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Abstract

Purpose: The primary objective of this work is to present the development of a dual-port RF bandpass filter with the unique capability of offering a programmable center frequency along with selectable passbands or stopbands. The design emphasizes adaptability, compactness, and efficiency, aiming to provide a versatile solution for multiband RF applications. By ensuring reconfigurability without significantly enlarging the circuit footprint, the filter is tailored to operate effectively under diverse signal conditions.

Methodology: The proposed design is formed of six multi-resonator units as a separate bandpass filter. These half-units are connected by 180° lines for signal routing. The resonator sees a G-type topology to guarantee the precise capture of the desired frequency response. A variable impedance transformer is used to couple the resonators in parallel, which is also the key element in controlling the signal attenuation and combination of passbands. By tuning the structural parameters applied to the gradient resonant system, the resonant frequency of each unit could be dynamically changed. Furthermore, the architecture includes several communication links to enable separate control of bandwidths. The overall behavior of the filter was demonstrated by both his analytical analysis and experimental results.

Findings: The results show that the center frequency of the filter can be dynamically tuned by tuning the resonant properties of the individual elements. The variable impedance transformer facilitates programmable and flexible control of the number and position of the passbands, and transmission zeros can be used to contribute signal selectivity enhancement at edges of the upper and lower passbands. The design features a multiband mechanism with slight expansion of the circuit size. In addition, good agreement is reached between simulation and measurement results, which demonstrates the good stability and dependability of the proposed design.

Unique Contribution to Theory, Practice and Policy: In light of these results, the presented filter architecture is strongly recommended for multiband RF systems requiring compactness and adaptability. Potential future work could involve refining the gradient resonant system to achieve greater precision in bandwidth control and further enhancement of filtering selectivity. Moreover, the design methodology introduced in this study may be extended to advanced RF communication platforms where reconfigurability and efficient use of hardware resources are critical.

Keywords: *Multi-Band Filter, Microstrip, Hexa-Band Pass Filter, Open Ends Resonator, Microwave*

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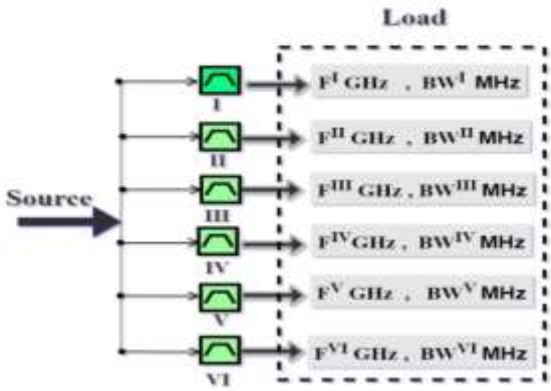
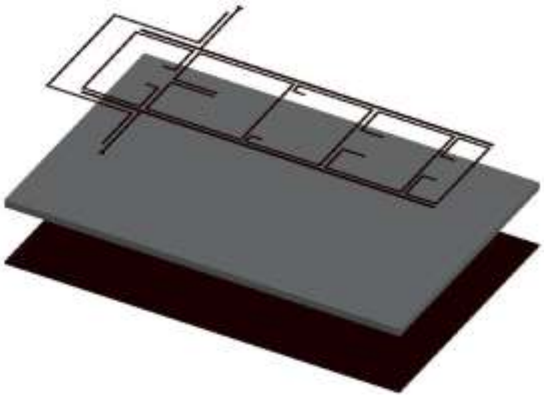
INTRODUCTION

