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Size Reduction and Harmonics Suppression in Microwave Power Dividers: A Comprehensive Review

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Abstract—**In this paper, several types of microstrip power divider are studied and compared in terms of harmonics suppression and size reductions. The importance of this research lies in the fact that power dividers are critical components in various communication systems, and their performance directly affects the overall system efficiency. The conventional structure of the power divider has an acceptable performance at operating frequency in terms of excellent output ports isolation, low insertion loss, and high return loss, but occupies large size and passes unwanted signals at higher frequencies along with desired signal without any suppression. Harmonics are popular distortion and has different distortion impacts in many different facilities. Recently, several techniques are introduced to overcome these drawbacks. Applied open stubs, applied resonators, lumped reactive components such as capacitors and inductors, coupled lines, defected ground structure (DGS), and electronic band gaps are common methods, which are widely used to overcome these drawbacks. Finally, the study results show that the resonator-based power dividers and coupled-line-based power dividers have good performances in terms of size reduction and harmonic suppression but increase insertion loss parameter. Furthermore, the lumped reactive component-based power dividers and applied DGS and electromagnetic bandgap cells suppress unwanted harmonics, but they need extra process to fabrication, which is undesirable. Moreover, the open-stub-based power dividers have moderate performance with simple structure, but size reduction and harmonics suppression are not so superior in this method. Overall, the results of this study can be used to design power dividers for desirable applications with high performances.**

***Index Terms*—Harmonics suppression, Microstrip, Power divider, Size reduction.**

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I. Introduction

Wilkinson power dividers (WPDs) are passive devices that are used to divide an input signal into two or more output signals. They are commonly used in microwave and RF systems, such as in antenna arrays, mixers, and filters. The main advantage of WPD is its ability to provide excellent isolation between the output ports, which helps to minimize the loss of signal power and reduce unwanted reflections. One of the key features of WPDs is their ability to operate over a wide frequency band with good performance. This makes them suitable for use in applications that require high performance and reliability, such as military and aerospace systems., WPDs can be easily integrated into circuit designs due to their compact size and simple construction.

The conventional structure of the Wilkinson divider as depicted in Fig. 1a occupies a large size and pass unwanted signals along with desired signal without any suppression as shown in Fig. 1b. Recently, several techniques are introduced to overcome these drawbacks.

The conventional Wilkinson power dividers (WPDs) have limited performance outside of the center frequency and require a large size. To improve on this, a modified microstrip WPD is presented in Moloudian, et al. (2023) that has better out-of-band performance and high isolation. This is achieved using a lowpass filter (LPF) structure in both branches of the power divider to suppress harmonics. The proposed WPD has a wide stopband from 2.54 GHz to 13.48 GHz and filters the second to seventh harmonics with attenuation levels

>20 dB. The size of this WPD is small at 33.8 mm × 27 mm (0.42 λg × 0.33 λg), where λg is the guided wavelength at the operating frequency of 1.8 GHz. This divider is a good candidate for LTE and GSM applications.

In some works, neural networks and artificial intelligence (Jamshidi, et al., 2019; Jamshidi, et al., 2020) are used to model microstrip resonators and power divider, which resulted in accurate model.

In this paper, several types of power dividers in terms of harmonics suppression and size reductions methods are studied.

II. Power Divider with Applied Open-Ended Stubs

Add microstrip stubs in the conventional divider improved divider performances in terms of reducing the size and eliminating harmonics. In Cheng and Ip (2010), by adding three open-ended stubs, the improved divider is designed as depicted in Fig. 2. This divider is fabricated on RT/Duroid substrate with thickness of 0.813 mm and relative permittivity of 3.38.

The frequency response of the proposed divider in Cheng and Ip (2010) is shown in Fig. 3. As results shown, this divider has acceptable results at 1 GHz frequency and suppresses the second up to fourth harmonics. This power divider has a simple structure and can be easily fabricated, but it only reduces the first three harmonics.

In Hayati and Roshani (2013), a power divider using open-end stubs is presented. The structure of this divider is depicted in Fig. 4. The mentioned power divider is implemented on RT/Duorid 5880 substrate with a relative permittivity of 2.2 and a thickness of 0.381 mm, which in this structure, three open-ended stubs are used at all three ports. The overall dimensions are 24 mm × 16 mm, which shows 35% reduction in size compared to the conventional power divider.

The frequency responses of this divider are shown in Fig. 5. This power divider (Hayati and Roshani, 2013) has a good performance at the frequency of 1.65 GHz and suppresses the third and fifth harmonics. The results of the measurements indicate that the power divider allows the 1.65 GHz fundamental signal to pass whereas simultaneously suppressing the 4.95 GHz third-order harmonic and the 8.25 GHz fifth-order harmonic. As shown in Fig. 4, the insertion loss at 1.65 GHz is only 0.1 dB, whereas the third- and fifth-order harmonics are suppressed by 43 dB and 41 dB, respectively.

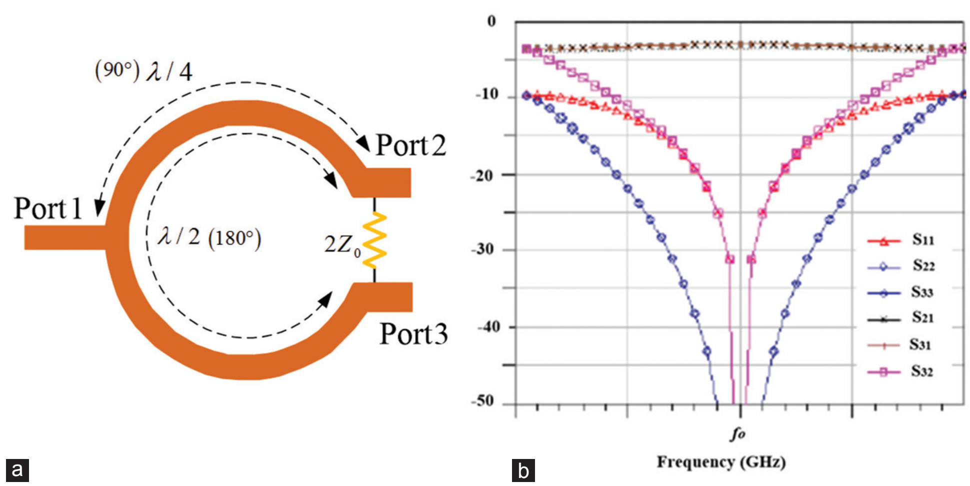

Fig. 1. The structure of the conventional WPD (a) layout; (b) frequency response.

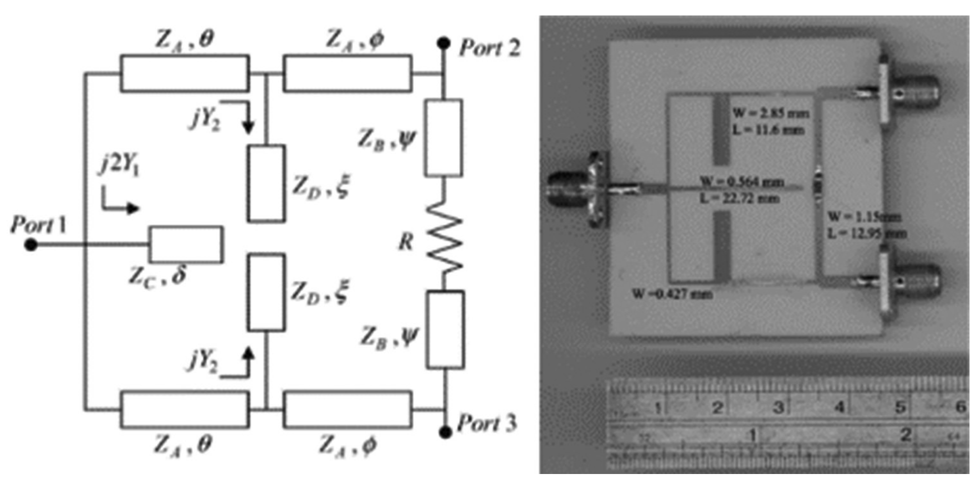

Fig. 2. The structure of the improved Wilkinson power divider with three open stubs (Cheng and Ip, 2010).

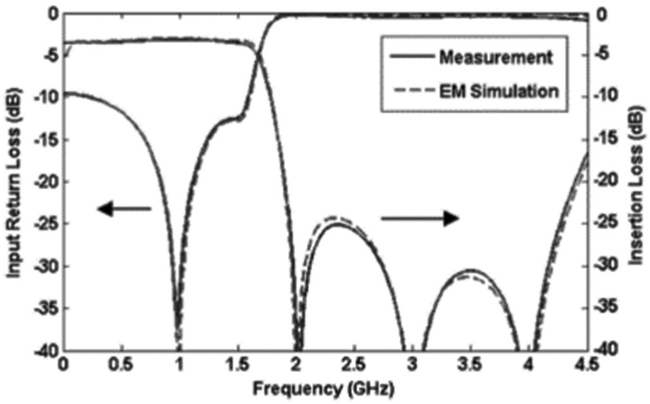

Fig. 3. The frequency response of the improved Wilkinson divider with three open stubs (Cheng and Ip, 2010).

