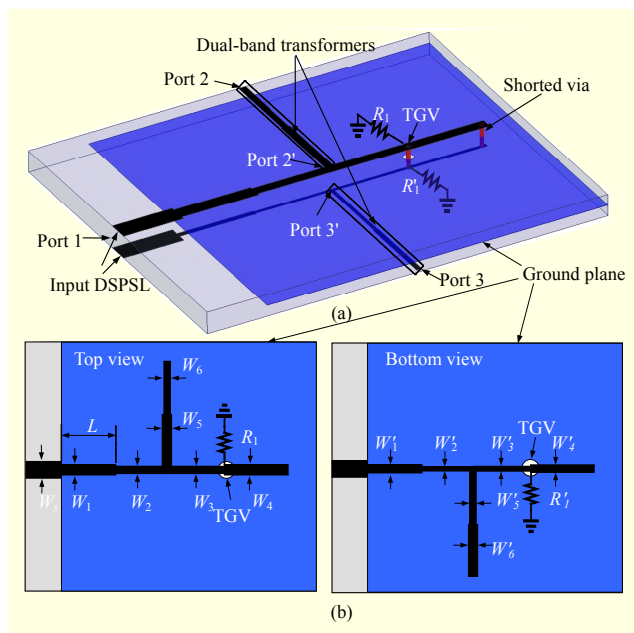


Fig. 1. Layout of proposed PD: (a) configuration, (b) dimension.

segregates the DSPSLs from back-to-back microstrip lines, as discussed in [14]-[17]. For odd mode excitation, the voltage at the TGV must be equal to zero. The absorbing resistors and DSPSL following the TGV are shorted. For even mode excitation, the voltage along the DSPSL has identical amplitude and phase. Figures 1 (a) and (b) illustrate the dimensions of the top and bottom circuits. When Port 1 of the proposed PD in Figs. 1(a) and 1 (b) is excited, the voltages on the top and bottom layers have identical amplitudes and opposite directions (out-of-phase). Therefore, the impedances of the transmission lines on the bottom layer must be k^2 times the impedances of those on the top layer to fulfill the PD ratio ($P_3 = k^2 P_2$).

We employ the odd and even mode methods to obtain the design equations derived from the matching conditions in the next section.

III. Even and Odd Mode Excitations for Proposed PD

1. Odd Mode Excitation

For the odd mode excitation, Port 1 is excited. The voltages on the top layer and bottom layer have identical amplitudes but opposite phases. On the other hand, the TGV connects the DSPSLs together so that the voltage is zero. In this case, the isolation resistors are shorted and the odd mode equivalent circuit of the proposed PD excluding the dual-band transformers can be simplified as shown in Fig. 2.

As the output power at Port 3' is k^2 times that at Port 2', the impedances at Ports 1, 2', and 3' must satisfy the following expressions:

$$Z_i = k^2 Z_i', \quad (i = 1, 2, 3, 4) \quad R_1' = k^2 R_1, \quad (1.1)$$

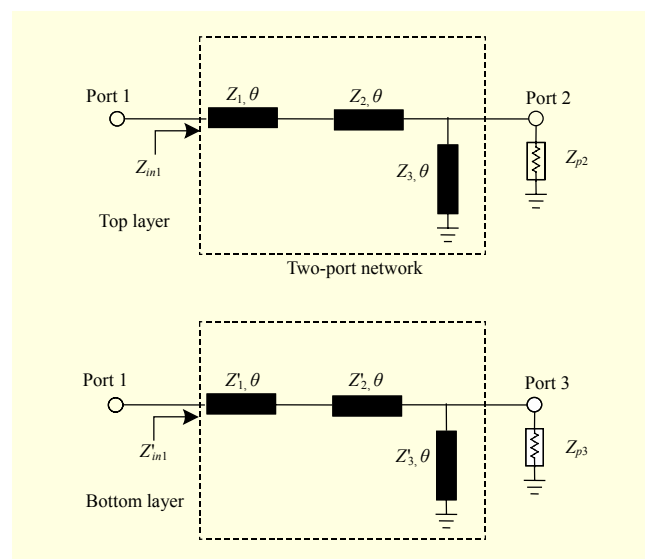


Fig. 2. Equivalent circuit of PD for odd mode excitation.