The increasing demand for wireless communication applications has created a need for RF components that operate in multiband modes. Multiband filter; wireless system components are known for their performance in enabling multiband preselection in RF transceivers and isolating specific bands from sources of interference. This seems to be a suitable solution for all-in-one systems. Recent technological advances in wireless communication systems have created a need for multiband filter topologies with high selectivity, compact size, and ease of replication. Among them, single-layer bandpass filters are known for their simplicity, low cost, and ease of manufacture. However, when designing filters built around line-pair resonators, little space or separation between lines is required. Very effective filters are difficult to find. Several multilevel methods have been investigated to solve this problem. At the same time, compact filter dimensions can be achieved without compromising the properties of bandpass filters. In (Gómez-García, R., 2016) and (Basheer, A. A., Alsahlany, 2020) a class of multiband bandpass filters (BPFs) based on half-band topology is presented. An additional transmit zero (TZ) is created by cross-coupling applied between adjacent pseudo bands via non-resonant nodes (NRNs). The lack of direct interaction between resonant nodes in this multiband BPF architecture makes the transfer function tuning more reliable. Additionally, fewer inverters are required when combining multiple conduction bands compared to known band gap BPF designs. We present a new bidirectional bandpass filter using a multimode resonator. For the WLAN band, two bandwidths are implemented built upon a multimode resonator with three open connections. By carefully selecting the characteristic impedance of the multimode resonant switch, the bandwidth of the two branches can be adjusted to accommodate both double-ohm and single-ohm modes. (Feng, W. J., Che, Q, 2012) and (Vikash, S., Natarajan, K., 2020).



(a)



(b)

Figure 1: (a)The layout of the multi-band BPF (b) The three layers of the multi-band BPF

A cascade type multi-resonant high-pass filter has the transfer function of a multi-band band-pass filter with an integrated notch stop. converting the standardized low-pass filter prototype into the proposed integrated bandpass/multiband filter cell. For example, highly selective bandpass filter (BPF) analogs are synthesized using higher order filter circuits (Gómez-García, R., Yang, L., & Psychogiou, 2021) and (Wahab, N. A., Khan, 2014). In (Ren, B., Ma, Z., Liu, H. , 2019) this article presents three types of multiband differential bandpass filter using multimode microstrip resonators The first design is a dual-frequency differential dispersion bandpass filter (BPF) using a rectangular ring resonator based on a partially loaded incremental resonator (SI-SRLR) that allows flexible frequency range tuning between common-mode (CM) and differential-dispersion (DM) responses.

We propose a tunable dual-band microstrip filter based on a transversely loaded dual-mode phase resonance. This structure has four linear zeros and two control voltages, which gives it high selectivity.. A combined withholding tax technique was used to improve the efficiency of bandwidth management (Aidoo, M. W., & Song, 2019) and (Al-Mudhafar, A. A, 2020). We propose a new three-way BPF built upon a circle multimode resonator (R-MMR). The layout BPF consists of a pair of wires connected in parallel with the R-MMR. Because R-MMR is symmetrical, single-mode/dual-mode analysis techniques can be used to analyze its resonance properties (Li, D., Wang, D., Liu, 2019). A dual-band narrowband filter with a multimode resonator (MMR) is proposed. The MMR consists of two pairs of closed-coupled lines, two pairs of open-coupled lines, and four coupled transmission lines. The structure used allows the creation of five leading zeros, leaving an overlapping control band and greatly suppressing the upper stopband (Zhu, H., Ahmed, E. A. M, 2015).

This paper (Sánchez-Renedo, Gómez-García, R, 2011) and (Al-Mudhafar, A. A, 2020) reports the design of a dual-select microstrip bandpass filter using non-resonant junctions. To achieve this objective, these nodes are used as cross-coupling paths to improve the signal interaction between the resonators. Therefore, multiple transmission zeros can be generated due to the principle of signal interference. In (Simpson, D., Gómez-García, R., & Psychogiou, 2020) paper on the development of a reconfigurable Advanced degree multiband filter (BPF). The proposed concept is based on multiband modes in a cascaded array, each containing two similar crossed multi-resonant cells. The transfer function for each frequency band is defined by a pair of resonant cavities contained within each unit cell of the design. This article (Simpson, D., &