This divider has a simple structure and can be easily fabricated, but it only suppresses two harmonics.

In Hayati, Roshani, and Roshani (2013), a simple divider using three open-ended stubs is presented. The layout of this divider is depicted in Fig. 6. This divider is implemented on RT/Duorid 5880 substrate with 2.2 relative permittivity and a thickness of 0.381 mm. In its structure, three open-ended stubs are applied at all three ports. Occupied size of this divider is 37.5 mm × 30 mm, which does not reduce the size compared to the typical divider.

The frequency responses of the mentioned divider (Hayati, Roshani, and Roshani, 2013) are depicted in Fig. 7. As can be seen, this power splitter has a very good performance at 900 MHz frequency and has the ability to reduce the second to sixth harmonics with a very high attenuation level. Therefore, this structure can be used to remove unwanted harmonics in other radio frequency circuits.

According to the simulations and measurements results, this divider effectively allows the fundamental signal at 0.9 GHz to pass through, whereas suppressing unwanted signals at higher frequencies. The proposed power divider also exhibits good performance in terms of insertion loss and harmonic suppression. The measured insertion loss is better than 0.3 dB at the center frequency of 0.9 GHz, whereas the stopband bandwidth of 1.4–5 GHz has been achieved with a minimum attenuation level of 20 dB. The measured spurious attenuations for the second to sixth harmonic frequencies are 71, 77, 36, 26, and 34 dB, respectively. In addition, this divider provides more than 34 dB of port isolation at the center frequency and good port isolation at harmonic frequencies.

Fig. 8, shows the schematic and implemented photo of the proposed divider (Hayati, Roshani, and Roshani 2013) with the help of microstrip stubs to remove the second and third harmonics. As can be seen, this power divider has a very simple structure, in which, two open-ended stubs and three grounded stubs are used.

Fig. 9 depicted the frequency response of the mentioned divider using two open stubs and three grounded stubs. As can be seen, this divider has a very good performance at 2 GHz frequency and has the ability to eliminate the second and third harmonics with high attenuation level.

According to results, this power divider has an insertion loss of 0.1 dB and an isolation of approximately 30 dB at the operating frequency. The input and output return losses are around 28 dB and 44 dB, respectively. In addition, the third and second harmonics are effectively suppressed with high attenuation levels.

Fig. 10 illustrates the structure of the divider (Lotfi, et al., 2020) using six open-ended and four grounded stubs to eliminate the second up to fourth harmonics. As can be seen, this power divider has a simple structure, which is designed by using six open-end microstrip stubs and four grounded microstrip stubs symmetrically. The mentioned power divider is implemented on RT/Duorid 5880 substrate with 2.2 relative permittivity and a thickness of 0.79 mm.

The frequency responses of this divider are shown in Fig. 11, which shows good performance at 0.9 GHz frequency, with 0.17 dB insertion loss. This WPD can suppress second, third, and fourth harmonics with attenuation levels of 64 dB, 45 dB, and 43 dB, respectively.

In Fig. 12 (Roshani and Roshani, 2020), the structure, fabricated photo, and frequency response of the compact size divider using aperiodic stubs are depicted. This WPD correctly works at 700 MHz and consists of several aperiodic stubs, which each stubs suppresses one desired harmonic. This divider suppresses 2^{nd}–15^{th} harmonics. These applied stubs reduce circuit size, which this divider has 73% size reductions, compared to the 700 MHz typical divider. This divider is implemented on RO4003 substrate with ε_r = 3.36 and thickness of 20 mil.

Layout, substrate, and advantage of some designed power dividers using open stubs are listed in Table I as follows:

III. Power Divider with Resonators

Resonators are widely used in the communication devices such as filters (Yahya, Rezaei, and Khaleel, 2021), diplexers (Yahya and Rezaei, 2021; Rezaei and Yahya, 2022), and antenna (Roshani, et al., 2023) to improve the functionality of the performance of devices.

Another way to remove harmonics and reduce the size of the power divider is to use resonators in the output branches of the power divider structure. In this method, according to the main frequency of the power divider, specific resonator is designed to remove unwanted frequencies. In Hayati, Roshani, and Roshani (2013), a power divider using a resonator is presented. The layout of this divider is depicted in Fig. 13.

This divider is implemented on RT/Duorid 5880 substrate with ε_r = 2.2 and thickness of 0.381 mm, which works at frequency of 2 GHz and the applied resonator is designed to eliminate the third to fifth harmonics. The frequency response of this divider (Hayati, Roshani, and Roshani, 2013) is shown in Fig. 14. As can be seen, this power divider has a very good performance at 2 GHz frequency and has the ability to reduce the third to fifth harmonics with a good attenuation level.

A microstrip power divider with filtering response is reported in this paper, which uses a front-coupled tapered

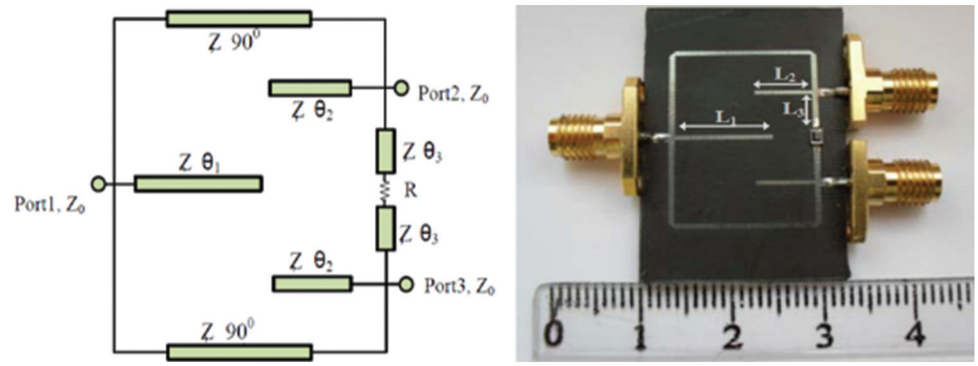

Fig. 4. The structure of the improved Wilkinson power divider with three open stubs (Hayati and Roshani 2013).

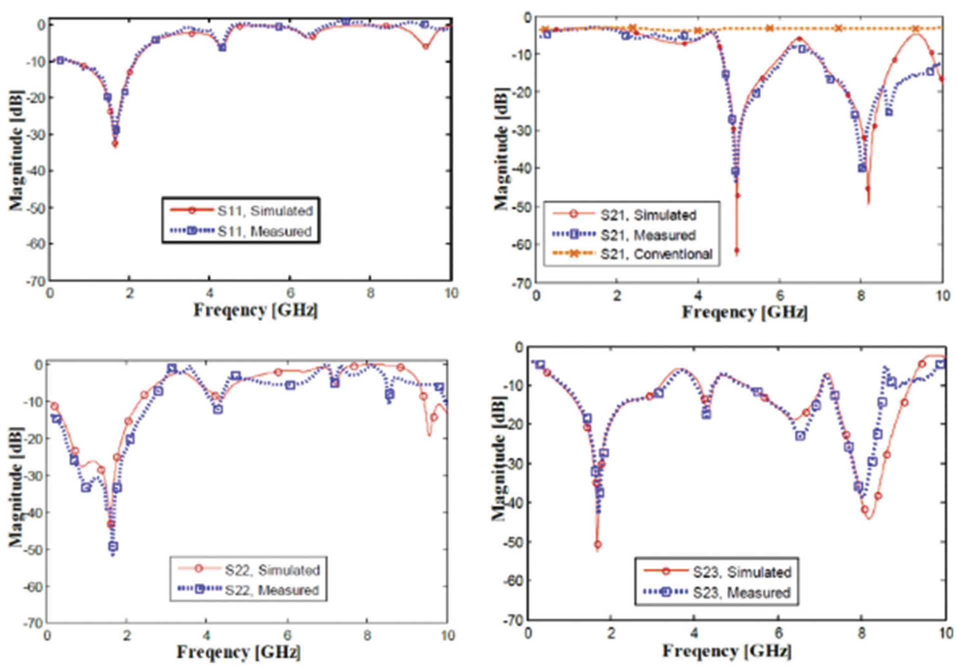

Fig. 5. The frequency response of the improved Wilkinson power divider with three open stubs (Hayati and Roshani 2013).

