Design and Modeling of a Compact Power Divider with Squared Resonators Using Artificial Intelligence

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Abstract
In this paper, a novel miniaturized microstrip Wilkinson power divider (WPD) using squared resonators and open-ended stubs is designed, fabricated, and measured. The proposed divider is designed at 1.9 GHz, which suppresses 2nd, 3rd, and 4th harmonics with high attenuation levels. Moreover, the size of the proposed divider is only $0.1\ \lambda_g \times 0.07\ \lambda_g$, which reduces the circuit size by more than 55%, compared to the conventional Wilkinson divider. In the design process, the neural network model and LC-equivalent circuit model are used to predict the transmission zeros of the circuit. These transmission zeros are used to provide the suppression at the desired harmonics. Also, the main circuit elements could be predicted with the neural network model, which results in a performance improvement of the proposed divider. The results show that the proposed model can predict the frequency response of the designed WPD, accurately.

1 Introduction

The microstrip divider is an essential passive component, which has wide applications in the communication systems [1, 2]. The typical Wilkinson power divider (WPD) occupies a large area and cannot remove the effects of unwanted harmonics [3–5]. The microwave devices with compact size and harmonics suppression abilities are necessary demands for modern wireless communication systems [5–8].

Recently, several works are reported to improve the performance of power dividers. The main methods, which have recently been used for harmonic suppression and size reduction

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of the divider can be categorized as specifically shaped resonators [2, 3], low pass filters [4, 5], defected ground structures (DGS) [9], electronic bandgap (EBG) cells [10], lumped elements [11–13], stepped impedances [14], open-ended stubs [15–18] and artificial intelligent [19].

In [9–13], EBG cells, defected ground structures DGS and lumped reactive elements techniques are used to achieve size reduction and harmonics suppression. These structures can partially overcome the large circuit size and suppress unwanted harmonics. Unfortunately, it is a complicated process to extract DGS and EBG pattern, which needs to etch the backside ground structure [14]. Moreover, using a lumped reactive component is undesirable for mass production environments [15].

In many kinds of research, microstrip open-ended stubs are applied to remove the effects of harmonics and to reduce the size, such as reported works in [15–18]. These structures have simple designs, but this method only suppresses a few lower harmonics and cannot decrease the size of the circuit. Using open-ended stubs can create transmission zeros, which provides a suppression band. In other words, each stub can create a corresponding transmission zero in the frequency response. Therefore, achieving a wide suppression band needs several open-ended stubs in the structure of the divider. Also, resonators can be used to achieve suppression bands in the divider. For instance, U-shaped [3], T-shaped [3], Π-shaped [17], triangle-shaped [2], and stepped impedance resonators are widely used resonators in power dividers.

Recently, artificial neural networks (ANNs) are applied as useful tools for modeling and prediction of the electrical and electronic devices [19–27]. In [19], a feed-forward neural network is used to design a WPD. The neural network is used in this work to predict the S-parameters of the divider, which resulted in harmonic suppression and performance optimization of the divider.

In this paper, a new WPD with harmonics suppression and size reduction is proposed using resonators. To improve the operation of resonators, the LC-equivalent circuit (LC-EC) and the neural network models are presented to predict the desired circuit parameters. The optimum circuit parameters are found with the neural network model, which results in a performance improvement of the proposed divider. The Advanced Design System (ADS) software is utilized to simulate the divider and MATLAB R2017a is used to model the presented divider using proposed neural networks. The final structure is fabricated and measured with an HP8757A network analyzer. There is good agreement between the simulations and measured results, which confirms the validity of the presented divider.

2 Power Divider Design Process

In this section, at first, the convention WPD is described. Then, the design procedure of the proposed divider is explained, which are as follows.

