Progress In Electromagnetics Research Letters, Vol. 68, 39–46, 2017

Employing a Pair of T-Shaped Stepped-Impedance-Stubs inside the Free Area of Miniaturized Wilkinson Power Dividers with Harmonic Suppression Capable of Operating at Optional Frequencies

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Abstract—In this article, a pair of T-shaped stepped-impedance-stubs plays a key role in the structure of a Wilkinson power divider. In the first step, to find a general relation between electrical lengths and characteristic impedances of the mentioned stubs and consequently how the operating frequency can be chosen, an equation based on a mathematical analysis is obtained. Then, by using this equation, several miniaturized Wilkinson power dividers with the same configurations at different operating frequencies and capable of suppressing spurious frequencies are designed. Moreover, in each of these circuits 2nd to 16th unwanted frequencies are suppressed. The simulation results of the designed dividers are in good agreement with the expected responses predicted by the obtained equation. To validate the proposed method, a Wilkinson power divider at 0.85 GHz as a sample is fabricated, and 77.83% size reduction is obtained. Furthermore, the fabricated divider suppresses 3rd to 21st harmonics better than −20 dB.

1. INTRODUCTION

A miniaturized Wilkinson power divider (WPD) capable of suppressing unwanted harmonics with an acceptable frequency response can be employed in many microwave systems such as mixers, amplifiers, the feeding network for an antenna array and the like. Several WPDs with these remarkable features have been proposed so far. In [2], adding transmission line segments between two transformers leads to rejecting the nth-order harmonics. However, this straightforward method increases the total size of the circuit. In [3], by utilizing two pairs of parallel coupled lines with one end connected in series with an open stub more than 37 dB suppression for the second, the third and fourth harmonics and about 20% size reduction are obtained. To improve the slow-wave factor of the proposed divider in [4], crossing bond wires are adopted, and better than 40 dB suppression for the third and fifth harmonics and 50% branch line length reduction are achieved. To suppress high-order harmonics due to slow-wave and bandstop characteristics, several effective methods such as electromagnetic bandgap (EBG) [5, 6] and defected ground structure (DGS) [7, 8] have been applied to design Wilkinson power dividers. In some cases, Wilkinson power dividers are proposed to either suppress unwanted harmonics [9] or reduce the overall circuit size [10]. In [11], to obtain both miniaturization and harmonic suppression, slow-wave loading his utilized, and second to fifth spurious harmonics are suppressed. In [13], a wideband bandpass power divider using a simple harmonic-suppressed ring resonator is designed. However, the proposed structure in this case occupies a large area. As another method, open-stub transmission lines are utilized to design a Wilkinson power divider with enhanced spurious suppression performance, in [14]. In this letter, a mathematical method to apply a pair of T-shaped stepped-impedance-stubs (TSSIS) in the structure of WPD is cited. Next, based on the obtained equation in the previous step, several miniaturized WPDs with the same configuration capable of harmonic suppression at different operating

Received 22 March 2017, Accepted 3 May 2017, Scheduled 19 May 2017
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frequencies are designed and simulated. Moreover, to verify the feasibility of fabricating based on the mentioned method, an optimized WPD using asymmetric TSSISs capable of harmonic suppression and size reduction at 0.85 GHz is designed and constructed. In this case, to have more degree of freedom in controlling the performance of the proposed WPD, asymmetric TSSISs are employed.

2. THE PROCEDURE OF DESIGNING

The aim of this section is finding an efficient equation to find how changing electrical lengths and characteristic impedances can affect the operating frequency of a pair of TSSISs. The configuration of the proposed tri-section SIR in [12] is shown in Fig. 1(a). The -3 dB cutoff frequency of this LPF can be obtained as:

$$\theta = \tan^{-1}\left(\sqrt{\frac{K_1 K_2}{K_1 + K_2 + 1}}\right) \tag{1}$$

where $k_1 = (Z_{0\,(\text{High}-\text{Impedance})}/Z_{0\,(\text{Low}-\text{Impedance})})$ and $k_2 = (Z_{0\,(\text{Low}-\text{Impedance})}/Z_1)$. It is observed that, by changing the values of k_1 and k_2, the -3 dB cutoff frequency can be arbitrarily chosen. According to Eq. (1), the operating frequency of the designed filter shown in Fig. 1(a) can be controlled by Z_1, $Z_{0\,(\text{High}-\text{Impedance})}$ and $Z_{0\,(\text{Low}-\text{Impedance})}$). By replacing the conventional $\lambda/4$ transmission line of a

