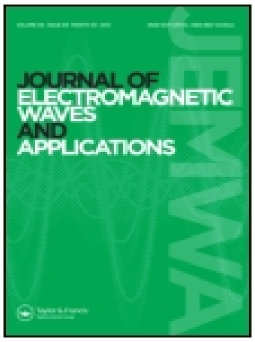

Taylor & Francis
Taylor & Francis Group

Journal of Electromagnetic Waves and Applications

ISSN: 0920-5071 (Print) 1569-3937 (Online) Journal homepage: http://www.tandfonline.com/loi/tewa20

A novel miniaturized Wilkinson power divider with n th harmonic suppression

Mohsen Hayati , Sobhan Roshani , Saeed Roshani & Farzin Shama

To cite this article: Mohsen Hayati , Sobhan Roshani , Saeed Roshani & Farzin Shama (2013) A novel miniaturized Wilkinson power divider with n th harmonic suppression, Journal of Electromagnetic Waves and Applications, 27:6, 726-735, DOI: 10.1080/09205071.2013.786204

To link to this article: http://dx.doi.org/10.1080/09205071.2013.786204

Published online: 10 Apr 2013.

Journal of Electromagnetic Waves and Applications, 2013
Vol. 27, No. 6, 726–735, http://dx.doi.org/10.1080/09205071.2013.786204

A novel miniaturized Wilkinson power divider with *n*th harmonic suppression

Mohsen Hayati*, Sobhan Roshani, Saeed Roshani and Farzin Shama

Faculty of Engineering, Department of Electrical Engineering, Razi University, Tagh-E-Bostan, Kermanshah, Iran

(*Received 19 December 2012; accepted 9 March 2013*)

In this paper, a miniaturized Wilkinson power divider using a novel technique for ***n***th harmonic suppression is presented. In this technique, a novel low-pass filter (LPF) is inserted into each quarter-wavelength transmission line of the conventional Wilkinson power divider and open stubs are used at each port. For verification, the proposed 1 GHz power divider and the miniaturized LPF are fabricated and measured. The presented structure not only impressively suppresses the harmonics (2nd–12th) with high levels of attenuation, but also significantly reduces the size over 71% of the conventional one. The overall size of the fabricated power divider is only 14.1 mm × 18.2 mm ($0.06\ \lambda_g \times 0.08\lambda_g$).

1. Introduction

The Wilkinson power divider is one of the most widely used components in the wireless communication systems for power division or combination, such as power amplifiers, mixers, and frequency multipliers.[1] The main drawback of the conventional Wilkinson power divider is the presence of spurious response due to the adoption of quarter-wavelength transmission lines.[2]

Several methods have been proposed to design miniaturized harmonic suppressed power dividers.[2–24] Previously, this problem has been partially overcome using the electromagnetic band gap (EBG) cells or defected ground structure (DGS).[3–6] EBG, DGS, and lumped reactive components [7–9] have been applied to reduce the occupied area of power dividers and suppress the harmonics. Unfortunately, these methods usually require either backside etching or additional lumped reactive element, which is undesirable for low-cost and mass production environment.[2] Furthermore, other techniques have been used for harmonic suppression and size reduction, such as applying resonators cells,[10–15] microstrip open stubs, [2,16–18] and the nonuniform transmission line transformers.[19] However, in all the mentioned structures, obtaining harmonic suppression with high level of attenuation and extreme size reduction is still the most important challenge.

In this paper, a superior harmonic suppressed Wilkinson power divider with 71% size reduction is designed and fabricated using low-pass filters (LPFs) and open stubs. The microstrip open stubs suppress the second and third harmonics, while LPFs suppress the

*Corresponding author. Email: hayati@razi.ac.ir

4th–12th harmonics with high level of attenuation. As compared with the other approaches, the proposed structure has the best performance for harmonic suppression and size reduction.

2. Circuit design

The proposed power divider is based on the modified structure, in which three open stubs suppress the second and third harmonics as shown in Figure 1(a). The associate lengths and impedances of these open stubs and their relation with main structure are discussed under the odd- and even-mode excitation as depicted in Figures 1 and 2.