2.1 Conventional WPD

A conventional WPD at 1.9 GHz is depicted in Fig. 1. According to this figure, the WPD has one input and two output ports. Input power will be divided into two equal parts at output ports. Therefore, each port has half power of the original signal. The conventional

Fig. 1 Schematic of the conventional WPD
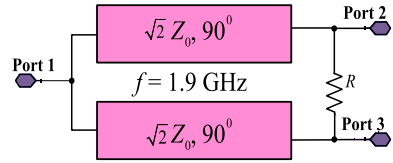
WPD includes two quarter-wave lines and a resistor, which provides isolation between ports 2 and 3.
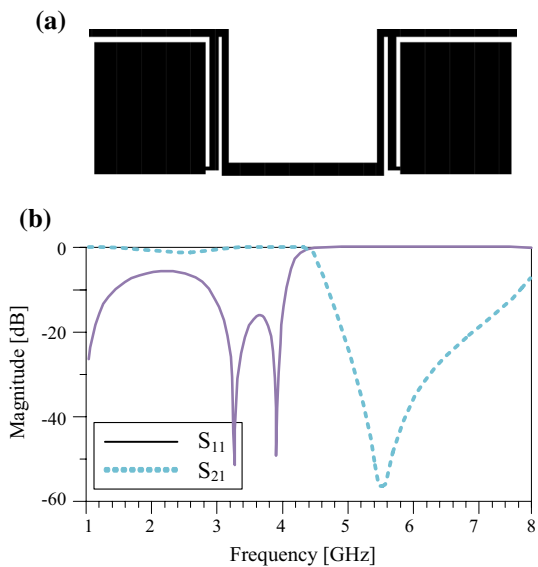
2.2 Presented Resonators and WPD

The first resonator, which is designed in this paper, is called resonator1. This resonator is made up of two modified T-shaped resonators, which provide a strong transmission zero near the third harmonic of the presented WPD. Resonator1 is shown in Fig. 2a and the scattering parameters S_{11} and S_{21} of resonator1 are illustrated in Fig. 2b.

The second resonator is made up of a U-shaped structure, loaded by two open stubs. This resonator is called resonator2, which is shown in Fig. 3a. The scattering parameters S_{11} and S_{21} of resonator2 are depicted in Fig. 3b. According to this figure, resonotar2 provides a transmission zero at the second harmonic. As shown in Figs. 2 and 3, the presented resonators could be used to obtain the desired WPD.

The harmonic suppression and size reduction will be achieved, using resonator1 and resonator2 instead of each quarter-wave line, in the conventional WPD. The final layout of the proposed low size and harmonic suppressed WPD is illustrated in Fig. 4.

An LC-EC model and an ANN (artificial neural network) model are presented in the next sections, to study and predict the behavior of the presented WPD.
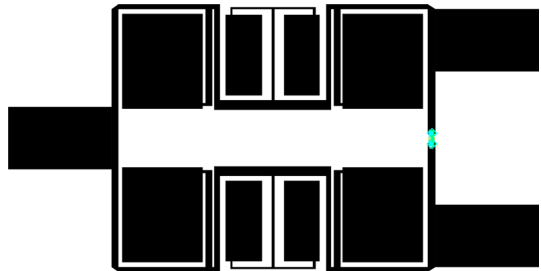
Fig. 2 (**a**) Structure of presented resonator1 and (**b**) its simulated S-parameters

Fig. 3 (**a**) Structure of presented resonator2 and (**b**) its simulated S-parameters
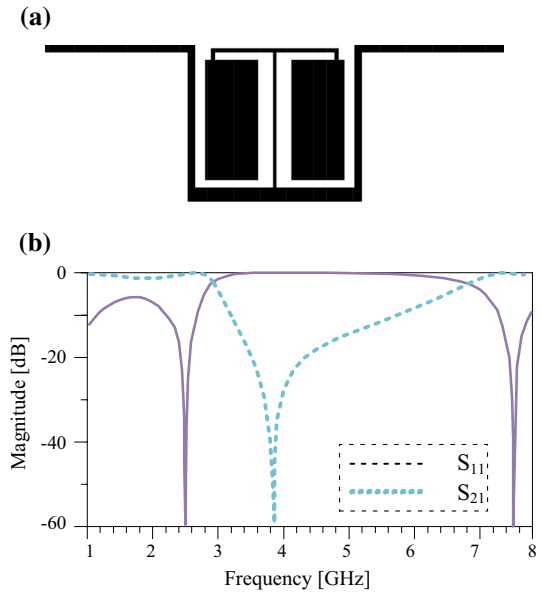
Fig. 4 Structure of proposed WPD

3 Modeling of the Presented WPD

In this section, at first, the LC-EC model of the proposed divider is extracted. Then, an artificial neural network is presented to model the proposed divider according to the LC-EC model.