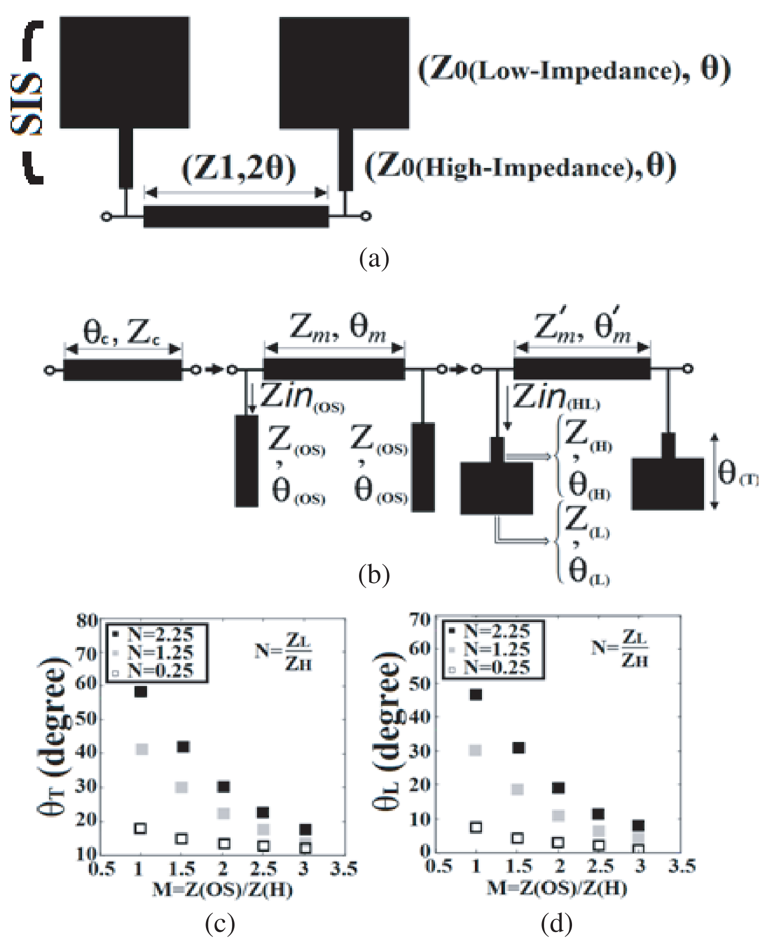


Figure 1. (a) The diagram of the proposed LPF utilizing symmetrical tri-section SIR [12]. (b) The procedure of replacing a basic unit of the microstrip with T-shaped stepped-impedance-stubs. (c) Total electrical length θ_L versus M for different values of N. (d) Electrical length θ_T versus M for different values of N.

Wilkinson power divider (WPD) with this lowpass filter (LPF), not only the operating frequency of the divider can be controlled, but also high-order harmonics can be suppressed. However, the shown LPF in Fig. 1(a) with equal electrical lengths inside the structure of a WPD occupies a large area. To control both the operating frequency of the WPD and its occupied area, the transmission lines with corresponding characteristic impedances of $Z_{0\,(\text{High}-\text{Impedance})}$ and $Z_{0\,(\text{Low}-\text{Impedance})}$ can be optimized. It is clear that by replacing the open-stubs of a π-shaped transmission line with a stepped-impedance stubs (SISs), the shown LPF in Fig. 1(a) can be obtained, which leads to a better performance in suppressing spurious frequencies. The procedure of this replacement is illustrated in Fig. 1(b). By equating $Zin_{(\text{OS})}$ with $Zin_{(\text{HL})}$, the following can be obtained:

$$\theta_{(L)} = \tan^{-1}\left[\frac{\left(N\times\tan\theta_{(\text{OS})}\right) - M\left(N\times\tan\theta_{(H)}\right)}{M + \left(\tan\theta_{(H)}\times\tan\theta_{(\text{OS})}\right)}\right] \tag{2}$$

where $N = Z_{(L)}/Z_{(H)}$ and $M = Z_{(\text{OS})}/Z_{(H)}$. The behavior of the electrical length of Low-Impedance transmission line of SIS against changing M for different values of N is plotted in Fig. 1(c).