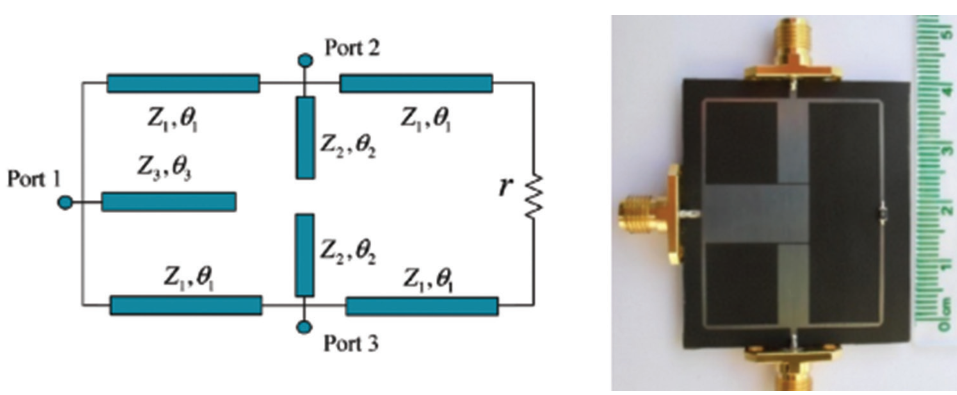

Fig. 6. The structure of the simple Wilkinson power divider with three open stubs (Hayati, Roshani, and Roshani 2013).

compact microstrip resonant cell (FCTCMRC) to achieve high harmonic suppression. This cell is inserted into a quarter-wavelength transmission line of the conventional WPD. This divider not only improves harmonic suppression but also reduces the length of a quarter-wave line by over 29.3% compared to the conventional divider. Measured results show that the proposed structure achieves wide stop-band bandwidth (6 GHz – 12 GHz) with a minimum attenuation level of 24 dB, whereas maintaining the characteristics of the conventional WPD. The input and output return losses at 2 GHz are 48 and 44 dB, respectively, and the insertion loss is about 0.1 dB. The isolation obtained is better than 45 dB.

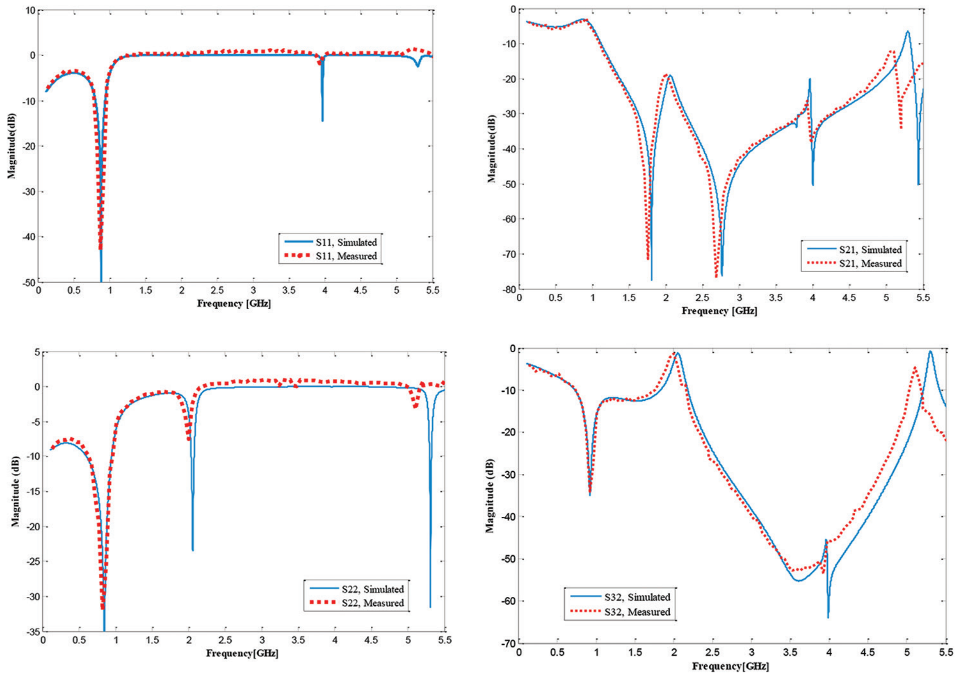

Fig. 7. The frequency response of the simple Wilkinson divider with three open stubs (Hayati, Roshani, and Roshani 2013).

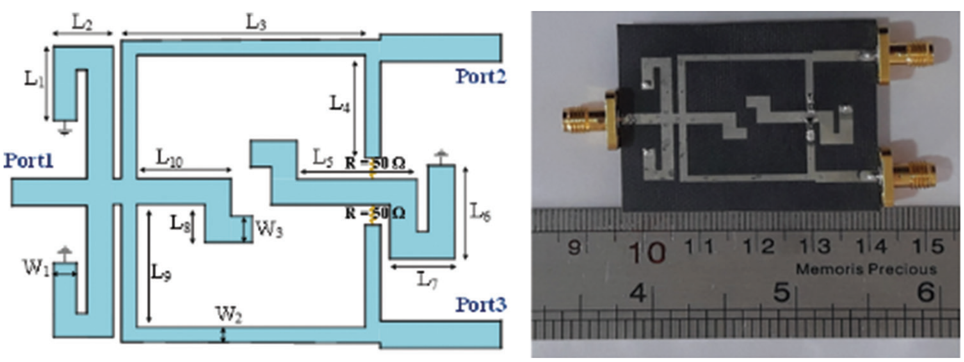

Fig. 8. The structure and fabricated photo of the Wilkinson divider with open and short stubs (Roshani, et al., 2022).

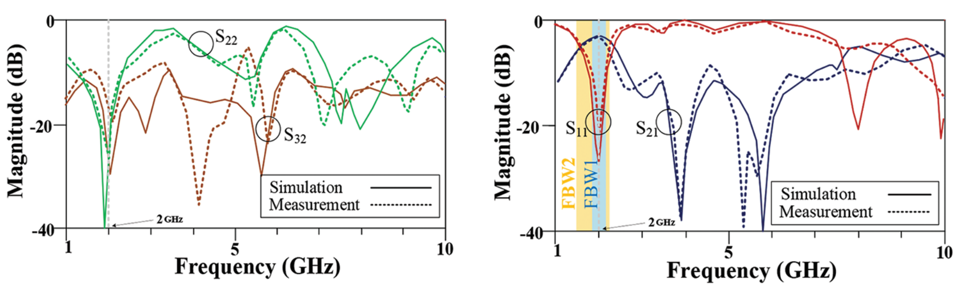

Fig. 9. The frequency response of the Wilkinson divider with open and short stubs (Roshani, et al., 2022).

In Hayati, et al. (2013), a compact low pass filter is designed and located between input and output ports of the Wilkinson divider. The structure of this divider is depicted in Fig. 15. This power divider is more than 71% smaller compared to the conventional power divider. This divider is implemented on RT/Duorid 5880 substrate with $\varepsilon_r = 2.2$ and thickness of 0.508 mm, which works at frequency of 1 GHz and the LPF is designed to eliminate the 4^{th}–12^{th} harmonics and to suppress second and third harmonics open stubs are used in the divider structure. In the final structure, to occupy small size, the applied microstrip lines are bent symmetrically. The frequency response of this divider (Hayati, et al., 2013) is shown in Fig. 16. As can be seen, this power divider has a very good performance at 1GHz frequency and has the ability to reduce the 2^{nd}–12^{th} harmonics with a good attenuation level.

In Roshani (2017), a power divider using resonator and stub is presented. The layout of this divider is depicted in Fig. 17.

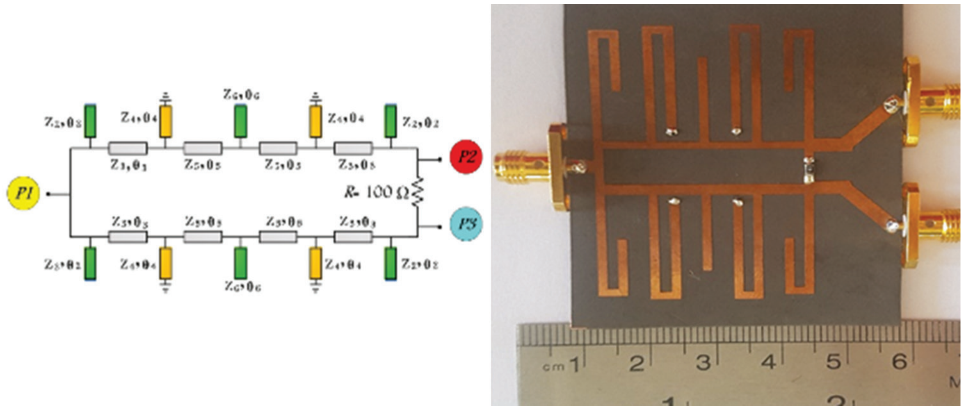

Fig. 10. The structure and fabricated photo of the Wilkinson divider with open and short stubs (Lotfi, et al., 2020).

