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Design and implementation of a bandpass Wilkinson power divider with wide bandwidth and harmonic suppression

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Abstract: In this paper a Wilkinson power divider (WPD) is presented with ultrawide-band operation and harmonic suppression. This WPD is designed using coupling lines and meandered open stubs at main branches. The center frequency of the presented WPD is 4.25 GHz, which is fabricated and measured on RT/Duroid substrate with dielectric constant of 2.2. The proposed WPD provides good filtering band with high attenuation level. The 15 dB return loss operational bandwidth (BW) of the WPD is obtained between 3.2 GHz and 5.3 GHz, which shows 50% operational bandwidth.

Key words: Bandpass filter, harmonic suppression, wide operation band, Wilkinson power divider

1. Introduction

Power dividers (PDs) are important elements in microwave devices which can divide or combine the input signal. WPDs are type of PDs which not only provide good isolation between output ports, but also can reduce the return losses of each port [1–5]. Microstrip transmission lines are used to fabricate the WPD devices in microwave applications. The microstrip lines are composed of a conducting line on a dielectric substrate which is separated from a ground plane [6].

Recently, wide-band and multiband operations has become very important in the modern communication system. In the following, several techniques in the field of wide-band and harmonic suppression are discussed.

Coupled transmission lines were used instead of the conventional transmission line to reduce the circuit size and obtain wide-band operation in [7, 8]. A relative wide-band operation was obtained in [7]; however, the overall size of the WPD was rather large. A compact WPD with high selectivity and filtering response was presented in [9]. Five resonators were applied to provide the desired transmission zeros but the WPD suffers from about 1 dB of insertion loss in the pass band. In [10] a divider using hook-shaped resonator was presented at 2.4 GHz with second and third harmonic suppression. High out of band attenuation was obtained in this WPD but the operating pass band was not wide enough. A wide-band WPD using distributed stepped impedance resonators, operating at 2.3 GHz, was presented in [11]. The aim of the WPD presented in [11] was to obtain wide-band operation and harmonic suppression. Moreover, a fractional bandwidth (FBW) of 31% was achieved in this work. Another WPD with wide-band operation and harmonic suppression was designed in [12]. Microstrip-coupled lines were used in this divider to achieve a wide operating bandwidth. Moreover, a series-connected extra resistor and capacitor were presented in this work to enhance the isolation of the WPD;

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however, this extra elements increase the cost and complexity of the divider. A filtering WPD with π-shaped structures was presented in [13]. In this work, the π-shaped resonators were used to realize the harmonic suppression. The achieved isolation and return losses were good but the operating bandwidth was totally poor. Another filtering WPD with high in-band isolation was designed in [14]. The folded resonator was presented in this work to reduce the size and harmonics effects in the WPD. An in-band isolation of about 30 dB was obtained in this work. However, the return loss was not acceptable in the pass-band and the fractional bandwidth was 3.5%, which is very narrow. A WPD with bandpass response was fabricated in [15]. Two low pass filters and one band pass filter (BPF) were embedded in the structure of this work. The harmonic suppression level in this work is very high but the obtained FBW is 11%, which is not wide enough. The BPF embedding technique was also applied in [16] to realize the bandpass response and good isolation between output ports. However, the insertion loss of about 1 dB was obtained in this work, which means that the main frequency signal would be attenuated.

Using open-ended stubs [17–22] or a compact resonant cell [23] in the main structure of the WPD are other techniques for harmonic suppression and size reduction. However, both wide-band and harmonic suppression merits are not realized simultaneously in the cited works.

In this paper, a WPD with the coupled lines and open-ended stubs techniques are designed and implemented to realize harmonic suppression and ultrawide-band operation, simultaneously.

2. Design procedure of the presented divider

The basic schematic of the applied topology is illustrated in Figure 1. The aim of the presented WPD is to achieve both harmonic suppression and wide-band frequency simultaneously. In this paper, the coupled lines and harmonic suppression techniques are selected to widen the bandwidth and suppress the unwanted harmonics, simultaneously.