As observed, increasing the values of M and N leads to decreasing $\theta_{(\text{Low}-\text{Impedance of SIS})}$ and consequently a decrease in total electrical length of SIS. Note that the electrical length of a transmission line can be controlled by changing its physical length (see Eq. (3)). Moreover, based on Eq. (1), by changing the values of M and N the operating frequency can be chosen. According to Fig. 2, a pair of TSSISs can be placed in front of each other; therefore, decreasing the total length of SISs (see Fig. 1(a)) makes a free area inside the WPD, which can be used to decrease the length of the main transmission line (see Fig. 2) located between two SISs (see Eqs. (3)–(6)).

$$\theta = \beta L \tag{3}$$

$$\beta = \frac{2\pi}{\lambda} \tag{4}$$

where

$$\lambda = \frac{c}{f\sqrt{\varepsilon}} \tag{5}$$

By combining Eqs. (3)–(5) the following can be given:

$$\theta = \frac{2\pi}{c} f L\sqrt{\varepsilon} \tag{6}$$

where β is the propagation constant; λ determines guided wavelength; L and θ are the physical and electrical lengths, respectively. Thus, the operating frequency of the proposed WPD can be controlled more accurately.

In summary, both the main transmission line and the employed TSSISs play a vital role in determining the operating frequency. It means that employing two TSSISs in series in the structure of the conventional WPD leads to designing several dividers with the same configurations and performances at different operating frequencies. To prove it, the frequency responses of the proposed structure in Fig. 2 at different optional operating frequencies of 0.5, 0.9, 1 and 1.5 GHz are illustrated in Figs. 3(a), (b), (c) and (d), respectively. The dimensions of the designed power divider at different operating frequencies are as follows: at operating frequency of 0.5 GHz: $W1 = 8.4$, $W2 = 7.9$, $W3 = 0.1$, $W4 = 0.1$, $W5 = 1.56$, $D1 = 1.15$, $D2 = 1.1$, $D3 = 0.2$, $L1 = 8.9$, $L2 = 9.6$, $L3 = 0.7$, $L4 = 4$, $L5 = 30.2$, $L6 = 5$, $g1 = 0.8$, $g2 = 0.3$ and $g3 = 1.5$ (All in millimeter); at operating frequency of 0.9 GHz: $W1 = 3.9$, $W2 = 4.1$, $W3 = 0.1$, $W4 = 0.2$, $W5 = 1.56$, $D1 = 1.15$, $D2 = 1.1$, $D3 = 0.2$, $L1 = 8.8$, $L2 = 8.2$, $L3 = 0.8$, $L4 = 3.4$, $L5 = 20.7$, $L6 = 3.4$, $g1 = 0.15$, $g2 = 0.9$ and $g3 = 0.45$ (all in millimeter); at operating frequency of 1 GHz: $W1 = 3.6$, $W2 = 3.9$, $W3 = 0.1$, $W4 = 0.1$, $W5 = 1.56$, $D1 = 1.15$, $D2 = 1.1$, $D3 = 0.2$, $L1 = 8.6$, $L2 = 8$, $L3 = 0.7$, $L4 = 3.6$, $L5 = 19.3$, $L6 = 3.2$, $g1 = 0.35$, $g2 = 0.6$ and $g3 = 0.25$ (All in millimeter); at operating frequency of 1.5 GHz: $W1 = 2.7$, $W2 = 3$, $W3 = 1.2$, $W4 = 0.3$, $W5 = 1.56$, $D1 = 1.15$, $D2 = 1.1$, $D3 = 0.2$, $L1 = 6.7$, $L2 = 6.8$, $L3 = 0.4$, $L4 = 2.7$, $L5 = 13.75$, $L6 = 2.3$, $g1 = 0.85$, $g2 = 0.5$ and $g3 = 0.35$ (All in millimeter). According to the results of simulations in each case, not only 3rd to 16th spurious harmonics are suppressed, but also about 77% size reduction is achieved. Table 1 shows the simulation results of the presented WPDs at the above-mentioned operating frequencies. Moreover, to prove the efficiency of the mentioned method,