$$Z'_{in1} = k^2 Z_{in1}, \quad Z_{p3} = k^2 Z_{p2}, \quad (1.2)$$

where the input impedance from Port 1 looking into the top layer and bottom layer is Z_{in1} and Z'_{in1} , respectively, and the termination of Port 3' and Port 2' is Z_{p3} and Z_{p2} , respectively.

To achieve perfect matching at Port 1, the following is applied:

$$Z_{in1} + Z'_{in1} = Z_0. \quad (2)$$

Using (1.2) as a substitute in (2) results in the following:

$$Z_{in1} = \frac{Z_0}{1+k^2}, \quad (3)$$

$$Z'_{in1} = \frac{k^2 Z_0}{1+k^2}. \quad (4)$$

Mathematically, for the top layer, the ABCD matrix of the two-port network can be calculated as follows [15]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos \theta & jZ_1 \sin \theta \\ j\frac{1}{Z_1} \sin \theta & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} \cos \theta & jZ_2 \sin \theta \\ j\frac{1}{Z_2} \sin \theta & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{1}{jZ_3 \tan \theta} & 1 \end{bmatrix}, \quad (5)$$

where

$$A = \cos^2 \theta - \frac{Z_1}{Z_2} \sin^2 \theta + \frac{Z_1 + Z_2}{Z_3} \cos^2 \theta, \quad (6.1)$$

$$B = j(Z_1 + Z_2) \sin \theta \cos \theta, \quad (6.2)$$

$$C = j\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right) \sin \theta \cos \theta + j\frac{Z_2}{Z_1 Z_3} \sin \theta \cos \theta - j\frac{1}{Z_3} \frac{\cos^2 \theta}{\tan \theta}, \quad (6.3)$$

$$D = -\frac{Z_2}{Z_1} \sin^2 \theta + \cos^2 \theta. \quad (6.4)$$

Subsequently, the input impedance can be expressed as

$$Z_{in1} = \frac{AZ_{p2} + B}{CZ_{p2} + D}. \quad (7)$$

To achieve reasonable results, Z_{p2} and Z_{p3} are defined as

$$Z_{p3} = kZ_0, \quad Z_{p2} = \frac{Z_0}{k}. \quad (8)$$

By combining (3), (6), and (8), we obtain

$$Z_2 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, \quad (9.1)$$

$$Z_3 = \frac{(1+k^2)(Z_1 + Z_2)}{\left[(1+k^2) \frac{Z_1}{Z_2} - k \frac{Z_2}{Z_1} \right] \tan^2 \theta - (1-k+k^2)}, \quad (9.2)$$

where

$$a = \frac{Z_0^2}{Z_1^2} k \tan^2 \theta + k(1+k^2)^2, \quad (10.1)$$

$$b = -2k \frac{Z_0^2}{Z_1} + 2k(1+k^2)^2 Z_1, \quad (10.2)$$

$$c = Z_0^2 \left[-(1+k^2) \tan^2 \theta - \frac{1-k+k^2}{\tan^2 \theta} - 2(1+k^2) \right] + k(1+k^2)^2 Z_1^2. \quad (10.3)$$

To fulfill the dual-band impedance matching condition, the electrical length (θ) of the transmission lines at f_1 should be satisfied as follows [19]:

$$\theta = \frac{\pi}{1+m}, \quad (11)$$

where m is the frequency ratio of the dual-band operation. For the bottom layer, the impedances of the transmission lines can be calculated by using (1). Consequently, the impedances of Z_2 and Z_3 can be uniquely determined for a selected Z_1 once the designed frequency ratio m is fixed.

