A New Compact Bandpass Filter Design Using Overlapping Resonator for Enhanced 5G Performance

Ahmed S. Al-Jawadi, Kahlan Hasan Hamed, Shamil H. Hussein, and Mohammed Idrees Dawod

***Abstract*—As wireless technology has grown at an unprecedented rate and a growing number of users are wanting to create high speed systems. Small, efficient bandpass filters are essential for 5G technology. The present paper provides an innovative methodology for designing a micro-sized bandpass filter operating at 2.4GHz (5G ISM-band). Three types of compact microstrip bandpass filters (BPFs) were developed, including the overlapped resonator filter, the coupled-line filter, and the hairpin filter. The three filter structures are based on a third-order Chebyshev prototype with a 0.1 dB ripple and were implemented and developed in Advanced Design System (ADS) simulator. The simulated results showed that the proposed overlapped resonator filter achieved the lowest insertion loss (-0.001 dB) and the best reflection coefficient (-36.346 dB), compared to the coupled-line filter (insertion loss: -0.009 dB, reflection coefficient: -26.85 dB) and the hairpin filter (insertion loss: -0.005dB, reflection coefficient: -29.77dB). The proposed filter also achieved a more compact size (11.7 x 15.3 mm²) than the others. Superior impedance matching, lower insertion loss, and a substantial reduction in size make the overlapped resonator filter a strong candidate for compact and high-performance 5G front-end systems.**

***Index terms*—ADS simulation, bandpass filter, coupled lines, 5th generation, Microstrip filter, overlapping resonator.**

I. Introduction

As the emergence of new types of wireless communication systems has increased, so has the development of compact and efficient Radio Frequency (RF) components. Next-generation requires developed components to ensure users receive high-quality signals (i.e., free from interference). Bandpass filters (BPFs) play a significant role in maintaining signal integrity during both transmission and reception over the radio frequencies. A BPF's primary function is to filter out unwanted signals and provide selectivity for the desired signal. Therefore, a high-performance BPF must have a small physical size, high stopband rejection, low insertion loss, and wide bandwidth (BW) to meet new demands for increased data rate and improved spectrum efficiency [1], [2].

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Microstrip BPFs have received considerable attention due to their planar structure, ease of integration, and ability to deliver outstanding high-frequency performance. The simplicity of their construction and ease of manufacture make them a perfect match for printed circuit board (PCB) technologies [3], [4]. Several BPF topologies have been explored in the literature, such as coupled-line [5], [6], hairpin [7], DC filters for medical applications [8], and step-impedance resonators [9]. However, most structures suffer from trade-offs among bandwidth, insertion loss, and physical dimensions [10].

A multilayer hairpin BPF proposed in [11] achieved an insertion loss (S_{21}) of -1.8 dB but required a large area (31.4×38.6 mm²). Concurrently, hairpin filters employing defective ground structures, as depicted in [12], exhibited superior compactness but constrained bandwidth.

Many advanced microstrip filter topologies have been developed to meet 5G requirements. These include hairpin resonators, step-impedance structures, and coupled-line configurations. For example, Purohit and Toshniwal [13] made and tested a small microstrip hairpin BPF on different substrates. They achieved an excellent insertion loss of -0.1 dB and a return loss of -22.5 dB at 3 GHz, with a small footprint of 18.4 × 30 mm². Amrullah et al. [14] also used a symmetric step-impedance resonator filter at 2.4 GHz, which had a bandwidth of 180 MHz and a low insertion loss of -0.77 dB. Letavin [15] proposed a BPF with U-shaped resonators covering a wideband (2.5 GHz operating frequency, 700 MHz bandwidth, and -30 dB return loss). However, it required a larger area (35 × 35 mm²). Also, El Khorassani et al. [16] reported a square open-loop cross-coupled BPF with a return loss of -35 dB and an insertion loss of -6 dB over a 100 MHz bandwidth. Its insertion was fair; however, it was very good at blocking signals. Chami et al. [17] obtained a two-layer bandpass filter with aperture-coupled hairpin resonators operating at 2.45 GHz. The structure indicated an insertion loss of -2 dB and a return loss of -34 dB. They noted that the circuit size was only 21.8 × 21.6 mm², which illustrated that the multilayer coupling method could be employed to reduce the design's dimensions.

Although previous literature has proposed topologies and improved filter characteristics, it remains difficult to achieve ultra-low insertion loss, high return loss, wide bandwidth, and small size simultaneously. The present paper proposes an overlapping resonator BPF at 2.4 GHz (5G ISM-band applications) overlapping resonator BPF based on a low-cost FR-4 substrate and optimized using ADS software. The insertion loss of the structure is -0.001 dB, while a return loss of -36.35 dB is recorded, at a 500 MHz bandwidth. This design occupies only 11.7 × 15.3 mm², making it promising for fifth-generation (5G) communications, where performance and small size are key.

This paper presents an innovative methodology for micro-sized bandpass filter designs required for 5G technology, compatible with microcircuit technologies. The key contributions include:

- propose an overlapping resonator filter which provides superior frequency selectivity, minimal loss, and a compact size.
- The proposed overlapping resonator filter provides an optimal compromise between size and performance compared with other filters, such as coupled-line and hairpin filters.
- Convert the proposed filter designs from microstrip technology to a physical layout, ensuring practical applicability.