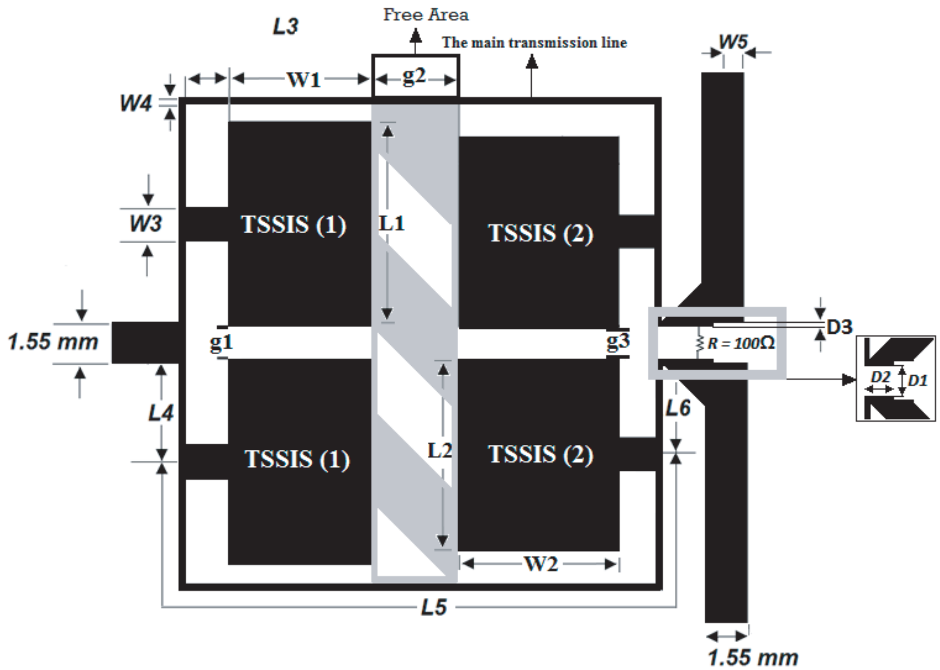


Figure 2. The procedure of maintaining T-shaped stepped-impedance-stubs inside the free area of the conventional power divider.

Table 1. The simulation results of the designed WPDs at 0.5, 0.9, 1 and 1.5 GHz (NB: $L_{\min}$ = the lowest level of suppression).

Operating Frequency	0.5 GHz	0.9 GHz	1 GHz	1.5 GHz
Size Reduction	82.5%	77.51%	77. 12%	76.68%
Harmonics Suppressed	3rd–20th $L_{\min} = -24.03$ dB	3rd–21st $L_{\min} = -16.76$ dB	3rd–16th $L_{\min} = -12.64$	3rd–19th $L_{\min} = -15.13$ dB
S_{11}	−61.42 dB	−50.69 dB	−49.11 dB	−42.56 dB
S_{21}	−3.053 dB	−3.076 dB	−3.063 dB	−3.02 dB
S_{22}	−38.73 dB	−32.91 dB	−42.12 dB	−60.93 dB
S_{23}	−43.76 dB	−46.2 dB	−45.26 dB	−40.13 dB

an optimized WPD using asymmetric TSSISs capable of harmonic suppression and size reduction at another operating frequency of 0.85 GHz is designed and fabricated. In this case, to have more degree of freedom in changing dimensions asymmetric TSSISs are employed.

The results of measurements of the proposed WPD operating at 0.85 GHz are discussed in the following section.

3. MEASUREMENT AND SIMULATION RESULTS

To verify the efficiency of the discussed method in fabrication, a WPD with −3 dB operating frequency of 0.85 GHz is constructed, as mentioned before. The results of simulation and measurement of scattering parameters are accomplished by using Agilent's ADS Electromagnetic simulator (EM Simulator) software and "HP 8720B" vector network analyzer, respectively. The designed microstrip Wilkinson power divider is fabricated on an RT/Duroid 5880 substrate with the thickness of 0.508 mm, permittivity of 2.2 and loss tangent of 0.0009. The dimensions of the fabricated WPD are shown in Table 2.