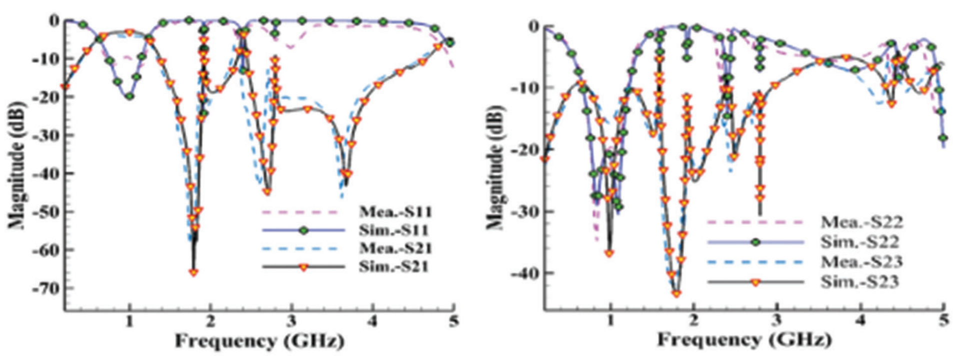

Fig. 11. The frequency responses of the Wilkinson divider with open and short stubs (Lotfi, et al., 2020).

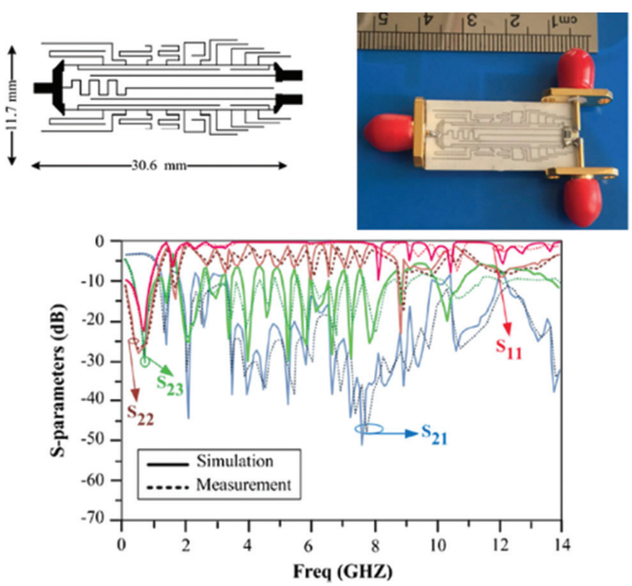

Fig. 12. The structure, fabricated photo, and frequency response of the compact divider using aperiodic stubs (Roshani and Roshani, 2020).

This power divider is more than 65% smaller compared to the typical divider. This divider is implemented on RT/Duorid 5880 substrate with $\varepsilon_r = 2.2$ and thickness of 0.508 mm.

The frequency response of this power divider using resonator and open stub is shown in Fig. 18. This divider works at a frequency of 2 GHz. The design of this divider involves the use of an open stub to suppress the second harmonic, whereas two MCMRC units are inserted into the quarter-wavelength lines of the conventional divider to suppress the 3rd–7th harmonics. The proposed power divider is significantly smaller than the conventional one, with a reduction in size of over 65%. The resonator and power divider are fabricated and measured, and the results show impressive harmonic suppression with high attenuation levels.

In Roshani and Siahkamari (2022), a WPD is designed at 2.75 GHz frequency. A compact resonator is designed and placed in this structure, which reduces the size and eliminates harmonics. Fig. 19 illustrates the structure of the Wilkinson divider which is designed and manufactured on RT/Duorid 5880 substrate with thickness of 0.787 mm and 2.2 relative permeability. This divider reduces circuit size more than 37% compared with the typical divider and suppressed 2nd–5th unwanted harmonics.

In Roshani, et al. (2021), with H-shaped resonators and open stubs, a patch power divider is designed. The structure of the designed patch power is depicted in Fig. 20. This divider is implemented on RT/Duorid 5880 substrate with a relative permeability of 2.2 and a thickness of 0.508 mm.

The frequency response of the designed patch divider is depicted in Fig. 21. This divider is designed to operate at 1.8 GHz and has good performance within the operating bandwidth. It uses two low-pass filters and three open-ended stubs at each port to achieve its performance. The divider has an operating band from 1.62 GHz to 2.1 GHz with a fractional bandwidth of 25.8%. It provides ultra-

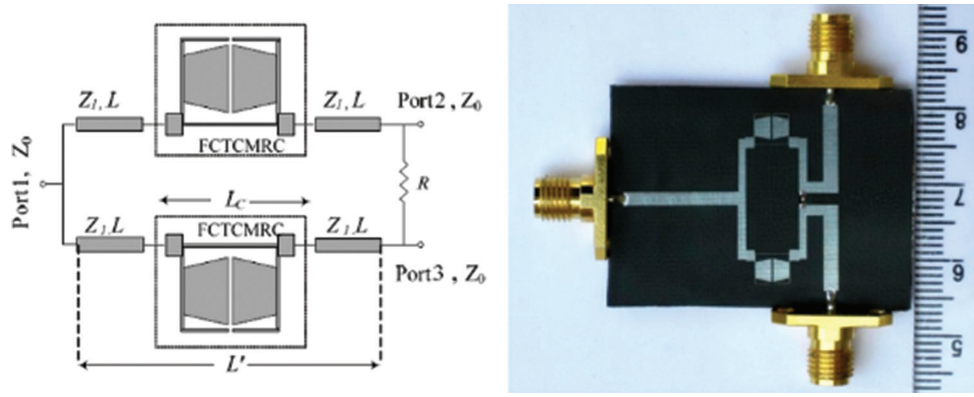

Fig. 13. The structure and implemented photo of the power divider using FCTCMRC (Hayati, Roshani, and Roshani, 2013).

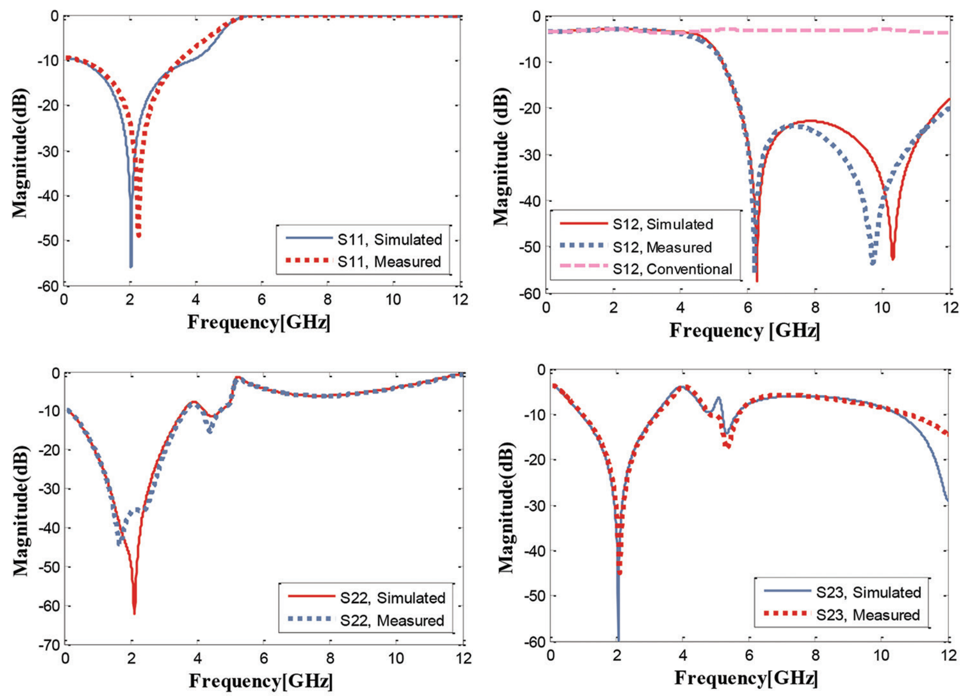

Fig. 14. The frequency responses of the power divider using FCTCMRC (Hayati, Roshani, and Roshani, 2013).