The paper is structured as follows. The proposed filters: the coupled-line filter, hairpin filter, and overlapping resonant filter are described in Section II. In Section III, we compare the results (bandwidth, insertion loss (S_{21}), return loss (S_{11}), and physical size) of designs to those reported in the literature. Finally, the conclusion summarizes the results and verifies that the proposed filter, with small size, low loss, and wide bandwidth, is well-suited for 5G applications.

II. Bandpass Filter Design and Analysis

The resonant series and shunt inductor-capacitor (LC) networks are combined to form a BPF, as illustrated in Figure 1. The resonant shunt LC network directs undesired frequencies outside the passband toward ground, while the series LC resonant networks permit only the intended frequency spectrum to pass [18]. Figure 2 presents a flowchart that outlines the entire design process, starting from filter specifications to final layout optimization, in a clear and systematic manner.

There are two main approaches to designing BPFs. The configuration examined in this work includes a cascade of a low-pass filter (LPF) and a high-pass filter (HPF), as well as resonant structures that use quarter-wave coupled lines or inductor-capacitor (LC) resonators. In PCB-based implementations, resonant structures are preferred for their compact size and ease of fabrication. These structures use capacitive or inductive coupling mechanisms to achieve the desired frequency response [19]. The design process is initiated with the development of a low-pass prototype, as all other filter types (high-pass filter (HPF), band-pass filter (BPF), and band-stop filter (BSF) can be derived through frequency transformations of LPF prototypes [20]. This work focuses on a Chebyshev-type BPF with the following specifications:

- Center frequency (f_0): 2.4 GHz.
- bandwidth: (100 – 500) MHz.
- Passband ripple: ≤ 0.1 dB for amplitude flatness.
- Stopband attenuation: > 20 dB for interference rejection.
- System impedance: 50 Ω (standard for RF applications).

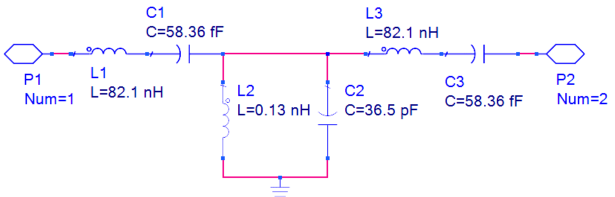

Fig. 1. Resonant series and shunt LC networks.

In designing a BPF, the first step is to determine the filter order. The filter order is the number of capacitive and inductive components required when initializing the filter. The filter order can be calculated using Eq. (1) [21].

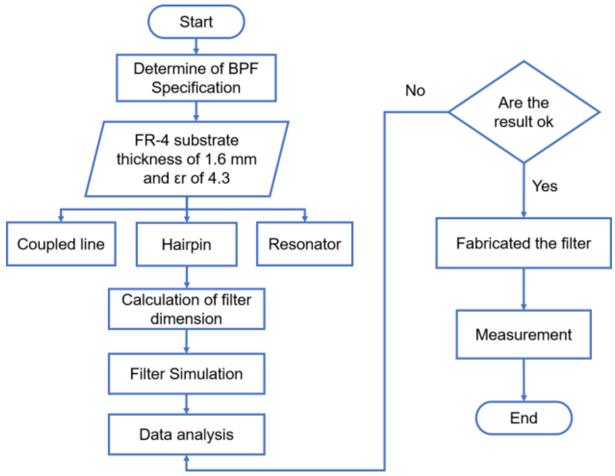

Fig. 2. Flow diagram of the complete bandpass filter design methodology.

$$n = \frac{\cosh^{-1}\left(\sqrt{\frac{(10^{\frac{-A}{10}}-1)}{(10^{\frac{-R}{10}}-1)}}\right)}{\cosh^{-1}(\frac{f}{f_0})} \tag{1}$$

where R and A respectively represent the passband attenuation and passband ripple, the normalized frequency and fractional bandwidth (FBW) are given by Eqs. (2) and (3).

$$\text{FBW} = \frac{f_h - f_L}{f_o} \tag{2}$$

$$\frac{f}{f_o} = \frac{1}{FBW}\left(\frac{f}{f_o} - \frac{f_o}{f}\right). \tag{3}$$

At minimal attenuation = 30 dB, the filter order is n = 3, the fractional bandwidth is 0.043, and the normalized frequency is 3.84. Table I is used to evaluate the component values for the 3rd-order filter.

For the third-order filter implementation, the normalized prototype values (g_1=1.0315, g_2=1.1474, g_3=1.0315) obtained from Table I are transformed into actual lumped component values (L, C) using frequency and impedance-scaling techniques [22].

TABLE I
NORMALIZED ELEMENT VALUES (g_n) FOR LOW-PASS FILTER PROTOTYPES WITH 0.1 dB CHEBYSHEV RIPPLE

Filter Order (n)	g_1	g_2	g_3	g_4	g_5	g_6
1	0.30	1.0				
2	0.84	0.62	1.36			
3	1.03	1.15	1.03	1.00		
4	1.11	1.31	1.77	0.82	1.36	
5	1.15	1.37	1.98	1.37	1.15	1.00

The derived LC network, which is designed for a center frequency of 2.4 GHz and has a fractional bandwidth of 4.3%, is modeled in the Advanced Design System simulator, as shown in Figure 3. Figure 4 shows the filter's performance metrics, specifically insertion loss (S_{21}) and return loss (S_{11}), which validate the theoretical calculations and provide a basis for subsequent distributed- element implementations.

