A Novel Wilkinson Power Divider Using Open Stubs for The Suppression of Harmonics

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Abstract **─** In this paper, the design process of a novel Wilkinson power divider is presented. The proposed power divider features a simple structure with open stubs at each port. With slight changes of the dimensions of open stubs, designed power divider can suppress combinations of each two desired order harmonic simultaneously. From the measured results, 45 dB and 43 dB suppression for 3rd and 5th harmonics is obtained, respectively. The proposed power divider has an insertion loss less than 0.1 dB, input return loss better than 31 dB, output return loss better than 51 dB, and better than 43 dB of isolation at 1.65 GHz.

Index Terms **─** Harmonic suppression, open stub, and Wilkinson power divider.

I. INTRODUCTION

Wilkinson power dividers are widely applied in microwave communication such as power amplifiers, mixers, and frequency multipliers. Wilkinson power divider is designed for the single/dual band applications [1-2].

In many applications, the unwanted harmonics caused by nonlinear property of the active circuit dluohs be removed. Minimizing harmonics distortion is a great challenge in modern wireless communications with the high data-rate. It is cost-effective if the unwanted harmonics are suppressed in the power divider or the combiner structure [3]. Several methods have been proposed so far to design miniaturized harmonic suppressed power dividers with improved performance [3-17]. In [3-6] power dividers with two microstrip electromagnetic band-gap (EBG) cells for harmonics suppression are presented. In [7, 8] harmonics suppression is demonstrated with defected ground structure (DGS). Nevertheless, DGS and EBG, need etching process on backside ground plane and accurate position calibration, which improve time-consumption and difficulty in machining [9]. Nowadays resonators, filters [10-12] and shunt open stubs elements have been widely used to suppress the unwanted harmonics and size reduction. In [13, 14] a compact size Wilkinson power divider, based on non-uniform transmission lines is presented and in [15-17], Π- and T-shaped shunt open-stubs are used for harmonics suppression.

However, in these works, obtaining harmonics suppression with high level of attenuation is still subject of discussion and challenge. In this paper, a novel Wilkinson power divider for harmonics suppression with high level of attenuation is presented. This structure has significant advantages in terms of simple topology and superior harmonic suppression. The major advantage of the new structure is its high flexibility capability. The power divider is fabricated based on 3rd and 5th harmonics suppression. Moreover, simulation results show that the proposed structure can suppress the 2nd and 3rd harmonics.

II. POWER DIVIDER DESIGN

Figure 1 (a) shows the conventional Wilkinson

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power divider that consists of two quarter-wavelength transmission lines ($\sqrt{2}\ Z_0$) and an isolation resistor (100 ohms). Figure 1 (b) shows the structure of the proposed Wilkinson power divider. It consists of two quarter-wavelength transmission lines, two branch-lines (θ_3), three open shunt stubs (two θ_2 and one θ_1) and an isolation resistor. This power divider is symmetric, so the odd- and even-mode analyses can be used to determine the circuit parameters for harmonic suppression [18].

A. Odd-mode analysis

With referring to the diagram shown in Fig. 2 (a), the output admittance of the half-circuit is simply equal to,

$$Y_A = -\frac{j\cot 90^0}{Z} = 0 \tag{1}$$

$$Y_B = \frac{j\tan\theta_2}{Z}\quad , \tag{2}$$

$$Y_c = \frac{Z + j\frac{R}{2}\tan\theta_3}{\frac{R}{2}Z + jZ^2\tan\theta_3}\,, \tag{3}$$

$$Y_0 = Y_A + Y_B + Y_C\ . \tag{4}$$

The real part of equation (4) becomes,

$$R = 2Z_0(1 - \tan\theta_2\tan\theta_3)\,, \tag{5}$$

while the imaginary part yields

$$Z^2\tan\theta_3 = \frac{R}{2}Z_0(\tan\theta_2 + \tan\theta_3)\,. \tag{6}$$

Substituting equation (5) into equation(6), results in,

$$Z = Z_0\sqrt{(\tan\theta_2 + \tan\theta_3)(\cot\theta_3 - \tan\theta_2)}\,. \tag{7}$$