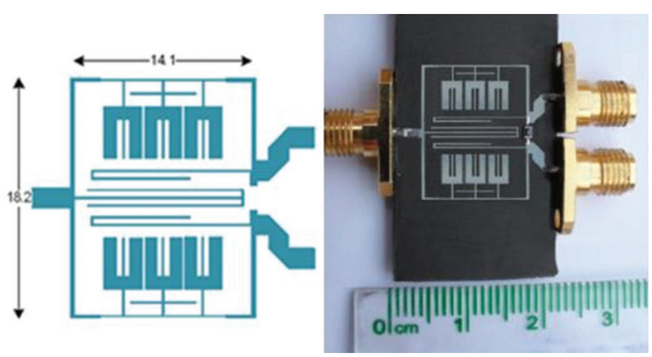

Fig. 15. The structure and fabricated photo of the power divider using LPF (Hayati, et al., 2013).

wide suppression from 3 GHz to 20 GHz, which covers the 2nd up to the 11th harmonic. The measured results show good agreement with the simulated results, with |S11|, |S12|, |S22|, and |S23| equal to −17 dB, −3.5 dB, −20 dB, and −17 dB, respectively, at the operating frequency.

The Lalbakhsh, et al. (2020) describes a simple and effective design method for a microstrip LPF that outperforms other filters in its class. The proposed filter consists of three polygonal-shaped resonators, two of which improve the stopband and the third enhances selectivity. The filter's performance is evaluated using a Figure of Merit and compared to other filters, demonstrating its superiority. A prototype of the filter was fabricated and tested, with a 3-dB cutoff frequency at 1.27 GHz and a wide stopband with 25 dB suppression from 1.6 to 25 GHz. This device is suitable for satellite communication systems.

In some works like Roshani, et al. (2023) and Roshani and Shahveisi (2022), resonators are applied to reduce mutual coupling effects in microstrip patch antenna arrays. These applied ladder resonators impressively block the surface current between two patch antennas at the operating frequency, which results in mutual effect reduction.

In Jamshidi, et al. (2020), symmetrical modified T-shaped resonators are used to design a WPD. This technique

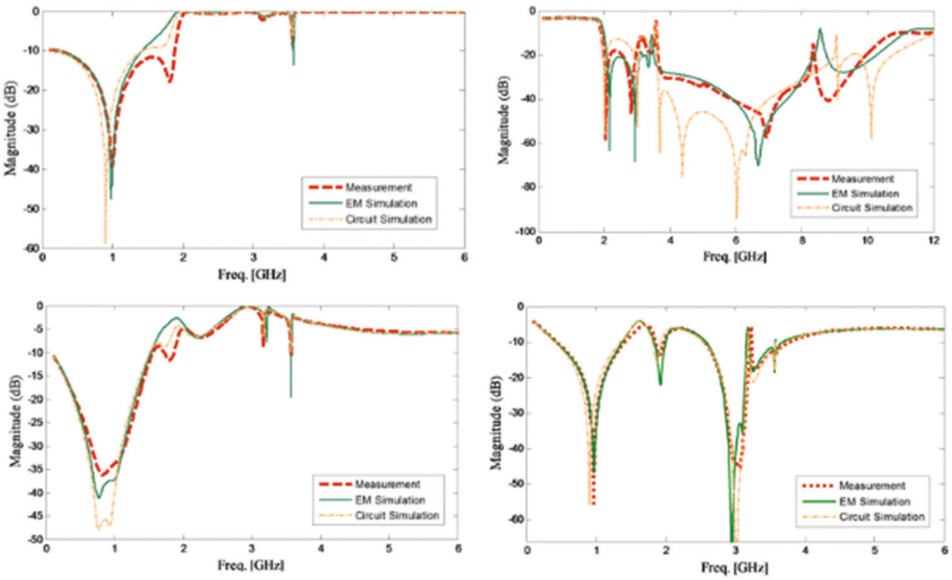

Fig. 16. The frequency responses of the power divider using LPF (Hayati, et al., 2013).

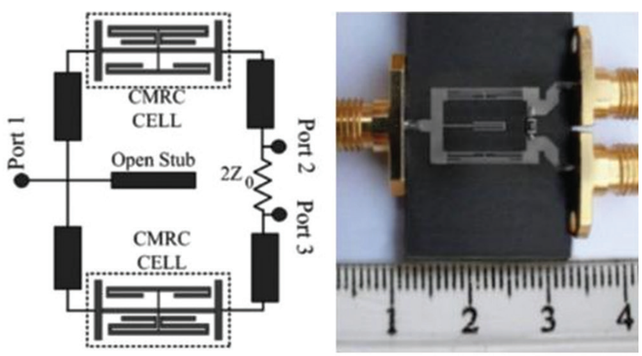

Fig. 17. The structure and implemented photo of the divider using resonator and open stub (Roshani 2017).

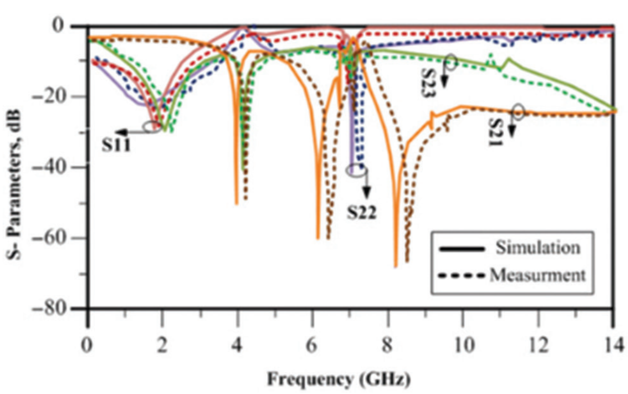

Fig. 18. The frequency responses of the power divider using resonator and open stub (Roshani 2017).

reduces the size of the power divider by 45% and suppresses unwanted bands up to the fifth harmonics. The results show that the insertion loss and the isolation at the center frequency are 0.1 dB and 23 dB, respectively.

In Lalbakhsh, et al., (2020) a narrowband dual-band bandpass filter and in Lalbakhsh, et al. (2020) a simple

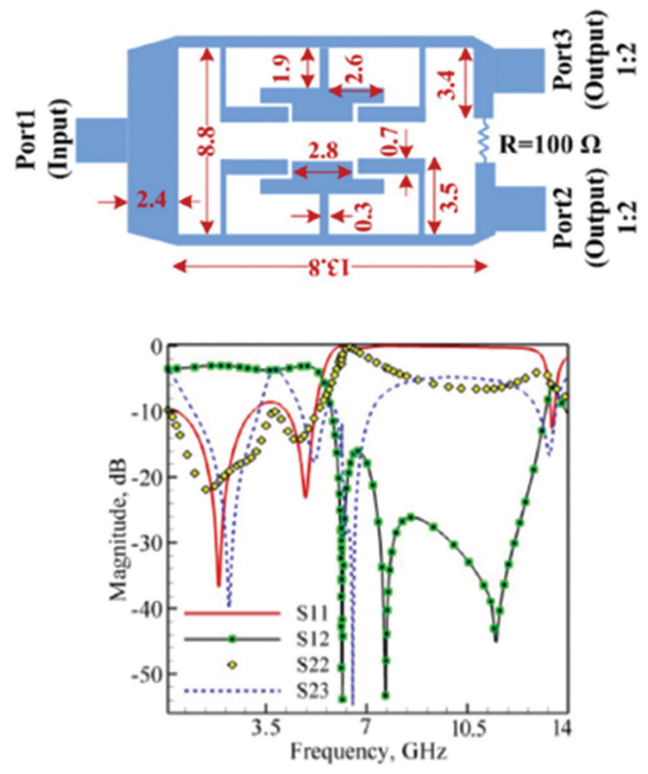

Fig. 19. The structure and frequency responses of the power divider using resonator (Roshani and Siahkamari 2022).

LPF with an ultrawide stopband from 1.6 to 25 GHz, in Pradhan, et al. (2023), substrate integrated waveguide (SIW) bandpass filters using open-loop ring resonators and in Pradhan, et al. (2023) SIW bandpass filters using semi-circular cavities and in Barik, Koziel and Pietrenko-Dabrowska (2023) a compact filter using a half-mode substrate-integrated rectangular cavity are presented, which all of these resonators can be used in dividers structure for harmonics suppression purpose.

Layout, substrate, and advantage of some designed power dividers using resonators are listed in Table II as follows:

IV. Power Divider with Lumped Reactive Components

Using lumped reactive elements (L and C) in power divider design is another method to suppress unwanted harmonics and reduce circuit size, which affect the quality of the final product.

In Jamshidi, et al. (2021), as shown in Fig. 22, the structure and layout of the proposed divider using compact elements are depicted. In the above structure, using series inductor and capacitor, very efficient method is presented with 100% size reduction and infinite harmonic elimination theoretically. This power divider is fabricated on RT/Duorid 5880 substrate with a relative permeability of 2.2 and a thickness of 0.508 mm.