2.1. Odd mode analysis

According to Figure 1(b), the output admittance of the odd-mode equivalent circuit is [25]

$$Y_A = \frac{-j}{Z_1 \tan\theta_1}, \tag{1}$$

$$Y_B = \frac{j \tan\theta_2}{Z_2}, \tag{2}$$

$$Y_C = \frac{2}{R}, \tag{3}$$

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

$$Y_0 = \frac{-j\cot\theta_1}{Z_1} + \frac{j\tan\theta_2}{Z_2} + \frac{2}{R}. \tag{5}$$

The real part of Equation (5) yields

$$R = 2Z_0, \tag{6}$$

while the imaginary part becomes

$$\frac{Z_2}{Z_1} = \tan\theta_1 \tan\theta_2. \tag{7}$$

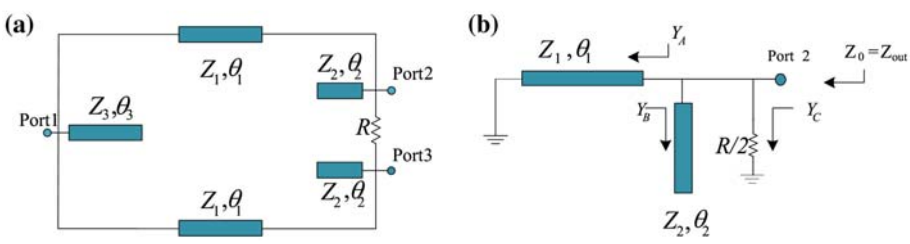

Figure 1. (a) Schematic diagram of the modified Wilkinson power divider and (b) odd-mode equivalent circuit.

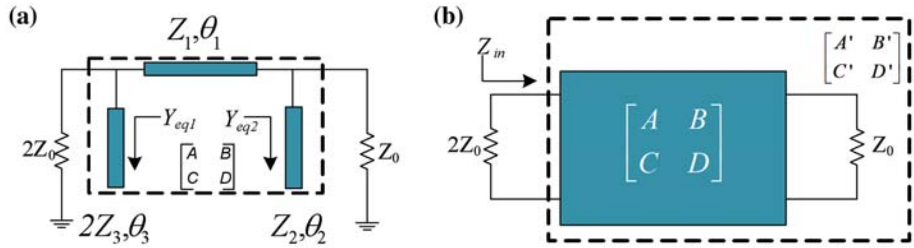

Figure 2. (a) Even-mode equivalent circuit and (b) equal matrix of power divider in even mode.

2.2. Even-mode analysis

From Figure 2(a), the ABCD matrix can be presented under the even-mode excitation, as follows [25]:

$$\begin{bmatrix} 1 & 0 \\ Y_{eq1} & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta_1 & \cos\theta_1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y_{eq2} & 1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \tag{8}$$

where

$$Y_{eq1} = j\frac{Y_3}{2}\tan\theta_3, \tag{9}$$

$$Y_{eq2} = jY_2\tan\theta_2. \tag{10}$$

Equation (8) can be reduced to

$$A = \cos\theta_1 - Z_1Y_2\sin\theta_1\tan\theta_2, \tag{11}$$

$$B = jZ_1\sin\theta_1, \tag{12}$$

$$C = \frac{1-AD}{B}, \tag{13}$$

$$D = -\frac{Z_1Y_3}{2}\sin\theta_1\tan\theta_3 + \cos\theta_1, \tag{14}$$

According to Figure 2(b), the new equation for matrix can be written as

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_0} & 1 \end{bmatrix}, \tag{15}$$

$$Z_{in} = 2Z_0 = \frac{A'}{C'}, \tag{16}$$

$$A = 2D, \tag{17}$$

$$A^2 - \left(\frac{B}{Z_0}\right)^2 = 2. \tag{18}$$

Equation (17) implies

$$\frac{Z_1}{Z_2}\tan\theta_2 + \cot\theta_1 = \frac{Z_1}{Z_3}\tan\theta_3 \tag{19}$$

and Equation (18) can be written as

$$\frac{Z_1}{Z_0} = \pm\frac{\sqrt{2}}{\sin\theta_1}. \tag{20}$$

From combination of Equations (7) and (19), we obtain

$$\frac{Z_3}{Z_1} = \frac{\tan\theta_1\tan\theta_3}{2}. \tag{21}$$

Since ***n***th harmonic suppression is desired, θ_n is assigned to be $\pi/2n$.[2] For second and third harmonic suppression, θ_2 and θ_3 are obtained as $\pi/6$ and $\pi/4$, respectively. Substituting these values into Equations (7) and (21), the relation between Z_2 and Z_3 is obtained as follows:

$$\frac{Z_3}{Z_2} = \frac{\sqrt{3}}{2}. \tag{22}$$

The obtained lengths of the open stubs, to have a good suppression at second and third harmonics, are longer than the overall width of the designed power divider. Therefore, the open stubs are symmetrically bended and modified in order to be placed within the size of the proposed power divider. This symmetric property results very good output phase imbalance between two output ports. Based on Equation (22) and limitation of size, Z_2 and Z_3 are chosen to be 180 and 155 ohms, respectively. Therefore, the values of Z_1 and θ_1 can be obtained from Equations (20) and (21), which are $Z_1 = 72$ ohms and $\theta_1 = 76$. The simulated S-parameters of the modified structure in Figure 1(a) are shown in Figure 3. As illustrated in Figure 3, the second and third harmonics are suppressed with attenuation levels of −48 and −45 dB, respectively.

3. Proposed structure

Figure 4(a) shows the conventional Wilkinson power divider that consists of two quarter-wavelength transmission lines ($\sqrt{2}Z_0$) and an isolation resistor (100 Ω). In the proposed structure, two miniaturized LPFs are inserted into each quarter-wavelength transmission line of the conventional Wilkinson power divider (Z_1, θ_1). The schematic diagram of the proposed power divider is shown in Figure 4(b), including a resistor ($r = 100$ Ω), four similar branch-line sections, three open-ended stubs, and two proposed LPFs.

3.1. Proposed LPF

The inserted LPF is based on a stepped impedance resonator. The proposed microstrip resonator is shown in Figure 5(a). The dimensions optimization for the proposed resonator is

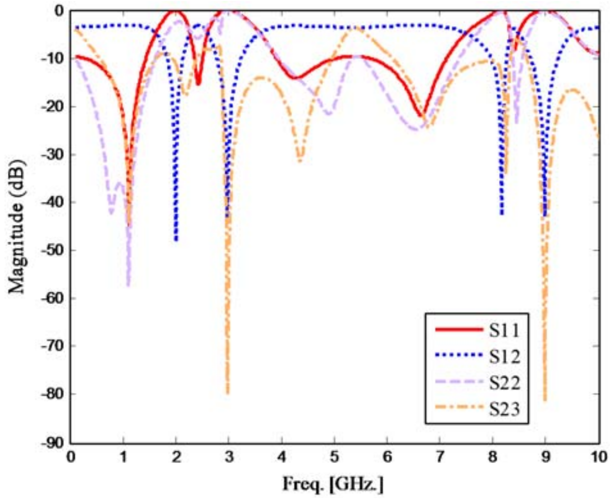

Figure 3. Simulated S-parameters of the modified structure.

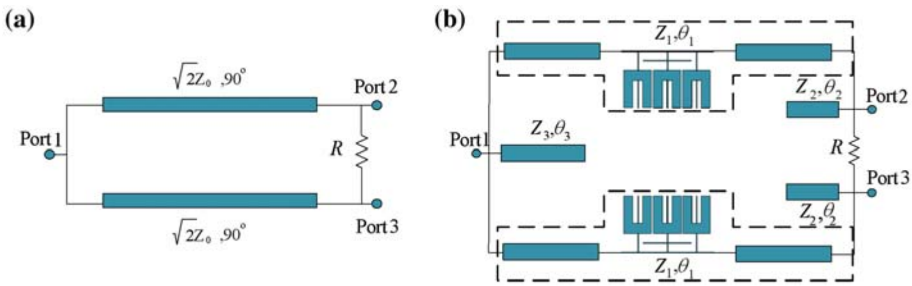

Figure 4. Schematic diagram of the (a) conventional Wilkinson power divider and (b) proposed power divider.

