Microstrip Passive Components for Energy Harvesting and 5G Applications: A Comprehensive Review

Leila Nouri[1,2,*], Salah I. Yahya[3,4], Abbas Rezaei[5], Sohrab Majidifar[5]

[1]Institute of Research and Development, Duy Tan University,
Da Nang, Vietnam

[2]School of Engineering and Technology, Duy Tan University
Da Nang, Vietnam

[3]Department of Communication and Computer Engineering, Cihan University-Erbil,
Erbil, Kurdistan region – F.R. Iraq

[4]Department of Software Engineering, Faculty of Engineering, Koya University,
Koya KOY45, Kurdistan region – F.R. Iraq

[5]Department of Electrical Engineering, Kermanshah University of Technology,
Kermanshah, Iran

Abstract—**This paper provides a comprehensive overview of microstrip passive components for energy harvesting and 5G applications. The paper covers the structure, fabrication, and performance of various microstrip passive components such as filters, couplers, diplexers, and triplexers. The size and performance of several 5G and energy harvester microstrip passive devices are compared and discussed. The review highlights the importance of these components in enabling efficient energy harvesting and high-speed communication in 5G networks. In addition, the paper discusses the latest advancements in microstrip technology and identifies key research challenges and future directions in this field. Overall, this review serves as a valuable resource for researchers and engineers working on microstrip passive components for energy harvesting and 5G applications.**

***Index Terms*—5G, Diplexer, Energy harvesting, Filter, Microstrip, Passive component, Triplexer.**

I. Introduction

Microstrip passive devices are fundamental components in the realm of microwave and RF engineering, offering a versatile and efficient means of implementing essential functions such as filtering (Yahya, et al., 2024; Capstick, 1994; Chen, et al., 2015; Feng, Zhang and Che, 2017), coupling (Arriola, Lee and Kim, 2021; Yahya, et al., 2023; Abouelnaga and Mohra, 2017; Alhalabi, et al., 2018; Kim, et al., 2004), matching (Salehi, Noori and Abiri, 2016), and power division (Chi, 2012; Chen, et al., 2019). With applications spanning across communication systems, radar systems, satellite communications, and more, microstrip passive devices play a pivotal role in enabling the development of high-performance and reliable electronic systems operating at microwave and millimeter-wave frequencies (Shukor and Seman, 2020; Shukor and Seman, 2016; Shi, et al., 2016; Rezaei and Noori, 2018). In recent years, the demand for efficient and high-performance communication systems has driven the development of advanced technologies in the field of microstrip passive devices. These devices, including couplers (Kim and Kong, 2010; Rezaei, Yahya and Nouri, 2023; Lai and Ma, 2013; Li, Qu and Xue, 2007), diplexers (Nouri, Yahya and Rezaei, 2020; Rezaei, Noori and Mohammadi, 2019; Bukuru, Song and Xue, 2015; Capstick, 1999), filters (Nouri, et al., 2024; Feng, Zhang and Che, 2017; Rezaei, et al., 2022), and triplexers (Nouri, et al., 2024; Nouri, et al., 2023; Jamshidi, et al., 2023), play a crucial role in various applications such as energy harvesting and 5G networks. By leveraging the unique properties of microstrip technology, these passive devices offer compact size, low cost, and excellent performance characteristics (Rezaei, Yahya and Nouri, 2024; Yahya, et al., 2023). In the context of energy harvesting, microstrip passive devices are utilized to efficiently capture and convert ambient energy sources such as solar, thermal, and kinetic energy into usable electrical power. Couplers are commonly employed to split or combine power signals (Liou, et al., 2009), whereas diplexers and triplexers enable the simultaneous transmission and reception of multiple frequency bands (Chen, et al., 2006; Nouri, et al., 2023). Filters are also essential components for ensuring the

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Corresponding author's e-mail: leilanouri@duytan.edu.vn

purity and stability of harvested energy signals (Salehi and Noori, 2015; Zakaria, et al., 2013). Moreover, in the rapidly evolving landscape of 5G networks, microstrip passive devices are indispensable for enabling high-speed data transfer, low latency communication, and increased network capacity (Nouri, et al., 2023; Jamshidi, et al., 2023; Yahya, et al., 2023). Overall, the application of microstrip passive devices in energy harvesting and 5G networks represents a promising avenue for advancing communication technologies and addressing the growing demand for efficient and reliable wireless systems (Nouri, et al., 2023). Passive microstrip devices that have less losses are suitable for energy-harvesting applications such as the proposed structures in (Rezaei and Noori, 2018). On the other hand, several passive microstrip structures which work at 1GHz up to 6GHz are appropriate for 5G mid-band applications (Chinig, et al., 2015; Chinig, et al., 2015; Heshmati and Roshani, 2018).

