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Design of a Compact Wilkinson Power Divider with High Order Harmonics Suppression

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Abstract—A new method for designing compact Wilkinson power dividers with three order harmonics suppression is presented. The quarter-wavelength transmission line in the traditional Wilkinson power divider is replaced by two pairs of parallel coupled lines with one end connected in series with an open stub. With this structure, the quarter-wavelength line will be shorter and three attenuation poles can be added in the stopband. As a result, this newly proposed structure carries the functions of impedance matching at operating frequency and three orders harmonics suppression. In this study, an example of power divider operating at 1 GHz is designed and fabricated. The measured results show good performance at the operating frequency. In addition, the second, third and fourth harmonics suppressions are 43 dB, 49 dB and 37 dB, respectively, which validates the feasibility of the proposed design.

1. INTRODUCTION

Power dividers are widely used in microwave and millimeter-wave circuits and systems to split an input signal into two or more output signals. The original power divider used in practice is the Wilkinson divider with an excellent isolation between the two output ports at the centre frequency [1]. However, the quarter-wavelength transmission lines in the conventional Wilkinson power dividers result in the presence of the spurious passbands. In recent years, some new structures for size reducing [2–6] or harmonics suppression [7–13] have been developed. In [7], an $\lambda/4n$ open stub is placed at the center of each $\lambda/4$ branch of the power divider to suppress the nth harmonic component and its odd multiples, but an additional inductor is required. An asymmetric spiral defected ground structure (DGS) is proposed in [8] to suppress the second and third harmonics simultaneously, however, it introduces complication in the fabrication of such circuit. In [9], the power divider consists of a pair of anti-coupled lines shorted by a low impedance line for harmonic suppression, which demonstrates a poor return loss at input and output ports. A planar power divider with microstrip electromagnetic band gap (EBG) cells for harmonics suppression is presented in [10]. Spur-lines are also used to suppress the high order harmonics in [11]. The method of using microstrip high-low impedance resonator cells is presented in [12] to reduce the size of the power divider and suppress high order harmonics. In [13], a simple structure using two transmission line segments is proposed to suppress the first, second and third harmonic frequencies.

In this paper, a new method for designing the microstrip Wilkinson power divider with high order harmonics suppression is presented. The proposed power divider not only reduces the length of the transmission line by 20% at 1 GHz, but also has more than 37 dB suppression for the second, third and fourth harmonics. The proposed Wilkinson power divider performs well, as compared with a conventional Wilkinson power divider at the operating frequency.

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2. STRUCTURE AND THEORY

The proposed structure of the power divider is shown in Figure 1(a). The quarter-wavelength line in the conventional Wilkinson power divider is replaced by two pairs of parallel coupled lines with one end connected in series with an open stub. With this structure, the quarter-wavelength line will be shorter and three attenuation poles can be added in the stopband.

2.1. Harmonic Suppression Analysis

First, we consider the coupled-line section in Figure 1(b) including a pair of coupled lines with one end connected together. To simplify the analysis, we assume that $\theta = \theta_e = \theta_o$, then the $ABCD$ matrix can be derived as [14]

$$A = \cos\theta_1 \text{ or } m_3 \tag{1a}$$

$$B = jZ_{i+} \sin\theta_i \tag{1b}$$

$$C = 2j \sin\theta_i / Z_{ie} \tag{1c}$$

$$D = m_1 \text{ or } \cos\theta_3 \tag{1d}$$

where Z_{ie} and Z_{io} are the even- and odd-mode impedances of the coupled-line sections, $Z_{i+} = \frac{Z_{ie}+Z_{io}}{2}$, $k_i = \frac{Z_{ie}}{Z_{io}}$, $m_i = \cos\theta_i - \frac{\sin\theta_i \tan\theta_i}{k_i}$ $(i = 1 \text{ or } 3)$. The $|S_{21}|$ of the coupled-line section is calculated according to (1) and plotted in Figure 2.