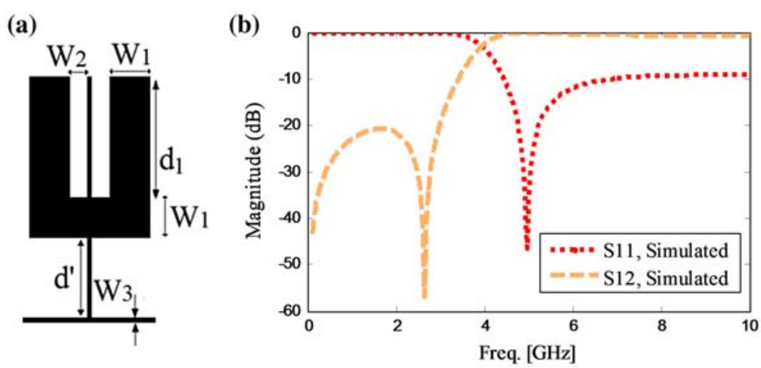

Figure 5. (a) The proposed microstrip resonator and (b) the simulated S-parameters for the proposed resonator.

achieved by an EM simulator named Advanced Design System (ADS) to have a desired cut-off frequency and sharp roll-off. As can be seen from Figure 5(b), the resonator creates a transmission zero at 4.84 GHz with the attenuation level of −48 dB, which can provide the −3 dB cut-off frequency nearby 3.6 GHz. However, to have a sharper roll-off, smaller transmission zero is needed.

Very sharp transition band and a wider stopband can be achieved by tripling the proposed resonator with same cut-off frequency, as illustrated in Figure 6(a). In this structure, by adding two high-impedance open-end lines (with length of d_5) to the central resonator, the insertion loss is improved to nearby 0 dB. The desired dimensions for the layout of the proposed LPF are: $W = 1.5$ mm, $W_1 = 1$ mm, $W_2 = 0.45$ mm, $W_3 = 0.1$ mm, $d = d_5 = 2.5$ mm, $d_2 = 9.8$ mm, $d_3 = d_4 = 0.95$ mm, $d' = 2$ mm.

The filter is fabricated on the RT/Duroid 5880 substrate ($\varepsilon_r = 2.2$, thickness = 0.508 mm, loss tangent of 0.0009), as shown in Figure 6(b). The measurement is carried out on a HP8757A network analyzer. As shown in Figure 6(c), the simulated and measured results are in good agreement. The return loss is nearby 0 dB in the stopband. The transition band is very sharp, approximately 0.07 GHz from 3.6 to 3.67 GHz with corresponding attenuation levels of −3 and −20 dB, respectively. The proposed LPF shows high suppression in a wide stopband from 3.67 to 10.5 GHz with the attenuation level of −20 dB. The size of the filter is only 9.8 mm × 6.1 mm (59.78 mm^2).

The frequency response of the proposed filter illustrates three transmission zeros, at 3.7, 4.3, and 6.2 GHz with attenuation levels of −42.38, −69.78, and −55.5 dB, respectively. These transmission zeros can provide the high rejection levels for eliminating the desired harmonics in the proposed power divider.

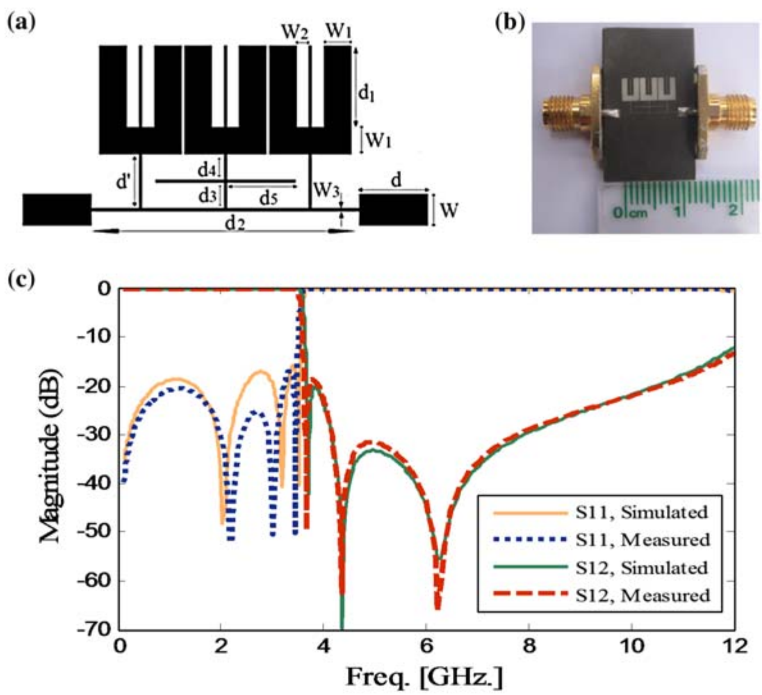

Figure 6. (a) The layout of the proposed LPF, (b) the photograph of the fabricated proposed LPF, and (c) the simulated and measured S-parameters.