In this paper, we will examine the structure of passive microstrip devices suitable for 5G and energy harvesting users. Furthermore, their performance and advantages and disadvantages will be examined. The paper is organized as follows: First, the structure and performance of some 5G passive microstrip devices will be studied, and then, the structure and performance of microstrip passive devices suitable for energy harvesting will be reviewed. Finally, the importance of microstrip passive devices in 5G and energy harvesting is investigated. These studied devices are diplexers, filters, couplers, and triplexers.

II. Structures and Performance of 5g Passive Microstrip Devices

The 5G frequencies are divided into three frequency bands, which are low, mid, and high. Each band has different capabilities. The low band frequencies are <1 GHz. This frequency band has greater coverage but lower speeds. The mid band covers from 1 GHz up to 6 GHz and offers a balance of both. The high band is from 24 GHz up to 40 GHz offers higher speeds but a smaller coverage radius. The operating frequencies of most of the microstrip devices can be tuned at low and mid bands. However, the design of a microstrip passive device for high band 5G is difficult. Because to set an operating frequency in this band, the dimensions should be very small, which makes the fabrication process difficult. For example, the GSM association describes spectrum in the 3.3 GHz-3.8 GHz range as ideal because many countries worldwide have already designated it for 5G. However, other mid-band spectrum is also being used. Table I shows a comparison between some of 5G microstrip passive devices. In Table I, the parameters band-pass filter (BPF), low-pass to band-pass (LP-BP), and band-pass-band-pass (BP-BP) are band-pass filter, LP-BP, and BP-BP, respectively. Moreover, λg is the guided wavelength calculated at the first operating frequency of each device.

As depicted in this Table, only the designed microstrip coupler in (Shukor and Seman, 2020) is suitable for High-Band 5G applications. Its passband is from 22.55 GHz up to 30 GHz. This branch-line coupler (BLC) has a traditional simple structure presented in Fig. 1. Furthermore, Fig. 2 shows its simulated and measured frequency responses. As shown in Fig. 2, the S_{21} and S_{31} of this BLC are better than −4.6 dB within the passbands. The phase difference between S_{21} and S_{31} from 22 GHz to 30 GHz fluctuates in the range of 86°-94° in (Shukor and Seman, 2020). Fig. 3 illustrates the isolation factor (S_{41}) and return loss (S_{11}) of this coupler.

It can be seen that from 20 GHz to 30 GHz, the isolation is better than −10 dB, but the in-band return loss is not well. The LP-BP triplexers in (Yahya, et al., 2024), (Zhu, et al., 2017), and (Xu, Chen and Wan, 2020) are designed for 5G Mid-Band and Low-Band applications. The proposed structures in (Yahya, et al., 2024) and (Zhu, et al., 2017) are implemented only on a microstrip substrate but in (Zhu, et al., 2017), in addition to microstrip transition lines, lumped elements are used too. The introduced 4-Chanel BPF in (Rezaei, et al., 2022) occupies a very compact area of 0.0012 λg^2, which is suitable for 5G Mid-Band and Low-Band applications. The layouts of some 5G microstrip devices are presented in (Fig. 4a-d). The frequency responses of these devices are depicted in (Fig. 5a-d). The coupled meandrous microstrip lines presented in (Fig. 4a) are implemented on Taconic RF-35 (tm) substrate with thickness of 0.508 mm, dielectric constant of 3.5, and loss tangent of 0.0018. Using this structure leads to suppressed harmonics up to 15 GHz, which is presented in (Fig. 5a). Meanwhile, the illustrated structure in (Fig. 4b) is fabricated on a RT/duroid® 5880 substrate with $\varepsilon_r = 2.22$, h = 31 mil, and a loss tangent of 0.0009. It has four narrow channels as shown in (Fig. 5b). The height of the substrate of the simple microstrip band-pass filter which is presented in (Fig. 4c) is 1.524 mm, whereas it has a relative permittivity of 3.38, conductor thickness of 0.07 mm, and loss tangent of 0.0025. As shown in (Fig. 5c), it works at 5.4 GHz which makes it suitable for 5G networks. To obtain the switchable triplexer in (Fig. 4d), in addition to microstrip structure, p-i-n diode and some resistances are used. This BP-BP triplexer has some harmonics, which are depicted in (Fig. 5d).