3.1 LC Equivalent Circuit (LC-EC) Model

To model the presented WPD, the LC-EC of the divider is derived in this section. In the first step, the LC-EC of the circuit components should be defined. Two main components of the designed structures are typical transmission lines and open stubs, which their LC-ECs are illustrated in Fig. 5a and b, respectively.

According to equivalent circuits in Fig. 5 and the layout structure of the proposed WPD, the final LC-EC of the divider is derived, as illustrated in Fig. 6.
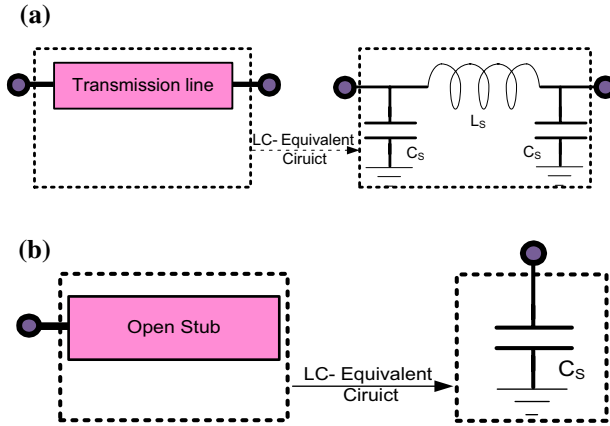
Fig. 5 LC-ECs of (**a**) a typical transmission line and (**b**) an open stub
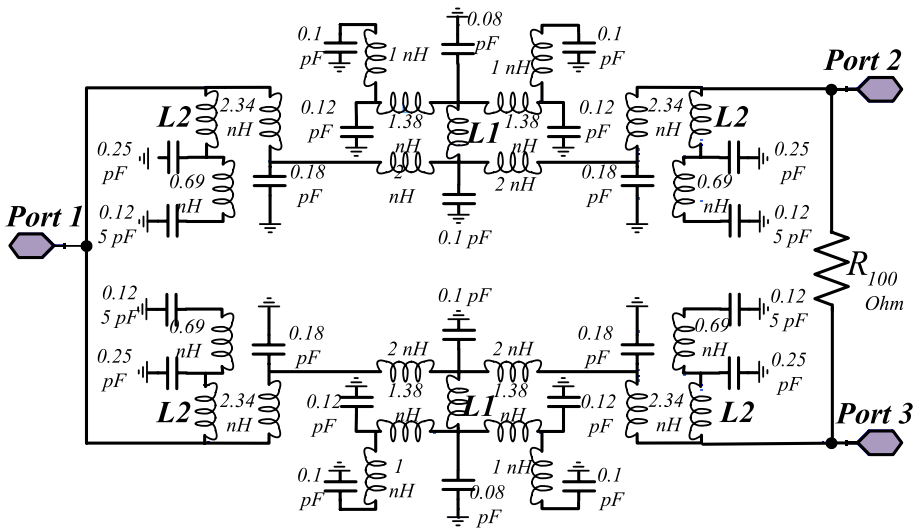

Fig. 6 The final LC-EC of the proposed WPD

As seen in Fig. 6, the LC-EC of the proposed WPD is made up of several inductors and capacitors, each of which affects the frequency response of the circuit. However, two main elements, which have the main effects on the second and third harmonics (L1 and L2 inductors) are selected in the circuit as the circuit parameters. The scattering parameters S_{11} and S_{21} of the WPD LC-EC are depicted in Fig. 7. As can be seen, two strong desired transmission zeros at the second and third harmonics are achieved for the presented WPD. Changing the value of L1 moves the transmission zero corresponding to the second harmonic. Also, changing the value of L2 moves the transmission zero corresponding to the third harmonic.