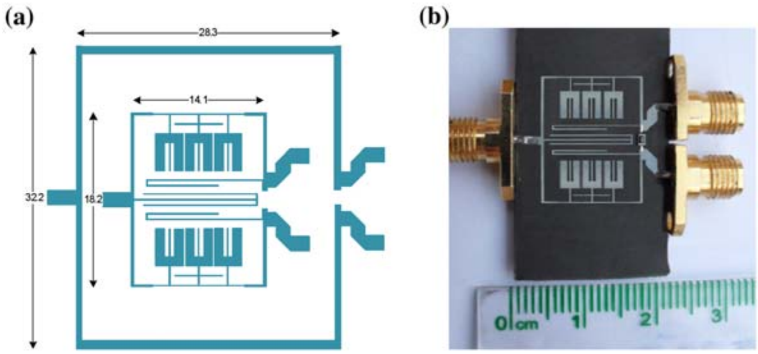

Figure 7. (a) The schematic of the proposed and conventional power divider and (b) photograph of the fabricated power divider.

3.2. Proposed power divider

The final structure of the proposed Wilkinson power divider is illustrated in Figure 7, which shows extra size reduction. The size reduction of the proposed power divider as compared to the conventional one is depicted in Figure 7(a). The size of the fabricated power divider is 14.1 mm × 18.2 mm (256.62 mm^2), which shows over 71% size reduction as compared to the conventional one.

Figure 7(b) shows the fabricated power divider on a RT/Duroid 5880 substrate ($\varepsilon_r = 2.2$, thickness = 0.508 mm, and loss tangent of 0.0009). The S-parameters are measured using a HP8757A network analyzer.

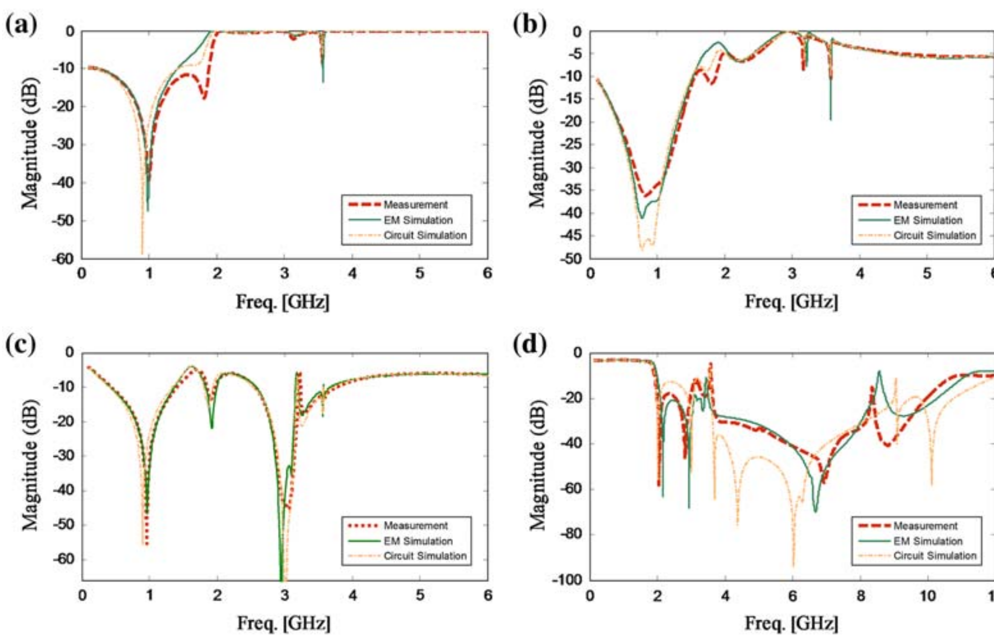

Figure 8. Measured and simulated (a) input port matching parameter, (b) output port matching parameter, (c) isolation of the proposed power divider, and (d) transmission parameter.