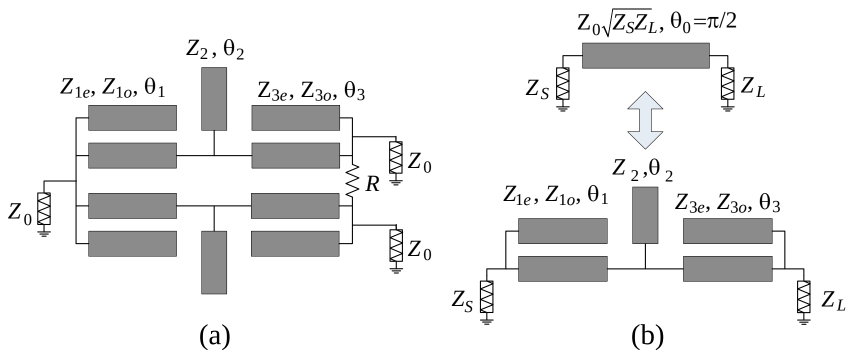

Figure 1. (a) Proposed Wilkinson power divider. (b) Equivalent quarter-wavelength transmission line.

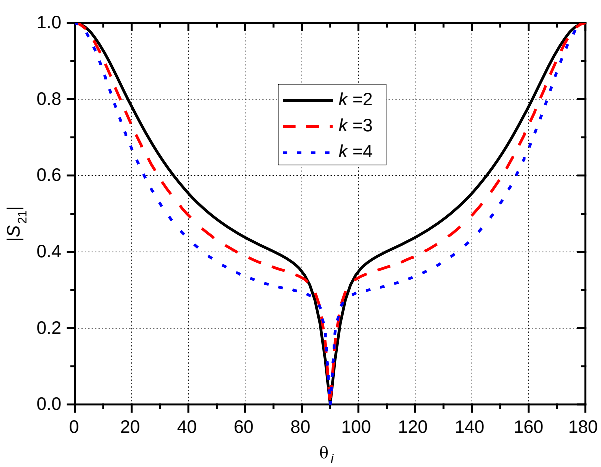

Figure 2. $|S_{21}|$ response with different k.

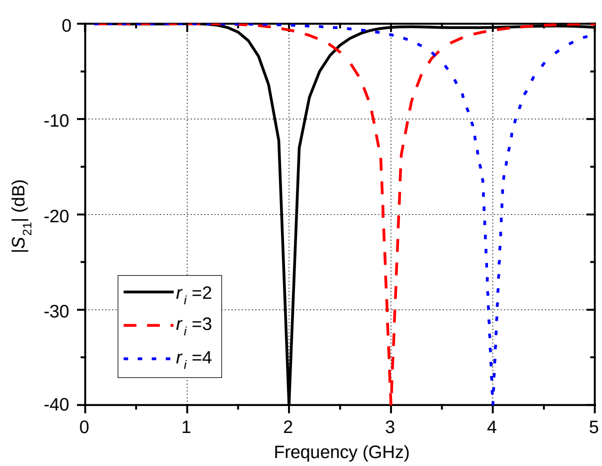

Figure 3. $|S_{21}|$ responses of the coupled-line section.

As can be seen from Figure 2, the coupled-line section will add a transmission zero under the condition that $\theta_i = \pi/2$. Moreover, the different k_i only has an effect on the skirt selectively. Assuming that the operating frequency of the power divider is f_0, and the harmonic is $f_i = r_i f_0$, wherein r_i is the frequency ratio. When the transmission zero is located at f_i, the electrical length of the coupled-line section will be determined by

$$\theta_i = \frac{\pi}{2r_i} \tag{2}$$

Figure 3 plots the $|S_{21}|$ responses of three examples with different frequency ratios ($r_i = 2$, 3 and 4) designed at $f_0 = 1\,\text{GHz}$. It can be found that the location of the transmission zero is controlled by the frequency ratio, only. Thus, in addition to the transmission zero introduced by the open stub [15], there are two other transmission zeros caused by the coupled-line sections in the proposed structure.

2.2. Selection of Circuit Parameters

Because the proposed structure is equal to the quarter-wavelength transmission line at the operating frequency, the isolation resistor will be $R = 2Z_0$. The $ABCD$ matrix of the proposed structure under even-mode excitation can be derived as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & jZ_{1+}\sin\theta_1 \\ j2Y_{1e}\sin\theta_1 & m_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_2\tan\theta_2 & 1 \end{bmatrix} \begin{bmatrix} m_3 & jZ_{3+}\sin\theta_3 \\ j2Y_{3e}\sin\theta_3 & \cos\theta_3 \end{bmatrix} \tag{3}$$