B. Even-mode analysis

According to Figure 2 (b) under even mode excitation, the ABCD matrix can be expressed for the equivalent circuit of the proposed power divider as follows,

$$\begin{bmatrix} 1 & 0 \\ \frac{jY\tan\theta_1}{2} & 1 \end{bmatrix} \times \begin{bmatrix} 0 & jZ \\ jY & 0 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ jY\tan\theta_2 + jY\tan\theta_3 & 1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\,. \tag{8}$$

Subsequently, the ABCD parameters can be obtained as,

$$A = -(\tan\theta_2 + \theta_3) \tag{9}$$

$$B = jZ\quad , \tag{10}$$

$$C = jY - j\frac{Y}{2}\tan\theta_1\tan\theta_2 - j\frac{Y}{2}\tan\theta_1\tan\theta_3\,, \tag{11}$$

$$D = -\frac{\tan\theta_1}{2}\,. \tag{12}$$

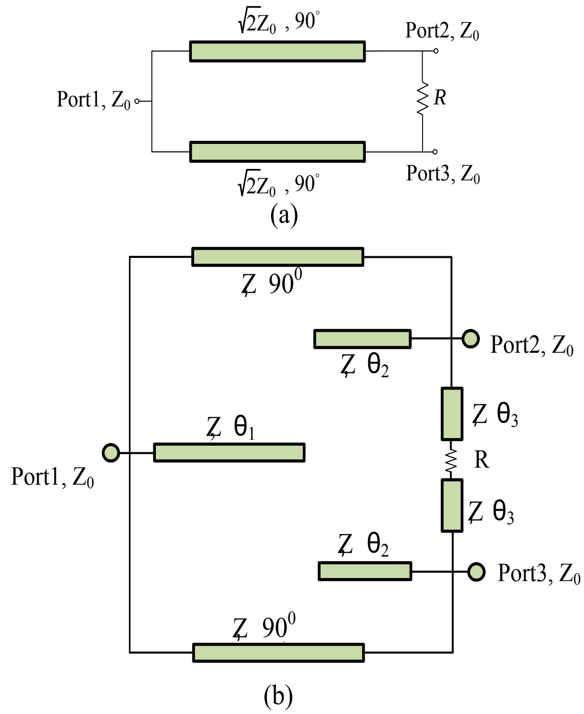

Fig. 1. Schematic diagram of the (a) conventional Wilkinson power divider and the (b) proposed power divider.

The input impedance of the even mode equivalent circuit is expressed as [18],

$$Z_{in} = 2Z_0 = \frac{AZ_0 + B}{CZ_0 + D}\,. \tag{13}$$

Assuming the network is reciprocal and lossless, then equation (13) can be written as,

$$A = 2D \tag{14}$$

and

$$A^2 - \left(\frac{B}{Z_0}\right)^2 = 2\,. \tag{15}$$

Using equations (9) - (12), equations (14) and (15) can then be modified as follows,

$$\tan\theta_1 = \tan\theta_2 + \tan\theta_3 \tag{16}$$

and

$$(\tan\theta_2 + \tan\theta_3)^2 + \frac{Z^2}{{Z_0}^2} = 2\,. \tag{17}$$

Substituting equations (16) and (7) into equation (17), yields,

$${\tan\theta_1}^2 + \tan\theta_1(\cot\theta_3 - \tan\theta_2) = 2. \tag{18}$$

Since n^{th} harmonic suppression is desired, θ_1 and θ_2 are assigned to be $\pi/2n$ [19]. For the 3^{rd} and 5^{th}

harmonic suppressions, θ_1 and θ_2 are obtained to be $\pi/6$ and $\pi/10$, respectively. Substituting these values into equation (16), θ_3 is obtained, which is 14.1°. The value of R and Z are obtained from equations (5) and (7), as 92 ohms and 72 ohms, respectively.