Psychogiou, 2019), (Feng, W., Che, W, 2012) describes the RF design of 2-way and 3-way semi-elliptic bandpass filters (BPFs). This architecture is based on several series-connected resonant circuits, each exhibiting a quasi-elliptical differential distribution with 3N poles and 3N-1 transmission zeros (TZ), where N represents the number of channels, and ii) the multi-band high level of higher order modes. Single-band or multi-band planar resistive transformers with bandpass filter and frequency shift capability are recommended. These transformers combine bandpass filter sections into a broadband impedance transformer, and tuning is achieved by controlling the resonator's frequency using variable capacitors. For demonstration purposes, a prototype three-band microstrip line with a frequency of 1.2 to 1.8 GHz was developed and tested in (Gómez-García, R., Psychogiou, D., & Peroulis, 2016). In (Doan, M., Nguyen, T., & Le, H, 2013), a three-band dense bandpass filter (DBPF) is presented, using a three-band modulated resonator for downscaling. The frequencies of the first and third passbands are adjustable, and the second is fixed with multiple null transfers to increase the selectivity and efficiency of the upper suppression band.

A prototype is supporting 2.4/3.5/5.2 GHz frequencies for WLAN/WiMAX applications. A multi-bandpass filter (BPF) was designed using a simple tuning method to recover the transfer function. The design uses multiple resonant cells in a dual structure to create a semi-elliptical bandwidth and control it in terms of center frequency, bandwidth, and amount. A three-band BPF prototype was built and tested (Simpson, D., Gómez-García, R., & Psychogiou, 2019). In (Yan, J. M., Cao, L. Z., Xu, 2015) microstrip filter structure is presented for dual-band filters with independent signal paths for each bandwidth. The design allows simultaneous control of external communication and inter-radiator communication, taking into account the interaction between transmission bands. The fourth-order dual-band filter is designed and fabricated for WLAN applications. A four-band bandpass filter with a two-layer structure with a small size and a high bandwidth. The multi-path effect consists of four two-phase impedance resonators in two metal layers and creates transmission zeros for sharp bends (Hsu, K. W., & Tu, W. H, 2012).

In the paper (Chen, Y. W., Tai, T. C., Wu, H. W., Su, Y. K., &, 2017) describes a compact four-pass filter (BPF) using multilayer substrate technology with bandwidths of 1.8, 2.4, 3.5, and 4.2 GHz. This filter is designed with a split ground (DGS) coupling structure (SIR). It provides a wide stopband from 4.2 to 12 GHz.In paper (Gómez-García, R., Psychogiou, D., 2016) and (Qasim, A. A., Abdullah, M. F. L., Talib, R., Alsahlany, A. M., & Gismalla, M. S. M, 2020) describes the use of parallel dual-beam linear converters for the design of microwave multibandpass filters (BPF). This approach improves performance by creating multiple bandwidths, eliminating DC transmission, and enabling fast dual filtering with separate bandwidths. Two design examples are given, including a four-band BPF and a two-band BPF, along with a measurement example for the former. In paper (Liu, H., Xu, Y., Ren, B., Wen, P., Peng, , C, 2016) presents a compact and highly selective three-band microstrip bandpass filter (BPF) using a multi-mode symmetric short-stop loop resonator power structure. In this paper, we study mode segmentation in quad multi-mode symmetric short-stop loop resonators using odd-even mode theory and demonstrate its application in dual-band BPFs. A tri-band BPF targeting 1.4/2.7/3.57 GHz.

The research gap lies in the fact that most conventional multiband microwave filter designs are limited to only two or three bands, which restricts their adaptability in complex signal environments. Introducing six bands provides greater flexibility to accommodate multiple applications within a single system while enhancing spectral efficiency and reducing the need for additional components. This wider band coverage ensures better support for modern communication systems operating over diverse frequencies. Hence, the proposed design addresses the limitations of earlier filters and delivers a more comprehensive and efficient solution. In this paper, we propose a simple and high-performance technique to layout multiband BPFs without significantly increasing the circuit scale. Additionally, a new-mode meandered open ends resonator is used to reduce the number of installed resonators and minimize filter size.

