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Compact Wilkinson Power Divider with Higher Order Harmonics Suppression for LTE Application

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Abstract—This paper presents a compact Wilkinson power divider (WPD) operating at 0.7 GHz (LTE band) with higher order harmonics suppression based on step impedance shunt stubs (SISSs) and defected ground structure (DGS). The quarter wavelength lines of conventional WPD are replaced by a host line loaded with a DGS and a pair of SISSs. The DGS and SISS of the proposed line serve as a high series inductance and shunt capacitance, respectively. Therefore, a compact quarter wavelength line is designed compared to conventional one. A prototype of the proposed power divider is designed based on the proposed line, which provides a size reduction of 71% as compared to conventional WPD (CWPD) at 0.7 GHz. In addition, upper edge selectivity is found to be 40 dB/GHz along with higher order harmonics suppression up to the 10th order (7 GHz) by a level better than 20 dB. The proposed power divider is experimentally verified with the simulated one and found to be same.

1. INTRODUCTION

Power divider (PD) is used for many microwave subsystems, such as power amplifiers, modulators, and antenna array systems [1]. However, PD size is large due to quarter wavelength lines. Another problem is unwanted harmonics (spurious responses) caused by nonlinear properties of the active circuit in transceiver system at higher frequencies. Therefore, several design geometries are proposed by various researchers to reduce the circuit size as well as to suppress the harmonics of the microwave circuits [2–7]. In [2], a π-shaped transmission line is used to design a compact WPD, but it is not capable of higher orders harmonic suppression. In [3], a transmission line loaded with high-low impedance line is used to design a miniaturized PD with suppressed harmonics, but only limited numbers of harmonics are suppressed. Electromagnetic band-gap (EBG) structures are also used to miniaturize the circuit of PD to 39% in [4] with the 2nd and 3rd order harmonics suppression. In [7], an asymmetric DGS is used to suppress the 2nd and 3rd harmonics with 10% reduction in size.

In [8], DGS and T-shaped line decrease 31%, and in [9] combination of parallel coupled line and DGS is used to miniaturize the size of WPD up to 66%, but it is not capable of suppressing up to higher order harmonics. However, all the above techniques are not capable of reducing the circuit size as well as suppressing harmonics to a greater extent. In [10–13], different low-pass filters and compact microstrip resonator cells are also used to reduce the circuit size as well as suppress the harmonics. Compact filtering characteristics of power divider are also studied in [14] with harmonic suppression. In [15], miniaturization of unequal WPD using lumped component elements is used to reduce the circuit size, but it offers parasitic effect at higher frequencies. In [16–18], resonator cells of the power divider are modified in order to reduce the overall circuit area. Although the size of the power divider is significantly reduced, it is not capable of suppressing higher order harmonics.

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In this paper, a pair of SISSs and a metal incorporated split ring DGS (MISRDGS) are used as shunt capacitors (C) and series inductance (L), respectively to make a quarter wavelength lines. Due to the slow wave characteristics of both SISS and DGS the proposed power divider occupies only 29% of the circuit area compared to CWPD at 0.7 GHz. Besides, unwanted harmonics are well suppressed better than 20 dB up to 10 GHz. The proposed design is simulated using HFSS full-wave EM simulator and fabricated on an Arlon substrate having dielectric constant (ε_r) = 2.2, thickness (h) = 0.787 mm, and loss tangent 0.009.

2. DESIGN OF COMPACT LINE AND ITS APPLICATION TO MINIMIZE THE CIRCUIT SIZE OF WPD

The conventional WPD consists of two quarter wavelength lines connected between the input (port 1) and output ports (port 2 & 3) of characteristic impedance $Z_b = Z_a \times \sqrt{2} = 70.7\,\Omega$, as shown in Fig. 1(a). The impedance of all the ports (Z_a) and isolation resistor (R) are 50 Ω and 100 Ω, respectively [1]. To reduce the overall circuit size of the WPD, a host line loaded with SISS and MISRDGS is used in place of conventional quarter wavelength lines, and the resulting structure is shown in Fig. 1(b). In this figure the transmission line model and the LC equivalent circuit of the conventional and proposed quarter wavelength line are also shown. The series parallel LC (L_{DGS}, C_{DGS}) and shunt series LC (L_{SISS}, C_{SISS}) resonators represent the DGS and SISS, respectively, whereas L_{line} and C_{line} represent