Due to the complex design process, the number of reported microstrip multiplexers is few. Meanwhile, reducing the loss level in multiple channels simultaneously is a difficult process. However, the resonance frequencies can be tuned for 5G applications. A switchable eight-channel microstrip multiplexer is proposed by (Chen, et al., 2018). The resonance frequencies of this multiplexer are located at 0.85, 1.05, 1.3, 1.5, 1.65, 1.85, 2.05, and 2.3 GHz. Therefore, it is suitable for low-band and mid-band 5G applications. A quadruplexer is designed by (Zeng, Wu and Tu, 2011) using microstrip structure. This multiplexer operates at 2.3, 3.7, 5, and 6.1 GHz. The 1st, 2nd and 3rd channels of this device can be used for 5G applications. Another microstrip quadruplexer is reported by (Rezaei and Noori, 2018) which works at 3.211, 3.276, 3.38, and 3.491 GHz for IEEE 802.16 WiMAX and 5G mid-band applications. This multiplexer is designed using four semicircular microstrip resonators and its overall size is 0.36 λg^2.

TABLE I
A COMPARISON BETWEEN 5G MICROSTRIP PASSIVE DEVICES

References	Operating frequencies (GHz)	Type	FBWs%	Size (λg^2)	5G application
(Yahya, et al., 2024)	0.87, 1.33, 2.05	LP-BP Triplexer	14.1, 25.5	0.0038	Low & Mid Bands
(Chen, et al., 2015)	3.967	BPF	5	---	Mid-Band
(Abouelnaga and Mohra, 2017)	2.5	Coupler	---	---	Mid-Band
(Shukor and Seman, 2020)	26	Coupler	32	---	High-Band
(Shukor and Seman, 2016)	From 2.9 to 4.1	Coupler	34.4	---	Mid-Band
(Rezaei and Noori, 2018)	2.82	Coupler	---	0.0754	Mid-Band
(Lai and Ma, 2013)	2.4	Coupler	18.8	0.0231	Mid-Band
(Bukuru, Song and Xue, 2015)	3.65, 5.2	BP-BP Diplexer	8.2, 7.69	0.0506	Mid-Band
(Rezaei, et al., 2022)	0.7, 2.2, 3.8, and 5.6	4-Chanel BPF	---	0.0012	Low & Mid Bands
(Chen, et al., 2006)	1.35, 1.76	BP-BP Diplexer	3.4, 3.4	---	Mid-Band
(Zakaria, et al., 2013)	5.4	BPF	---	---	Mid-Band
(Yahya, et al., 2023)	5.2	Coupler	---	0.04	Mid-Band
(Chen, et al., 2015)	1.1, 1.3	BP-BP Diplexer	8, 9.2	0.705	Mid-Band
(Rezaei, Yahya and Nouri, 2023)	1.65, 2.57	LP-BP Diplexer	14	0.037	Mid-Band
(Deng and Tsai, 2013)	1.5, 2.4	LP-BP Diplexer	8	---	Mid-Band
(Feng, Gao and Che, 2014)	1.84, 2.42	BP-BP Diplexer	6, 5.8	---	Mid-Band
(Zhu, et al., 2017)	0.85, 1.6, 2.1	LP-BP Triplexer	13.9, 12.7	0.048	Low & Mid Bands
(Chen, et al., 2015)	1, 2.4, 5.8	LP-BP Triplexer	10, 7	---	Mid-Band
(Xu, Chen and Wan, 2020)	0.95, 1.58, 2.8	LP-BP Triplexer	17, 8.1	0.018	Low & Mid Bands
(Noori and Rezaei, 2017)	2.62, 2.88, 4.34, 4.67	4-Chanel BPF	5.3, 5.5, 3.2, 3.6	0.079	Mid-Band
(Noori and Rezaei, 2018)	1.67, 2.54, 3.45, 4.57	4-Chanel Diplexer	1.2, 1.96, 1.15, 1.09	0.029	Mid-Band
(Hsu, Hung and Tu, 2016)	0.9, 1.5, 2.4, 3.5	4-Chanel Diplexer	4.3, 4.6, 3.3, 4	0.041	Low & Mid Bands
(Rezaei and Noori, 2018)	1.8, 2.4	BP-BP Diplexer	11, 7.1	0.022	Mid-Band
(Salehi and Noori, 2015)	2.39	BPF	46	0.0045	Mid-Band
(Salehi and Noori, 2014)	2.4	Coupler	---	0.023	Mid-Band
(Salehi, et al., 2016)	2.3, 2.55	BP-BP Diplexer	3.6, 3.4	---	Mid-Band
(Xu and Zhu, 2017)	1.21, 1.8, 2.41	BP-BP Triplexer	14.4, 14, 13.6	0.0553	Mid-Band