Fig. 7 Scattering parameters S_{11} and S_{21} of the WPD LC-EC versus changing (**a**) L1 (nH) and (**b**) L2 (nH) inductors
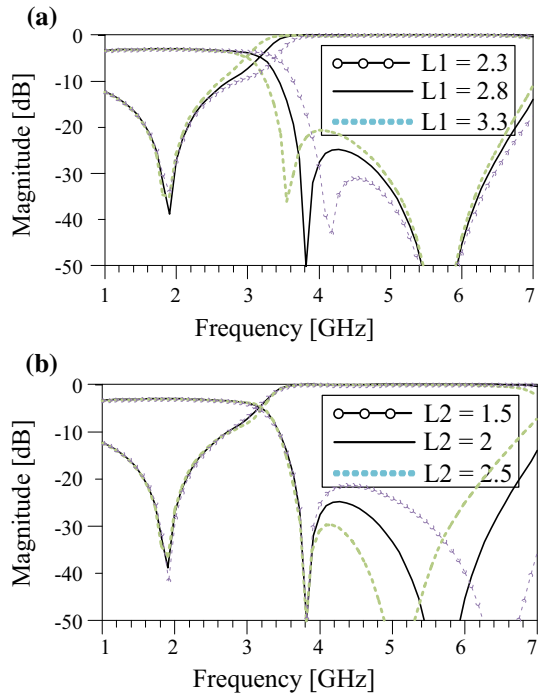

3.2 Artificial Neural Network Model

As seen in Fig. 6, the circuit model of the presented WPD is very difficult to be analyzed. A simple way to model the designed WPD is the artificial neural network (ANN) model, which is proposed in this section. The ANN is a widespread solution in the electronics field which has been recently used in several approaches. To propose the ANN model of the designed WPD, the input and output parameters of this model should be defined. For the proposed divider, the scattering parameters of the WPD are selected as the output parameters, while frequency, L1, and L2 are selected for the input parameters. The proposed ANN model of the presented WPD is illustrated in Fig. 8. The LC-EC of the designed WPD is simulated by the Advanced Design System (ADS) software and also, the applied data for the ANN is obtained from ADS software. An MLP network is used for the desired ANN Model. The specifications of the proposed MLP model are given in Table 1.

The Levenberg Marquardt (LM) algorithm is utilized for the network training procedure. The values of 80% and 20% of data are applied for training and testing procedures,

Fig. 8 The proposed ANN model of the presented WPD
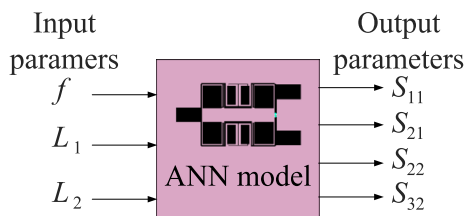
Table 1 The specifications of the proposed MLP model

Type of the ANN	MLP
Input layer neurons	3
Hidden layers	1
Hidden layer neurons	7
Output layer neurons	4
Number of epochs	2000
Activation functions	Tansig

respectively. In the proposed ANN model, mean absolute error (MAE) and root mean squared error (RMSE) are defined by Eqs. (1)–(2) respectively as below:

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |X_i(\text{Exp}) - X_i(\text{Pred})| \, , \tag{1}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N} \left(X_i(\text{Exp}) - X_i(\text{Pred}) \right)^2}{N} \right]^{0.5} . \tag{2}$$

The achieved error results of the presented MLP model are shown in Table 2. As results show, the S_{11} model demonstrates better prediction with fewer error values. The train and test results of the presented WPD ANN model are shown in Fig. 9. As can be seen, the predicted S-parameters by the MLP model are close to the real values, which confirms the validity of the presented model to predict the frequency response of the designed WPD. The presented ANN model could be applied to any divider or other microwave devices.