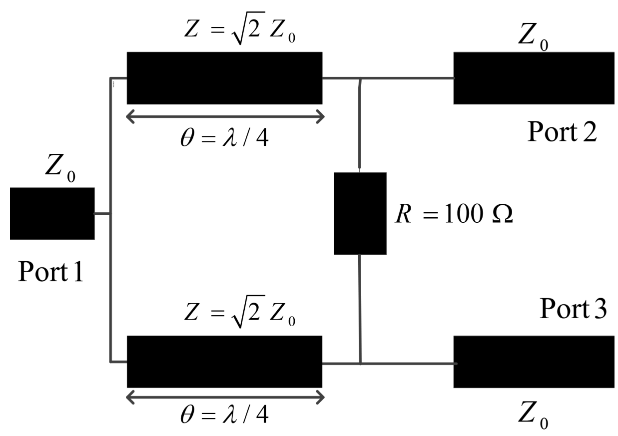

Figure 1. The basic schematic of the applied topology.

Conventional quarter wave length transmission lines could be replaced by coupled transmission lines. By applying these main coupled transmission lines, the basic structure of the WPD will be changed as in Figure 2. The values of the coupled transmission lines could be described using Equations (1)–(3) [1]:

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}, \tag{1}$$

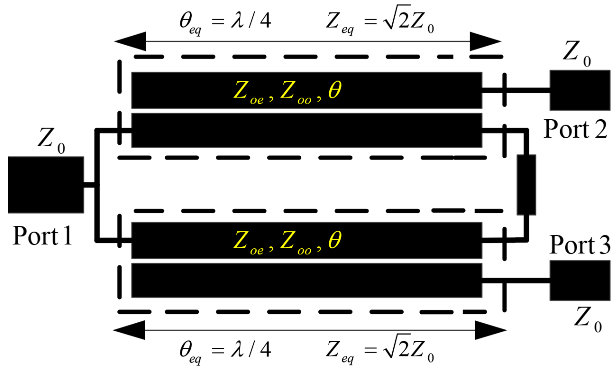

Figure 2. The basic WPD structure after applying the coupled lines.

where C is the coupling coefficient. Moreover, Z_{0e} and Z_{0o} are the even- and odd- characteristic impedance of the coupled lines, respectively, which could be obtained as follows [1]:

$$Z_{0e} = Z_o\sqrt{\frac{1+C}{1-C}}, \tag{2}$$

$$Z_{0o} = Z_o\sqrt{\frac{1-C}{1+C}}, \tag{3}$$

where Z_0 is the transmission lines' characteristic impedance. The coupling lines can provide the wide-band operation of the amplifiers. In addition, the open-ended stubs could produce transmission zeros in the frequency response; therefore, they could be used for realizing harmonic suppression. Subsequently, two open stubs are added near the output ports of the WPD as shown in Figure 3, which forms the primitive WPD.

The $ABCD$ matrices of the coupled line ($ABCD_{CL}$) and output open stubs ($ABCD_{OS1}$) are defined in Equations (4) [24] and (5) as below:

$$ABCD_{CL} = \begin{bmatrix} \frac{Z_{0e}+Z_{0o}}{Z_{0e}-Z_{0o}}\cos\theta & j\frac{(Z_{0e}-Z_{0o})^2+(Z_{0e}+Z_{0o})^2\cos^2\theta}{2(Z_{0e}-Z_{0o})\sin\theta} \\ j\frac{2\sin\theta}{Z_{0e}-Z_{0o}} & \frac{Z_{0e}+Z_{0o}}{Z_{0e}-Z_{0o}}\cos\theta \end{bmatrix}, \tag{4}$$

$$ABCD_{OS1} = \begin{bmatrix} 1 & 0 \\ \frac{j\tan\theta_{OS1}}{Z_{OS1}} & 1 \end{bmatrix}. \tag{5}$$