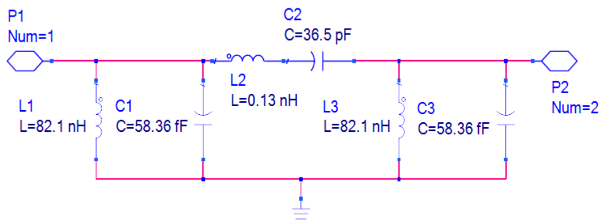

Fig. 3. Circuit schematic of the lumped-element bandpass filter design.

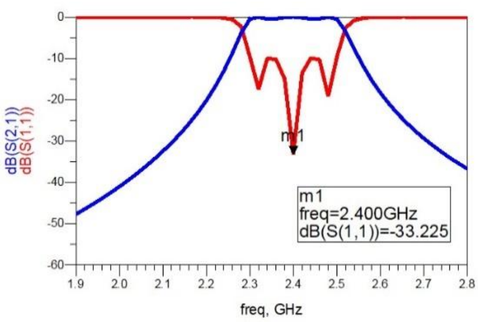

Fig. 4. BPF shunt LC resonator network frequency response.

A. Coupled Line Filter Design

Coupled line bandpass filters (BPFs) are a popular solution in microstrip-based RF systems due to their compact size, low insertion loss, and ease of fabrication, especially for narrow-bandwidth applications. Although the design of this type of filter is simple in narrow-band applications, its complexity increases with wider bandwidth due to the need to consider additional factors, such as impedance matching, coupling strength, and the optimization of element distribution on the board [23]. In this work, a microstrip-paired bandpass filter (BPF) is designed for 5G applications at a center frequency of 2.4 GHz with a fractional bandwidth of about 4.3%. A third-order Chebyshev response is adopted to achieve the selectivity and performance requirements.

Based on the intended filter specifications, the odd- and even-mode characteristic impedances were computed in order to determine the design parameters. These impedances significantly influence the coupling coefficient between neighboring resonator sections. Using common design equations (4-6) [24], Table II displays the calculated odd (Zo_o) and even (Zo_e) mode impedances for the various filter stages.

$$J_{i,i+1} = \frac{1}{Z_o}\left[\frac{\pi \times FBW}{2 \times g_i \times g_{i+1}}\right]^{0.5} \quad (4)$$

$$Z_{o_o}\Big|_{i,i+1} = Z_o\left[1 - Z_o \times J_{i,i+1} + \left(Z_o \times J_{i,i+1}\right)^2\right] \quad (5)$$

$$Z_{o_e}\Big|_{i,i+1} = Z_o\left[1 + Z_o \times J_{i,i+1} + \left(Z_o \times J_{i,i+1}\right)^2\right] \quad (6)$$

where $J_{i,i+1}$ are the characteristic admittances.

TABLE II
ODD AND EVEN CHARACTERISTIC IMPEDANCES

Stage (i, i+1)	Zo_e (Ω)	Zo_o (Ω)
1,4	66.15	40.45
2,3	64.89	40.87

The LineCalc tool in Advanced Design Software (ADS) was used to extract the physical dimensions of the paired lines, such as width, length, and spacing, based on the calculated impedance values. The dielectric loss tangent was set to 0.018 [25, 26], and the conductor conductivity was set to $5.8{\times}10^7$ S/m [27], as shown in Figure 5. Table III shows these dimensions for each filter section.

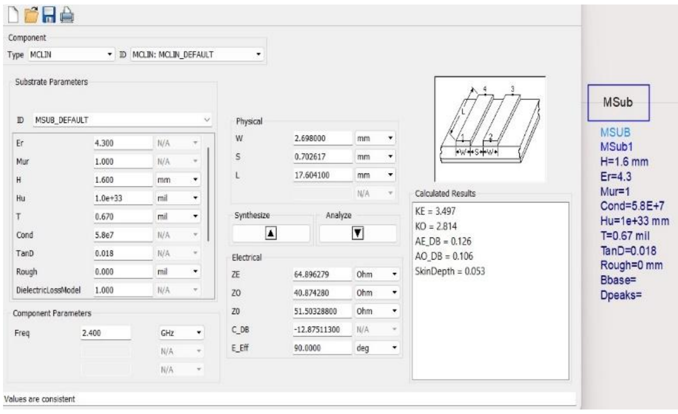

Fig. 5. LineCalc Tool in ADS

TABLE III
DIMENSIONS OF COUPLED LINE FILTER SEGMENTS

Line of description	Width (mm)	Length (mm)	Space (mm)
50 Ω line	2.53	3.09	-
A couple of lines (1&4)	2.63	18.34	0.63
A couple of lines (2&3)	2.68	18.31	0.70

To match the impedance to the remainder of the system, 50 Ω microstrips were used at both the input and output of the filter. Once the initial dimensions were determined, an optimization was performed using ADS software to improve the model's performance in both consistency and frequency response. A simulated model of a Coupled-line filter in ADS is shown in Figure 6. The filter configuration is a three-stage coupling structure with I/O lines at 50 Ω for good interfacing with the surrounding circuit. The model's good accuracy with respect to the geometric representation of element distribution contributes to minimizing parasitic losses and optimizing the line spacing.