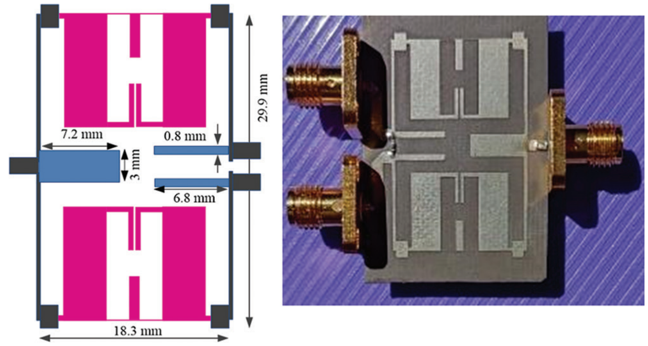

Fig. 20. The structure and fabricated photo of the patch divider using resonator and three open stubs (Roshani, et al., 2021).

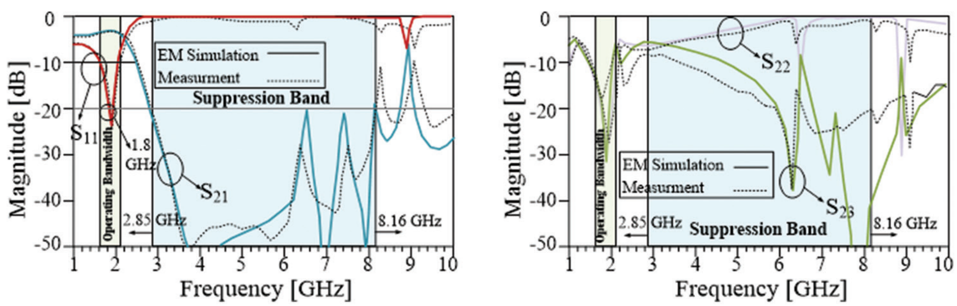

Fig. 21. The frequency responses of the patch divider using resonator and three open stubs (Roshani, et al., 2021).

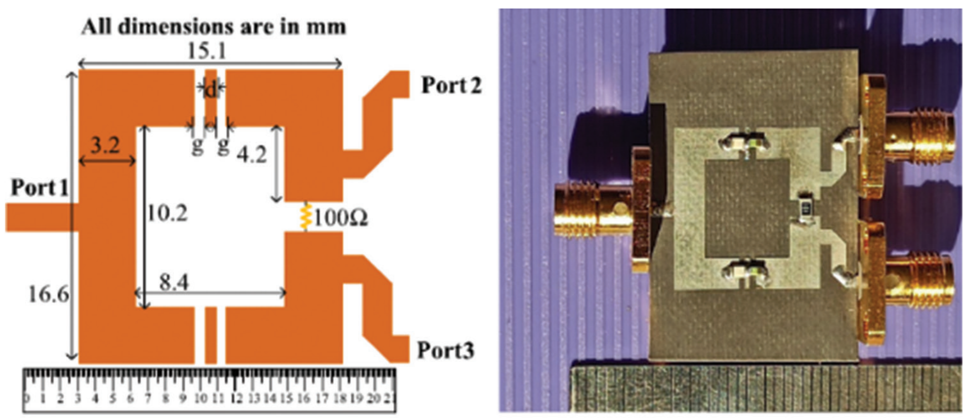

Fig. 22. The structure and fabricated photo of the hybrid power divider using series LC (Jamshidi, et al., 2021).

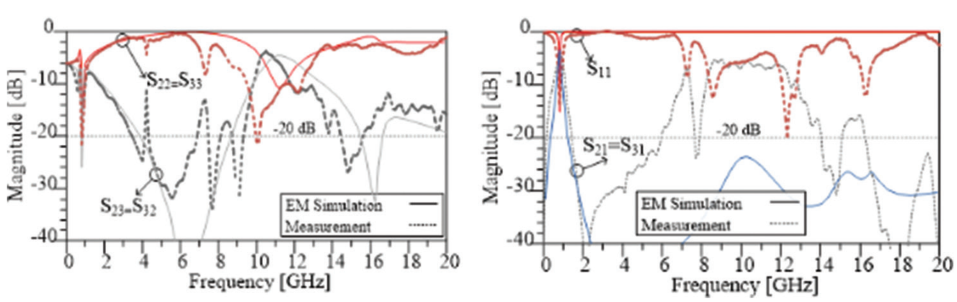

Fig. 23. The frequency responses of the hybrid power divider using series LC (Jamshidi, et al., 2021).

This power divider is designed at 800 MHz frequency and has a very small size which is 82.5% smaller compared to the conventional divider. This structure is a general design method for working at different frequencies and desired size reduction percentages in reference Jamshidi, et al. (2021), and several examples are designed with different size reduction percentages. In practice, the above structure was implemented on a frequency of 800 MHz and good results were obtained. The fabricated divider suppresses the 2nd–25th harmonics with a suitable attenuation level, which frequency response is shown in Fig. 23. The insertion loss of the divider is below 0.1 dB in the operating frequency, and the isolation between output ports is better than 38 dB at the operating frequency.

In Heydari and Roshani (2021), with using resonators, lumped inductors, and capacitors, a compact divider is designed with harmonic suppression. This divider is implemented on RT/Duorid 5880 substrate with a ε_r of 2.2. In this divider, two series inductors and a parallel capacitor are used as shown in Fig. 24. This divider works at 1500 MHz frequency and has a very small size, which

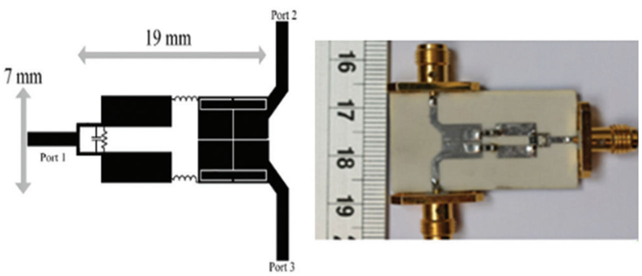

Fig. 24. The structure and fabricated photo of the divider using series inductors and parallel capacitor(Heydari and Roshani 2021).

shows 52% size reduction in compared with the typical divider at 1500 MHz frequency. The frequency response of this divider is depicted in Fig. 25, as seen in this divider, removes the 3rd up to 6th harmonics well, and has 0.15 dB insertion loss, which shows the proper performance of this designed divider.

A dual-band divider using lumped capacitors, with compact size and suppressed harmonics, is designed in Rostami and Roshani (2018). This divider correctly works at two frequencies of 0.9 and 1.8 GHz. To reduce the size and also eliminate harmonics, lumped capacitors are used in the structure of this divider as seen in Fig. 26. This divider has 80% size reduction compared with the typical dual-band divider at same frequencies.

The frequency response of this divider shows in Fig. 27, as results show, this divider correctly works at two frequencies of 0.9 and 1.8 GHz, with 0.1 dB insertion loss and provides a wide suppression level from 3.1 to 10.6 GHz frequencies.

Layout, substrate, and advantage of some designed power dividers using LC components are listed in Table III as follows:

V. Power Divider with Coupled Lines Techniques

Using coupled lines, in microwave devices particularly in power dividers, can improve the performance of the devices, such as efficient power division, impedance transformation, filtering capabilities, size reduction, and improved performance characteristics. These benefits make coupled-line structures valuable building blocks

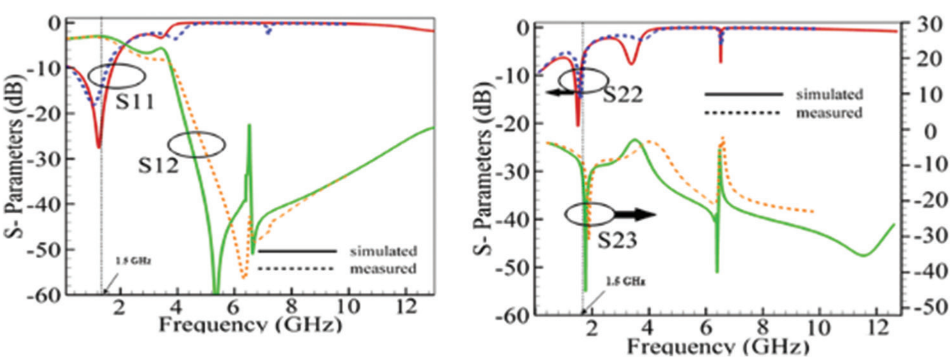

Fig. 25. The frequency responses of the power divider using series inductors and parallel capacitor (Heydari and Roshani 2021).