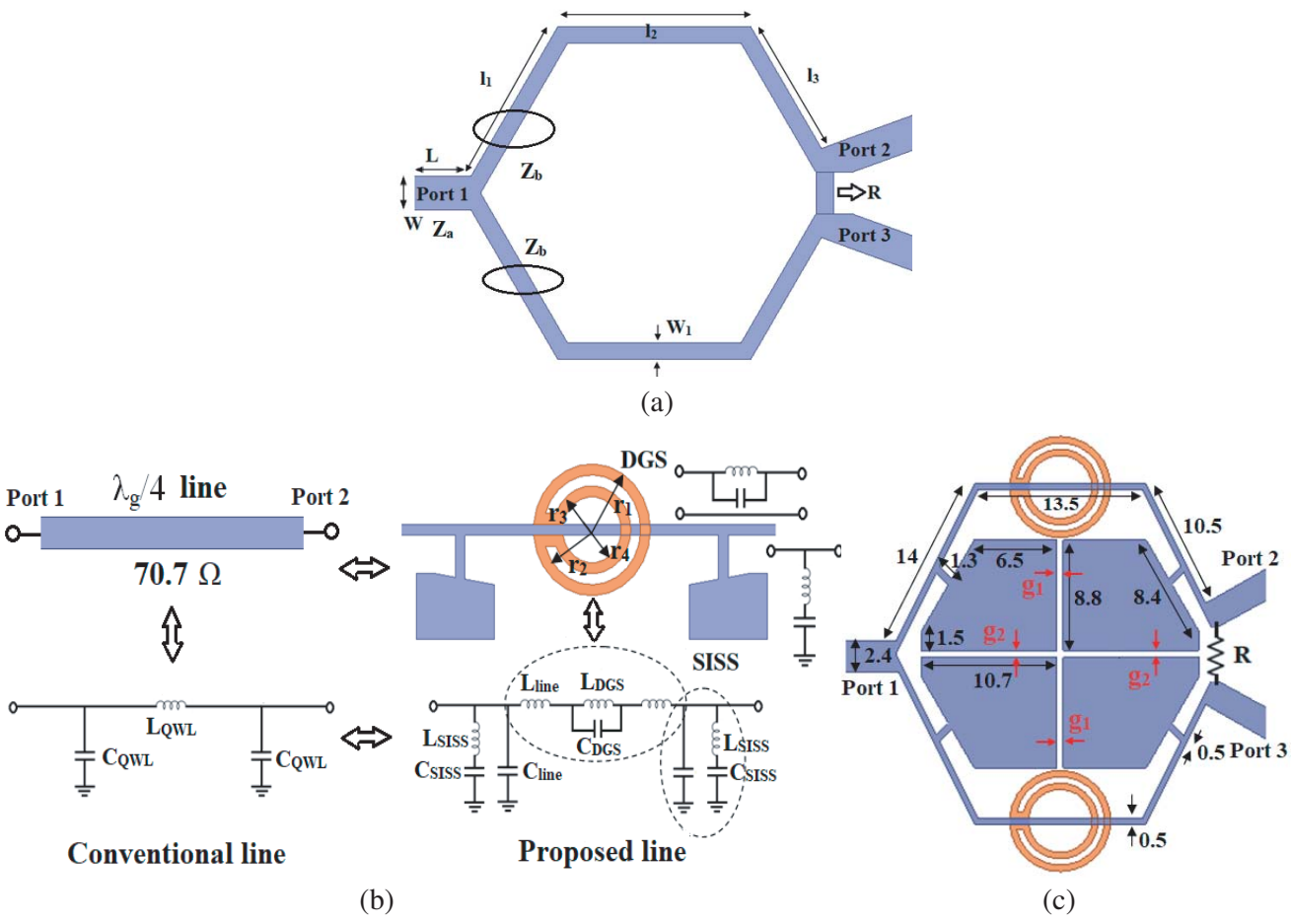


Figure 1. (a) Conventional WPD, (b) transmission line and LC equivalent circuit of conventional and proposed line, (c) proposed WPD. (All dimensions are in mm: $r_1 = 4$, $r_2 = 3.5$, $r_3 = 3$, $r_4 = 2.5$, $W = 2.4$, $L = 5$, $W_1 = 1.4$, $l_1 = 25.6$, $l_2 = 27$, $l_3 = 22.2$, $g_1 = 0.5$, $g_2 = 0.5$).