FILTER DESIGN AND ANALYSIS

Analysis Open Ends Filter

This study introduces a novel open-ended resonator that achieves enhanced efficiency through compact size, multimode operation, and broadband characteristics. By applying the half-wavelength principle to single-mode open-ended resonators, the design attains a more space-efficient structure while simultaneously improving suppression in the higher-frequency stopband, as depicted in Figure 2. The proposed resonator configuration is implemented using a parallel network in conjunction with two open sections within a microstrip framework. According to [11], precise adjustment of the design parameters allows accurate control of the resonant frequencies across the operating range. Furthermore, the asymmetric nature of the resonator can be modeled as a half-wavelength resonator, where reducing the impedance coefficient below unity not only minimizes the overall footprint but also significantly broadens the upper stopband bandwidth.

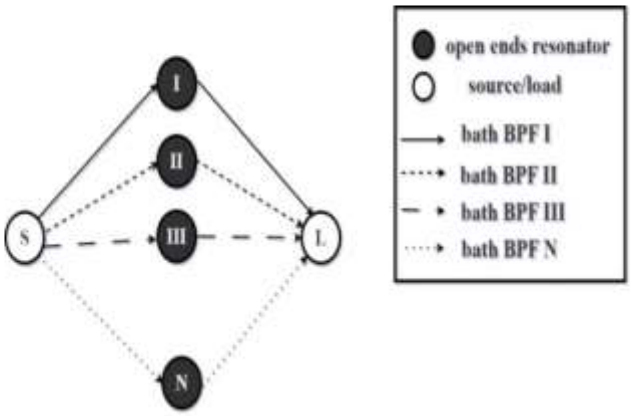


Figure 2: The Scheme of Coupling for Multi-Band BPFs

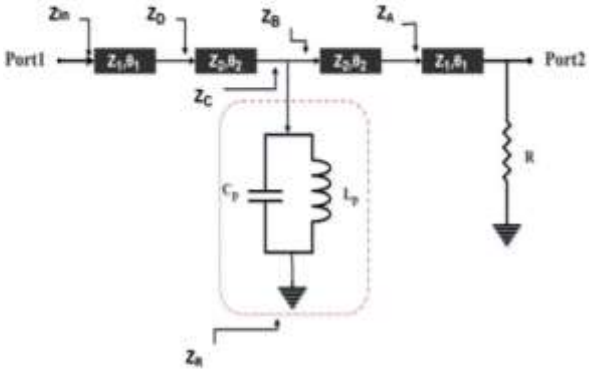


Figure 3: Circuit of the Proposed Single Filter

This one-mode functionality is attractive in that a rudimentary first-order filter can be carried out with a single-mode resonator, reducing the number of resonators needed for a second-order filter to one and reducing the filter scale. Figure 3 shows a schematic model of the first-order open ends resonator. Actually, the physical dimension of the presented U-shaped half-wavelength resonator is much smaller than that dual mode resonator (DMR). We can calculate the input impedance for a single resonant circuit through the equations below, and through them, we calculate (S11 and S21) $(Z_A, Z_B, Z_C, Z_R, Z_D, Z_{in}, Z_1, Z_2)$ characteristics impedance.

$$Z_A = \frac{Z_1(R + jZ_1 \tan\theta_1)}{Z_1 + jR\tan\theta_1} \quad (1)$$

$$Z_B = \frac{Z_2(Z_A + jZ_2 \tan\theta_2)}{Z_2 + jZ_A\tan\theta_2} \quad (2)$$

$$Z_R = \frac{1}{\frac{1}{X_L} + \frac{1}{X_C}} \quad (3)$$

$$Z_C = \frac{Z_R * Z_B}{Z_R + Z_B} \quad (4)$$

$$Z_D = \frac{Z_2(Z_C + jZ_2 \tan\theta_2)}{Z_2 + jZ_C\tan\theta_2} \quad (5)$$

$$Z_{in} = \frac{Z_1(Z_D + jZ_1 \tan\theta_1)}{Z_1 + jZ_D\tan\theta_1} \quad (6)$$