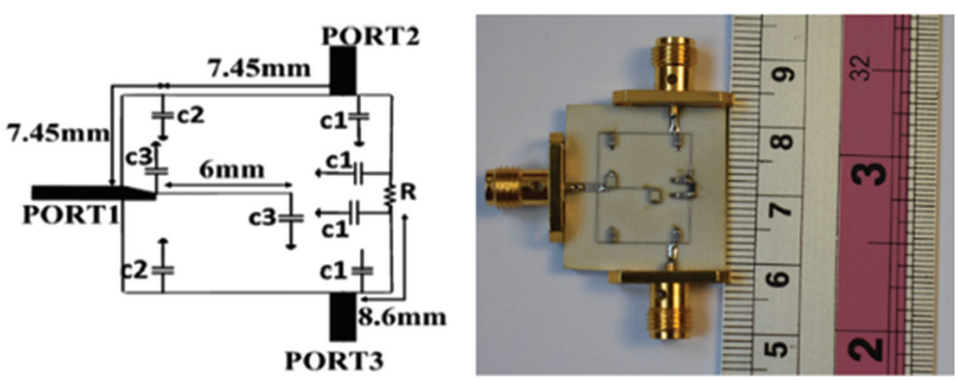

Fig. 26. The structure and fabricated photo of the dual-band divider using lumped capacitors (Rostami and Roshani 2018).

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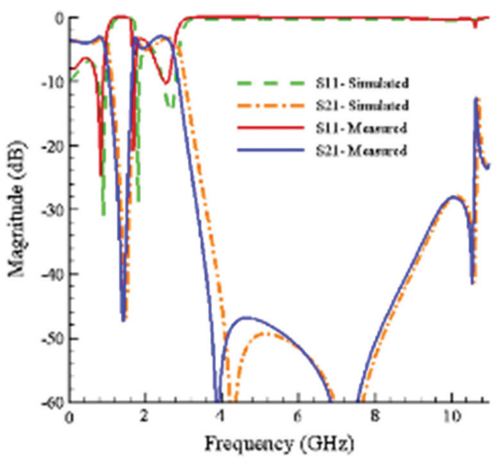


Fig. 27. The frequency responses of the dual-band divider using lumped capacitors (Rostami and Roshani 2018).

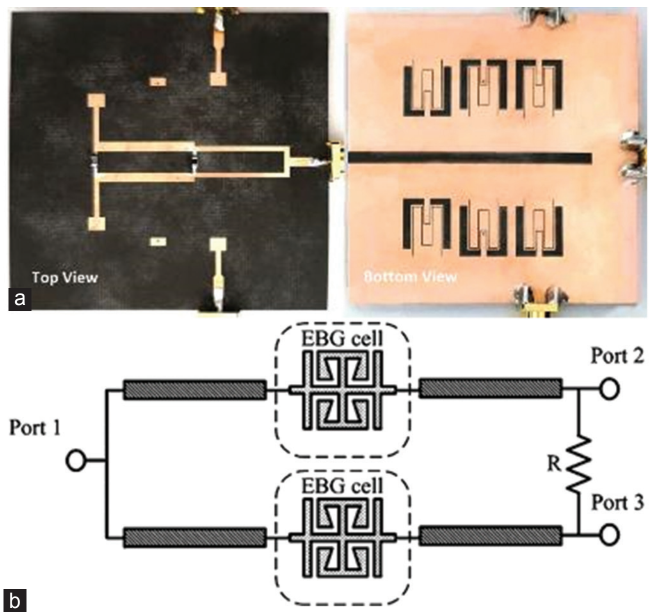


Fig. 28. (a and b) Using defected ground structure (Rao, et al., 2020) and EBG techniques (Lin, et al., 2007) in power divider for performance improvement.

in microwave circuit design and enable the development of advanced and high-performance microwave systems. Coupled-line structures can be used to implement bandpass or band-stop filtering functions. By exploiting the coupling between the lines, specific frequencies can be allowed to propagate whereas suppressing others. Furthermore, coupled-line structures can help in reducing the size of microwave devices.

The presented work in Chen and Ho (2017) introduces the design equations for a coupled-line divider. These equations provide analytical solutions for the design parameters, allowing the divider to be suitable for a desired two-pole Butterworth or Chebyshev response. The derived design equations enable the design of dividers with desired frequency responses, and the concept presented in the paper can be extended to higher-order filtering dividers for improved selectivity. In Lin and Chu (2010), an approach is introduced to designing a dual-band divider with a selective dividing ratio based on coupled-lines. A dual-band quarter-wave length transformer using coupled-lines is presented as a replacement for the traditional quarter-wave length transformer in a typical divider. The designed divider exhibits a simple and structure with compact size and wide bandwidth performance for a small frequency ratio. A divider using coupled lines and compact size is presented in Singh, Basu and Wang (2009). In this divider, a single-stage coupled line is used in the typical Wilkinson divider structure, resulting in a compact layout. According to the results of this paper, the designed power divider improves bandpass frequency response and offers a compact size.

The performances of some power dividers approaches, which have exploited coupled line techniques, are compared in Table IV.

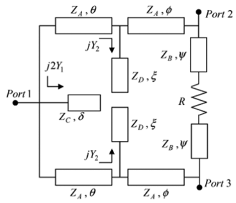
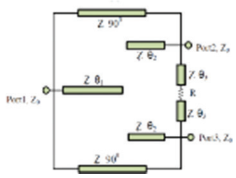
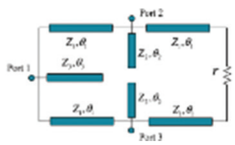
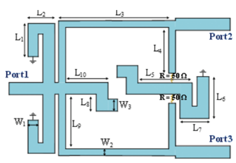
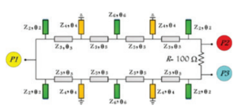
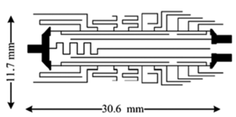
VI. Power Divider with Electromagnetic Bandgap (EBG) and Defected Ground Structure (DGS) Techniques

EBG and DGS techniques are two important concepts which have commonly used in microwave engineering, particularly in the design of power dividers, as shown in Fig. 28. DGS is a technique used to create specific patterns or structures in the ground plane of a microwave circuit to achieve desired electromagnetic characteristics. The DGS is typically implemented by etching slots, patches, or other shapes into the ground plane beneath the transmission lines or other components. Using DGS structures in the power dividers may result in improving isolation between output ports, improve return loss, or provide frequency selectivity, depending on the specific requirements of the design.

On the other hand, EBG techniques involve the use of periodic structures to create bandgaps in the electromagnetic spectrum. In power divider design, EBG techniques can be utilized to achieve performance improvement in terms of isolation, insertion loss, and bandwidth. By using EBG structures into the power divider circuit, unwanted harmonics can be suppressed.

A miniaturized WPD for GSM applications is presented in Gupta, Ghosh, and Toppo (2011). The conventional design is modified by replacing the quarter-wave sections with fractals, resulting in a smaller device. To compensate for the performance degradation caused by miniaturization, a DGS is employed. The proposed design occupies only 56% of the area, compared to the typical divider. In He, et al. (2013), a novel divider that combines SIW and DGS techniques together is presented to provide filtering response. The integration of SIW offers advantages, such as low loss, easy implementation, and seamless integration with planar circuits. By incorporating DGS, the proposed power divider achieves filtering capabilities, reducing the need for an additional filter and resulting in size and cost reduction. Furthermore, the presented work in Mohassieb, et al. (2010), focuses on the design, simulation, and fabrication

TABLE I
LAYOUT, SUBSTRATE, AND ADVANTAGE OF SOME POWER DIVIDERS USING OPEN STUBS

References	Layout of BLCs	Method	Substrate	ε_r	Thickness	Advantages
Cheng and Ip, 2010		Open stubs	RT_Duroid 5880	3.38	0.813 mm	1. Simple structure 2. 2nd–4th harmonics suppression 3. No size reduction
Hayati and Roshani, 2013		Open stubs	RT_Duroid 5880	2.2	0.381 mm	1. Simple structure 2. 3rd–5th harmonics suppression 3. 35% size reduction
Hayati, Roshani and Roshani, 2013		Open stubs	RT/Duroid	2.2	0.381 mm	1. Simple structure 2. 2nd–6th harmonics suppression 3. No size reduction
Roshani, et al., 2022		Open and Short stubs	RT/Duroid	2.2	0.508 mm	1. Simple structure 2. 2nd–3rd harmonics suppression 3. No size reduction
Lotfi, et al., 2020		Open and Short stubs	RT/Duroid	2.2	0.787 mm	1. Simple structure 2. 2nd–4th harmonics suppression 3. No size reduction
Roshani and Roshani 2020		Open stubs	RO4003	3.65	0.508 mm	1. Semi complex 2. 2nd–15th harmonics suppression 3. 73% size reduction

of miniaturized branch-line couplers (BLCs) operating at 2.4 GHz. Two techniques are employed to reduce the size of the conventional BLC: High impedance open stubs (HIOS) and DGS. The HIOS approach reduces the size by over 57.5% without compromising power handling capability. The DGS technique further reduces the size by more than 18% whereas achieving any desired dividing ratio and suppressing higher-order modes.