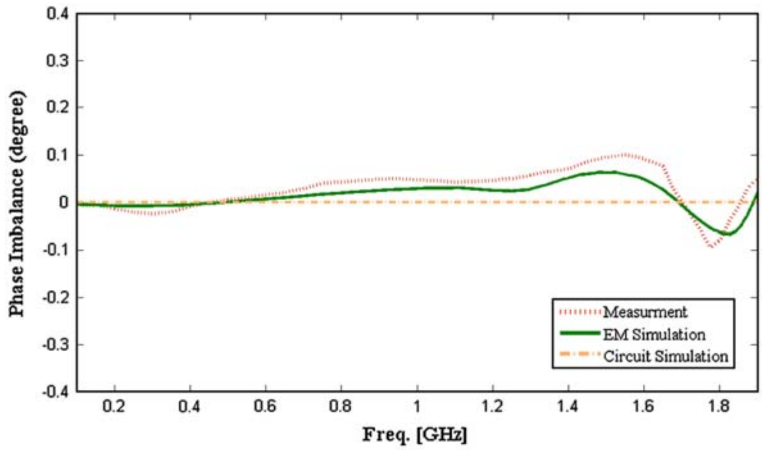

Figure 9. Measured and simulated phase imbalances between ports 2 and 3 around center operation frequency.

Table 1. Performance summary of the proposed power divider and previous works.

		Harmonic suppression (dB)										
Ref.	Size reduction (%)	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
[2]	–	40	40	40	–	–	–	–	–	–	–	–
[3]	70	8	32	10	12	–	–	–	–	–	–	–
[4]	–	18	15	–	–	–	–	–	–	–	–	–
[5]	39	26	25	–	–	–	–	–	–	–	–	–
[6]	66	13	35	–	–	–	–	–	–	–	–	–
[7]	–	4	40	–	–	–	–	–	–	–	–	–
[10]	44	20	40	–	–	–	–	–	–	–	–	–
[14]	47	–	22	–	–	–	–	–	–	–	–	–
[17]	55	30	30	20	20	–	–	–	–	–	–	–
[18]	–	39	34	37	39	30	–	–	–	–	–	–
[20]	63	13	29	32	34	–	–	–	–	–	–	–
[21]	54	10	18	22.5	35	45	28	–	–	–	–	–
This work	71	58	46	30	32	41	57	33	39	21	10	10

Figure 8 illustrates the simulated and measured S-parameters of the proposed power divider. As it is seen, the simulated and measured results are in good agreement. The central frequency of the power divider is located at 1 GHz. The experimental results show that input return loss is over than 40 dB and output return loss is over than 33 dB, as shown in Figure 8 (a) and (b), respectively. The port isolation of over 55 dB and an insertion loss of less than 0.1 dB are also observed as illustrated in Figure 8(c) and (d), respectively. It is seen from Figure 8(d), the proposed power divider suppresses the 2nd–12th harmonics, simultaneously. As shown in Figure 9, good output phase imbalance around the center operation frequency (1 GHz) is achieved.

A comparison of the power dividers for ***n***th harmonic suppression and size reduction is summarized in Table 1. The results show that this work presents very good size reduction with excellent harmonic suppressions as compared to the reported works.

4. Conclusion

A Wilkinson power divider with a novel technique for size reduction and ***n***th harmonic suppression is proposed and implemented. A new structure is presented by employing open stubs and a wide stopband LPF with good specifications, such as very sharp transition band and low insertion loss in the passband. The open stubs can provide a high suppression at second and third harmonics, while the proposed LPF suppresses the higher order harmonics. For verification, the proposed filter and Wilkinson power divider are fabricated and tested, which have miniaturized size of 9.8 mm × 6.1 mm and 14.1 mm × 18.2 mm, respectively. More than 71% size reduction is obtained in the proposed power divider. A good agreement is observed between the simulated and measured results of the fabricated power divider. With above discussion, the proposed power divider can be employed in modern communication systems.