Solving (3), we can get

$$A = m_3\cos\theta_1 - m_3Z_{1+}Y_2\sin\theta_1\tan\theta_2 - 2Z_{1+}Y_{3e}\sin\theta_1\sin\theta_3 \tag{4a}$$
$$B = Z_{3+}\cos\theta_1\sin\theta_3 - Z_{1+}Y_2Z_{3+}\sin\theta_1\tan\theta_2\sin\theta_3 + Z_{1+}\sin\theta_1\cos\theta_3 \tag{4b}$$
$$C = 2m_3Y_{1e}\sin\theta_1 + m_1m_3Y_2\tan\theta_2 + 2m_1Y_{3e}\sin\theta_3 \tag{4c}$$
$$D = m_1\cos\theta_3 - m_1Y_2Z_{3+}\tan\theta_2\sin\theta_3 - 2Y_{1e}Z_{3+}\sin\theta_1\sin\theta_3 \tag{4d}$$

The input impedance can be expressed as

$$Z_{in} = \frac{AZ_L + jB}{jCZ_L + D} \tag{5}$$

It can be observed from Equation (4) that there are eight free variables: Z_{1o}, k_1, θ_1, Z_2, θ_2, Z_{3o}, k_3 and θ_3. In order to simplify the design procedure, we need to reduce the number of free variables before computer optimization. Making (4) be equals to the $ABCD$ matrix ($A = D = 0$) of the quarter-wavelength line at the operating frequency, we can obtain

$$Z_{1o} = \frac{2Z_2}{\tan\theta_2}\left[\frac{k_3m_3\cot\theta_1\cot\theta_3}{(1+k_1)(1+k_3)\sin\theta_3} - \frac{\sin\theta_1}{k_1m_1}\right]\bigg/\left[1 + \frac{k_3m_3\cot\theta_3}{(1+k_3)\sin\theta_3}\right] \tag{6a}$$
$$Z_{3o} = \frac{2Z_2}{\tan\theta_2}\left[\frac{\cot\theta_3}{1+k_3} - \frac{(1+k_1)\sin\theta_1\sin\theta_3}{k_1k_3m_1m_3\cot\theta_1}\right]\bigg/\left[1 + \frac{(1+k_1)\sin\theta_1}{k_1m_1\cot\theta_1}\right] \tag{6b}$$

So (5) will be simplified as

$$Z_{in} = \frac{B}{CZ_L} \tag{7}$$

For ideal input matching at operating frequency, $Z_{in} = Z_S$ must be satisfied. As mentioned before, the locations of the three transmission zeros are determined by θ_1, θ_2 and θ_3. In our designed power divider, we want to suppress the second, third and fourth harmonics. So the electrical length of each section can be calculated from Equation (2): $\theta_1 = \frac{\pi}{4}$, $\theta_2 = \frac{\pi}{6}$ and $\theta_3 = \frac{\pi}{8}$. Thus, the free variables are reduced to: k_1, Z_2 and k_3. To start up the design of the power divider, the terminal impedances are ordinarily chosen as $Z_S = 100\,\Omega$ and $Z_L = 50\,\Omega$.

Figure 4 plots the calculated design parameters of the proposed power divider for various k_1, Z_2 and k_3. It can be observed from Figure 4 that, as k_1, Z_2 and k_3 increase, the voltage standing wave ratio (VSWR) decreases, while the odd-mode characteristic impedance Z_{1o} increases. The odd-mode characteristic impedance Z_{3o} increases as k_1 and Z_2 increase. Whereas Z_{3o} increases firstly and then decreases as k_3 increases.