4 Results of the Proposed WPD

According to the discussed design procedure, the arbitrary harmonic suppression could be achieved in the designed WPD. For verification, the designed WPD is fabricated on a substrate of RT/Duroid with $\varepsilon_r = 2.2$. The operating frequency of the fabricated divider is 1.9 GHz and the achieved bandwidth is 32% considering 15dB attenuation. The fabricated photograph and frequency responses of the designed WPD are shown in Fig. 10a and b, respectively. According to this figure, the measured and simulated data are in good agreements, which verify the validity of the design process of the proposed WPD. The fabricated WPD dimensions are 11.5 mm×8.5 mm or 0.1 λg×0.07 λg which shows more than

Table 2 The achieved error results of the presented MLP model

Output	MAE test error	MAE train error	RMSE test error	RMSE train error
S_{11}	0.18	0.15	0.28	0.33
S_{21}	2.28	2.12	3.41	3.50
S_{22}	0.61	0.5	0.82	0.91
S_{32}	1.93	1.36	2.68	1.73

Fig. 9 (**a**) Train and test results of the presented WPD ANN model for S_{11}, S_{21}, (**b**) S_{22} and S_{32}
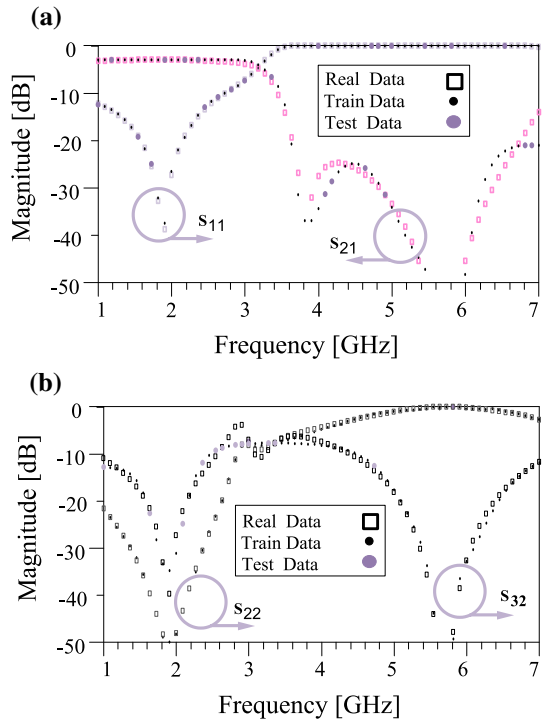
Fig. 10 (**a**) Fabricated photograph and (**b**) measured frequency response of the designed WPD
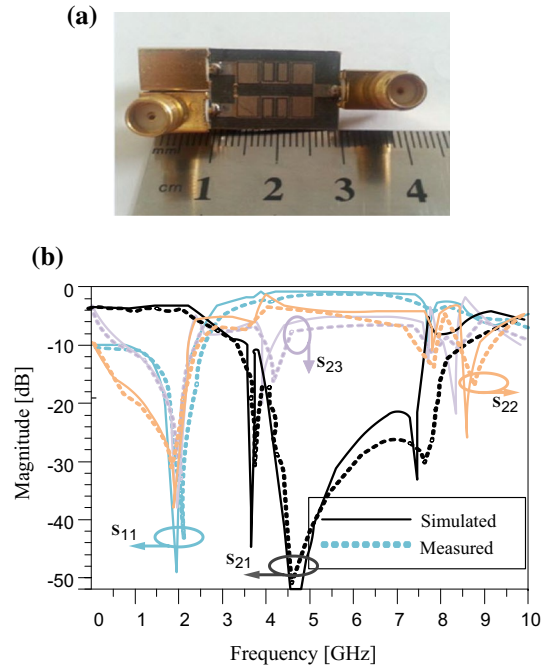
Table 3 A comparison between fabricated WPD and the other similar WPDs

References	Size reduction	Harmonic suppression (dB)		
		2nd	3rd	4th
[9]	–	18	15	–
[28]	39%	26	25	–
[29]	66%	13	35	–
[30]	–	4	40	–
[31]	44%	20	40	–
[32]	33%	15	28	27
Proposed work	55%	30.5	33	28.8

55% size reduction, compared to the typical WPD. In the operating frequency, measured input return loss, output return loss, port isolation, and insertion loss are better than 30 dB, 38 dB, 26 dB, and 1 dB, respectively. A comparison between fabricated WPD and the other similar WPDs are reported in Table 3.