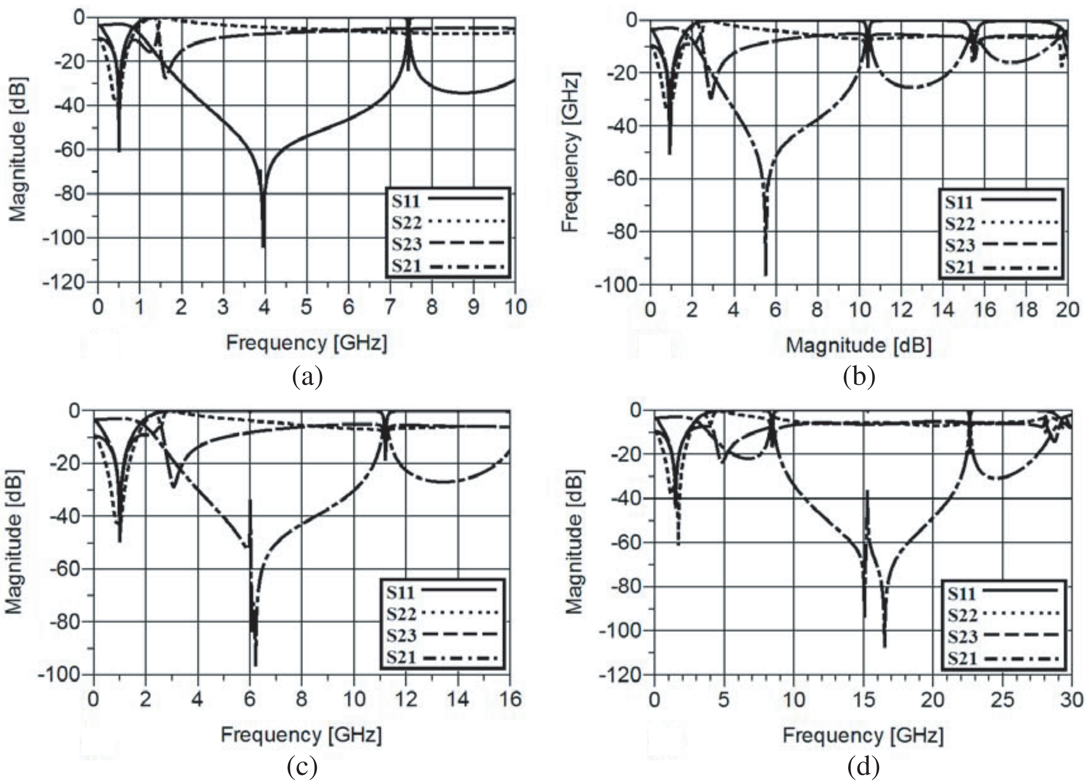


Figure 3. (a) The frequency response of the proposed Wilkinson power divider at 0.5 GHz. (b) The frequency response of the proposed Wilkinson power divider at 0.9 GHz. (c) The frequency response of the proposed Wilkinson power divider at 1 GHz. (d) The frequency response of the proposed Wilkinson power divider at 1.5 GHz.