References

[1] Sun Z, Zhang L, Liu Y, Tong X. Modified Gysel power divider for dual-band applications. IEEE Microw. Wireless Comp. Lett. 2011;21:16–18.
[2] Cheng KKM, Ip WC. A novel power divider design with enhanced spurious suppression and simple structure. IEEE Trans. Microw. Theory Tech. 2010;58:3903–3908.
[3] Lin CM, Su HH, Chiu JC, Wang YH. Wilkinson power divider using microstrip EBG cells for the suppression of harmonics. IEEE Microw. Wireless Comp. Lett. 2007;17:700–702.
[4] Woo DJ, Lee TK. Suppression of harmonics in Wilkinson power divider using dual-band rejection by asymmetric DGS. IEEE Trans. Microw. Theory Tech. 2005;53:2139–2144.
[5] Zhang F, Li C. Power divider with microstrip electromagnetic band gap element for miniaturization and harmonic rejection. Electron. Lett. 2008;44:422–423.
[6] Yang J, Gu C, Wu W. Design of novel compact coupled microstrip power divider with harmonic suppression. IEEE Microw. Wireless Comp. Lett. 2008;18:572–574.
[7] Li J-L, Qu S-W, Xue Q. Capacitively loaded Wilkinson power divider with size reduction and harmonic suppression. Microw. Opt. Technol. Lett. 2007;49:2737–2739.
[8] Perrier A-L, Duchamp J-M, Ferrari P. A miniaturized three-port divider/combiner. Microw. Opt. Technol. Lett. 2008;50:72–75.
[9] Huang W, Liu CJ, Yan L, Huang KM. A miniaturized dual-band power divider with harmonic suppression for GSM applications. J. Electromag. Waves Appl. 2010;24:81–91.
[10] Gu JZ, Yu XJ, Sun XW. A compact harmonic-suppressed Wilkinson power divider using C-SCMRC resonators. Microw. Opt. Technol. Lett. 2006;48:2382–2384.
[11] Shao JY, Huang SC, Pang YH. Wilkinson power divider incorporating quasi-elliptic filters for improved out-of-band rejection. Electron. Lett. 2011;47:1288–1289.
[12] Zhang Z, Jiao YC, Weng ZB. Design of 2.4 GHz power divider with harmonic suppression. Electron. Lett. 2012;48:705–707.
[13] Gil M, Bonache J, Martin F. Synthesis and applications of new left handed microstrip lines with complementary split-ring resonators etched on the signal strip. IET Microw. Anten. Propaga. 2008;2:324–330.
[14] Karthikeyan SS, Kshetrimayum RS. Compact, harmonic suppressed power divider using open complementary split-ring resonator. Microw. Opt. Technol. Lett. 2011;53:2897–2899.
[15] Zhang J, Cui B, Gu J-Z, Sun X-W. A harmonic suppressed Wilkinson power divider using complementary split ring resonators (csrrs). J. Electromag. Waves Appl. 2007;21:811–819.
[16] Yi KH, Kang B. Modified Wilkinson power divider for nth harmonic suppression. IEEE Microw. Wireless Comp. Lett. 2003;13:178–180.
[17] He J, Feng Chen Z, Hai Yang B, Ying Xiong M. Miniaturized microstrip Wilkinson power divider with capacitor loading. Microw. Opt. Technol. Lett 54; 2012:61–63.
[18] Yang N, Li B, Wu X. Closed-form design of Wilkinson power divider with broadband harmonic suppression and size reduction. J. Electromag. Waves Appl. 2012;26:307–318.
[19] Shamaileh K, Qaroot A, Dib N. Non-uniform transmission line transformers and their application in the design of compact multi-band bagley power dividers with harmonics suppression. Prog. Electromagn. Res. 113;2011:269–284.

[20] Wang J, Ni J, Guo YX, Fang D. Miniaturized microstrip Wilkinson power divider with harmonic suppression. IEEE Microw. Wireless Comp. Lett. 2009;19:440–442.
[21] Hazeri AR. A new miniaturization and the nth harmonic suppression of Wilkinson power. IEICE Trans. Electron. 2011;94:215–219.
[22] Sedighy SH, Khalaj-Amirhosseini M. Compact Wilkinson power divider using stepped impedance transmission lines. J. Electromag. Waves Appl. 2011;25:1773–1782.
[23] Wang XY, Li JL, Shao W. Flexible design of a compact coupled-line power divider. J. Electromag. Waves Appl. 2011;25:2168–2177.
[24] Huang W, Liu CJ, Chen Q, Li YN, Chen X, Huang KM. Compact unequal Wilkinson power dividers using planar artificial transmission lines. J. Electromag. Waves Appl. 2011;25:2201–2211.
[25] Pozar DM. Microwave Engineering. 3rd ed. New York (NY): Wiley; 2005.