Note that to ideally obtain an independently tunable six-band filter with varied absolute bandwidth in all passbands, this design should take into account three important aspects: please. First, it is important to ensure that the bandwidth is independent of the settings used. Second, during the bandwidth adjustment process, the generated bandwidth for even and odd numbers must remain constant. Finally, as stated in (Hong, J. S. G., & Lancaster, M. J, 2004), the bandwidth external quality factor (Q_{ext}) condition specified in Eq. (7), must be satisfied throughout the tuning domain.

$$Q_{ext-P1} = \frac{g_0 g_1}{FBW} \quad Q_{ext-P2} = \frac{g_1 g_2}{FBW} \quad (7)$$

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Vol.6, Issue 1 No.3, pp 32 - 47, 2025

Six-band Bandpass Filter Design

Figure 1(a) presents the three-dimensional configuration of a six-band microstrip bandpass filter (BPF) implemented on an FR4 substrate characterized by a dielectric constant of εr = 4.6, a loss tangent of δ = 0.01, copper thickness of 0.035 µm, and an overall substrate thickness of 1.5 mm. The structure of the BPF is realized using twelve open-ended stubs etched on the top metallic layer, forming the resonant elements required for multiband operation. As illustrated in Figure 1, the designed hexa-band BPF supports six distinct passbands, denoted as I, II, III, IV, V, and VI, each corresponding to a specific operating frequency range. The half-wavelength resonators embedded in the upper layer are optimized to achieve center frequencies of 0.8, 1.1, 1.22, 1.5, 1.62, and 1.82 GHz, with respective bandwidths of 43, 44, 52, 120, 75, and 67 MHz. All resonators are connected through identical feed lines designed with a characteristic impedance of 50 Ω to ensure proper matching and minimal reflection.

In addition to compactness, the use of multiple open-ended resonators enhances frequency selectivity and provides stronger control over the transmission characteristics of each passband. This design approach allows efficient utilization of the available spectrum while maintaining low insertion loss across the targeted frequency ranges. Moreover, the implementation on a low-cost FR4 substrate ensures the practicality and affordability of the filter for real-world RF and wireless communication systems.