The completed filter layout is displayed in Figure 7, which was obtained from the actual schematic. In terms of the efficient use of volume: The filter has a final board size measuring 80 mm width by 25 mm length, which is considered relatively small in comparison to similar types of products documented in the past. The layout was created with the intention to minimize EMI between other functional parts, as well as to minimize the variation in signal flow.

The simulated S-parameter results for the proposed filter are shown in Figure 8. Passband insertion loss (S_{21}) is as low as -0.009 dB at 2.4 GHz, providing efficient signal transmission with minimal loss. The value of the reflection coefficient (S_{11}) remains below -26.85 dB in this band, indicating a good impedance match and reduced signal intrusion. The results reveal that the filter satisfies the filtering performance requirements, with strong suppression and a wide 3 dB bandwidth (two significant specifications for 5G applications, which require accurate filtering within a narrow frequency range). The proposed filter offers a low-loss passband response and a smaller size than those of previous works [11], making it suitable for compact RF system integration.

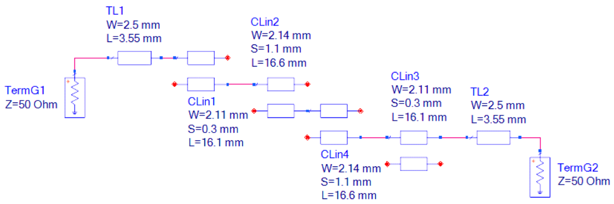

Fig. 6. Schematic diagram of the coupled-line filter.

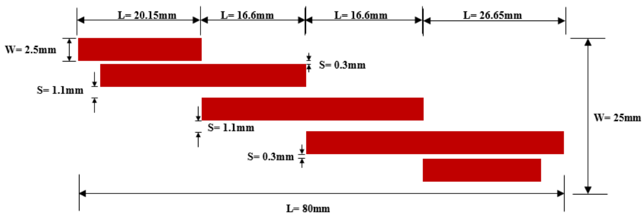

Fig. 7. Optimized physical layout of the coupled-line filter.

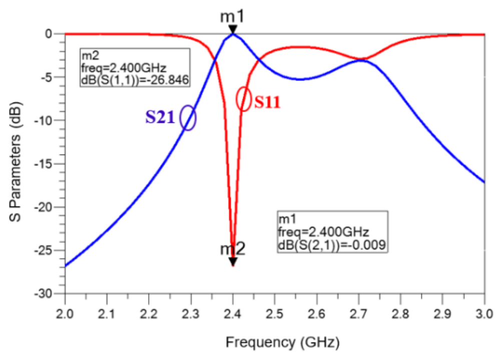

Fig. 8. The S-parameter response of the simulated coupled-line filter.

B. Hairpin Filter Design

Hairpin filters are highly efficient, compact, and easy to fabricate using microstrip technology; as a result, they have been widely used in microwave communications. The mentioned filters do not require lumped components or ground holes and can be easily integrated into a high-frequency circuit. Hairpin filters are widely used in radar, wireless communication systems, and 5G networks because of their superior bandwidth performance and flexible tunability [28]. The tapped hairpin filter structure is adopted for accurate frequency control at a center frequency of 2.4 GHz with an approximately 6.7% fractional bandwidth. The filter employs an array of folded U-shaped $\lambda/4$ resonators to reduce circuit board area, as shown in Figure 9.

The optimal tap point (T) was determined using the mathematical expression in Equation (7), which is related to finite impedance (Z_o), resonator line impedance (Z_r), length of resonator (L), and external quality factor (Q_e). Tuning those parameters achieves low insertion loss and optimal impedance matching [29].

$$T = \frac{2L}{\pi} \times \sin^{-1}\left(\left(\frac{\pi}{2} \times \left(\frac{Z_O}{Q_O \times Z_r}\right)\right)^{0.5}\right). \tag{7}$$

The alignment parameter and coupling coefficients (M_{ij}) of the neighboring resonators were calculated based on mathematical equations (8), (9), and (10), allowing for precise adjustment to achieve levels of electromagnetic interaction between the cavities that provide a steeper response in the passband as well as provide weak responses along a rejected band [29]. Figure 10 represents the final circuit diagram of the filter.

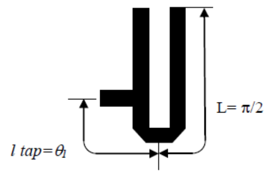

Fig. 9. Basic structure of a tapped hairpin resonator.

$$Q_{e1} = \frac{g_0 \times g_1}{FBW} \tag{8}$$

$$Q_{en} = \frac{g_n \times g_{n+1}}{FBW} \tag{9}$$

$$M_{ij} = \frac{FBW}{\sqrt{g_i \times g_{i+1}}}. \tag{10}$$

Once the theoretical design was achieved, we used Optimization Tools in ADS software to simulate the electromagnetic behaviour of the proposed filters. The simulated results are in close agreement with the design specifications. The passband attenuation (S_{21}) reached -0.005 dB at the central frequency, while the reflection coefficient (S_{11}) was above -29.77 dB, as illustrated in Figure 11.