BPF: Band band-pass filter, LP-BP: Low-pass to band-pass, BP-BP: Band-pass-band-pass

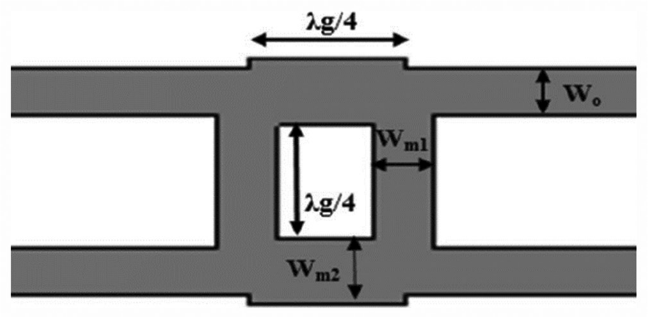

Fig. 1. Layout of a 5G high-band branch-line coupler in (Shukor and Seman, 2020).

III. STRUCTURES AND PERFORMANCE OF PASSIVE MICROSTRIP DEVICES FOR ENERGY HARVESTING

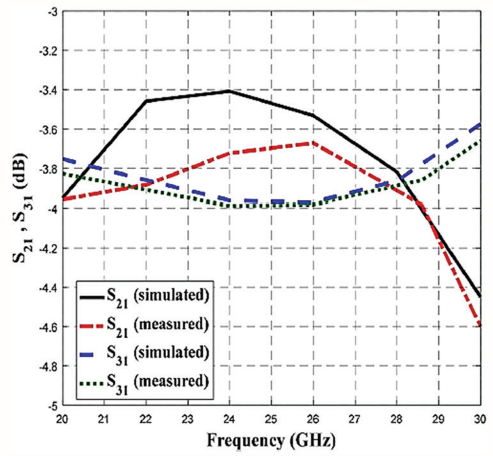

Fig. 2. Frequency response of the 5G high-band branch-line coupler in (Shukor and Seman, 2020).

Passive microstrip devices designed for energy harvesting are essential components in the field of wireless power transfer and autonomous sensor systems. These devices are used to efficiently capture and convert ambient electromagnetic or RF energy into electrical power for various applications. By leveraging the principles of electromagnetic induction and resonance, passive microstrip devices enable the extraction of energy from the surrounding environment without the need for an external power source. This technology has gained significant interest due to its potential to provide sustainable and autonomous power solutions for IoT devices, wearable electronics, and other low-power applications (Jamshidi, et al., 2023). Several types of passive microstrip devices are commonly used for energy harvesting applications. RF filters with low losses are used to filter out unwanted noise and interference from the RF signal before it is converted into electrical power. These filters help improve the overall efficiency of the energy harvesting system by reducing signal distortion and improving signal quality. Consequently, diplexers, triplexers, and filtering couplers (Shi, et al., 2016) with low insertion losses are suitable for energy harvesting. Overall, a combination of these passive microstrip devices is often used in energy harvesting systems to efficiently capture and convert ambient RF energy into electrical power for various applications. The size and performance of some microstrip passive devices useful for energy harvesting are depicted in Table II. In this Table, Fo, ILs, and RLs are operating frequencies, insertion losses, and return losses.

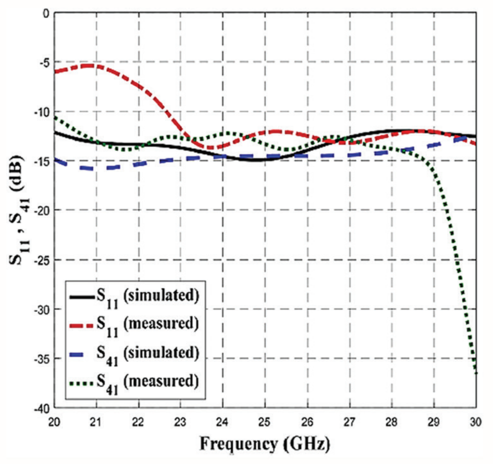

Fig. 3. Simulated and measured S_{11} and S_{41} of the proposed 5G high-band branch-line coupler in (Shukor and Seman, 2020).

