A Broadband Out-of-Phase Gysel Power Divider Based on a Dual-Band Circuit With a Single Fixed Isolation Resistor

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ABSTRACT: Based on the double-sided parallel-strip lines with an inserted conductor as a virtual ground, a high power divider with dual-band/broadband response and frequency-independent 180° phase difference between the output ports is implemented in this paper. The circuit topology employs a single commercially available external isolation resistor as well as moderate line impedances (15–100 ohm), making it suitable for high-power applications. Precise closed-form design equations on the basis of even- and odd-mode analysis are derived. In addition to the wide range of frequency band ratios from 1 to 2.65, broadband response is also obtained by selecting the proper value of frequency band ratios. To substantiate the design equations and theory, a circuit with 2:1 frequency ratio and 84.5% bandwidth referring to 16 dB isolation and 12 dB return loss values is developed. To the authors' knowledge, this is the widest bandwidth reported for out-of-phase high power dividers. Int J RF and Microwave CAE 00:000–000, 2016.

Keywords: out-of-phase power divider; even and odd mode analysis; broadband power divider; double-sided parallel-strip line with inserted conductor

I. INTRODUCTION

Applications of high power dividers and combiners in many microwave systems have been so prevalent during the last decade that many studies have focused on the performance improvement of Gysel power divider [1] as an integral part. Thanks to the introduction of computer software and optimization algorithms, many high power dividers featuring multi-band operation along with in-phase responses were proposed [2–8]. Nonetheless, balanced circuits, such as balanced mixers and push-pull amplifiers require out-of-phase power dividers to operate correctly. Thus far, double-sided parallel-strip lines (DSPSLs) have been extensively used to realize dual-band out-of-phase circuits [9–16]. The circuits presented in [9–13] utilize internal isolation resistors and are low-power. Besides, the swap structure in Refs. [9–11] requires additional optimizations for final implementation. The circuit presented in Ref. [14] is a T-junction with broadband response. Nevertheless, it is not lossless and when it is used for high-power application the lossy nature of it can be problematic because of the extra heat generation within the circuit. However, the circuits presented in Refs. [15–19] have external isolation resistors and are capable of handling high power. The circuit

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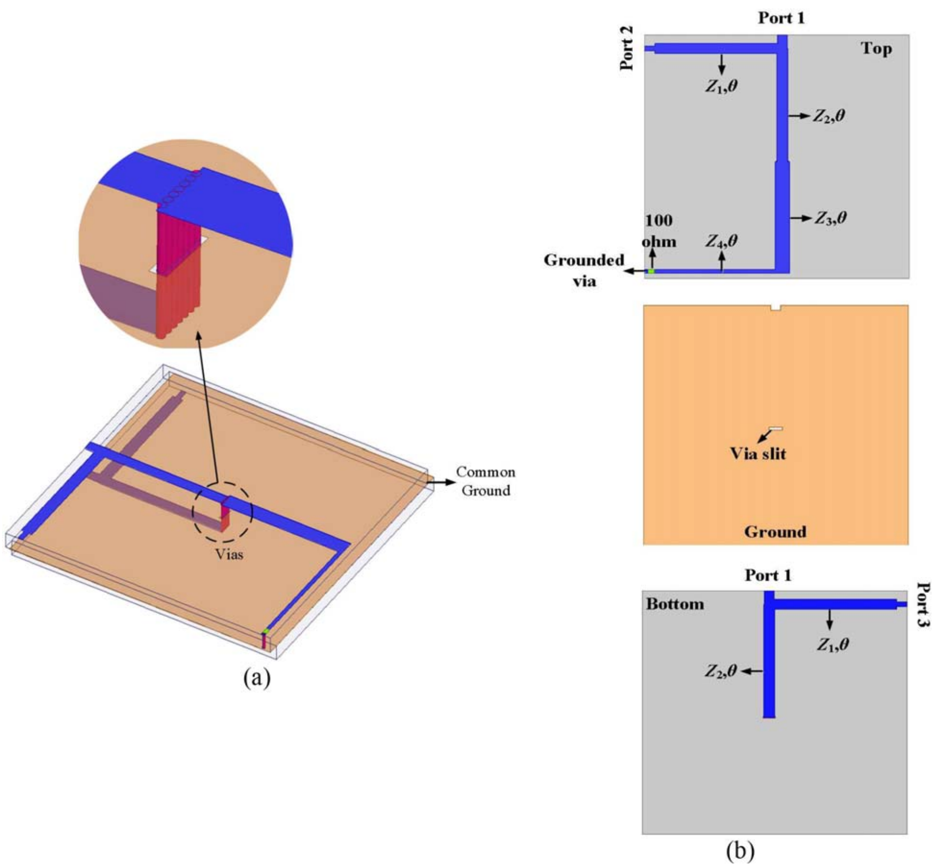