5 Conclusions

A compact and harmonic suppressed Wilkinson power divider is designed and fabricated in this paper. The LC-EC model and ANN model of the designed power divider are proposed. According to the results, the proposed models can predict the designed power divider behaviours with good precession. The obtained errors of the ANN model show that the presented ANN model can be used to predict the frequency response of the designed WPD, accurately. The proposed WPD has a compact size with high harmonics suppression ability. With the obtained desirable features, the proposed WPD could be used in the communication systems.

References

1. Roshani, S. (2017). A Wilkinson power divider with harmonics suppression and size reduction using meandered compact microstrip resonating cells. *Frequenz, 71*(11–12), 517–522.
2. Heydari, M., Rostami, P., & Roshani, S. (2019). Design of a modified wilkinson power divider with size reduction and harmonics suppression using triangle-shaped resonators. *Wireless Personal Communications, 109*(3), 1–9.
3. Jamshidi, M., Siahkamari, H., Roshani, S., & Roshani, S. (2019). A compact Gysel power divider design using U-shaped and T-shaped resonators with harmonics suppression. *Electromagnetics, 39*(7), 491–504.

4. Roshani, S., Hayati, M., Setayeshi, S., Roshani, S., & Mohamadpour, G. A. (2016). Miniaturized harmonic suppressed power amplifier integrated with lowpass filter for long term evolution application. *Analog Integrated Circuits and Signal Processing, 89*(1), 197–204.

5. Roshani, S., Roshani, S., & Zarinitabar, A. (2019). A modified Wilkinson power divider with ultra harmonic suppression using open stubs and lowpass filters. *Analog Integrated Circuits and Signal Processing, 98*(2), 395–399.

6. Heydari, M., & Roshani, S. (2017). Miniaturised unequal Wilkinson power divider using lumped component elements. *Electronics Letters, 53*(16), 1117–1119.

7. Liang, J. G., & Xu, H. X. (2012). Harmonic suppressed bandpass filter using composite right/left handed transmission line. *Journal of Zhejiang University Science C, 13*(7), 552–558.

8. Roshani, S., Golestanifar, A., Ghaderi, A., Siahkamari, H., & Abbott, D. (2018). High performance microstrip low pass filter for wireless communications. *Wireless Personal Communications, 99*(1), 497–507.

9. Woo, D. J., & Lee, T. K. (2005). Suppression of harmonics in Wilkinson power divider using dual-band rejection by asymmetric DGS. *IEEE Transactions on Microwave Theory and Techniques, 53*(6), 2139–2144.

10. Lin, C. M., Su, H. H., Chiu, J. C., & Wang, Y. H. (2007). Wilkinson power divider using microstrip EBG cells for the suppression of harmonics. *IEEE Microwave and Wireless Components Letters, 17*(10), 700–702.

11. Wang, X., Sakagami, I., Mase, A., & Ichimura, M. (2014). Trantanella Wilkinson power divider with additional transmission lines for simple layout. *IET Microwaves, Antennas & Propagation, 8*(9), 666–672.

12. Huang, W., Liu, C., Yan, L., & Huang, K. (2010). A miniaturized dual-band power divider with harmonic suppression for GSM applications. *Journal of Electromagnetic Waves and Applications, 24*(1), 81–91.

13. Wang, X., Sakagami, I., Mase, A., & Ichimura, M. (2014). Wilkinson power divider with complex isolation component and its miniaturization. *IEEE Transactions on Microwave Theory and Techniques, 62*(3), 422–430.

14. Kim, I. S., Lee, C. H., Lee, D., & Ahn, D. (2016). A smaller step impedance line Wilkinson power divider with an improved better stop-band. *Microwave and Optical Technology Letters, 58*(7), 1607–1610.

15. Cheng, K. K. M., & Ip, W. C. (2010). A novel power divider design with enhanced spurious suppression and simple structure. *IEEE Transactions on Microwave Theory and Techniques, 58*(12), 3903–3908.