2. Even Mode Excitation

Figure 3 shows the even mode equivalent circuit of the proposed PD excluding the dual-band transformers. Assume current sources of I_2 and I_3 ($I_2 = k_2 I_3$) to Ports 2' and 3', respectively, so that the voltage distribution on the top layer is identical to that on the bottom layer when measured at an equal distance from Port 2' and Port 3'. Therefore, the TGV can be ignored since it has no effect on the DSPSL. Also, the in-phase excitations at Ports 2' and 3' do not enable the signals to be combined at the interface, and the input port can be regarded as an open circuit.

Based on the transmission line theory, the input impedances of the top layer can be expressed as

$$Z_{in2} = \frac{Z_1}{j \tan \theta}, \quad (12.1)$$

$$Z_{in3} = Z_2 \frac{Z_{in2} + jZ_2 \tan \theta}{Z_2 + jZ_{in2} \tan \theta}, \quad (12.2)$$

$$Z_{pin} = \frac{Z_{p2} Z_{in3}}{Z_{p2} + Z_{in3}}, \quad (12.3)$$

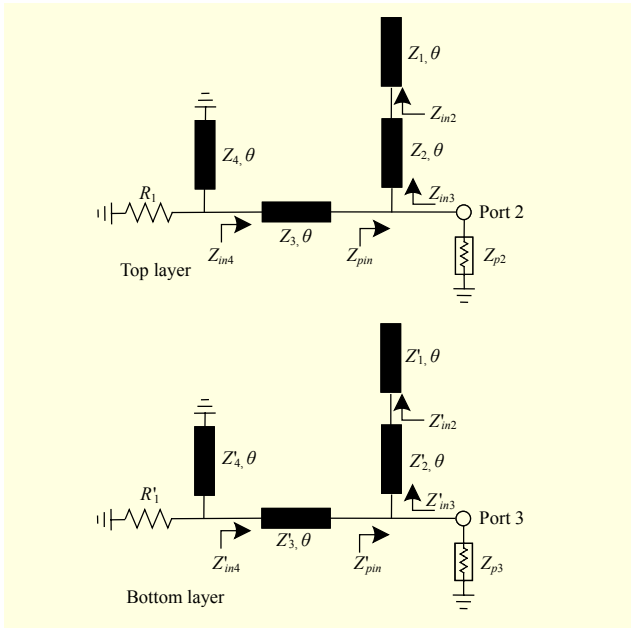


Fig. 3. Equivalent circuit of PD for even mode excitation.

$$Z_{in4} = Z_3 \frac{Z_{pin} + jZ_3 \tan \theta}{Z_3 + jZ_{pin} \tan \theta}. \quad (12.4)$$

The matching condition becomes

$$\left(\frac{1}{\frac{1}{R_1} + \frac{1}{jZ_4 \tan \theta}} \right)^* = Z_{in4}. \quad (13)$$

By separating the real and imaginary parts of (13), the designed parameters of R_1 and Z_4 can be achieved as follows:

$$R_1 = \frac{1}{\text{Re}(Z_{in4}^{-1})}, \quad (14.1)$$

$$Z_4 = \frac{1}{\tan \theta \cdot \text{Im}(Z_{in4}^{-1})}. \quad (14.2)$$

Similarly, the impedances Z_4' and R_1' can be calculated by using (1), as follows:

$$Z_4' = k^2 Z_4, \quad R_1' = k^2 R_1. \quad (15)$$

For the unequal out-of-phase PD, terminations Z_{p2} and Z_{p3} in Fig. 1 are not equal to Z_0 . Two dual-band transformers consisting of two sections of transmission lines are needed to respectively transform Z_{p2} and Z_{p3} into Z_0 . According to Monzon's analytical solution [18], the impedances of the dual-band transformers can be derived by

$$Z_5 = \sqrt{\frac{Z_0}{2p^2} (Z_{p2} - Z_0) + \sqrt{\left[\frac{Z_0}{2p^2} (Z_{p2} - Z_0) \right]^2 + Z_0^3 Z_{p2}}}, \quad (16.1)$$

$$Z_6 = \frac{Z_0 Z_{p2}}{Z_5}, \quad (16.2)$$

$$Z_5' = kZ_6, \quad (16.3)$$

$$Z_6' = kZ_5, \quad (16.4)$$

where $p = \tan \theta$, θ and Z_{p2} are defined by (8) and (11).