A physical realization of the filter developed based on the schematic model is depicted in Figure 12 while shrinking the circuit area to 24.6 mm × 15 mm (a total of as small as 369 mm²). The proposed design achieves high space efficiency and implementation accuracy, making it suitable for advanced communication applications.

The hairpin filter described in [11], operated at 2.58GHz, and exhibits performance characteristics, including a transmission loss of -1.8 dB and a reflection coefficient magnitude of -30 dB, with the dimensions of 31.4 × 38.6 mm (an area of only 1212 mm²), while the proposed design occupies approximately

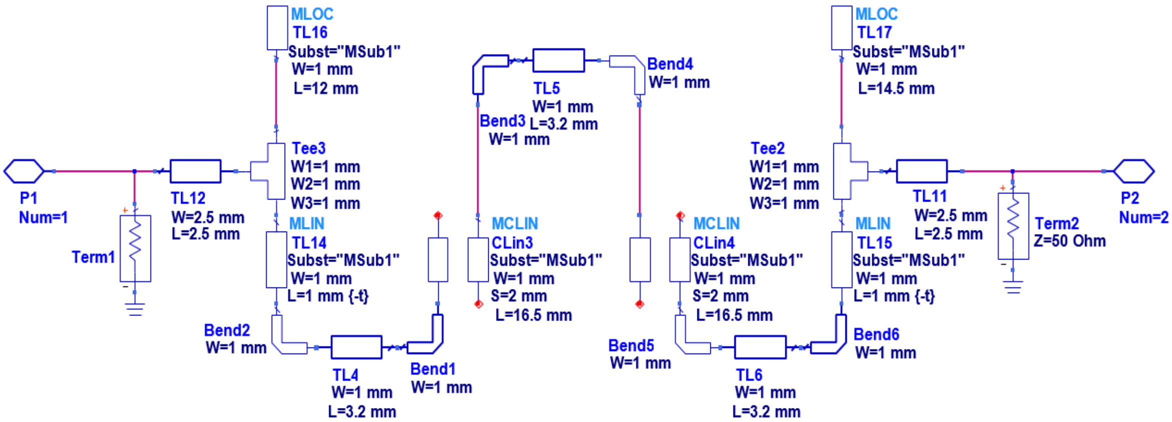

Fig. 10. Schematic model of the proposed hairpin filter.

70% of that area, greatly enhancing signal transfer efficiency. The proposed design's smaller size also suggests reduced power loss during operation. A distorted ground lattice filter with an insertion loss of -0.76 dB and a reflection coefficient of -29.9 dB was suggested for radar applications within the S-band (2.9 – 3.1 GHz) in [12]. This filter had dimensions of 53.7 × 17.6 mm (944.88 mm²). Cutting-edge technology was also used during the design process, but the occupied area was about 60% larger, and the efficiency loss was higher than in the proposed design.

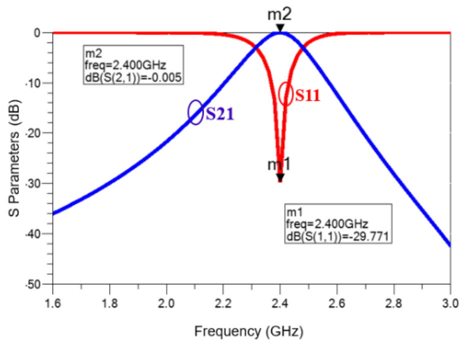

Fig. 11. Frequency response (S-parameters) of the simulated hairpin filter at the operating frequency of 2.4GHz.

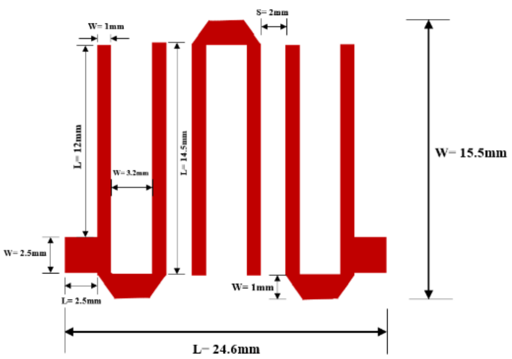

Fig. 12. Final physical layout of the hairpin filter.

The hairpin filter described in [11], operated at 2.58 GHz, and exhibits performance characteristics, including a transmission loss of -1.8 dB and a reflection coefficient magnitude of -30 dB, with the dimensions of 31.4 × 38.6 mm (an area of only 1212 mm²), while the proposed design occupies approximately 70% of that area, greatly enhancing signal transfer efficiency. The proposed design's smaller size also suggests reduced power loss during operation. A distorted ground lattice filter with an insertion loss of -0.76 dB and a reflection coefficient of -29.9 dB was suggested for radar applications within the S-band (2.9 – 3.1 GHz) in [12]. This filter had dimensions of 53.7 × 17.6 mm (944.88 mm²). Cutting-edge technology was also used during the design process, but the occupied area was about 60% larger, and the efficiency loss was higher than in the proposed design.