host microstrip line [1, 6]. The parallel LC and series LC resonator of DGS and SISS are represented as series inductance and shunt capacitance in the low-frequency region [6]. The circuit values of the proposed line are made equal to the corresponding element values obtained by a quarter wavelength line of the conventional WPD at the operating frequency (f) by adjusting the dimensions of DGS and SISS. In the proposed line, the microstrip section between the SISS and DGS is electrically short with respect to design frequency. Thus, one can ignore [5], but here it has to be taken into consideration since it significantly affects the overall performance as well as the operating frequency. However, the right most and left most sections of the host line with respect to SISS of the proposed line can be ignored because their electrical lengths are too short. Generally, the short section line can be represented as an L-shaped network (series L_{line} and shunt C_{line}) which is shown in Fig. 1(b). The values of L_{line} and C_{line} can be evaluated using Eq. (1) by equating the approximated $ABCD$ matrix elements for short section line with $ABCD$ elements of L-shaped line [1], where Z, θs, and ω are the characteristic impedance, electrical length of the short section line, and angular frequency, respectively. The same procedure is followed as given in [6] for determining the line parameters of C_{QWL} and L_{QWL} using LC equivalent circuit of SISS and DGS, respectively. The relation between line parameters (C_{QWL}, L_{QWL}) with DGS parameters (L_{DGS}, C_{DGS}) and SISS parameters (C_{SISS}, L_{SISS}) are given in Eqs. (2)–(3), where L_{QWL} and C_{QWL} represent the inductance and capacitance values for quarter wavelength line. Finally, the proposed line is used to design a compact WPD operating at 0.7 GHz (LTE band), and the resulting structure is shown in Fig. 1(c). The circuit parameters (LC values) of the proposed line for DGS, microstrip section and SISS are (7.29 nH, 0.11 pF), (4.99 nH, 0.19 pF), and (0.7 nH, 3.05 pF), respectively, whereas conventional quarter wavelength line is L_{QWL}, C_{QWL} (16 nH, 3.2 pF) with respect to operating frequency (0.7 GHz).

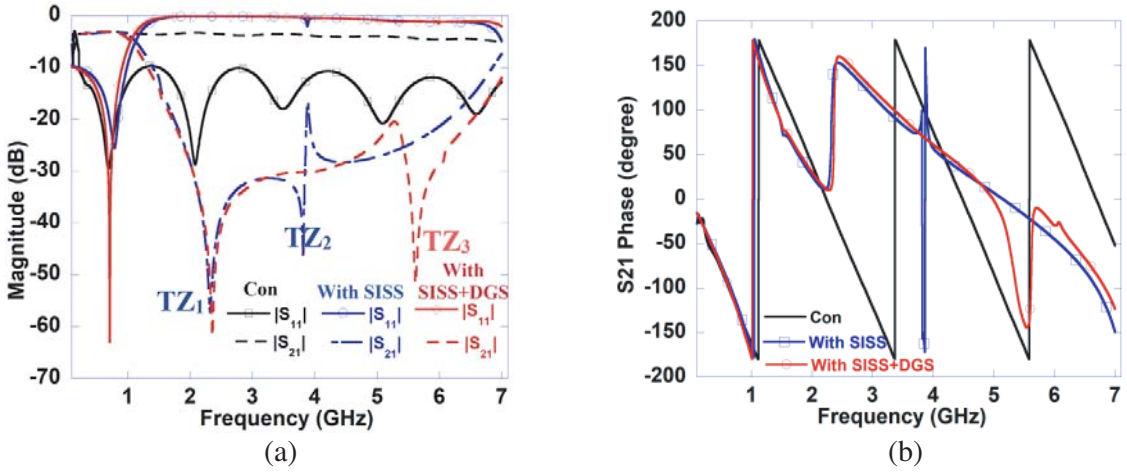
$$C_{\text{line}} = \frac{\theta s}{\omega Z} \tag{1a}$$