Moreover, the $ABCD$ matrix of the conventional $\lambda/4$ line in WPD is equal to

$$ABCD_{QWL} = \begin{bmatrix} 0 & j\sqrt{2}Z_0 \\ j/(\sqrt{2}Z_0) & 0 \end{bmatrix}. \tag{6}$$

In the structure shown in Figure 3, the circuit parameters can be calculated as follows:

$$ABCD_{QWL} = ABCD_{CL} \times ABCD_{OS1}. \tag{7}$$

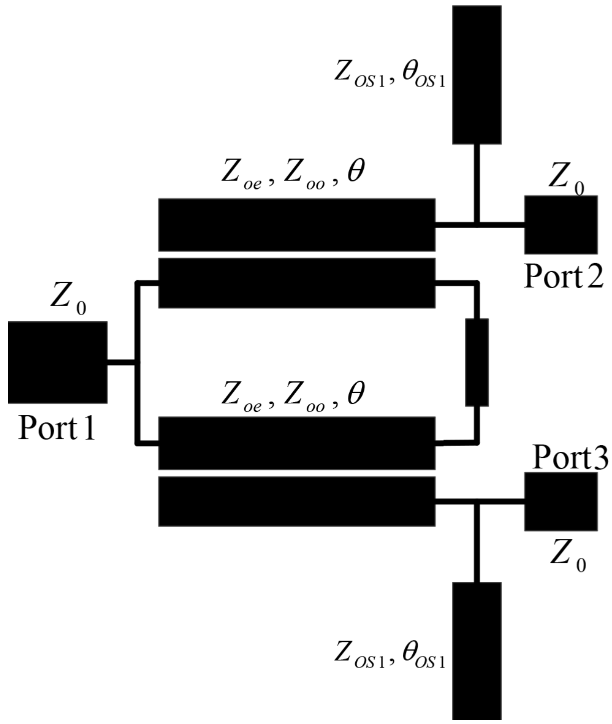

Figure 3. Structure of the primitive WPD.

The electromagnetic (EM) simulation results of the primitive WPD frequency response are depicted in Figure 4. All of the simulations in this paper are performed in Momentum section of Advanced Design System (ADS) software. The ADS software uses electromagnetic simulation (EM simulation) for simulating layout structures in Momentum section. EM simulation is a tool which solves the Maxwell's equation that satisfies the given boundary and initial conditions. According to the frequency response of the primitive WPD, the values of insertion loss and isolation are better than 0.04 dB and 18 dB, respectively. In addition, the 15 dB bandwidth of 0.6 GHz from 3.5 GHZ up to 4.1 GHZ has been obtained for the primitive WPD.

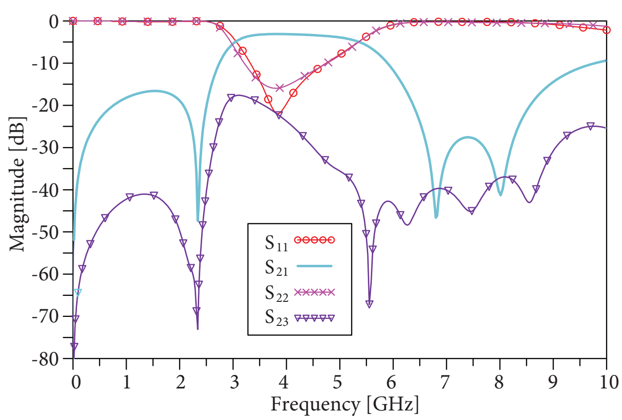

Figure 4. The simulated frequency response of the primitive WPD.

For size reduction realization for the presented WPD, the primitive WPD should be miniaturized as illustrated in Figure 5. The main couple transmission lines and open-ended stubs are meandered to obtain overall size reduction of the divider. Moreover, the simulated frequency response of the primitive WPD after size reduction is illustrated in Figure 6. As can be seen in Figures 5 and 6, not only the size reduction has been obtained for the primitive WPD, but also the parameters of the WPD have been slightly improved.

