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Design of a Novel Compact Microstrip Triple-Band Bandpass Filter Utilizing a Symmetric Stepped-Impedance Resonator (SIR) Structure

Morteza Khajavi[1], Ebrahim Farshidi[1]*, Mohammad Soroosh[1], and Shahrzad Ajabi[1]

***Abstract*-- In this research, an innovative design of a tri-band microstrip bandpass filter is presented, utilizing a combination of Stepped-Impedance Resonators (SIRs). The design methodology of the proposed filter is based on a systematic and goal-oriented approach. In the initial design phase, a specific topology is employed as the baseline structure. Subsequently, through a targeted process involving several stages of optimization and structural/parametric modifications to the baseline design, the original single-band structure is effectively evolved into a tri-band structure with desirable frequency characteristics and quality factors. The final filter designed in this study features three passbands with central frequencies of 5 GHz, 7.8 GHz, and 14.5 GHz. The passband insertion losses are 1.4 dB, 0.7 dB, and 0.6 dB, respectively, while the return losses are 41.2 dB, 21 dB, and 25.1 dB, respectively. The quality factors of the passbands are 8.4, 7.9, and 26.3, respectively. This design offers the advantages of a compact size, simple structure, and multiband operation.**

***Index Terms*- Triple-band bandpass filter, Resonator, Stepped-impedance resonator (SIR), Insertion loss, Return loss.**

I. Introduction

In recent years, the use of microstrip multiband filters has attracted significant attention due to their enhanced efficiency. These filters allow the simultaneous passage of multiple frequency bands according to defined specifications; in other words, a multiband filter performs the function of two or more single-band filters concurrently. This efficiency improvement comes with structural complexity and numerous design challenges. A major challenge in designing multiband filters is providing sufficient isolation between the passbands to prevent information interference. To create this isolation and address the aforementioned challenge, high transmission loss can be introduced at frequencies between the passbands to minimize signal transfer. Put differently, the transmission loss, which is minimized in the passbands, reaches its maximum value at the isolation frequencies (between the bands) [1, 2]. Another prominent technique involves the hybrid integration of two or more distinct resonator types to achieve a final multiband architecture [3-5]. For instance, reference [6] employs a multimode loaded-ring resonator alongside split-ring resonators to realize a multiband filter. The concurrent utilization of multiple resonator types allows the final design to cater to diverse applications such as wireless systems, C-band, and X-band operations. Similarly, the work in [7] adopts the technique of co-integrating several resonator types to attain a structure with optimal frequency response. The proposed filter's final topology is a triple-band microstrip filter that combines slotted waveguide structures with stubs and ring resonators.

Stepped-Impedance Resonators (SIRs) constitute a category of resonators that have gained substantial attention in recent research for the design of multiband microstrip filters. This interest stems from their high efficiency, capability for circuit miniaturization, and enhanced frequency characteristics, most notably their superior insertion loss and return loss performance. In this context, reference [8] presents a triple-band bandpass filter whose design is based on a loaded symmetrical double-stub SIR, incorporating multiple open- and short-circuited stubs.

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1. Department of Electrical Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
*Corresponding author Email: farshidi@scu.ac.ir

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Another crucial technique in multiband filter design is to ensure that, in addition to hybrid integration of resonators, their design enables tunability of parameters such as center frequency, bandwidth, and even the shifting of passbands. Consequently, the final designed filter structure not only comprises multiple resonator types but also incorporates resonator designs that facilitate tunability, thereby enhancing filter agility and performance [9]. Passbands themselves are a key tunable feature. In [10], the tunability of passbands has been investigated by implementing modifications within the resonators used in the filter's final structure. The resonator type employed in this triple-band bandpass filter design is a quarter-wavelength dual-mode T-shaped resonator, which enables the final structure to feature three passbands for GSM, GPS, and WiFi wireless applications.