$$L_{\text{line}} = \frac{Z\theta s}{\omega} \tag{1b}$$

$$\frac{1}{\omega\left(L_{\text{QWL}} - 2L_{\text{line}}\right)} = -\left(\omega C_{\text{DGS}} - \frac{1}{\omega L_{\text{DGS}}}\right) \tag{2}$$

$$\frac{1}{\omega\left(C_{\text{QWL}} - C_{\text{line}}\right)} = -\left(\omega L_{\text{SISS}} - \frac{1}{\omega C_{\text{SISS}}}\right) \tag{3}$$

Figure 2 shows the comparison between S-parameter responses of the proposed line with conventional line when port 1 and port 2 are shorted with 70.7 Ω. From Fig. 2(a), the simulated



(a) (b)

Figure 2. Comparison of S-parameter responses of proposed line with conventional one (a) $|S_{21}|$ and $|S_{11}|$, (b) S_{21} phase.

S-parameters $|S_{11}|$ and $|S_{21}|$ are -62.7 dB and -3.2 dB at 0.7 GHz, whereas the conventional line offers $|S_{11}|$ and $|S_{21}|$, which are -29 dB and -3.1 dB, respectively. In addition, two transmissions zeros (TZs) are obtained due to shunt patches, and one TZ due to DGS is obtained to suppress the harmonics at higher frequencies. The S_{21} phase response of the proposed design is exactly the same as conventional line at the design frequency as shown in Fig. 2(b).

The simulated frequency responses of the proposed WPD are compared with the CWPD as shown in Fig. 3(a). From Fig. 3(a), the simulated S-parameters $|S_{11}|$, $|S_{21}| = |S_{31}|$, and $|S_{23}|$ are -62 dB, -3.22 dB, and -30 dB at 0.7 GHz, whereas the conventional offers $|S_{11}|$, $|S_{21}| = |S_{31}|$, and $|S_{23}|$ which are -29 dB, -3.15 dB, and -30 dB, respectively. Besides, the unwanted harmonics are well suppressed better than 20 dB for the frequency range up to 7 GHz. Therefore, the proposed WPD requires only 29% of the circuit size compared to CWPD with good in-band response compared to CWPD. The effect of gap (g_1) between two SISSs of the proposed line and gap (g_2) between SISSs of two individual lines is studied while other parameters are fixed as shown in Fig. 1(c). Figs. 3(b) & (c) show the S-parameter responses of WPD with different values of g_1 and g_2. From Fig. 3(b) it is evident that return loss performance is improved, and transmission zero moves towards the operating frequency which improves the upper edge selectivity of the PD while reducing g_1. From this figure, it is also found that there is not much variation in insertion loss with g_1. From Fig. 3(c) it is clear that insertion loss is not affected with g_2, although it has some effect on impedance matching.