Figure 1 Structure of the proposed power divider. (a) 3D layout. (b) 2D layout.

presented in Ref. [15] has some drawbacks including: (1) frequency- dependent isolation resistors, resulting in inaccurate design implementation at some frequency ratios; (2) utilizing narrow transmission lines up to 150 ohm; (3) limited frequency band ratios (1:62 $< f_2/f_1 <$ 3) using 10–150 ohm transmission lines; (4) limited bandwidth. Although the circuits in Refs. [16] and [17] have wide bandwidth, they still use narrow transmission lines and frequency-dependent resistor values, whereas the frequency band ratios are limited to a range of 1 to 1.7, restricting the overall bandwidth of the system [18], utilizes a planar circuit with additional optimization and modifications on transmission line widths to improve the bandwidth of the circuit but it still has a limited bandwidth along with a high amplitude imbalance. A dual-band out-of-phase is reported in Ref. [19] with wide frequency ratio. This power divider however operates over a narrow bandwidth and needs extra surface area to accommodate impedance transformers at the input and output ports.

In this paper, a new out-of-phase high power divider with broadband performance and analytical approach is proposed based on reciprocity and matching at all ports. The proposed circuit is based on a dual-band circuit analysis and offers some features encompassing: (1) wide range of frequency band ratios ($1 < f_2/f_1 <$ 2.65); (2) using a single 100 ohm isolation resistor within this range of frequency band ratios; (3) employing moderate line impedances (15$\sim$100 ohm) within this range of frequency band ratios; (4) broadband response based on selecting proper values of f_2/f_1; (5) frequency-independent 180° phase difference between the output ports.

II. CIRCUIT STRUCTURE AND DESIGN PROCEDURE

The structure of proposed design is illustrated in Figure 1, consisting of six transmission lines with identical electrical lengths. Four transmission lines located at the top layer are connected to the two lines in the bottom layer through via holes. There is merely one isolation resistor required for this structure. Odd- and even-mode analyses Refs. [20, 21] are applied to this structure for deriving the necessary equations.

A. Odd-Mode Analysis

In the case of odd-mode, the conductor inserted in the middle of the substrate is regarded as a virtual ground and the via hole is short circuited. Besides, the input port impedance is $Z_{0/}2$, where Z_0 is the port impedance and

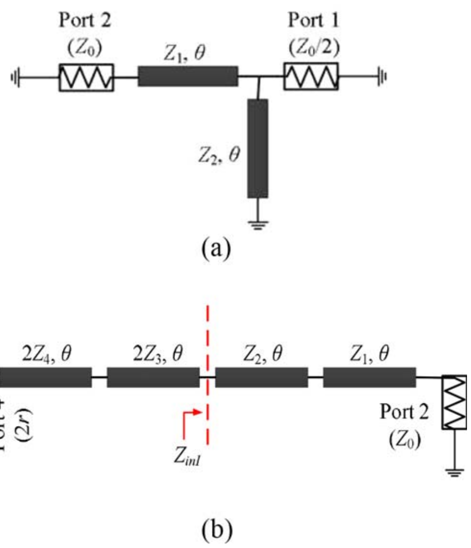

Figure 2 (a) Odd-mode equivalent circuit of the proposed divider. (b) Even-mode equivalent circuit of the proposed power divider.

equal to 50 ohm. Based on this information, Figure 2(a) depicts the odd-mode equivalent circuit. According to the odd-mode analysis, if we define $q = \tan\ \theta$ $(\theta(f_1) = f_1/(f_1 + f_2)$ and $\theta(f_2) = \pi f_2/(f_1 + f_2)$, the values of Z_1 and Z_2 are obtained based on the solution of real and imaginary parts of Eq. (1).