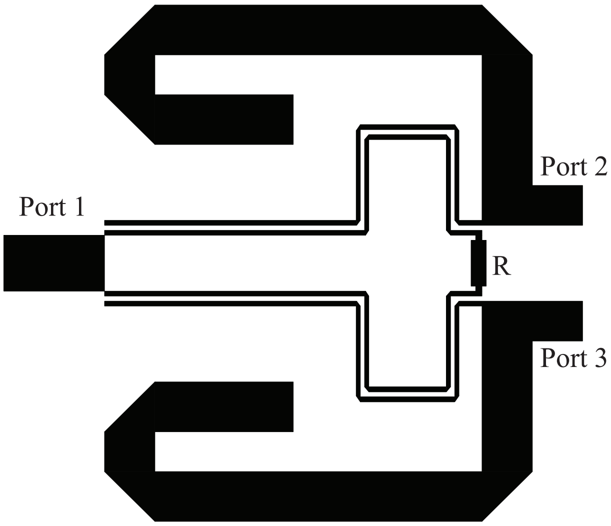

Figure 5. Structure of the primitive WPD after size reduction.

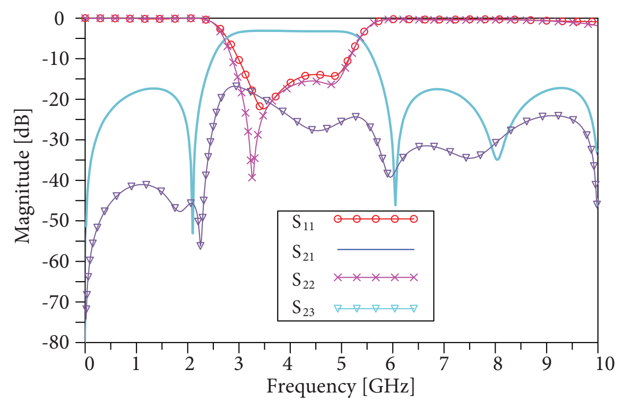

Figure 6. The simulated frequency response of the primitive WPD after size reduction.

2.1. The proposed power divider

As previously mentioned, the primitive WPD after size reduction has a relatively good response but it should be improved. For example, good suppression band has been obtained for the divider but the suppression level is not yet acceptable. Therefore, extra transmission zeros should be added in the frequency response. Subsequently, two extra open-ended stubs are added in the structure of the divider. After adding these extra open stubs, the final structure of the proposed WPD, which is shown in Figure 7, has been obtained. The two extra open-ended stubs are added near input port. They are also meandered to reduce the overall size of the divider. In the final structure shown in Figure 7, the circuit parameters can be calculated as follows:

$$ABCD_{QWL} = ABCD_{OS2} \times ABCD_{CL} \times ABCD_{OS1}, \tag{8}$$

where the ABCD matrix of the input open stubs ($ABCD_{OS2}$) can be obtained similar to equation (5).

The EM simulation results of the proposed WPD frequency response are depicted in Figure 8. As shown in this figure, the suppression level of the frequency response is improved. Moreover, the insertion losses are enhanced after adding two extra open-ended stubs.

Applied dimensions in the proposed WPD which are shown in Figure 7 are listed in Table 1.

Table 1. The applied dimensions in the proposed WPD.

Dimensions	A	B	C	D	E	F	G	H	I	J	K	L
(mm)	11	7	1.8	2.3	1.6	8	2.2	3.2	0.1	0.2	10.6	0.2