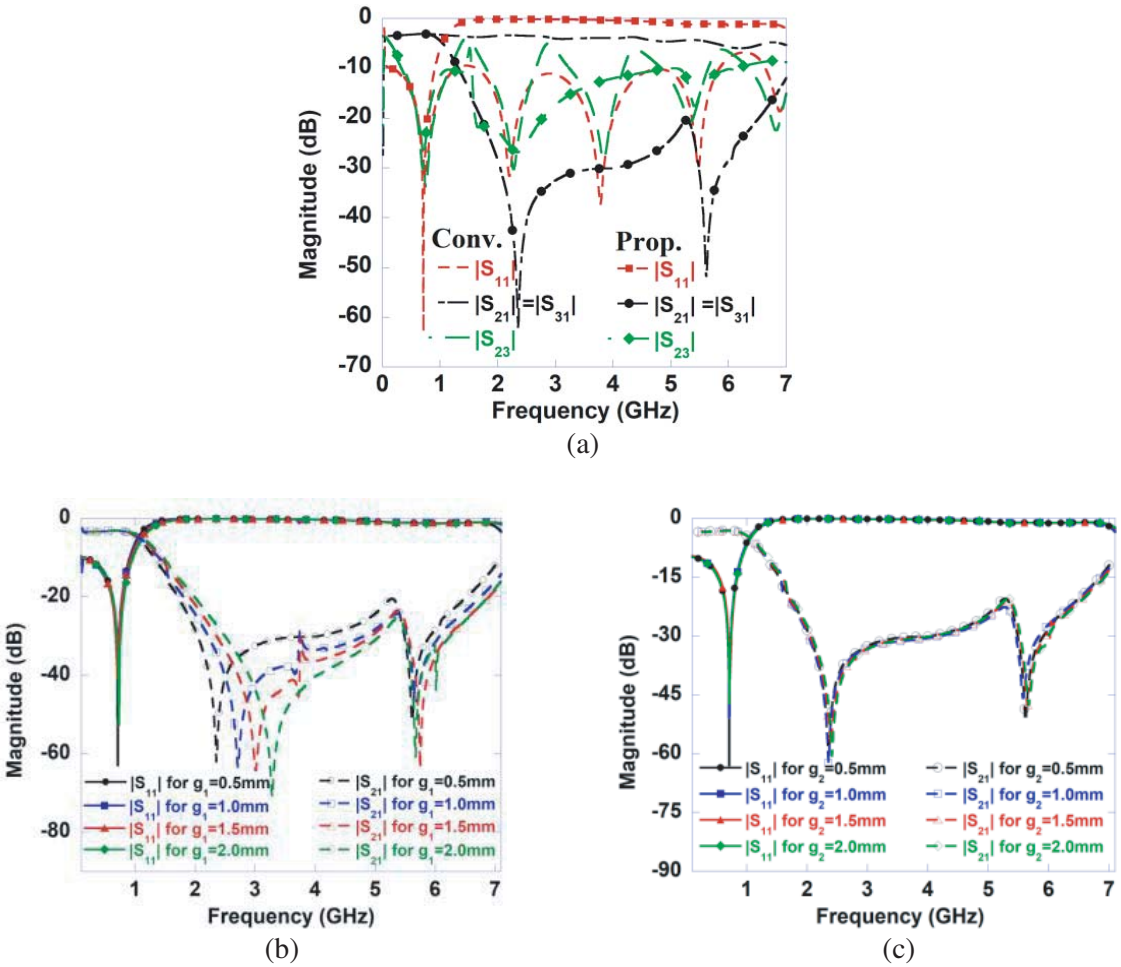


Figure 3. (a) Frequency response of conventional and proposed WPD, (b) and (c) variation of S-parameter results ($|S_{11}|$, $|S_{21}|$) of proposed WPD: for g_1 and g_2.

3. EXPERIMENTAL RESULTS

To validate the simulated results, the proposed WPD has been fabricated, measured, and compared in Fig. 4. Photographs of the fabricated structure are shown in Figs. 4(a) & (b), and an Agilent vector network analyzer is used to test the performances and shown in Figs. 4(c) & (d). It is found that measured $|S_{11}|$, $|S_{21}| = |S_{31}|$, and $|S_{23}|$ are -30 dB, -3.2 dB, and -30 dB, respectively at 0.7 GHz