IV. Analysis of Impedance Values and High Power-Handling Feature

By using the design equations (1), (10), and (15) through (17), we can obtain the available ranges of frequency ratios for different power-division ratios when the value of Z_1 is fixed. According to the analysis in sections II and III, we only need to calculate the impedances on the top layer; the high impedances on the bottom layer can be derived by using (1). To simplify the analysis, we set $Z_1 = 42.5 \Omega$ and $Z_1 = 26.5 \Omega$ for $k^2 = 1$ and $k^2 = 2$, respectively. For the top layer with lower impedances, we assume that the source impedance is $Z_0 = 50 \Omega$ and all the available impedance values are in a practical range of $10 \Omega < Z_i < 150 \Omega$ ($10 \Omega < Z_i < 75 \Omega$ when $k^2 = 2$). The corresponding design parameters against frequency ratio $m = f_1/f_2$ can be calculated by using MATLAB, which are shown in Table 1. Therefore, a frequency ratio range covering $1 < m < 1.6$ can

Table 1. Design parameters with typical frequency ratio $1 < m < 1.6$.

Power-division ratio	Frequency ratio range	Impedance value (Ω)						
		Z_1	Z_2	Z_3	Z_4	R_1	Z_5	Z_6
$k^2=1$	m	Z_1	Z_2	Z_3	Z_4	R_1	Z_5	Z_6
	1.0	42.5	60.1	33.7	10.2	22.8	50.0	50.0
	1.1	42.5	59.3	33.9	10.7	23.9	50.0	50.0
	1.2	42.5	57.2	34.2	12.3	27.2	50.0	50.0
	1.3	42.5	54.4	34.7	15.1	33.0	50.0	50.0
	1.4	42.5	51.3	35.5	19.7	41.9	50.0	50.0
	1.5	42.5	48.2	36.4	27.7	55.5	50.0	50.0
1.6	42.5	45.2	37.5	42.6	76.1	50.0	50.0	
$k^2=2$	1.0	26.5	38.6	31.1	15.2	27.3	45.9	38.6
	1.1	26.5	38.2	31.3	16.1	28.7	45.8	38.6
	1.2	26.5	37.2	31.8	18.7	32.5	45.8	38.6
	1.3	26.5	35.8	32.7	23.6	39.2	45.7	38.7
	1.4	26.5	34.2	33.8	32.5	49.6	45.6	38.8
	1.5	26.5	32.6	35.3	50.0	65.2	45.4	38.9
	1.6	26.5	31.5	36.5	74.7	80.6	45.3	39.0