$$\frac{Z_1\left(\dfrac{\dfrac{Z_0}{2}\times jZ_2q}{\dfrac{Z_0}{2}+jZ_2q}+jZ_1q\right)}{Z_1+j\left(\dfrac{\dfrac{Z_0}{2}\times jZ_2q}{\dfrac{Z_0}{2}+jZ_2q}\right)q}=Z_0 \tag{1}$$

$$Z_1=Z_2=Z_0\sqrt{\frac{q^2-1}{2q^2}} \tag{2}$$

B. Even-Mode Analysis

In the even-mode case, the input port is regarded as an open-circuit since the magnitude and phase of the signals at the input port are the same. In the same way, Z_3, Z_4, and r (isolation resistance) are doubled. Therefore, the equivalent circuit is illustrated in Figure 2(b). Since Z_1 and Z_2 were obtained from the odd-mode state, we can simplify Z_{inI} as follows.

$$Z_{inI}=R+jX \tag{3}$$

Where

$$R=\frac{(-1+q^2)(1+q^2)^2Z_0^2}{8q^4+(-1+q^2)^3Z_0^2} \tag{4}$$

And

$$X=-\frac{\sqrt{2-\frac{2}{q^2}}(-Z_0^2+q^2(-2+Z_0^2))(-1+q^2)qZ_0}{8q^4+(-1+q^2)^3Z_0^2} \tag{5}$$

Matching port 4 in this case yields the following equation.

$$\frac{2Z_4\left(\dfrac{2Z_3(Z_{inI}+2jqZ_3)}{2Z_3+jqZ_{inI}}+2jqZ_4\right)}{2Z_4+jq\dfrac{2Z_3(Z_{inI}+2jqZ_3)}{2Z_3+jqZ_{inI}}}=2r \tag{6}$$

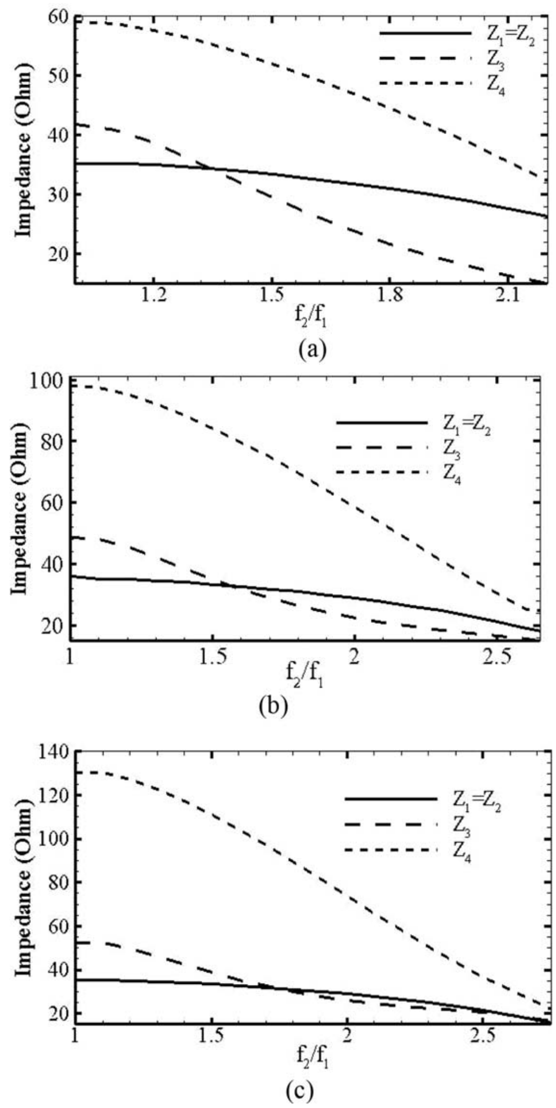

Figure 3 Variation of transmission line impedances versus frequency band ratios. (a) $r = 50$. (b) $r = 100$. (c) $r = 150$.