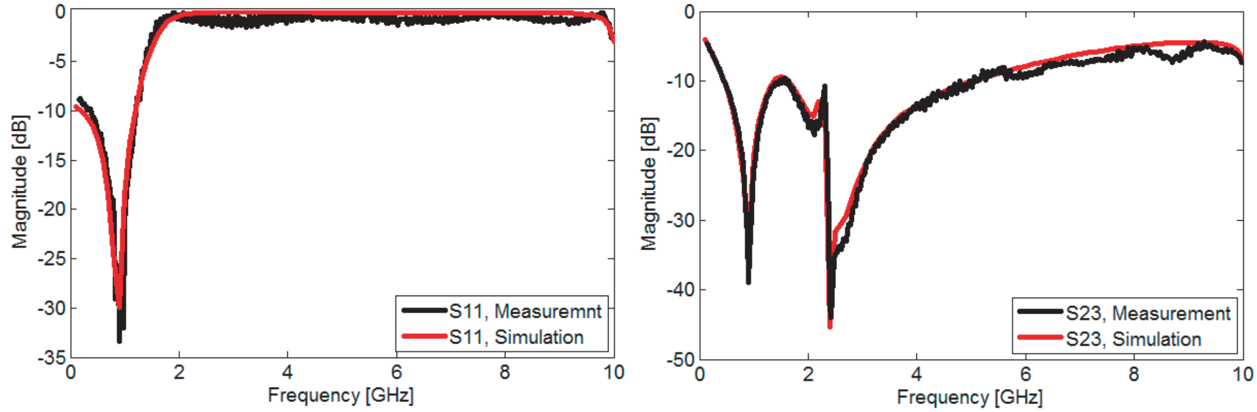
Table 2. The dimensions of the fabricated WPD (all in millimeter).

$W1$	$W2$	$W3$	$W4$	$W5$	$D1$	$D2$	$D3$	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$	$g1$	$g2$	$g3$
4.1	4.3	0.5	0.2	1.56	1.15	1.1	0.2	8.2	7.8	1.5	3.6	21.5	3.5	0.1	0.1	0.3

The results of measurement and simulation of S-parameters are illustrated in Figs. 4 and 5. As shown in Fig. 4(a), the measured return loss (S_{11}) from 0.63 GHz to 1.15 GHz is at least -15 dB. As shown in Fig. 4(b), over the frequency range of 0.61–1.13 GHz, the measured isolation (S_{23}) is better than -15 dB. According to Fig. 5(a), the output return loss (S_{22}) less than -16 dB from 0.23 GHz to 1.29 GHz is achieved. It can be observed from the measured insertion loss (S_{21}) in Fig. 5(b) that both even and odd spurious harmonics from 2.41 GHz to 18.1 GHz, i.e., third to twentieth harmonics, are suppressed (see Table 2). The measured results precisely at operating frequency of 0.85 GHz for S_{11}, S_{32}, and S_{22} are -32 dB, -39.43 dB and -43.2 dB, respectively. Furthermore, the measured insertion loss shows that S_{21} at 0.85 GHz is -3.079 dB. The characteristic impedance of all three ports is 50 Ω.

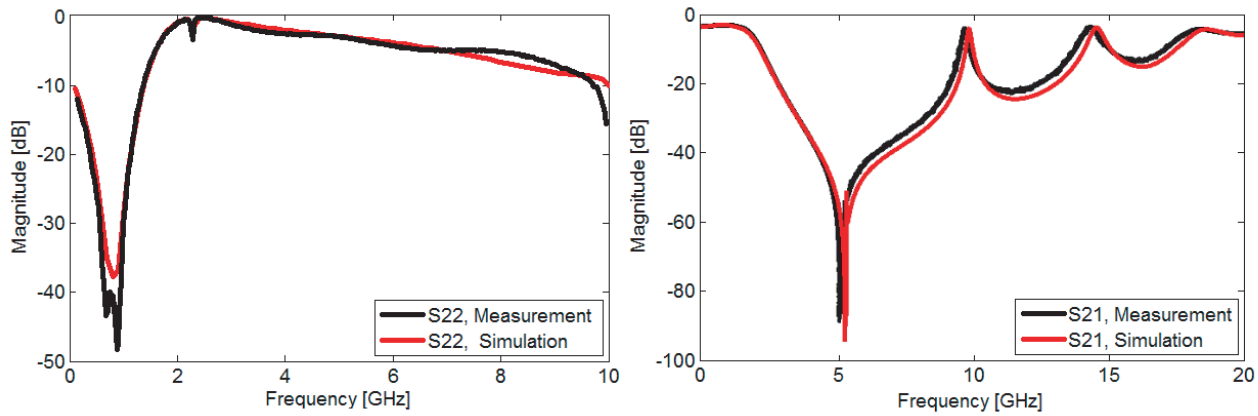
Table 2 shows the comparison between the proposed power divider and other published works. Based on the results of measurement shown in Fig. 6(a), an appropriate phase performance between two output ports around operating frequency of 0.85 GHz is achieved.