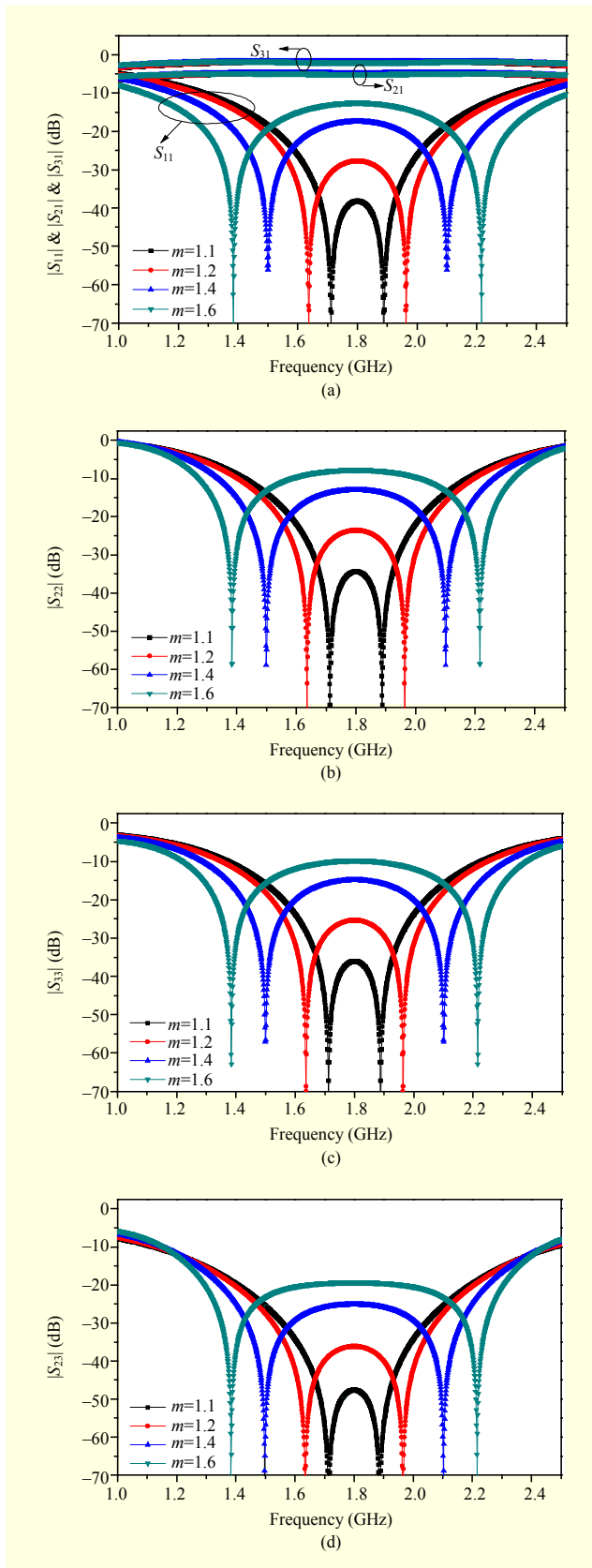


Fig. 4. Calculated S-parameters of proposed PD under different frequency ratio m .

be obtained for different power-division ratios.

As discussed in [7]-[11], [15], the proposed PD has a high power-handling feature due to the external isolation resistors. However, for the PDs presented in [7]-[11], [15], the external isolation resistors are generally shorted by transmission lines. Therefore, the out-of-band signal power is partly dissipated on the isolation resistors because of the frequency-dependent transmission lines. In the design presented herein, the isolation resistors are shorted by the TGV structure. Based on the analysis in section III, when Port 1 is excited, the voltage at the TGV equals zero and the isolation resistors are shorted at the full-frequency band. Thus, there is no power dissipated on the isolation resistors. With this structure, the proposed PD has a high power capacity both in and out of the operation bands.

V. Analysis of Broadband Characteristic

To investigate the broadband characteristic of the proposed unequal PD, we choose the power-division ratio $k^2 = 2$. The transmission and reflection coefficients of the proposed PD can be calculated according to the transmission theory [15], [19]. The corresponding calculated results of the PD are obtained as shown in Fig. 4. As evidenced in this figure, it is found that the proposed PD with power-division ratio $k^2 = 2$ can operate at broadband response when proper frequency ratios are adopted.

VI. Designed Example and Measurement

The proposed broadband unequal (2:1) out-of-phase PD is

Table 2. Dimensions of experimental PD.