Usually, triplexers have higher losses than filters and diplexers. Because, controlling three channels are more difficult. However, the LP-BP triplexer designed in (Yahya, et al., 2024) has very low losses, with the most compact size in comparison with the introduced structures in Table II. Furthermore, in (Yahya, Rezaei and Nouri, 2021), the insertion losses are very low and the size is small. The reported devices in Table II are designed based on various types of microstrip structures. (Fig. 6a-d) illustrates the layouts of some energy harvester microstrip passive devices. Meanwhile, the frequency responses of these devices are shown in (Fig. 7a-d). As shown in (Fig. 6a), two open loops are coupled to port 1 to obtain a BP-BP diplexer with a frequency response presented in (Fig. 7a). This diplexer is suitable for energy harvesting, but it has several problems in terms of low selectivity, large size, and narrow channels. The layouts of two energy harvester lowpass filters are depicted in (Fig. 6b and c).

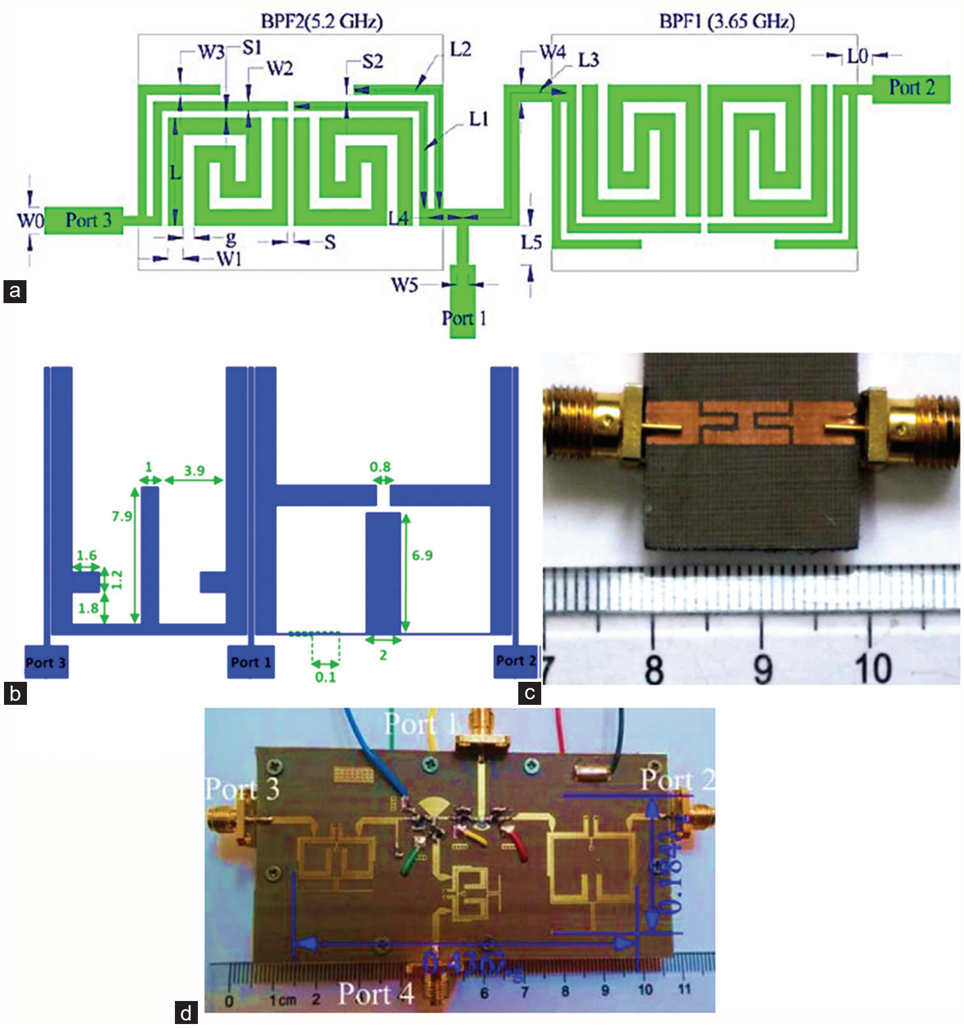

Fig. 4. Geometrical structures of the 5G microstrip (a) BP-BP diplexer in (Bukuru, Song and Xue, 2015), (b) 4-channel diplexer (unit: mm) in (Noori and Rezaei, 2018), (c) fabricated band band-pass filter in (Zakaria, et al., 2013), (d) fabricated BP-BP triplexer in (Xu and Zhu, 2017). BP-BP: Band-pass-band-pass.