The measured phase difference of ports 2 and 3 as output ports is $\pm 0.16°$. It is shown that the proposed Wilkinson power divider is symmetric, so $S_{22} = |S_{33}|$ and $|S_{21}| = |S_{31}|$. Thus, harmonic suppression is related to both S_{21} and S_{31}. A photograph of the proposed Wilkinson power divider is shown in Fig. 6(b).



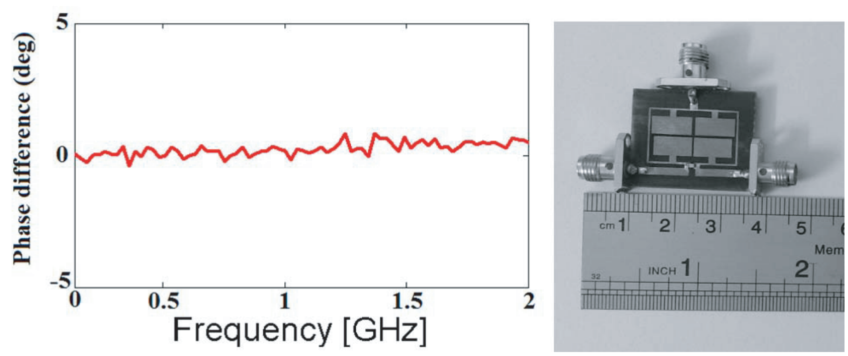
(a) (b)

Figure 4. (a) The measured and simulated results of the input returns loss (S_{11}) of the proposed power divider. (b) The measured and simulated results of the isolation (S_{23}) of the proposed power divider.



(a) (b)

Figure 5. (a) The measured and simulated results of the output returns (S_{22}) loss of the proposed power divider. (b) The measured and simulated results of the insertion loss (S_{21}) of the proposed power divider.



(a) (b)

Figure 6. (a) The measured phase difference between two output ports of the proposed power divider ($|\angle S_{31} - \angle S_{21}|$). (b) The photograph of the proposed Wilkinson power divider.

Table 3. Comparison between the performance of the proposed Wilkinson power divider and previous works.

Ref.	Size Reduction	Harmonic suppression (dB)									
		2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
[1]	-	-	-	-	-	-	-	-	-	-	-
[2]	-	45.3	46.4	-	-	-	-	-	-	-	-
[3]	20%	43	49	37	-	-	-	-	-	-	-
[4]	50%	-	40	-	50	-	-	-	-	-	-
[5]	70%	8	32	10	12	-	-	-	-	-	-
[6]	39%	26	25	-	-	-	-	-	-	-	-
[7]	10%	18	15	-	-	-	-	-	-	-	-
[8]	66%	13	35	-	-	-	-	-	-	-	-
[9]	-	-	37	-	-	-	-	-	-	-	-
[10]	85.3%	-	-	-	-	-	-	-	-	-	-
[11]	63%	13	29	32	34	-	-	-	-	-	-
[13]	-	15.8	-	-	-	-	-	-	-	-	-
[14]	-	40	40	40	-	-	-	-	-	-	-
This work	**77.83%**	**12.0**	**32.3**	**36.7**	**34.6**	**33.2**	**31.1**	**26.1**	**25.9**	**23.4**	**17.5**
This work	Harmonic suppression (dB)	**12th**	**13th**	**14th**	**15th**	**16th**	**17th**	**18th**	**19th**	**20th**	**21st**
		18.0	**23.7**	**23.5**	**20.4**	**14.0**	**11.1**	**12.9**	**14.7**	**12.3**	

4. CONCLUSION

In this paper, a mathematical method to design Wilkinson power dividers using T-shaped stepped-impedance-stubs for harmonic suppression and size reduction is proposed, and similar compact WPDs capable of harmonic suppression are designed.

Finally, the presented dividers with T-shaped stepped-impedance-stubs and the applied mathematical procedure to have size reduction and harmonic suppression are validated by fabricating a sample of Wilkinson power divider at an operating frequency of 0.85 GHz, and all predicted characteristics have been obtained.

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