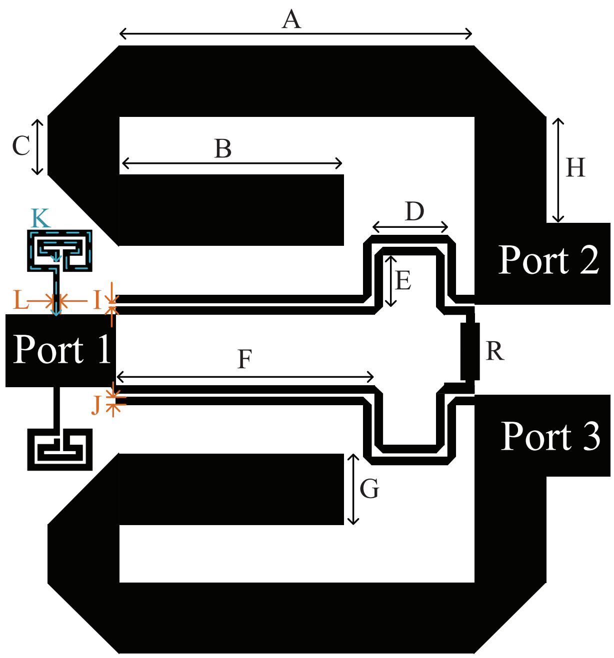

Figure 7. Structure of the proposed WPD.

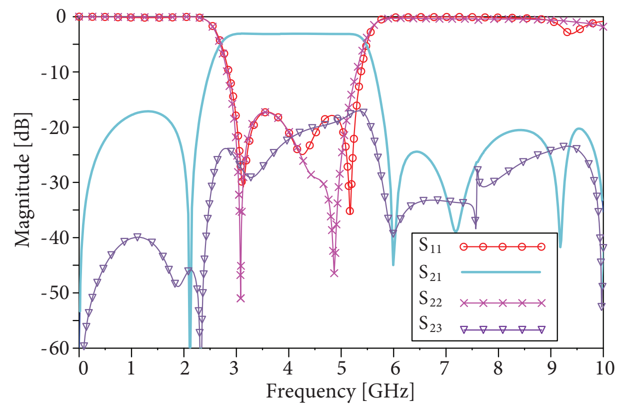

Figure 8. The simulated frequency response of the proposed WPD.

3. Results of the proposed WPD

RT/Duroid 5880 substrate with 31-mil thickness and $\varepsilon_r = 2.2$ is used for fabrication of the proposed WPD. Moreover, HP network analyzer 8720B, 130 MHz to 20 GHz, is used to measure the fabricated power divider. Figure 9 shows the photograph of the implemented WPD.

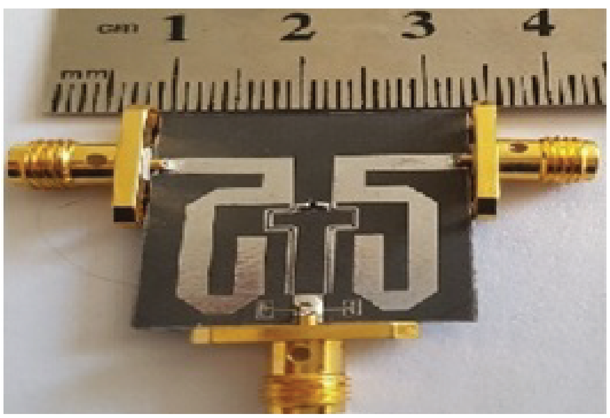

Figure 9. The photograph of the implemented WPD.

Final size of the implemented divider is 15.8 mm $\times$ 18.8 mm or $0.29\lambda_g \times 0.34\lambda_g$. The measured and EM simulation results of the proposed WPD frequency response are shown in Figures 10 and 11.

A 15 dB bandwidth of 50% with center frequency of 4.25 GHz corresponding to a 2.1 GHz operational bandwidth from 3.2 GHz up to 5.3 GHz is obtained as shown in Figure 10. The return loss is better than 15 dB in the entire operating bandwidth. Measured insertion loss and isolation are better than 0.8 dB and 16 dB in the entire frequency bandwidth. Moreover, the maximum output and input return losses are about 32 dB in the