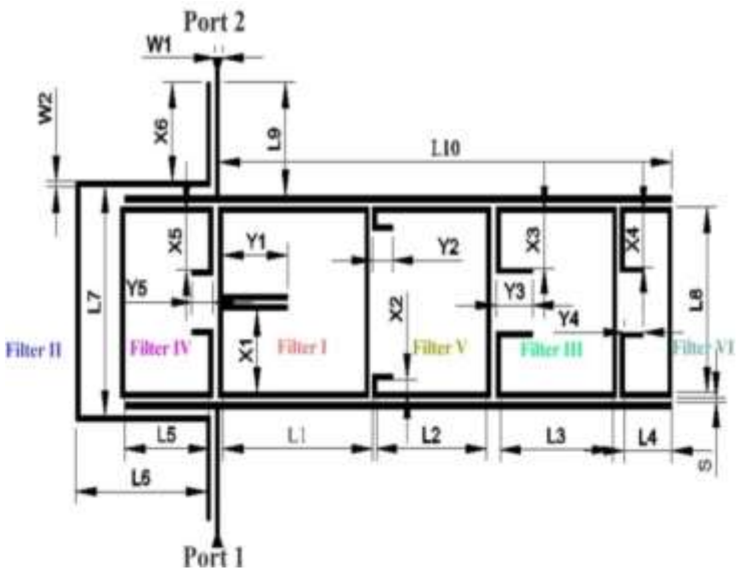

Figure 4: Circuit Layout of Hexa-Band Bandpass Filter

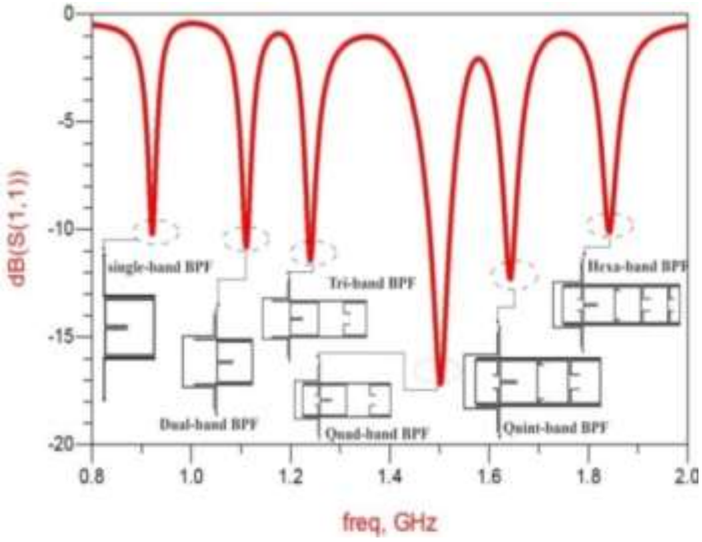

Figure 5: Simulated of the Proposed Design Demonstrate its Effectiveness and Performance across the Targeted Frequency Bands

Our design includes filters Hexa-band as shown in Figure 4. Is used to implement the 1st, 2nd, 3rd, 4th, 5th, and 6th passbands, all filter parts are created to work in various signal bands, so the coupling in various signal bands is very weak, so cross-loading effects are negligible, and completely independently controlled. A specific frequency before being combined into a multiband BPF. You can design six filter bands individually and combine them into her BPF in the 6th band. In Figure 5, it shows the simulation results for single band, dual bands, 3^{th} bands, 4^{th} bands, 5^{th} bands, and 6^{th} bands BPF. As you can see, the layout strategy is modifiable in terms of bandwidth assignment and can be extended by adding additional filter sections to create a multiband BPF with multiple operating bands.

As shown in the Figure 6, we took some of the parameters shown in Figure 4, where we notice that there is an inverse proportion to the frequency. As the length of the transmission line increases, the frequency decreases.

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ISSN 2959-1775 (online)
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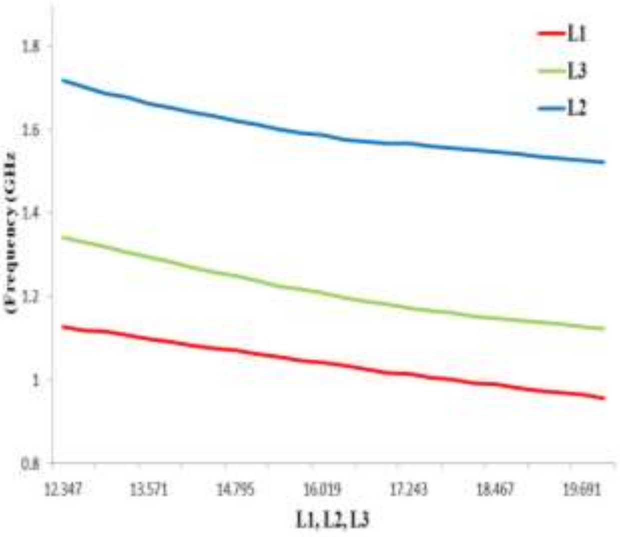
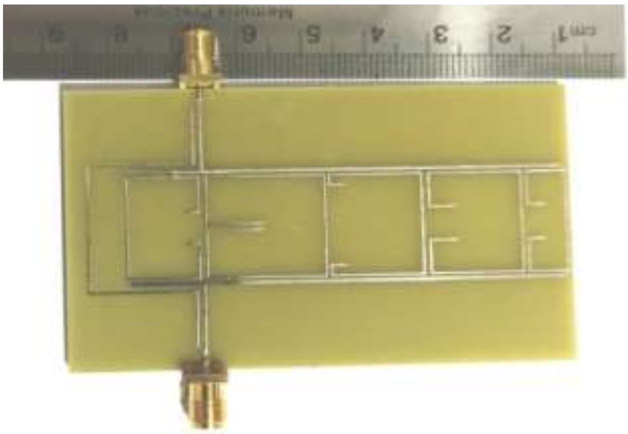