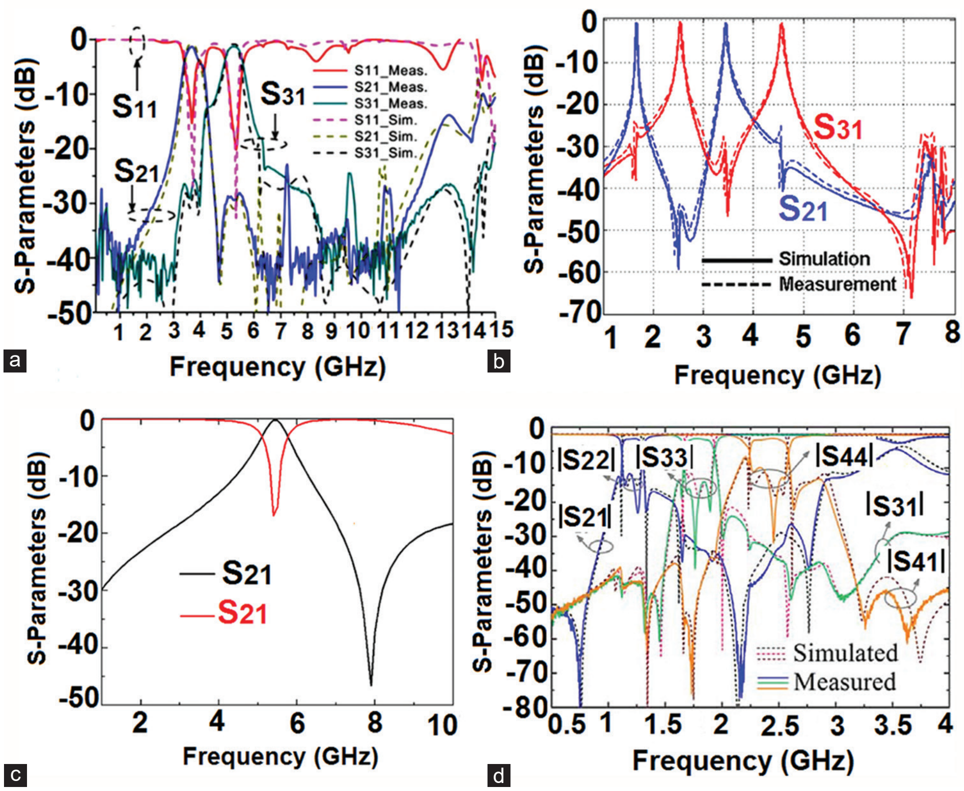

Fig. 5. Frequency responses of the 5G microstrip (a) BP-BP diplexer in (Bukuru, Song and Xue, 2015), (b) 4-channel diplexer (unit: mm) in (Noori and Rezaei, 2018), (c) fabricated band-pass filter in (Zakaria, et al., 2013), (d) fabricated BP-BP triplexer in (Xu and Zhu, 2017). BP-BP: Band-pass-band-pass.