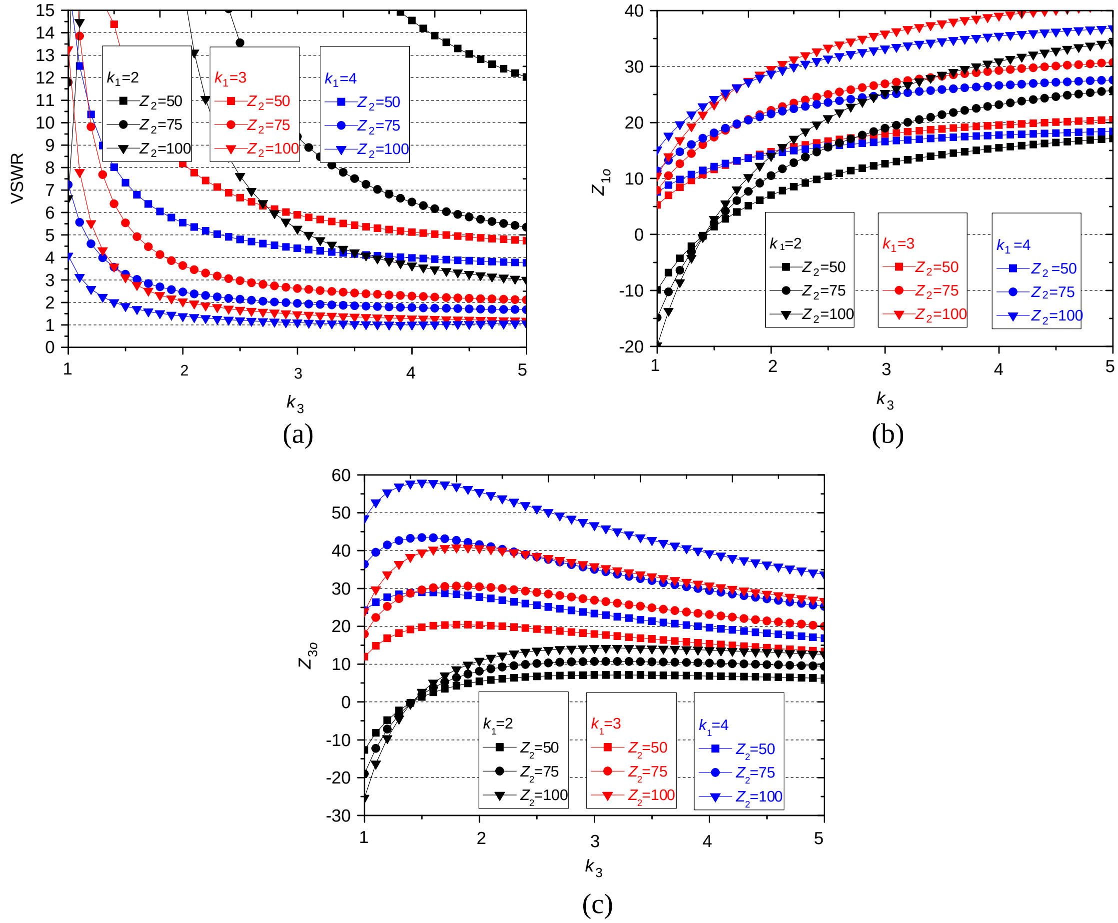

Figure 4. Calculated (a) VSWR, (b) Z_{1o}, (c) Z_{3o} of the proposed power divider for various k_1, Z_2 and k_3.

Thus, as long as the harmonics to be suppressed are selected, the electrical length of each section can be calculated firstly. Then, we can choose k_1, Z_2 and k_3 with the help of Figure 4 for required VSWR and corresponding odd-mode impedance of each coupled-line section. At last, the initial dimensions of the proposed power divider can be calculated from these parameters.

3. SIMULATION AND EXPERIMENT RESULTS

A simulation has been carried out based upon the above analysis. The operating frequency of the power divider is $f_0 = 1\,\text{GHz}$, and the harmonics to be suppressed are $f_i = 2$, 3 and 4 GHz. The design parameters are given from Figure 4: $Z_{1o} = 35.5\,\Omega$, $Z_{3o} = 39.3\,\Omega$, $Z_2 = 100\,\Omega$, $k_1 = k_3 = 4$, $\theta_1 = \frac{\pi}{4}$, $\theta_2 = \frac{\pi}{6}$ and $\theta_3 = \frac{\pi}{8}$. The corresponding frequency responses of the proposed structure and the conventional Wilkinson power divider are illustrated in Figure 5.

As shown in Figure 5, when the quarter-wavelength transmission line is replaced by the proposed structure, the port impedances are fully matched at the operating frequency and the transmission zeros are added at the desired position simultaneously.

For theoretical verification, a prototype power divider is designed and fabricated. Rogers RO4350 board with dielectric constant $\varepsilon_r = 3.66$ and thickness of 0.508 mm is used as the substrate.