Figure. 6: Change the Electrical Length with Frequency

Table 1: Measurement Hexa-BPF

Parameters	Measurements(mm)	Parameters	Measurements(mm)
L1	18.5	X1	8.1
L2	13.6	X2	1.3
L3	13.9	X3	5..5
L4	5.9	X4	5.4
L5	10.4	X5	5.7
L6	16.1	X6	9.7
L7	22.5	Y1	8
L8	18.2	Y2	2.5
L9	10.2	Y3	4.5
L10	55.9	Y4	2.4
W1	1.3	Y5	2.6
W2	0.7	S	0.4

A six-band bandpass filter was designed to test the above analysis. The structure of the proposed six-band filter is shown in Figure 2. Additionally, this filter was implemented using the symmetric feed structure with five transmission zeros (TZs). It is located at each side of the band that boundaries of the six bandwidths to obtain good selectivity. After ADS optimization, the dimensions of this filter were determined as Table 1.



(a)

(b)

(c)

Figure 7: (a) Photograph of the six-order bandpass filter (b) Network analyzer measured S11 (c) Network analyzer measured S21

Asian Journal of Computing and Engineering Technology
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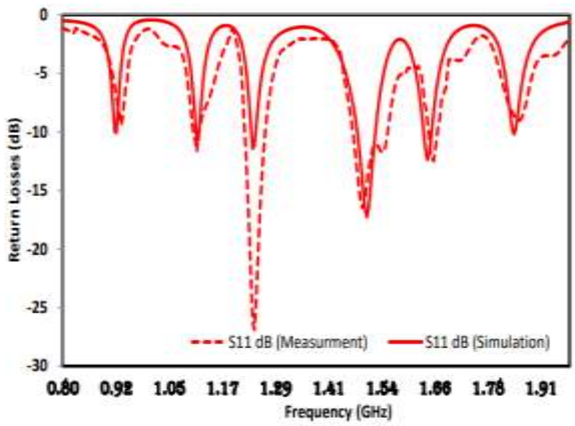
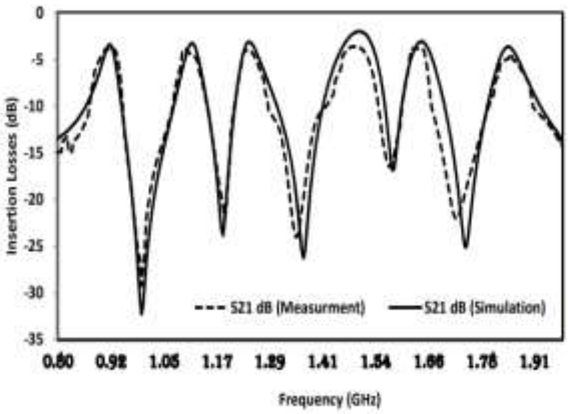
RUSALT FILTER AND FABRICATION

A prototype of the proposed six-band filter was fabricated to validate the design methodology and demonstrate its practical feasibility. The manufactured circuit, shown in Figure 7, occupies a compact footprint of 75.7 × 48.3 mm, which is significantly smaller compared to conventional filters of similar functionality. Experimental characterization was performed using an N9917A network analyzer. As shown in Figure 8, the measured results exhibit excellent agreement with the theoretical predictions, confirming the accuracy of the design model and the effectiveness of the proposed approach. The measured 3 dB fractional bandwidths for the six operating frequencies (0.8, 1.1, 1.22, 1.5, 1.62, and 1.82 GHz) were 43, 44, 52, 120, 75, and 67 MHz, respectively. The minimum insertion loss, including SMA connector contributions, was better than –4 dB across all bands, while the return losses were measured at 10.2, 10.8, 11.3, 16.9, 12.1, and 10.3 dB in sequence.