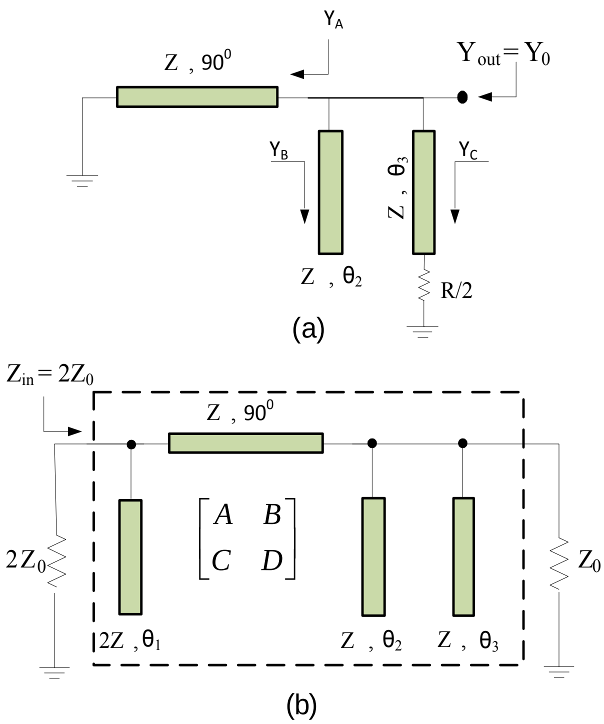

Fig. 2. Half-circuit of the proposed power divider for the (a) odd mode and the (b) even mode.

III. IMPLEMENTATION AND RESULTS

To demonstrate the proposed circuit, a power divider with a center frequency fixed at 1.65 GHz for harmonics suppression was designed and implemented, as shown in Fig. 3. It was fabricated on an RT/Duorid 5880 substrate with a relative permittivity of 2.2, thickness of 0.381 mm and loss tangent of 0.0009. The overall dimension of the circuit was about 24 mm × 16 mm (384 mm^2), which demonstrates a 35% size reduction compared to the conventional microstrip Wilkinson power divider with the same center frequency. The S-parameters were measured using an Agilent N5230A network analyzer. Figure 4 illustrates the simulated and measured S_{21} as a function of frequency.

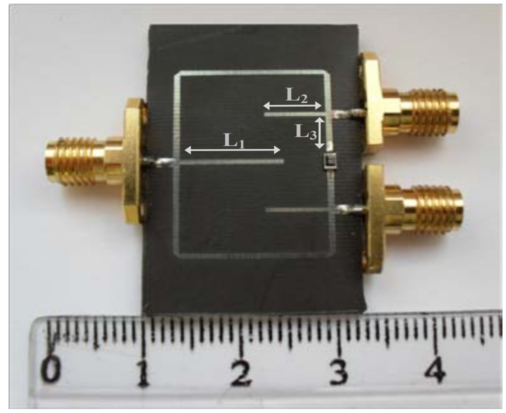

Fig. 3. Photograph of the fabricated power divider.

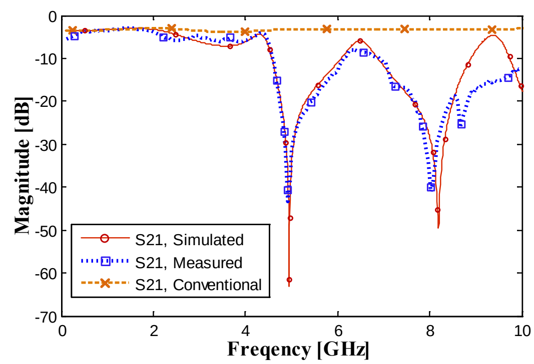

Fig. 4. Measured and simulated insertion loss of power divider for the 3rd and 5th harmonics suppression mode.