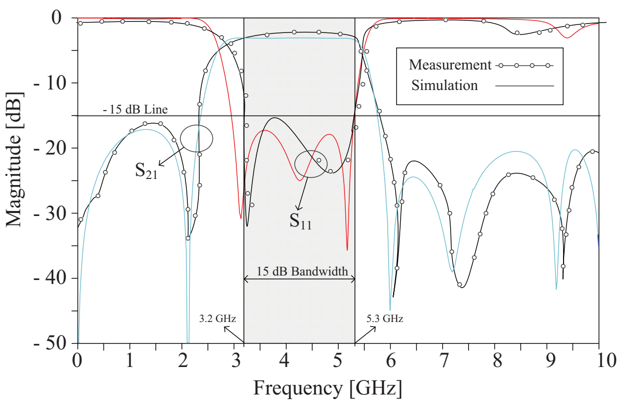

Figure 10. The measured and simulated S_{21} and S_{11} parameters of the proposed WPD.

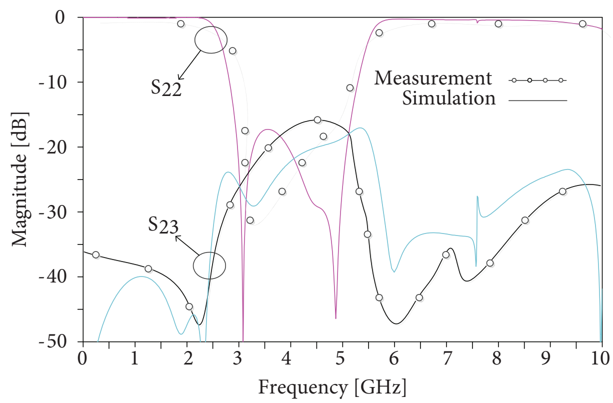

Figure 11. The measured and simulated S_{23} and S_{22} parameters of the proposed WPD.

operating bandwidth. The presented WPD provides filtering band between 6 GHz and 10 GHz with attenuation of better than 20 dB. This suppression band provides good harmonic suppression operation for the proposed WPD. In addition, a filtering band with attenuation level of better than 16 dB has been obtained for the lower frequencies up to 2.3 GHz. Parameters of the proposed WPD and the recently presented dividers are compared in Table 2.

Table 2. Parameters of the proposed WPD compared with the recently presented dividers.

References	Center frequency	Insertion loss	Wide band	BW	Harmonic suppression
[9]	0.92 GHz	0.99 dB	-	20 dB BW- 6.5%	✓
[10]	2.4 GHz	0.45 dB	-	-	✓
[11]	2.3 GHz	1.3 dB	✓	<10dB BW- 31%	✓
[12]	1 GHz	0.9 dB	✓	20 dB BW- 43%	✓
[13]	1 GHz	0.1 dB	-	-	✓
[14]	1.2 GHz	1.4 dB	-	16 dB BW- 3.5%	✓
[15]	0.9 GHz	0.68 dB	✓	13 dB BW- 11%	✓
[17]	2.05 GHz	1.6 dB	✓	10 dB BW- 62%	✓
[25]	2 GHz	0.9 dB	-	15 dB BW- 11%	-
This Work	4.25 GHz	0.8 dB	✓	15 dB BW- 50%	✓

As seen in Table 2, only a few reported studies have wide-band operation. However, the BW definitions are different among the reported studies because of different values of input return loss consideration in the bandwidth. For example, the highest BW in the table belongs to the WPD in [17]. However, the BW definition in [17] is the operating band in which the input return loss is considered better than 10 dB, which is not desirable. Moreover, insertion loss is another important parameter in power divider design; insertion loss greater than 1 dB is not desirable. Therefore, in the proposed work according to high BW with better than 15 dB input return loss and low value of insertion loss in the operating band, excellent parameters have been achieved, compared with those of other research. In addition, the proposed work shows good harmonic suppression for the entire operating bandwidth.

4. Conclusion

A harmonic-suppressed power divider with ultrawide operating band is presented in this paper. For verification, the designed divider is fabricated, and the simulation results are verified with the measurement data, which shows good agreement. The main merits of the proposed divider are harmonic suppression and ultrawide-band operation, simultaneously. Moreover, the other parameters of the divider are desirable which makes this divider applicable in the modern communication systems.

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