Another lattice filter design at 3 GHz was also discussed in [13], with transmission and reflection coefficients of -0.1 dB and -22.5 dB, respectively, for a surface area of 18.4 × 30 mm from the equivalent physical dimensions (552 mm²). Even though this design has relatively commendable performance, the proposed structure offers lower transmission loss, greater reflection (indicating better impedance matching), and dimensions that are at least 33% smaller.

These comparisons indicate that the proposed design not only achieves better frequency responses but also has smaller dimensions and is suitable for 5G ISM-band applications that require a high-performance filter with small dimensions and low fabrication cost.

C. *Overlapping Resonant Filter Design*

Microstrip resonator filters are a suitable approach for high-performance filter design, particularly in applications that require high-frequency performance and compact, optimized designs. Stepped resonator structures are particularly advantageous, which allows higher resonator density without increasing the substrate area. This filter is perfect for modern applications such as 5G networks and embedded systems. It reduces passband attenuation and yields a very accurate response. This sharp response results from directional interference within the resonators [30]. Stepped resonator structures are particularly advantageous.

The 2.4 GHz bandpass filter developed in this project employs two U-shaped resonators that overlap onto a single planar surface which allows them to achieve significantly improved performance and to be used to reduce interference among themselves. The geometry of the resonators is pictured in Figure 13.

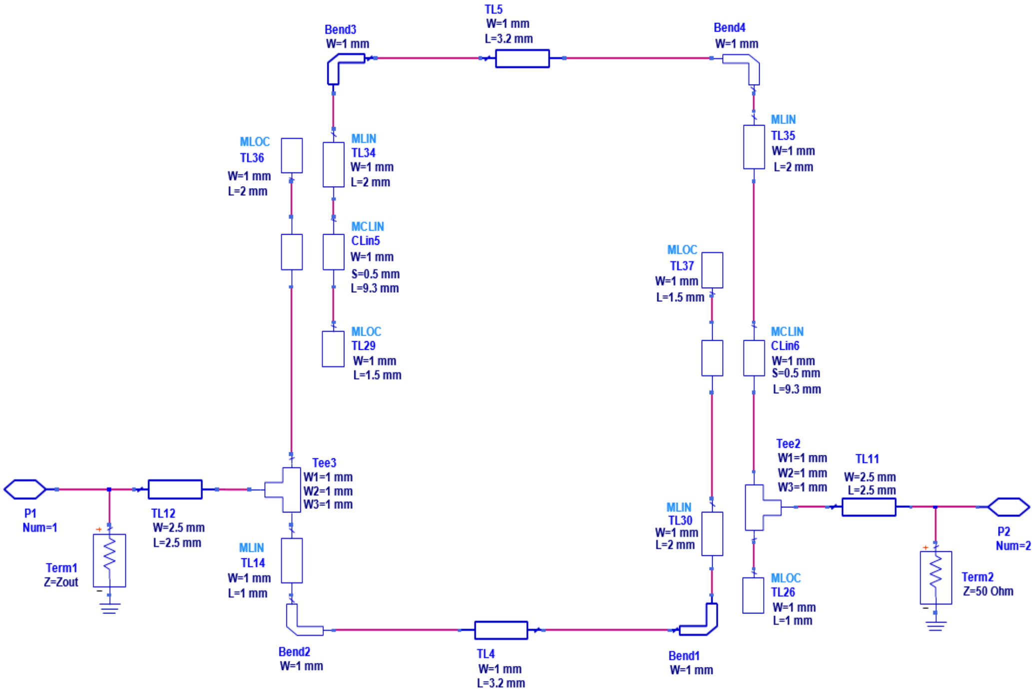

Fig. 13. The proposed geometry of the overlapped resonant filter.

The electromagnetic interaction between resonators can be understood by coupling the edges of the resonators together with a signal that passes through them. The dimensions of the resonators and the locations of the supply lines were optimized on a step-by-step basis to achieve optimal frequency response for the filter. The physical design of the filter is shown in Figure 14 and has dimensions of 11.7 mm x 15.3 mm and is fabricated on a PCB.

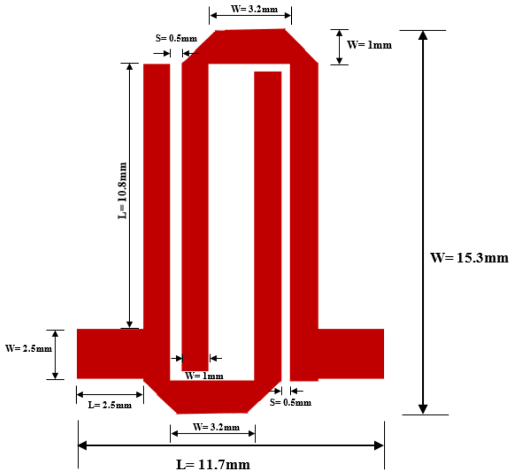

Fig. 14. Layout configuration of the overlapped resonator filter.

The S-parameter simulation results for this design are shown in Figure 15 and exhibit exceptional performance. The filter demonstrates an insertion loss (S_{21}) of -0.001 dB at its 2.4 GHz center frequency, indicating an almost perfect signal-passing efficiency. The reflection coefficient (S_{11}) results also showed an impressive value of -36.346 dB, indicating a high impedance match and minimized system reflection. The passband bandwidth is 500 MHz (2.2–2.7 GHz), corresponding to a fractional bandwidth (FBW) of 20.8%. This proposed design provides a viable solution for high-performance requirements in 5G ISM-band applications.