16. Ahmed, U. T., & Abbosh, A. M. (2015). Modified Wilkinson power divider using coupled microstrip lines and shunt open-ended stubs. *Electronics Letters, 51*(11), 838–839.

17. Wang, X., Ma, Z., Yoshikawa, M., Kohagura, J., Tokuzawa, T., Kuwahara, D., & Mase, A. (2017). Mixed π type structure in Wilkinson power divider design with 3rd harmonic suppression. *Microwave and Optical Technology Letters, 59*(6), 1245–1248.

18. Tang, C. W., & Chen, J. T. (2016). A design of 3-dB wideband microstrip power divider with an ultra-wide isolated frequency band. *IEEE Transactions on Microwave Theory and Techniques, 64*(6), 1806–1811.

19. Jamshidi, M., Lalbakhsh, A., Lotfi, S., Siahkamari, H., Mohamadzade, B., & Jalilian, J. (2020). A neuro-based approach to designing a Wilkinson power divider. *International Journal of RF and Microwave Computer-Aided Engineering, 30*(3), e22091.

20. Jamshidi, M., et al. (2020). Artificial intelligence and COVID-19: Deep learning approaches for diagnosis and treatment. *IEEE Access: Practical Innovations, Open Solutions, 12,* 109581–109595.

21. Zirak, A. R., & Roshani, S. (2016). Design and Modeling of RF Power Amplifiers with Radial Basis Function Artificial Neural Networks. *International Journal of Advanced Computer Science and Applications, 7*(6), 227–231.

22. Roshani, S., & Roshani, S. (2017). Two-section impedance transformer design and modeling for power amplifier applications. Applied Computational Electromagnetics Society Journal (ACES), 32(11).

23. Roshani, G. H., Roshani, S., Nazemi, E., & Roshani, S. (2018). Online measuring density of oil products in annular regime of gas-liquid two phase flows. *Measurement, 129,* 296–301.

24. Hayati, M., Shama, F., Roshani, S., & Abdipour, A. (2014). Linearization design method in class-F power amplifier using artificial neural network. *Journal of Computational Electronics, 13*(4), 943–949.

25. Jamshidi, M. B., Alibeigi, N., Lalbakhsh, A., & Roshani, S. An ANFIS Approach to Modeling a Small Satellite Power Source of NASA. In *2019 IEEE 16th International Conference on Networking, Sensing and Control (ICNSC) 2019 May 9* (pp. 459–464). IEEE.

26. Jamshidi, M. B., Lalbakhsh, A., Mohamadzade, B., Siahkamari, H., & Mousavi, S. M. (2019). A novel neural-based approach for design of microstrip filters. *AEU-International Journal of Electronics and Communications., 110,* 152847.

27. Jamshidi, M. B., Jamshidi, M., & Rostami, S. An intelligent approach for nonlinear system identification of a li-ion battery. In *2017 IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS) 2017 Oct 21* (pp. 98–103). IEEE.
28. Zhang, F., & Li, C. F. (2008). Power divider with microstrip electromagnetic bandgap element for miniaturisation and harmonic rejection. *Electronics Letters, 44*(6), 422–424.
29. Yang, J., Gu, C., & Wu, W. (2008). Design of novel compact coupled microstrip power divider with harmonic suppression. *IEEE Microwave and Wireless Components Letters, 18*(9), 572–574.
30. Li, J. L., Qu, S. W., & Xue, Q. (2007). Capacitively loaded Wilkinson power divider with size reduction and harmonic suppression. *Microwave and Optical Technology Letters, 49*(11), 2737–2739.
31. Gu, J. Z., Yu, X. J., & Sun, X. W. (2006). A compact harmonic-suppressed Wilkinson power divider using C-SCMRC resonators. *Microwave and Optical Technology Letters, 48*(12), 2382–2384.
32. Al Shamaileh, K., Qaroot, A., Dib, N., & Sheta, A. (2011). Design of miniaturized unequal split wilkinson power divider with harmonics suppression using non-uniform transmission lines. Applied Computational Electromagnetics Society Journal (ACES), 26(6).

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