TABLE II

A COMPARISON BETWEEN ENERGY HARVESTER MICROSTRIP PASSIVE DEVICES

References	Type	F_o (GHz)	ILs (dB)	RLs (dB)	Size (λg^2)
(Yahya, et al., 2024)	LP-BP Triplexer	0.87, 1.33, 2.05	0.2, 0.09, 0.04	25.6, 19.4, 25.1	0.0038
(Yahya, et al., 2023)	Coupler	1.61	0.45, 0.75	19.76	0.014
(Alhalabi, et al., 2018)	Coupler	2.45	0.6, 0.8	70	---
(Shi, et al., 2016)	Coupler	1.87	1.4*	20	0.1386
(Majdi and Mezaal, 2023)	BP-BP Diplexer	2.84, 4.08	0.7, 0.9	21.2, 17	---
(Yahya, Rezaei and Nouri, 2021)	BP-BP Diplexer	1.4, 3	0.06, 0.07	28.6, 20	0.004
(Rezaei and Nouri, 2020)	BP-BP Diplexer	1, 1.3	0.21, 0.21	32, 25	0.018
(Majidifar and Hayati, 2017)	Lowpass Filter	1.76	0.42	11	0.0215
(Majidifar, 2016)	Lowpass Filter	1.71	0.1	18	0.02
(Khajavi, AL-Din Makki and Majidifar, 2015)	Dual-band BPF	2.45, 3.7	0.458, 0.672	23.57, 17.2	---
(Fadaee, et al., 2023)	Lowpass Filter	2.42	0.1	22	0.042
(Afzali, et al., 2021)	BPF	2.4	1.2	---	0.037
(Heng, et al., 2014)	Multiplexer	2.8, 2.809, 2.81,2.82	0.4, 0.3, 0.3, 0.4	19,19,19, 20	1.114
(Elden and Gorur, 2021)	LP-BP Diplexer	2, 3.5	0.3, 1.28	Better than 15	0.095
(Deng and Tsai, 2013)	LP-BP Diplexer	1.5, 2.4	0.25, 2.42	---	---
(Heshmati and Roshani, 2018)	LP-BP Diplexer	1, 2.4	0.25, 0.58	15, 30	0.046

*The maximum IL within -3dB passband. BPF: Band band-pass filter, LP-BP: low-pass to band-pass, BP-BP: Band-pass-band-pass

Both of them are designed by loading some patch stubs on a thin transmission line. Theses filters could suppress the harmonics well, whereas they have high selectivity (Fig. 7b and c). However, a filter design is easier than the diplexer design. (Fig. 6a) presents a layout configuration of a BP-BP diplexer with compact size. Its frequency response is illustrated in (Fig. 7d). As shown, this diplexer can select the desired frequencies better than the proposed design in (Majdi and Mezaal, 2023).

IV. IMPORTANCE OF MICROSTRIP PASSIVE DEVICES IN 5G NETWORKS AND ENERGY HARVESTING

Microstrip passive devices play a crucial role in enabling efficient energy harvesting and high-speed communication in 5G networks due to several key reasons:

1. Compact Size: Microstrip passive components are inherently compact and can be integrated into small form factors, making them ideal for energy harvesting systems and miniaturized 5G devices where space is limited.

2. Low Cost: Microstrip components are cost-effective to manufacture compared to other technologies, making them attractive for mass production of energy harvesting systems and 5G devices.
3. High Efficiency: Microstrip passive components, such as filters and couplers, can be designed with high efficiency, enabling optimal energy transfer and signal reception in energy harvesting systems and 5G networks.
4. Frequency Selectivity: Microstrip filters provide frequency selectivity, allowing for the isolation of specific frequency bands in 5G communication systems, which is essential for efficient spectrum utilization and interference mitigation.
5. Low Insertion Loss: Microstrip components can be designed with low insertion loss, minimizing signal attenuation in communication systems and maximizing energy conversion efficiency in energy harvesting applications.
6. Versatility: Microstrip technology offers flexibility in design and fabrication, allowing for the customization of passive components to meet the specific requirements of energy harvesting systems and 5G networks.
7. Integration: Microstrip passive components can be easily integrated with active components, such as amplifiers and transceivers, to create complete energy harvesting systems and 5G communication modules.

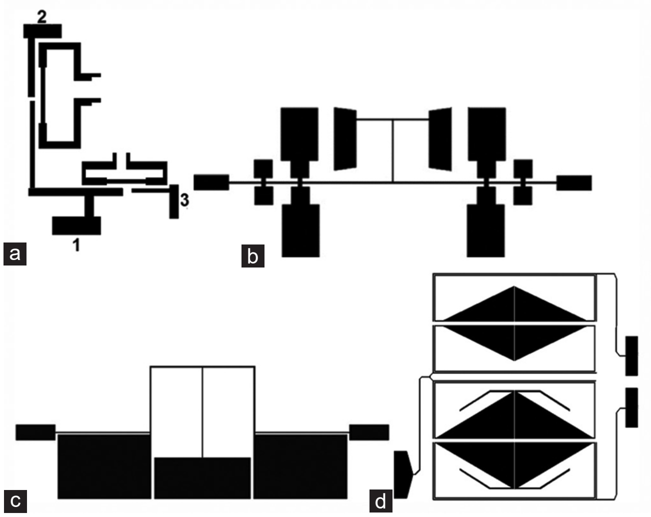

Fig. 6. Geometrical structures of the energy harvester microstrip (a) BP-BP diplexer in (Majdi and Mezaal, 2023), (b) lowpass filter in (Majidifar, 2016), (c) lowpass filter in (Fadaee, et al., 2023), (d) BP-BP diplexer in (Rezaei and Nouri, 2020). BP-BP: Band-pass-band-pass.