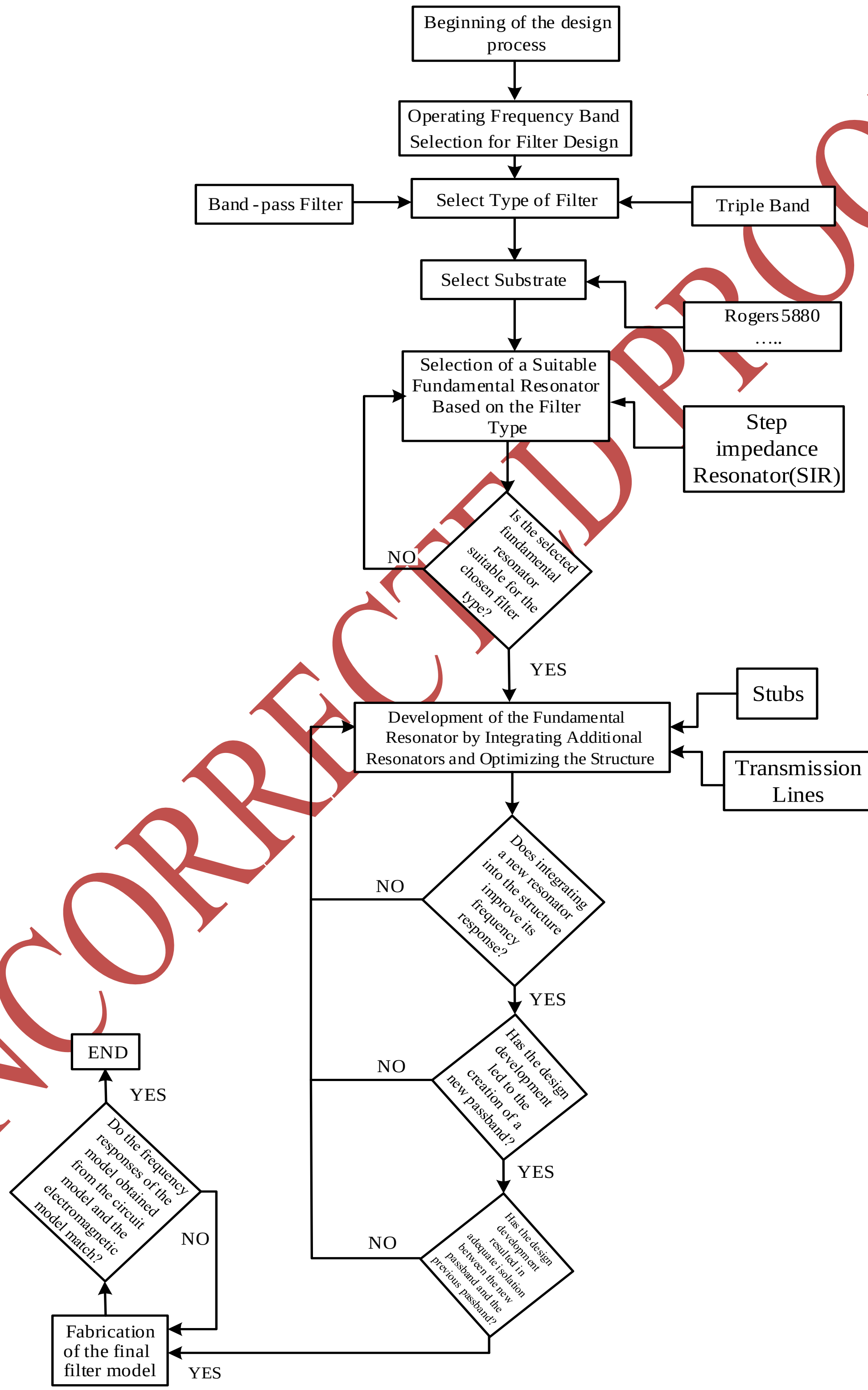


Fig. 1. Step-by-Step flowchart for filter design

In the design of multiband filters using diverse resonators, symmetric patterns (even and odd symmetry) or asymmetry can be leveraged in the final structure [11, 12]. The use of asymmetric stepped-impedance resonators (SIRs) is one method highlighted in [13] for enhancing the efficiency and improving the frequency characteristics of the designed final filter. In this design, the first and second passbands are created using asymmetric SIRs, while the third passband is generated by adding a uniform-impedance half-wavelength resonator. In [14], the structural flexibility for achieving frequency-band selectivity between the S, X, and C bands using interdigital resonators has been examined. Furthermore, [15] presents a technique based on the concurrent use of multiple resonator types, including a stub-loaded parallel-coupled resonator, a shortened-stub loaded parallel-coupled resonator, and a microstrip line coupled via a slot. The hybrid use of multiple resonator types has resulted in enhanced efficiency and improved inter-band isolation, achieving 25 dB of isolation between the first and second passbands and 40 dB between the third and fourth passbands. In [16], a triple-band bandpass filter is presented that leverages an asymmetric design technique in its final structure, utilizing both stepped-impedance resonators and uniform-impedance open-ended resonators. The application of asymmetry in the final design has led to excellent isolation characteristics between the passbands in terms of frequency response.

In this research, considering the necessity for increased efficiency, structural agility, and the significance of multiband filters in recent studies, a triple-band microstrip bandpass filter is designed and proposed. To achieve desirable frequency characteristics, with a particular focus on improved insertion loss and return loss, and to address multiple design challenges such as providing adequate isolation between passbands and attaining a satisfactory quality factor (Q_L), a combination of stepped-impedance resonators is employed. This is accomplished by utilizing an odd-symmetry technique and incorporating an air-gap section in the central part of the structure. The design process of the final structure proceeds as follows. Initially, a base filter structure is selected. Subsequently, fundamental modifications are applied to this base structure. These modifications, which involve adding and optimizing suitable resonators, lead to the realization of the ultimate filter structure possessing the desired frequency characteristics and quality factor. Fig. 1 presents the step-by-step design process for the tri-band bandpass filter separately and in detail.