A design procedure of an unequal Wilkinson divider using a DGS is presented in Lim, et al. (2001). Using the DGS in the unequal Wilkinson topology, a 4:1 power dividing ratio is easily achieved, which would be impractical with conventional microstrip lines due to thin conductor width and low aspect ratio. A 4:1 power divider is designed and measured at 1.5 GHz to validate the proposed approach. The measured performance demonstrates excellent matching, isolation, and accurate dividing ratios at different ports. The DGS implementation allows for a larger conductor width, reduced length, and overall smaller circuit size, making it advantageous for high-impedance lines. The presented work in Rao, et al. (2020) introduces two types of hybrid microstrip/DGS cells, for passive device fabrication with an ultra-wide stopband. These cells feature dual-resonance characteristics achieved through stepped-impedance DGS and embedded folded slot-line on the ground.

A planar WPD is designed for the suppression of harmonics using microstrip EBG cells in Lin, et al. (2007). The proposed technique utilizes the EBG cells to suppress unwanted harmonics and reduce the circuit size over 30% compared to the typical divider. The planar structure facilitates easy circuit design on printed circuit boards. The measured results demonstrate excellent performance, with third and fourth harmonics suppression. Furthermore, an EBG in-phase hybrid-ring equal power divider is presented in Ooi (2005). A systematic design technique is introduced, utilizing closed-form analytical expressions for the EBG structure. The proposed structure achieves an increase in both input and output impedance bandwidth of approximately 10%, compared to conventional hybrid-ring equal power dividers. The proposed EBG in-phase hybrid-ring equal power divider offers a broader bandwidth, occupies a smaller area, and exhibits good harmonic suppression characteristics. The performances of some power dividers approaches, which have exploited DGS and EBG techniques, are compared in Table V.

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TABLE II
Layout, Substrate, and Advantage of Some Power Divider using Resonator

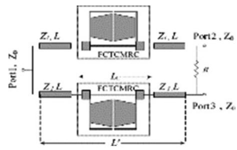
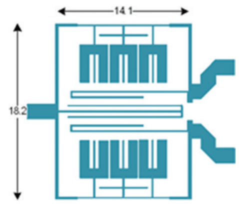
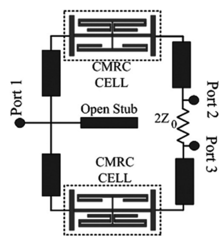
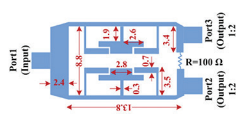
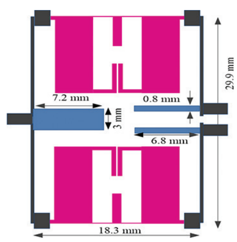
References	Layout of BLCs	Method	Substrate	ε_r	Thickness	Advantages
Hayati, Roshani and Roshani 2013		Resonator	RT_Duroid 5880	2.2	0.381 mm	1. Simple structure 2. 3rd–5th harmonics suppression 3. 29.3% size reduction
Hayati, et al., 2013		Resonator	RT_Duroid 5880	2.2	0.508 mm	1. Simple structure 2. 2nd–12th harmonics suppression 3. 71% size reduction
Roshani, 2017		Resonator	RT_Duroid 5880	2.2	0.508 mm	1. Simple structure 2. 2nd–4th harmonics suppression 3. 65% size reduction
Roshani and Siahkamari, 2022		Resonator	RT/Duroid	2.2	0.787 mm	1. Simple structure 2. 2nd–5th harmonics suppression 3. 37% size reduction
Roshani, et al., 2021		Resonator and Open stubs	RT_Duroid 5880	2.2	0.508 mm	1. Simple structure 2. 2nd–11th harmonics suppression 3. No size reduction

TABLE III
Layout, Substrate, and Advantage of Some Power Divider Using LC Components

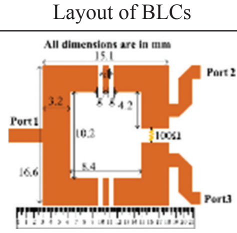
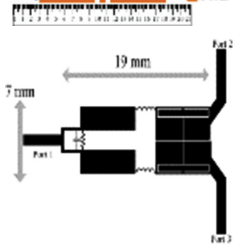
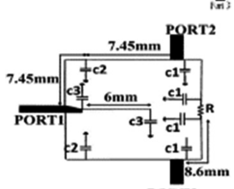
References	Layout of BLCs	Method	Substrate	ε_r	Thickness	Advantages
Jamshidi, et al., 2021		Lumped L and C	RT_Duroid 5880	2.2	0.508 mm	1. Complex structure 2. 2nd–25th harmonics suppression 3. 82.8% size reduction
Heydari and Roshani 2021		Lumped L and C	RT_Duroid 5880	2.2	0.508 mm	1. Complex structure 2. 2nd–8th harmonics suppression 3. 52% size reduction
Rostami and Roshani, 2018		Lumped L and C	RT_Duroid 5880	2.2	0.508 mm	1. Complex structure 2. 2nd–12th harmonics suppression 3. 80% size reduction

TABLE IV
Layout, Substrate, and Advantage of Some Power Divider using Coupled Line

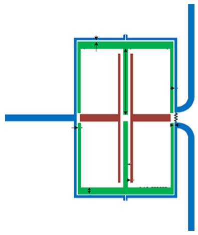
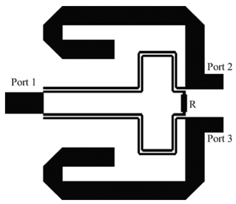
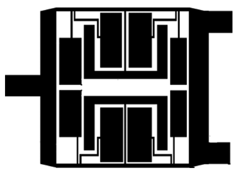
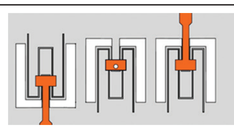
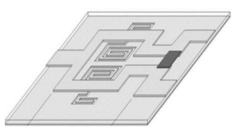
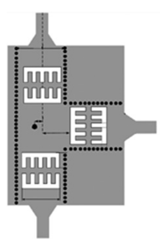
References	Layout of BLCs	Method	Substrate	ε_r	Thickness	Advantages and Comments
Roshani, et al., 2022		Coupled lines, open Stubs	RT_Duroid 5880	2.2	30 mil	1. Simple structure 2. 2^{nd}–6^{th} harmonic suppression 3. Dual band operation 4. No size reduction
Soleymani and Roshani, 2020		Coupled lines, Open stubs, bended lines	RT/Duroid	2.2	0.508 mm	1. Simple structure 2. The 2^{nd} Harmonics suppression 3. Wide band operation 4. No size reduction
Lotfi, Roshani and Roshani, 2020		Coupled lines, Open stubs,	RT/Duroid	2.2	31 mil	1. Simple structure 2. The 2^{nd}–14^{th} harmonics suppression 3. Wide band operation 4. Size reduction of 50%

TABLE V
Layout, Substrate, and Advantage of Some Power Divider using DGS (Rao, *et al.*, 2020) and EBG Techniques

References	Layout of BLCs	Method	Substrate	ε_r	Thickness	Advantages and Comments
Rao, et al., 2020		DGS Hybrid Microstrip	RT_Duroid 5880	2.2	0.508 mm	1. Dual band operation 2. Harmonics suppression 3. Filtering Response 4. No size reduction
Woo and Lee, 2005		Asymmetric DGS	GML1000	3.2	1.63 mm	1. Simple structure 2. 2^{nd}–3^{rd} harmonic suppression 3. Wide band operation 4. Size reduction of 9%
He, et al., 2013		DGS, SIW	RT_Duroid 5880	2.2	0.254 mm	1. Wide band operation 2. No size reduction

SIW: Substrate integrated waveguide, DGS: Defected ground structures

VII. Conclusion

Several methods for size reduction and harmonics suppression in microstrip power divider design, including open-ended stubs, resonators, coupled lines, DGS and EBG cells, and lumped reactive components are reviewed in this work. The topology, substrate, operating performance, advantages, and disadvantages of some of these dividers are investigated. The occupied size and numbers of suppressed harmonics, in these power dividers, are compared with conventional divider and reviewed. Most of reviewed dividers suppress unwanted harmonics and reduced occupied size compared with conventional divider, but some of them only suppress harmonics and increase circuit size.

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