The simulations were performed using ADS (advanced design system by Agilent technologies). From the measured results, it can be found that the power divider passes the 1.65 GHz fundamental signal and suppresses the 4.95 GHz third-order harmonic and the 8.25 GHz fifth-order harmonic, simultaneously. From Fig. 4, the insertion loss at 1.65 GHz is 0.1 dB, the suppression for the third- and fifth-order harmonics are 43 dB and 41 dB, respectively. However, the measured S-parameter is shifted from 8.25 GHz to 8 GHz for the fifth-order harmonic suppression. This error is due to the high-frequency parasitic effect [3].

The S_{21} response of the conventional Wilkinson power divider is also shown in Fig. 4. From the simulated and measured results, as shown in Fig. 5, the circuit provides good input return loss. The measured S_{11} is about 31 dB at the operation frequency of 1.65 GHz. Figure 6, demonstrates the simulated and measured output return loss. As seen from Fig. 6, the measured S_{22} is better than 51 dB at the operation frequency of 1.65 GHz.

Therefore, the designed circuit is well matched to the input and two output ports. In Fig. 7, the simulated and measured isolations of the two output ports are shown.

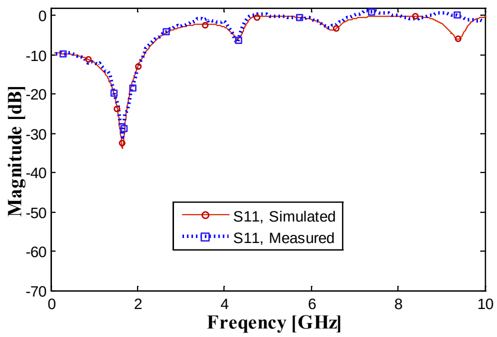

Fig. 5. Measured and simulated input return loss of power divider for the 3rd and 5th harmonics suppression mode.

The measured isolation between ports 2 and 3 is better than 43 dB. A comparison of the power dividers for the nth harmonics suppression is summarized in Table 1. As the results show, this work presents significant third- and fifth-order harmonic suppressions as compared to the reported works. The most significant advantage of this structure is that only by changing the dimensions of θ_1 and θ_2, it can suppress each two desired harmonics. With θ_1 = 45° (L_1= 15.3 mm) and θ_2 = 22.5° (L_2= 7.6 mm), 2nd and 4th harmonics are suppressed.

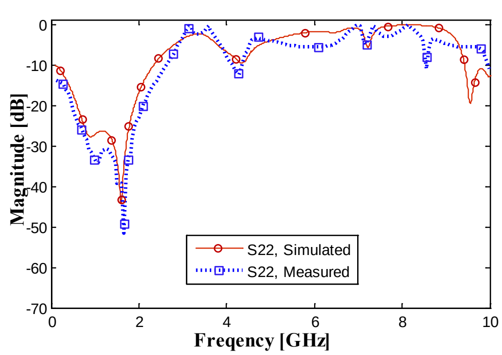

Fig. 6. Measured and simulated output return loss of power divider for 3rd and 5th harmonics suppression mode.

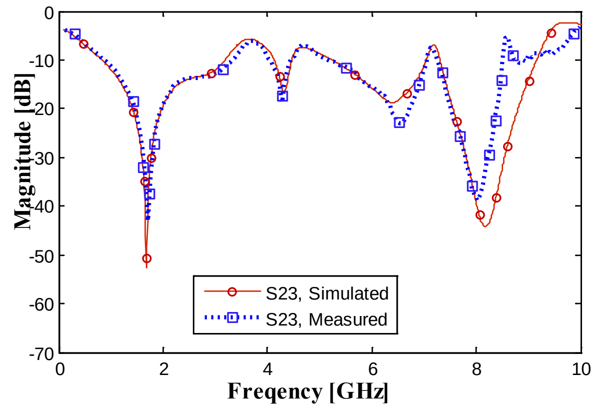

Fig. 7. Measured and simulated isolation of power divider for 3rd and 5th harmonics suppression mode.