Compared with the other filters presented in this work (coupled-line and hairpin filters), the overlapping resonator filter provides the optimal compromise between size and performance. It delivers outstanding frequency response and extremely low space requirements, making it ideally suited for an embedded system.

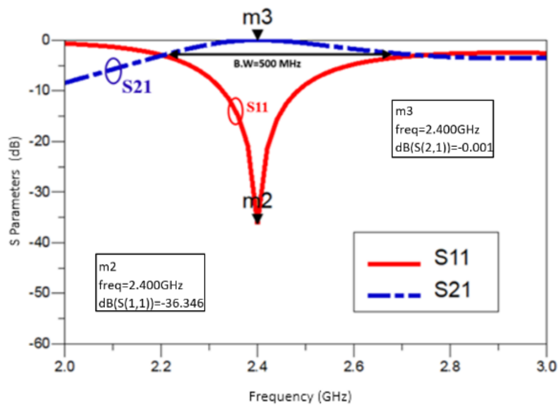

Fig. 15. The simulated overlapped resonator filter's frequency response. (S-parameters).

III. Discussion and Comparison of Results

Three different microstrip bandpass filter configurations were developed in order to assess their performance and compare the results of all three configurations. The three configurations studied are coupled-line, hairpin, and overlapped resonator filters. The bandpass filters were designed in Advanced Design System (ADS) software for operation at a frequency of 2.4 GHz and evaluated against several parameters, including bandwidth, fractional bandwidth

(FBW), insertion loss (S_{21}), return loss (S_{11}), and overall size. As such, the results obtained demonstrate the strengths and weaknesses of each configuration. Comparative studies performed with previous work show that the results obtained here also provide significant size reductions, and improved filter performance as compared to the more stringent specifications for 5G wireless communication systems.

The performance of the coupled-line bandpass filter (BPF) in the narrow-band range of 2.4 GHz is shown to be effective through the simulation results. At the frequency of 2.4 GHz, insertion loss will reach a minimum value of -0.009 dB, and return loss will reach -26.85 dB, with a 4.3% fractional bandwidth and a 100 MHz (2.355 - 2.457 GHz) passband between the two frequencies. The final design of the BPF used an 80 × 25 mm² circuit board which provides a good trade-off between size and performance. Another advantage of this topology is it can achieve extremely low insertion loss (less than 0.01 dB) while providing a compact footprint that compares favorably with published results from [11]. Based on the above results, the cross-coupled strip line is effective for narrowband microwave filters.

The hairpin bandpass filter (BPF) realized using tapped-line Quarter-wavelength folded resonators. The optimized geometry achieved a 160 MHz (2.33 - 2.49 GHz) passband with a minimum insertion loss of -0.005 dB and a return loss of -29.77dB. Physically, the layout of the presented filter demonstrated a considerable decrease in size to 24.6×15 mm² compared to the similar filters described in [11], [12] , and [13], which exhibited significantly larger physical size, such as 1212 mm² in [11] and 944 mm² in [12].

The third topology, based on overlapping U-shaped microstrip resonators, yielded the most promising results among all the designs. The filter exhibited an insertion loss of -0.001 dB, a return loss of -36.346 dB, and a fractional bandwidth of 20.8%, with a passband that was considerably wider, spanning 500 MHz. The design was not only more electrically efficient but also remarkably small, measuring only 11.7 × 15.3 mm², about (30 – 70) % smaller than the other designs and related works in the literature. Because of the strong electromagnetic coupling enabled by the overlapping resonator structure, the bandwidth is increased, and the insertion loss is extremely low.

A comparison of the three designed filters' frequency responses is shown in Figure 16. The performance of the overlapped resonator filter is optimized when its reflection coefficient reaches -36.346 dB, and its ultra-low transmission loss is set to -0.001 dB. The main role of the configuration is to provide a satisfying impedance match, resulting in relatively high efficiency. The insertion loss of the hairpin filter (-0.005 dB) and its compact size were found to be satisfactory. In contrast, the paired-line filter also delivers a stable and reliable response. The superiority of the considered overlapped resonator concept is demonstrated in this comparison, and a prototype has been developed and tested with good performance; therefore, it is a very promising configuration for 5G systems that require high fill factor.

Table IV presents a comparison of the proposed bandpass filter (BPF) configurations with previously published topologies [11-17] with respect to performance, size, topology used, and practical applicability. This work highlights the excellent performance of the proposed BPF designs, especially the overlapping resonator BPF. Among the structures analysed, the overlapping resonator filter exhibited the broadest bandwidth (500 MHz), the largest return loss (-36.346 dB), and the minimum insertion loss (-0.001 dB). Interestingly, this design was also the most compact (11.7 × 15.3 mm²). These properties make it a prime candidate for 5G applications. Alternatively, the designed coupled-line and hairpin filters exhibited better performance than their counterparts reported in [11], [12] , and [13], with much lower insertion losses and a compact size. This progress indicates an interesting improvement in two important aspects: signal performance and circuit miniaturization.