Overall, the importance of microstrip passive devices lies in their ability to provide efficient, cost-effective, and compact solutions for energy harvesting and high-speed communication applications in 5G networks. Their performance characteristics make them essential building blocks for enabling the next generation of wireless technologies.

Microstrip passive devices such as diplexers, triplexers, and multiplexers are essential components in modern communication systems. Diplexers are commonly used to combine or separate signals in two different frequency bands, allowing for efficient use of the available spectrum. Triplexers, on the other hand, can combine or separate signals in three different frequency bands. Multiplexers are used to combine multiple signals onto a single transmission line, enabling simultaneous transmission of different data streams. These components find wide applications in various communication systems, such as radar systems, satellite communication, wireless networks, and cellular base stations. They play a crucial role in managing signal interference,

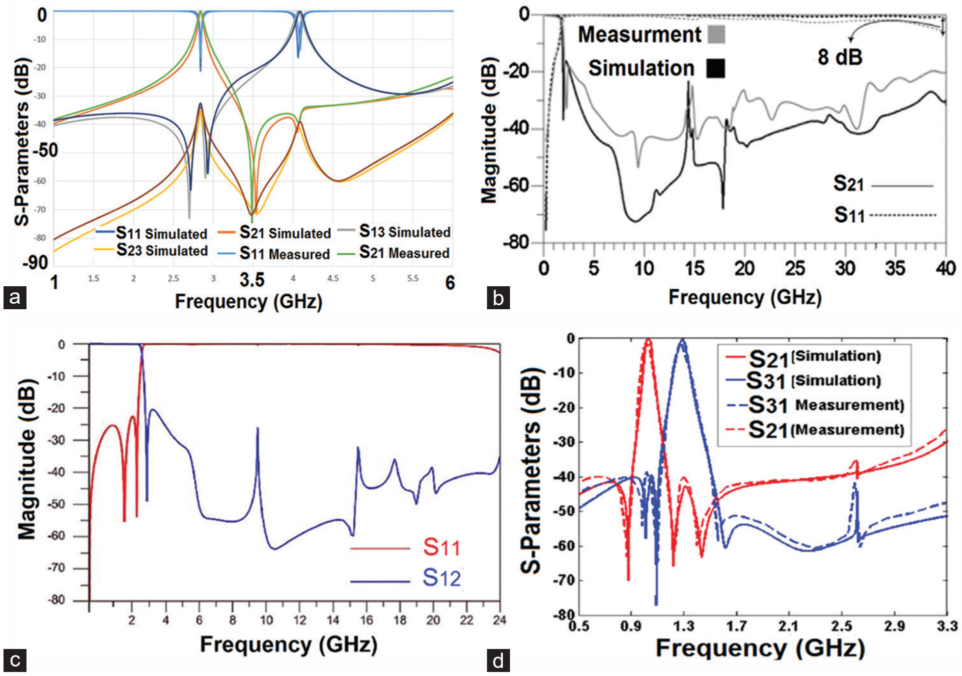

Fig. 7. Frequency responses of the energy harvester microstrip (a) BP-BP diplexer in (Majdi and Mezaal, 2023), (b) lowpass filter in (Majidifar, 2016), (c) lowpass filter in (Fadaee, et al., 2023), (d) BP-BP diplexer in (Rezaei and Nouri, 2020). BP-BP: Band-pass-band-pass.

improving system efficiency, and increasing bandwidth utilization. Using microstrip technology, these devices offer compact size, lightweight design, and cost-effective solutions for high-frequency applications.

V. Conclusion

This paper highlights the significance of microstrip passive components in enabling efficient energy harvesting and high-speed communication in 5G networks. The compact size, low cost, high efficiency, frequency selectivity, low insertion loss, versatility, and integration capabilities of microstrip devices make them essential building blocks for energy harvesting systems and 5G communication modules. By leveraging the unique characteristics of microstrip technology, researchers and engineers can develop innovative solutions that drive the advancement of wireless technologies, paving the way for a more connected and sustainable future.

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