Moreover, 3rd and 4th harmonics suppression is achieved with θ_1 = 30° (L_1= 10.2 mm) and θ_2 = 22.5° (L_2= 7.6 mm). With θ_1 = 45° (L_1= 15.3 mm) and θ_2 = 30° (L_2= 10.2 mm), after fine adjustment 2nd and 3rd harmonics suppression is occurred as shown in Fig. 8. The power divider passes the same fundamental signal (1.65 GHz) and suppresses the 3.3 GHz second-order harmonic and the 4.95 GHz third-order harmonic, simultaneously. The simulated S_{21} parameter at 1.65 GHz shows a power split of 3.04 dB. Furthermore, over than 70 dB suppression for the second- and third-order harmonic is obtained. Figure 9 shows that the isolation between the two ports, which is over 34 dB and the output return loss is more than 36 dB.

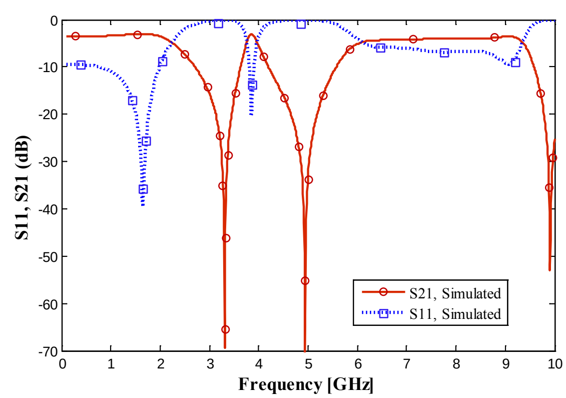

Fig. 8. The simulated results of S_{11}, S_{21} for 2nd and 3rd harmonics suppression mode.

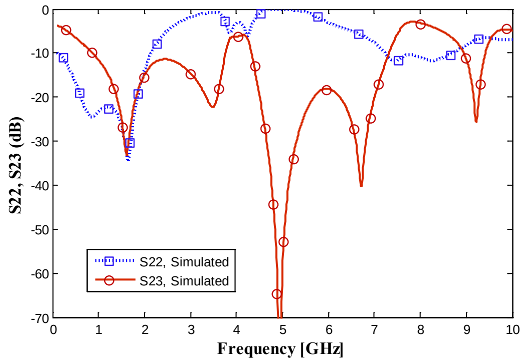

Fig. 9. Simulated results of S_{22} and S_{23} for 2nd and 3rd harmonic suppression modes.

Table 1: Performance comparison of the proposed power divider with other works.

Ref.	Freq.	Nth Harmonics Suppression	
[3]	2.4 GHz	3rd 5th	32.5 dB 12 dB
[4]	1.8 GHz	2nd 3rd	26 dB 25 dB
[5]	2.65 GHz	2nd 3rd	30 dB 18 dB
[6]	1.25 GHz	2nd 3rd 4th	17 dB 25 dB 22 dB
[7]	1.5 GHz	2nd 3rd	18 dB 15 dB
[11]	2.4 GHz	3rd 5th	46 dB 37 dB
[20]	2.05 GHz	3rd	44 dB
[21]	0.9 GHz	2nd 3rd	13 dB 35 dB
[22]	2.4 GHz	2nd 3rd	20 dB 40 dB
[23]	1.5 GHz	3rd	37 dB
This Works	**1.65 GHz**	**3rd** **5th**	**45 dB** **43 dB**

IV. CONCLUSION

A new Wilkinson power divider with novel structure for harmonics suppression is designed, simulated, and measured. This structure enables the power divider to work as harmonics suppresser with capability of suppressing each two desired harmonics. The proposed power divider with such performance can answer the demands of modern communication systems.

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