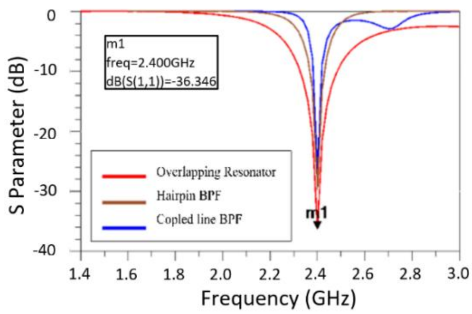

Fig. 16. Comparative frequency response of the proposed overlapping resonator BPF and other filter designs at 2.4 GHz.

The comparison with the designs in [14]-[17] also indicates that the proposed filters are superior, especially the overlapped resonator BPF. The U-shaped resonator filters and step-impedance filters in the references have too wide bandwidths, much higher insertion losses, and larger physical sizes. Similarly, the square open-loop structure in [16] and the two-layered aperture-coupled hairpin filter in [17] exhibit larger signal losses, although they achieve acceptable return loss. In contrast, the introduced designs provide better performance in terms of insertion loss at higher frequencies, matching stability values, and decreased circuit footprint, as demonstrated for both the nonoverlapping resonator filter and its overlapped counterpart. These features, represented by the design using standard PCB fabrication processes and ultra-low insertion loss, ensure low-cost manufacturing and directly enhance power efficiency. Additionally, its compact size meets the strict space constraints of modern devices. These features make the proposed design practically implementable for 2.4 GHz 5G ISM-band applications, such as the input stage of a power amplifier.

IV. Conclusion

In this work, we proposed and analyzed three different bandpass filters based on microstrip technology: the coupled-line filter, the hairpin filter, and the overlay-resonator filter. These topologies align with the requirements of modern communication systems, including 5G ISM-band networks. The results showed that all the designs operated effectively at a 2.4 GHz center frequency, performing accurate frequency responses and diminutive transmission losses. Among the three designs, the overlapped resonator filter performed optimally,

TABLE IV
COMPARATIVE PERFORMANCE ANALYSIS OF THE PROPOSED BANDPASS FILTERS WITH PREVIOUSLY REPORTED

Ref.	Freq. [GHz]	Filter Topology/ Filter Order	S_{11} [dB]/ S_{21} [dB]	Bandwidth [MHZ]	Total size [mm^2]	Typical applications
[11]	2.58	Coupled line BPF/3	-30.6/-5.6	130	73.76×27.5=2028.4	5G communication systems
		Hairpin BPF/3	-30/-1.8		31.4×38.6=1212.4	
[12]	3	Hairpin BPF with DGS/5	-29.9/-0.76	200	53.7×17.6=944.88	S-band radar systems
[13]	3	Hairpin BPF /5	-22.5/-0.1	---	18.4×30=552	Low-cost PCB RF applications
[14]	2.4	Step impedance resonator BPF/ ---	-22/-0.77	180	---	ISM-band /IoT wireless devices
[15]	2.5	U-shaped resonator BPF/ ---	-30/-1.52	700	35×35=1225	Wideband wireless systems
[16]	2.5	Cross-coupled BPF (Square open loop) / 4	-35/-6	100	27×34=918	High-selectivity narrowband filters
[17]	2.45	Two-layer BPF (Aperture-coupled hairpin resonator) / 5	-34/-2	100	21.8×21.6=471.48	Miniaturized multilayer 5G modules
[31]	3.5- 3.6	MEMS-based double-layer foldable concave bandpass filter	-18 / -2.5	100	195	5G communication systems
[32]	2.5	Microstrip hairpin bandpass filter with dual DGS	-54.19/-1.6	560	635.1	5G systems, and IoT
[33]	2.6/4.8	Dual-band microstrip BPF using multimode resonator	(-13.7/-23.6)/ (-0.37/-0.77)	450/420	376.5	5G communication systems
This work	2.4	Coupled line BPF/ 3	-26.85/-0.009	100	80×25=2000	Narrowband 5G RF subsystems
		Hairpin BPF /	-29.77/-0.005	160	24.6×15=369	Compact 5G /embedded RF modules
		Overlapped resonator BPF / 3	-36.346/-0.001	500	11.7×15.3=179.01	Ultra-compact high-performance 5G front-end systems

featuring almost zero insertion loss (-0.001 dB), a high reflection coefficient (-36.346 dB), and a wide bandwidth of 500 MHz, packaged into a small size (11.7 × 15.3 mm²). In a compact area of 24.6 x 15 mm², the hairpin filter has demonstrated an insertion loss of about -0.005 dB, including excellent performance in terms of size-performance trade-off and suitability for implementation in micro-systems. The coupled-line filter showed good results with an insertion loss of -0.009 dB and a reflection coefficient of -26.85dB, although it was larger than the others. Comparison with previous works reported in the literature indicates that our proposed designs (especially the overlapping resonator filter) achieved preferable improvements with respect to reducing the signal loss, improving impedance matching, and reducing circuit size; As a result, these designs demonstrate significant potential and practical viability. Future research could focus on designing filters that operate at higher band frequencies or on integrating these configurations into the input stage of advanced amplifier circuits to further improve overall circuit performance and efficiency.

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