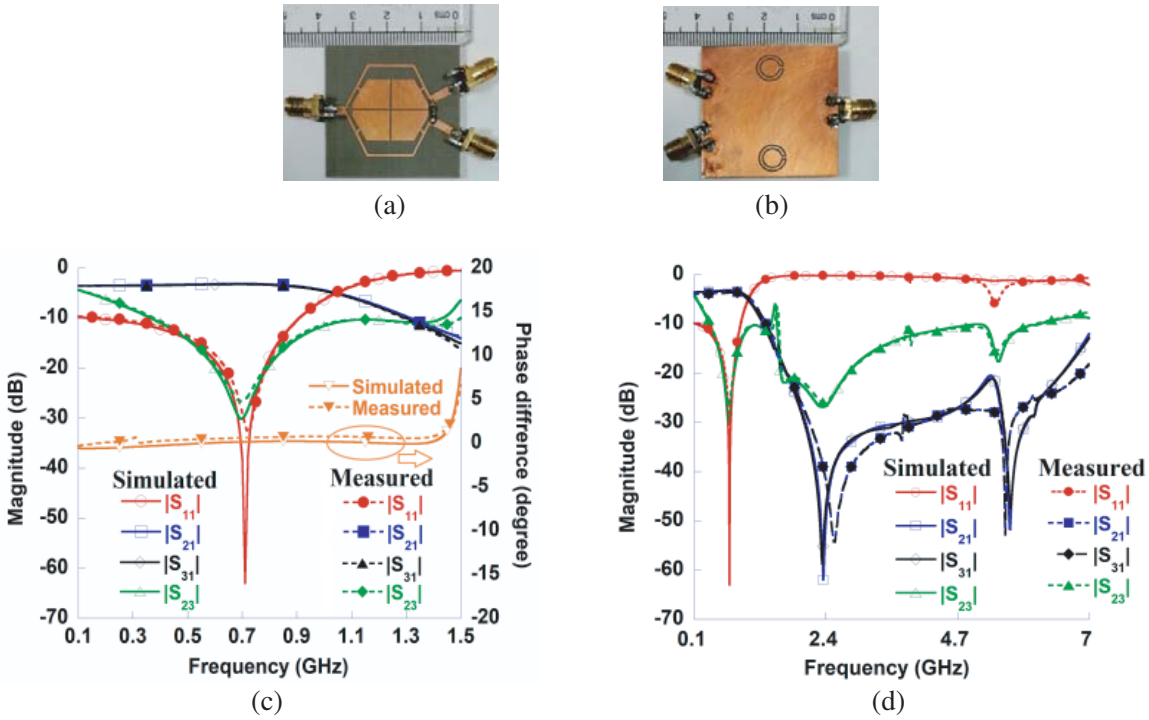


Figure 4. Photograph of fabricated unit and frequency responses of proposed WPD; (a) Top, (b) bottom, (c) magnifying scale of S-parameters and phase difference between outputs (S_{21} & S_{31}), (d) $|S_{11}|$, $|S_{21}|$, $|S_{31}|$, and $|S_{23}|$ up to 10th orders harmonics.

Table 1. Performance comparison between arts of literature and proposed WPD.

Ref., Year	Freq. (GHz)	Size Reduction (%)	$\|S_{21}\| = \|S_{31}\|$ (dB)	$\|S_{23}\|$ (dB)	$\|S_{11}\|$ (dB)	Harmonics suppression (dB)
						2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th, 10th
[8], 2018	1.8	31	-3.4	-20	-16	18.6, 15.8, 38, 38.5, 37.6, 23, 22.5, 27, -
[12], 2014	1	20	-4	< -20	< -20	43, 49, 37, -, -, -, -, -, -, -
[13], 2018	2.5	43	-3.01	-46.5	-28	20.6, 20.1, 23.3, 24.4, 32.1,-, -, -, -, -
[14], 2016	2.4	33	-3.8	< -20	< -20	32, 30, -, -, -, -, -, -, -, -
[15], 2017	1.5	75	-	< -25	< -20	-
[16], 2017	1	55	-3.1	-20	-20	31, 50, 20, 31, 45, 21, 15, -, -, -
[17], 2018	2.4	84	-3 ± 2	< -13	< -15	-
[18], 2018	2	40	-3.5	< -25	< -20	46, 36, 11, 27, -, -, -, -, -, -
This work	**0.7**	**71**	**-3.2**	**< -30**	**< -30**	**Better than 20 dB up to 10th order**

frequency. The measured fractional bandwidth (FBW) is found to be 40%, for $|S_{21}| = |S_{31}| = -3.2 \pm 0.1$ dB with return loss and isolation better than 30 dB, whereas simulated FBW is 42%. The phase difference is found to be 0.2° at the operating frequency. The comparative study of the proposed design is tabulated in Table 1 in terms of size reduction, S-parameters, and harmonics suppression with existing designs. From the table, the proposed design gives a better solution in terms of size reduction and harmonic suppression.