$W_1 = 4.16$ mm	$W_2 = 3$ mm	$W_3 = 3.4$ mm
$W_4 = 4.36$ mm	$W_5 = 2.54$ mm	$W_6 = 2$ mm
$W'_1 = 1.52$ mm	$W'_2 = 1$ mm	$W'_3 = 1.18$ mm
$W'_4 = 1.62$ mm	$W'_5 = 1.12$ mm	$W'_6 = 1.59$ mm
$L = 25.5$ mm	$W_s = 4.59$ mm	$R_1 = 51 \Omega$
$R'_1 = 100 \Omega$		

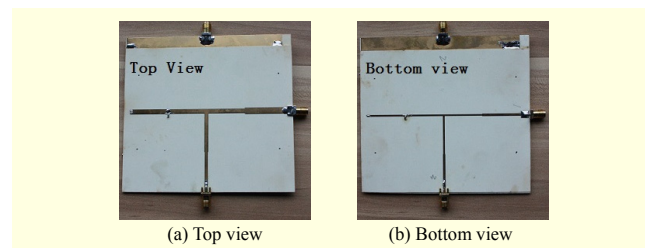


Fig. 5. Photographs of fabricated filter.

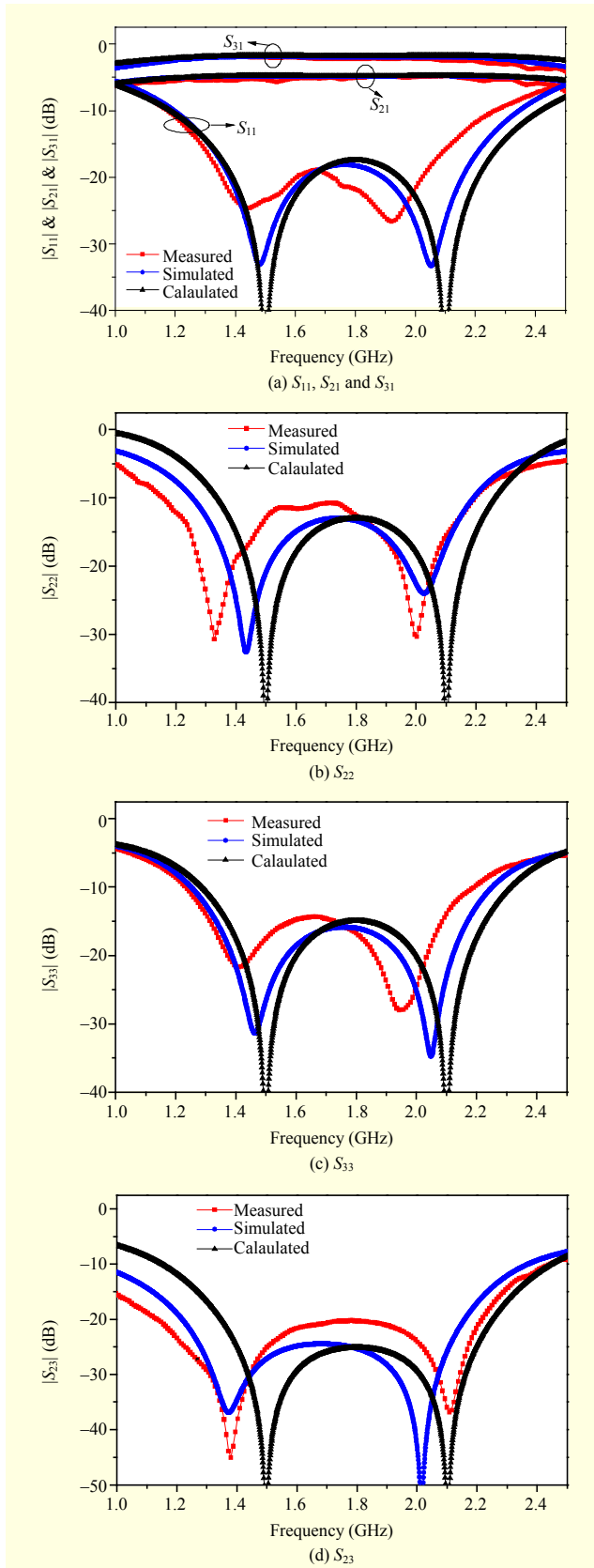


Fig. 6. Calculated, EM simulated, and measured S-parameters of proposed PD.