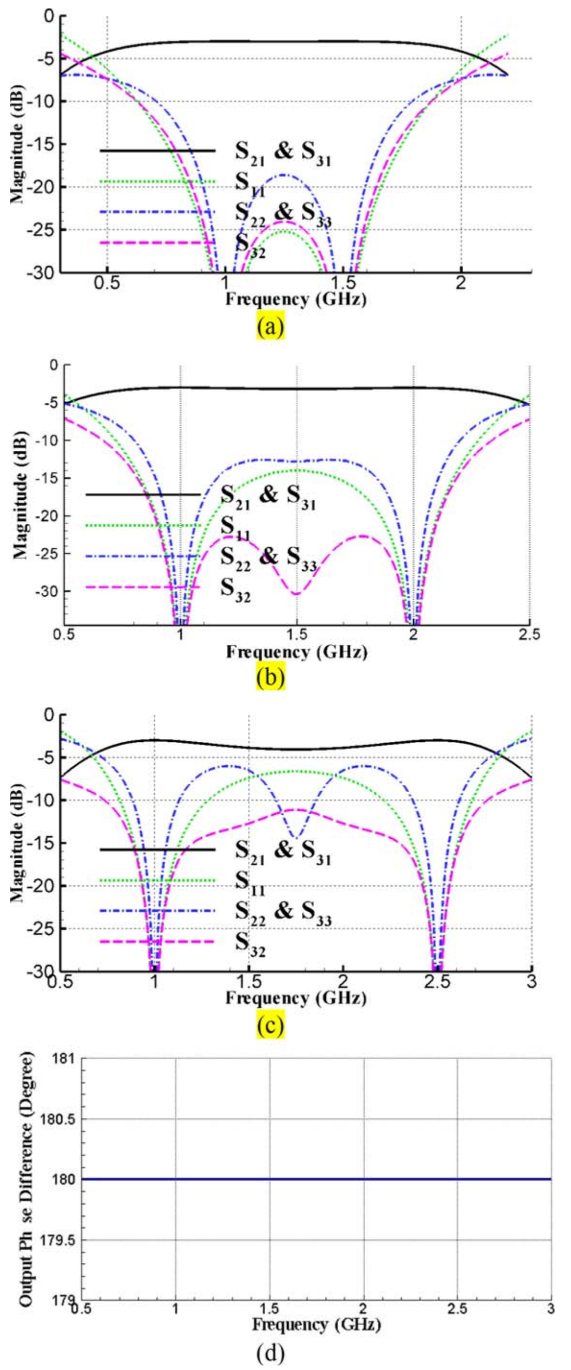

Figure 4 Calculated results of the power dividers. (a) Scattering parameters of the circuit with the frequency ratio of 1.5. (b) Scattering parameters of the circuit with the frequency ratio of 2. (c) Scattering parameters of the circuit with the frequency ratio of 2.5. (d) Phase difference between the output ports of all simulated circuits.

Solving the real part of Eq. (6), Z_4 is obtained as follows.

$$Z_4 = -\frac{qrZ_3\left(R^2q+(Xq-2Z_3)(X+2qZ_3)\right)}{R^2q^2r+r(Xq-2Z_3)^2-2R(1+q^2)Z_3^2} \tag{7}$$

Based on Eq. (7) and the imaginary part of Eq. (6), one obtains the following equation.

$$\begin{aligned}&R^4q^2r+r(Xq-2Z_3)^2(X+2qZ_3)^2-\\&2R^3(q^2r^2+Z_3^2)+2R^2r\\&\left(X^2q^2+2Xq(-1+q^2)Z_3+4Z_3^2\right)-\\&2R\begin{pmatrix}4XqZ_3(-r^2+Z_3^2)+\\X^2(q^2r^2+Z_3^2)+4Z_3^2(r^2+q^2Z_3^2)\end{pmatrix}=0\end{aligned} \tag{8}$$

In Eq. (8), the value of isolation resistor can arbitrarily be assigned. It is observed that choosing high values of the isolation resistor (> 100 ohm) can broaden the gamut of frequency band ratio at the expense of using narrower transmission lines at lower frequency ratios, thereby restricting power handling capability. On the other hand, choosing lower isolation resistors (< 100 ohm) can enhance the power handling capability at the expense of tightening the frequency ratios. Therefore, there is a trade-off between the power handling capability and frequency ratios. To inspect the behavior of transmission line impedances versus frequency ratios, a plot is illustrated in Figure 3. Note that the results in this figure are based the three isolation resistors indicated in Figure 3.

In the proposed power divider, there are four ports among which port 4 is connected through an isolation resistor to the external ground. This feature helps an efficient heat dissipation when the external resistor is mounted on a cooling system. This inherent feature of a Gysel power divider enables more power handling capacity.