In addition, five transmission zeros were strategically introduced near the edges of the passbands, achieving strong suppression of undesired signals and enhancing stopband performance. The measured results confirm that the proposed filter maintains high selectivity while supporting multiple frequency bands simultaneously. The compact design does not compromise performance, making it suitable for integration into modern RF systems with limited space. Overall, the prototype demonstrates that the proposed methodology provides a reliable and practical solution for high-performance multiband filtering applications.



(a)



(b)

Figure 8: Simulation Results and Measurements of the Six-Order BPF (a) Return Losses (b) Insertion Losses

CONCLUSION

A compact design procedure for multiband microstrip bandpass filters that does not require the use of excessively large circuits is proposed for the first time in this paper. According to the proposed method, the degree of freedom increases by designing all division bandwidths of the multiband BPF. Thus, the design concept is inherently scalable for high-selective multiband filter realizations with broader bandwidths. To show the feasibility, from the first to sixth BPF bands are implemented with a pair of compact one-mode open-ended resonators, which can greatly save the circuit size. In conclusion, the proposed multiband filter has several advantages, making it attractive to modern communication systems. The real advantage of this DCO is that with flexible bandwidth control, the frequency response can be adapted in an optimum way. Moreover, the high selectivity leads to a clean signal filtering with very little crosstalk. Last but not least, its small size suits it for space-limited applications. These dual benefits render such a design suitable for multiband communication devices.

Table 2: Comparisons of Several Types of Multi-band Bandpass Filter Structures

References	Substrate height(mm) / εr/ tangent δ	Number of passbands	Passbands (GHz)	Return losses	Insertion losses
Gómez-García, Roberto	1.52/3.38/0.0027	Dual-band	0.65, 0.75	<-25	>-9
Feng, W. J., W. Q. Che, and Q. Xue	0.5/2.65/0.002	Dual-band	2.5,5.45	<-25	>-2
Gómez-García, Roberto, Li Yang, and DimitraPsychogiou	1.52/3.38/0.0027	Quint-bands	0.91,1.02, 1.08, 1.28, 1.38	<-9	>-3.5
Aidoo, M. W., & Song,	0.508/3.5/-	Dual-band	1.02 , 2.3	<-30	>-1
Li, D., Wang, D., Liu, Y., Chen, X., & Wu	0.9/-/-	Tri-band	1.21, 2.16, 3.10	<-15	>-1.5
Zhu, H., Ahmed, E. S., & Abbosh, A. M	1.27/ 10.2	Dual-band	2.1, 3.6	<-18	<-0.5
Simpson, D., Gómez-García, R	1.19/9.8/0.0025	Dual-band	1.1/1.4	<-15	>-3
Simpson, D.,	1.5/-/-	Tri-band	0.89, 1.01, 1.13	<-20	>-4.5
Gómez-García, R., Psychogiou, D.	1.52/3.38/0.0027	Dual-band	2.53, 3.49	<-18	>-1.5
Proposed work	**1.5/4.6/0.01**	**Hexa-band**	**0.8,1.1,1.22, 1.5, 1.62,1.82**	**<-10.2**	**>-4**

A comparison with multiband filter structures, based on former resonator designs, is provided in Table 2. In contrast to existing works, most of which have been limited to two or three or four bands, six passbands can be obtained with high isolated group-delay responses in a compact configuration. Additionally, the parameter of the filter shows good results in return loss, where the performances of the proposed filter can be suppressed always about –20 dB, which indicates good impedance matching. Furthermore, insertion losses are cut to less than 1.5 dB over all operating bands, whereas higher losses were observed in previous implementations. Furthermore, the fractional bandwidths obtained in this paper are wider and more stable, which is conducive to better spectral utilization and selectivity. In summary, the six-band BPF exhibits more practicality, compactness, and preferable transmission properties compared with various counterparts.

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