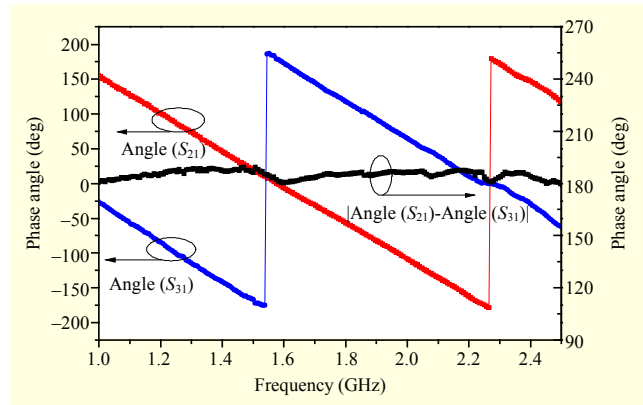


Fig. 7. Measured phase response of proposed PD.

implemented to verify the previous analysis. The divider is fabricated on two sandwiched Rogers 4350 substrates with a relative dielectric constant of 3.48, a thickness of 0.76 mm, and a loss tangent of 0.004.

The typical parameters of the designed PD are as follows: $Z_0 = 50 \Omega$, $f_1 = 1.5 \text{ GHz}$, $f_2 = 2.1 \text{ GHz}$, $m = 1.4$, and $k = \sqrt{2}$. The impedance values of the proposed PD calculated by using (1), (10), and (15) through (17) are as follows: $Z_1 = 26.5 \Omega$, $Z_2 = 34.2 \Omega$, $Z_3 = 33.8 \Omega$, $Z_4 = 32.5 \Omega$, $R_1 = 49.6 \Omega$, $Z_5 = 45.6 \Omega$, $Z_6 = 38.8 \Omega$, $Z'_1 = 53 \Omega$, $Z'_2 = 68.4 \Omega$, $Z'_3 = 67.6 \Omega$, $Z'_4 = 65 \Omega$, $R'_1 = 99.2 \Omega$, $Z'_5 = 54.9 \Omega$, and $Z'_6 = 64.5 \Omega$. The desired electrical length of the transmission lines is 75° . The physical dimensions of the circuit are achieved as illustrated in Table 2 by using Ansys HFSS. For the actual implementation, components $R_1 = 50 \Omega$ and $R'_1 = 100 \Omega$ are adopted in this design.

Photographs of the fabricated PD are shown in Fig. 5. The measurement is accomplished by using the Agilent 8358E network analyzer. Comparisons of the calculated, simulated, and measured results are shown in Figs. 6(a) through 6(d). The measured return loss (S_{11} , S_{22} , S_{33}) and isolation (S_{32}) are below between -10 dB and -15 dB from 1.19 GHz to 2.19 GHz (FBW: 59.2%). The measured value of S_{31} and S_{21} at a center frequency of 1.69 GHz is 2.25 dB and 5.12 dB, respectively, whereas, in the ideal case of the 2:1 PD, S_{31} is 1.77 dB and S_{21} is 4.77 dB. Furthermore, the measured phase difference between the two output ports is in the range of $180^\circ \pm 8^\circ$ from 1.19 GHz to 2.19 GHz, as shown in Fig. 7.

VII. Conclusion

In this paper, a novel unequal broadband out-of-phase PD was presented. The proposed PD employs external isolation resistors, which have advantages in heat sinking. The TGV structure is used to improve the bandwidth and high power capacity. The design equations of the proposed PD were

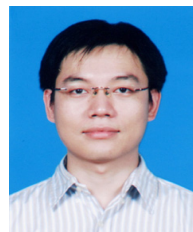
derived by using odd mode and even mode excitation. To demonstrate the proposed idea, an unequal (2:1) broadband out-of-phase PD was designed and fabricated. The simulated and measured results show agreement. This PD will be very useful for the high-power balanced systems and push-pull applications.

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