A photograph of the fabricated power divider is shown in Figure 6. The final sizes of the power divider are: $W_1 = 0.23\,\text{mm}$, $W_2 = 1.1\,\text{mm}$, $W_3 = 0.26\,\text{mm}$, $S_1 = 0.31\,\text{mm}$, $S_3 = 0.33\,\text{mm}$, $L_1 = 23.62\,\text{mm}$, $L_2 = 15.29\,\text{mm}$, and $L_3 = 11.67\,\text{mm}$. The isolation resistor is $R = 100\,\Omega$, which is similar to the traditional Wilkinson power divider. Figure 7 illustrates the measured and simulated

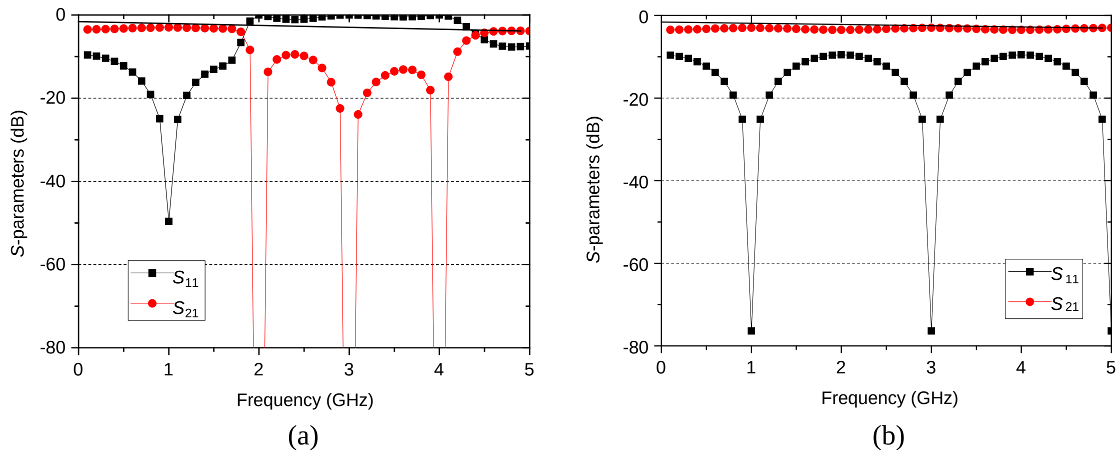

Figure 5. Frequency responses of (a) the proposed structures and (b) the conventional Wilkinson power divider.

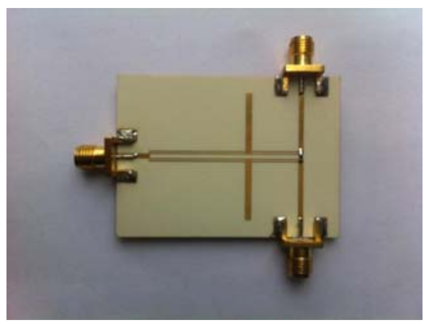

Figure 6. Photograph of the proposed power divider.

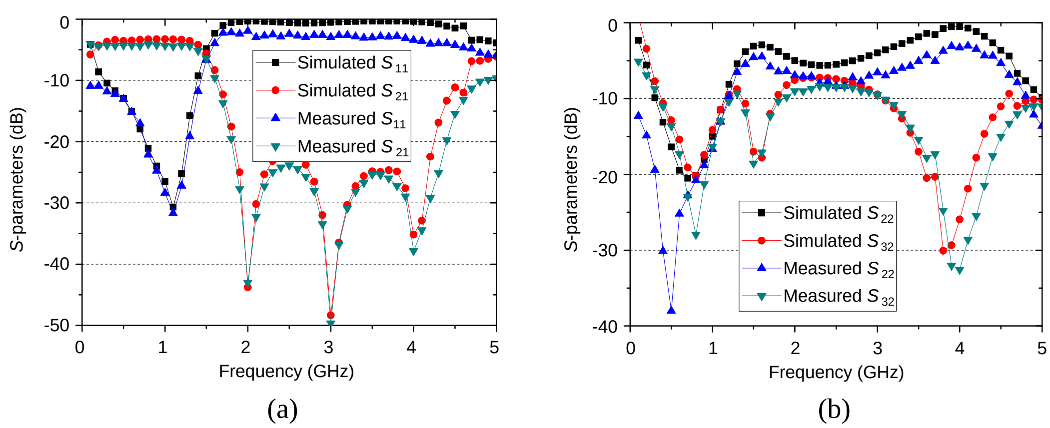

Figure 7. Simulated and measured S-parameters of the proposed power divider, (a) $|S_{11}|$ and $|S_{21}|$ (b) $|S_{22}|$ and $|S_{32}|$.