4. CONCLUSION

A compact WPD is designed based on the combination of SISS and DGS for LTE application. The proposed PD occupies only 29% circuit area of the CWPD at 0.7 GHz. Another attractive feature of the design includes higher order harmonics suppression better than 20 dB up to the 10th order along with good in-band performances (insertion loss = 3.2 dB, return loss = 30 dB, and FBW = 42%). The proposed solution gives a great tradeoff between size and performances as compared with the state of the art presented in the literature.

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REFERENCES

1. Pozar, D. M., *Microwave Engineering*, 3rd edition, Wiley, New York, 2005.
2. Tseng, C. H. and C. H. Wu, "Compact planar Wilkinson power divider using π-equivalent shunt-stub-based artificial transmission lines," *Electronics Letters*, Vol. 46, No. 19, 1327–1328, 2010.
3. Wang, J., J. Ni, Y. X. Guo, and D. Fang, "Miniaturized microstrip Wilkinson power divider with harmonic suppression," *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 7, 440–442, 2009.
4. Zhang, F. and C. F. Li, "Power divider with microstrip electromagnetic band gap element for miniaturization and harmonic rejection," *Electronics Letters*, Vol. 44, No. 6, 422–423, 2008.
5. Ahn, D., J.-S. Park, C.-S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 49, No. 1, 86–93, 2001.
6. Park, J., J. P. Kim, and S. Nam, "Design of a novel harmonic-suppressed microstrip low-pass filter," *IEEE Microwave and Wireless Components Letters*, Vol. 17, No. 6, 424–426, 2007.
7. 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.
8. Kumar, M., S. N. Islam, S. K. Parui, and S. Das, "Design of miniaturized Wilkinson power divider with higher order harmonic suppression for GSM application," *Progress In Electromagnetics Research C*, Vol. 85, 25–34, 2018.
9. Yang, J., C. Gu, and W. Wu, "Design of novel compact coupled microstrip power divider with harmonic suppression," *IEEE Microwave and Wireless Components Letters*, Vol. 18, No. 9, 572–574, 2008.
10. Shao, J.-Y., S.-C. Huang, and Y.-H. Pang, "Wilkinson power divider incorporating quasi-elliptic filters for improved out-of-band rejection," *Electronics Letters*, Vol. 47, No. 23, 1288–1289, 2011.
11. Hayati, M., S. Roshani, and S. Roshani, "Miniaturized Wilkinson power divider with nth harmonic suppression using front coupled tapered CMRC," *ACES J.*, Vol. 28, No. 2, 221–227, 2013.
12. Xu, X. and X. Tang, "Design of a compact Wilkinson power divider with high order harmonics suppression," *Progress In Electromagnetic Research Letters*, Vol. 50, 111–116, 2014.

13. Karimi, G. and S. Menbari, "A novel Wilkinson power divider using lowpass filter with harmonics suppression and high fractional bandwidth," *Microelectronics Journal*, Vol. 71, 61–69, 2018.
14. Zhan, W. L. and X. L. Zhao, "Compact filtering power divider with harmonic suppression," *Journal of Electromagnetic Waves and Applications*, Vol. 31, No. 3, 243–249, Feb. 2016.
15. Heydari, M. and S. Roshani, "Miniaturized unequal Wilkinson power divider using lumped component elements," *Electronics Letters*, Vol. 53, No. 16, 1117–1119, 2017.
16. Siahkamari, H., Z. Yasoubi, M. Jahanbakhshi, S. M. H. Mousavi, P. Siahkamari, M. E. Nouri, S. Azami, and R. Azadi, "Design of compact Wilkinson power divider with harmonic suppression using T-shaped resonators," *Journal of RF-Engineering and Telecommunications*, Vol. 72, Nos. 5–6, 2017.
17. Al-Areqi, N., K. Y. You, C. Y. Lee, N. H. Khamis, and M. N. Dimon, "Wideband and compact Wilkinson power divider utilizing series delta-stub and folded stepped-impedance transmission line," *Radioengineering*, Vol. 27, No. 1, Apr. 2018.
18. Mohamed, E. N., A. G. Sobih, and A. M. E. El-Tager, "A novel compact size Wilkinson power divider with two transmission zeros for enhanced harmonics suppression," *Progress In Electromagnetics Research C*, Vol. 82, 67–76, 2018.