III. SIMULATION RESULTS

In this section, three circuits are simulated based on the ideal components. The presented circuits are based on the dual-band circuit analysis with $r = 100\ \Omega$ and the impedances are calculated from Eqs. (2), (7), and (8). As can be seen, the simulation results also show broadband responses when the frequency ratio is low. For demonstration, in Figure 4, three circuits are simulated with the frequency ratios of 1.5 ($f_1 = 1$ GHz, $f_2 = 1.5$ GHz, and the impedances are $Z_1 = Z_2 = 33.43\ \Omega$, $Z3 = 35.1\ \Omega$, $Z_4 = 84.2\ \Omega$, and $\theta = 90^\circ$, at $(f_1 + f_2)/2$), 2 ($f_1 = 1$ GHz, $f_2 = 2$ GHz and the impedances are $Z_1 = Z_2 = 28.87\ \Omega$, $Z_3 = 22.5\ \Omega$, $Z_4 = 58.69\ \Omega$, and $\theta = 90^\circ$, at $(f_1 + f_2)/2$), and 2.5 ($f_1 = 1$ GHz, $f_2 = 2.5$ GHz, and the impedances are $Z_1 = Z_2 = 21.33\ \Omega$, $Z_3 = 16.62\ \Omega$, $Z_4 = 30.43\ \Omega$, and $\theta = 90^\circ$, at $(f_1 + f_2)/2$).

The circuit with frequency ratio of 1.5 exhibits a high bandwidth with exceptional mid-band performance. The circuit with frequency ratio of 2 also exhibits even a higher bandwidth with acceptable mid-band performance, while the last circuit with the frequency ratio of 2.5 shows

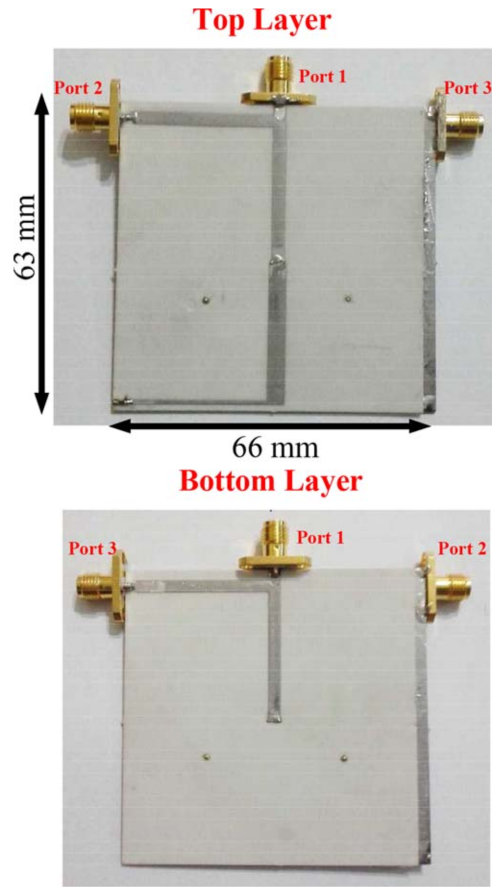

Figure 5 Photograph of the fabricated power divider.

a degradation in the mid-band performance and only exhibits the dual-band performance.

IV. MEASUREMENT RESULTS

In this section, the fabrication results of the proposed power divider are investigated. The circuit with 2: 1 frequency ratio (working at 1 GHz and 2 GHz) is selected for fabrication because of its wide bandwidth. The related impedances and electrical lengths were pointed out in Section 4. Converting the values of impedances and electrical lengths to widths and lengths of transmission lines, an Electromagnetic (EM) simulation is carried out with HFSS EM simulator using Rogers (RO4003C) substrate with relative permittivity (ε_r) of 3.38 and thickness of 0.508 × 2 mm. Photograph of the fabricated power divider is illustrated in Figure 5, where the two substrates are riveted together. The measurements were carried out using Agilent E8361C vector network analyzer. Figure 6 indicates the measurement results versus the EM simulation ones with reasonable correlation, from which it is evident that the input and output return losses are below 12 dB from 0.91 to 2.25 GHz, corresponding to 84.5% fractional bandwidth. Within this band of interest, the isolation value is better than 16 dB, whereas the worst insertion loss is 3.7 dB. It is seen that there is a negligible deviation from the ideal 180° phase difference between output ports within the entire measurement range. In order to justify the superiority of the proposed design to the former studies, a comprehensive comparison is made in Table I. It is evident that the proposed design outperforms formerly published works.