S-parameters. In Figure 7(a), the measured input return loss is greater than 20 dB at 1 GHz, while the measured insertion loss is about 4 dB. The measured suppression for the second harmonic (2 GHz) is 43 dB, for the third harmonic (3 GHz) is 49 dB and for the fourth harmonic (4 GHz) is 37 dB. In addition, a stopband bandwidth (1.8–4.4 GHz) has been achieved with a minimum attenuation of 20 dB. Figure 7(b) shows the output return loss and isolation between two output ports. The measured output return loss $|S_{22}|$ and $|S_{32}|$ between port 2 and port 3 are greater than 10 dB at the designing frequency.

Moreover, the length of the proposed structure is 36.8 mm, which has achieved a length reduction of 20% at the operating frequency.

4. CONCLUSION

In this paper, a compact Wilkinson power divider with three order harmonics suppression is presented. The size of conventional quarter-wavelength transmission lines can be reduced and the high order harmonics can be suppressed by the proposed structure. It also offers a high level of attenuation over a wide stopband bandwidth. A power divider with the proposed structure is designed and fabricated, and the measured results show good agreement with the simulation, which approves the validity of the structure.

REFERENCES

1. Wilkinson, E. J., "An N-way hybrid power divider," *IRE Transactions on Microwave Theory and Techniques*, Vol. 8, No. 1, 116–118, 1960.
2. Lee, D. H., Y. B. Park, and Y. Yun, "Highly miniaturised Wilkinson power divider employing π-type multiple coupled microstrip line structure," *Electronics Letters*, Vol. 42, No. 3, 763–765, 2006.
3. Lin, C. M., H. H. Su, J. C. Chiu, and Y. H. Wang, "Wilkinson powerdivider using microstrip EBG cells for the suppression of harmonics," *IEEE Microwave Wireless Components Letters*, Vol. 17, No. 10, 700–702, 2007.
4. Zhang, F. and C. F. Li, "Power divider with microstrip electromagnetic bandgap element for miniaturisation and harmonic rejection," *Electronics Letters*, Vol. 44, No. 6, 422–423, 2008.
5. Woo, D. J. and T. K. Lee, "Suppression of harmonics in Wilkinson power divider using dual-band rejection by asymmetric DGS," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 6, 2139–2144, 2005.
6. Gil, M., J. Bonache, I. Gil, J. García-García, and F. Martín, "Miniaturisation of planar microwave circuits by using resonant-type left-handed transmission lines," *IET Microwave, Antennas & Propagation*, Vol. 1, No. 1, 73–79, 2007.
7. Yi, K.-H. and B. Kang, "Modified Wilkinson power divider for nth harmonic suppression," *Microwave and Wireless Components Letters*, Vol. 13, No. 5, 178–180, 2003.
8. Woo, D.-J., and T.-K. Lee, "Suppression of harmonics in Wilkinson power divider using dual-band rejection by asymmetric DGS," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 6, 2139–2144, 2005.
9. Zhang, J., et al., "Compact and harmonic suppression Wilkinson power divider with short circuit anti-coupled line," *Microwave and Wireless Components Letters*, Vol. 17, No. 9, 661–663, 2007.
10. Lin, C.-M., et al., "Wilkinson power divider using microstrip EBG cells for the suppression of harmonics," *Microwave and Wireless Components Letters*, Vol. 17, No. 10, 700–702, 2007.
11. Liu, H. W., et al., "Harmonics suppression of Wilkinson power divider using spurlines with adjustable rejection bands," *Microwave and Optical Technology Letters*, Vol. 50, No. 3, 601–604, 2008.
12. Wang, J., et al., "Miniaturized microstrip Wilkinson power divider with harmonic suppression," *Microwave and Wireless Components Letters*, Vol. 19, No. 7, 440–442, 2009.
13. Peng, Y., L. Zhang, Y. Leng, and J. Guan, "A modified microstrip Wilkinson power divider with high order harmonics suppression," *Progress In Electromagnetics Research C*, Vol. 36, 159–168, 2013.
14. Zysman, G. I. and A. K. Johnson, "Coupled-transmission-line networks in an inhomogeneous medium," *IEEE Transaction on Microwave Theory and Techniques*, Vol. 17, No. 10, 753–759, 1969.
15. Hong, J. S. G. and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, John Wiley & Sons, 2004.