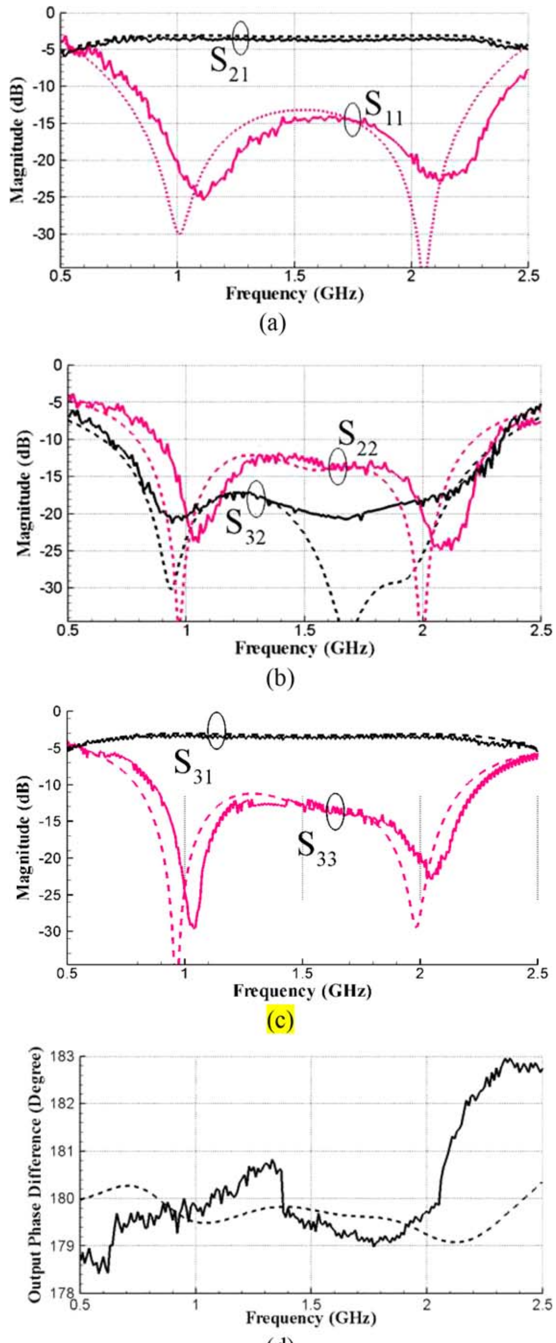

Figure 6 Electromagnetic (EM) simulation versus measured results of the proposed power divider (dashed lines indicate the simulation and solid lines indicate the measured results). (a) Port 2 Insertion loss and input return loss. (b) Port 2 return loss and isolation. (c) Port 3 return loss and insertion loss (d) Phase difference between the output ports.

TABLE I Comparison of the Proposed Power Divider With Other Recently Published Out-of-Phase High Power Dividers

	[15]	[16]	[17]	[18]	[19]	This Work
Frequency range (GHz)	0.96∼1.06/ 2.34∼2.44	1.11∼1.74	1.19∼2.19	4∼8	0.45∼0.55/ 3.55∼3.75	0.91∼ 2.25
Fractional Bandwidth (%)	10/4.2	44	59.2	66	20/5.55	84.5
Frequency ratio	1.62∼3	1∼1.7	1∼1.7	Single band	2.44∼7.31	1∼2.65
Isolation resistor (Ω)	Freq-dependent	Freq-dependent	Freq-dependent	50	variable	100
TLs impedance range (Ω)	10∼150	10∼150	10∼150	25∼100	20∼130	15∼100
Amplitude imbalance (dB)	0.5	0.3	–	>1	0.5	0.6
Phase imbalance ($180\pm\Delta°$)	4.5 (freq-independent)	6 (freq-independent)	8 (freq-independent)	9 (in-band)	5 (freq-independent)	2.5 (freq-independent)
Isolation (dB)	>15	>18	>15	>16	>10	>16
Return loss (dB)	>15	>15	>10	>10	>10	>12
Size ($\lambda^2{}_g$)	0.876 × 0.438	0.948 × 0.379	0.948 × 0.483	0.54×0.27	0.97 × 0.97	0.52 × 0.499

V. CONCLUSION

In this paper a novel design of broadband Gysel power divider with a fixed value of isolation resistor and moderate line impedances was presented on the basis of the dual-band circuit design. Maximum frequency band ratio was increased compared to the similar published works and because of using moderate impedance transmission lines and an external isolation resistor, the high-power handling capability were substantially enhanced compared to the other reported designs. Moreover, this design offered a frequency independent out-of-phase performance due to the implementation on DSPSLs with an inserted conductor. Finally, for demonstration, a circuit with 2:1 frequency ratio and 84.5% fractional bandwidth was fabricated and tested with a good consistency between the simulated and measured results.

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BIOGRAPHIES

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