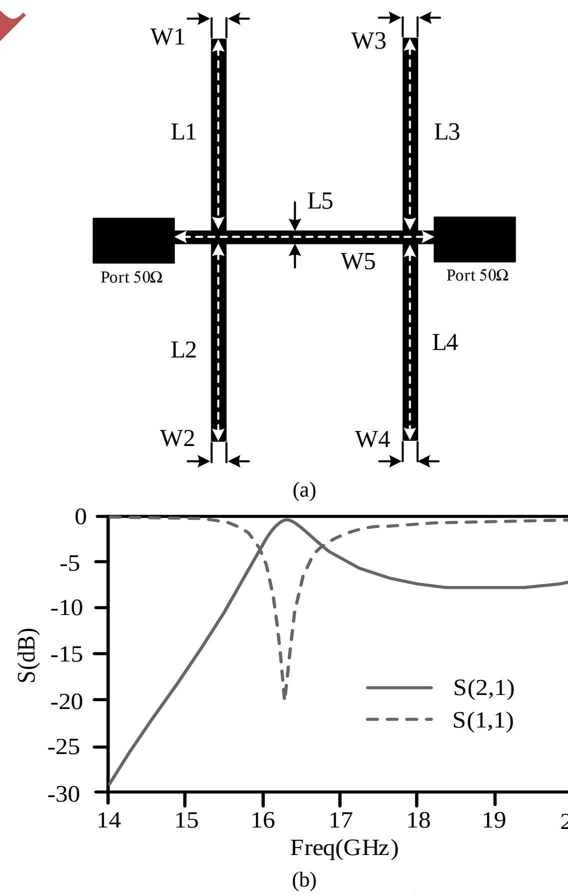
II. Filter Design Process

Fig. 2(a) illustrates the electromagnetic (EM) simulation model of the base structure, implemented using an array of stepped-impedance resonators (SIRs). The base resonator simulation was performed in the momentum environment of the ADS software. The base structure is a single-band wideband bandpass filter designed with a stepped-impedance resonator (SIR) configuration. It incorporates a central transmission line section and stub structures on both sides of the filter's base layout. The base resonator was designed on a Rogers 5880 substrate with the following properties: tanδ = 0.0009, ε_r = 2.2, and h = 0.38 mm.

As evident in Fig. 2(a), each resonator in the base design is labeled to specify the precise dimensions of the base structure. The exact dimensions of the various parts of the designed base resonators are as follows: Resonator L1 has a length L = 4.85 mm and width W = 0.4 mm; Resonator L2 has L = 4.98 mm and W = 0.4 mm; Resonator L3 has L = 4.85 mm and W = 0.4 mm; Resonator L4 has L = 4.98 mm and W = 0.4 mm; and Resonator L5 has L = 0.3 mm and W = 8.14 mm. Furthermore, due to the use of the Rogers 5880 substrate, the thickness (i.e., height from the ground plane) for all resonators is 0.38 mm, and the permittivity is ε_r = 2.2 for all. Fig. 2(b) shows the frequency response of the designed base filter. The base structure features a single passband centered at 16.2 GHz. This passband has an insertion loss of 0.7 dB, a return loss of 20.3 dB, and a bandwidth of 740 MHz.

The most critical aspect of designing the initial structure is achieving a desirable frequency response to define the passband. This structure serves as the foundation for evolving into a multiband configuration. In other words, from the perspective of frequency characteristics, particularly its insertion and return loss, it must meet the essential minimum requirements for further optimization and enhancement.

The primary design challenges in evolving the base structure, which aims to improve insertion and return loss, enhance bandwidth and quality factor, create second and third passbands, and establish adequate inter-band isolation, include the necessity of utilizing diverse resonator structures compatible with the base resonator type, determining the interconnection method between resonators, and optimizing the dimensions at each design stage. Subsequently, through targeted modifications and fundamental optimization of the base structure design, which is a single-band wideband bandpass filter, the design is evolved into a triple-band wideband bandpass filter with suitable frequency performance indices, including a desirable quality factor.



(a)

(b)

Fig. 2. (a) The base structure (b) Frequency response of the base structure

One of the key criteria in microstrip filter design is the quality factor. The quality factor directly influences frequency selectivity, loss, and filter size. By selecting appropriate materials, optimizing the resonator structure, and controlling coupling, a high-quality factor can be achieved, which is essential for advanced telecommunications and microwave systems. For microstrip filters, the loaded quality factor (Q_L) is calculated using the center frequency and bandwidth. The main relationship is as follows:

$$Q_L = \frac{C_F}{\mathrm{BW}} \quad (1)$$

In (1), the parameter Q_L represents the loaded quality factor, C_F denotes the center frequency, and BW is the passband bandwidth. The quality factor of the base structure is 21.89.

III. Design Development Process

Given the significant attention devoted to multiband filter design in recent research, the need to enhance functionality and define additional passbands for a single filter has led to a focused effort to achieve this objective. The foremost superiority of multi-band filters over single-band structures resides in their concurrent ability to support information transfer across several passbands. In essence, a singular filter configuration delivers the operational performance of multiple filters, which consequently leads to a more agile architecture and a marked enhancement in overall efficiency.

However, it is also crucial to note that increasing the number of passbands introduces design complexities. Achieving a structure with desirable frequency characteristics consequently presents considerable challenges for resonator design. In the continuation of this research, through fundamental modifications to the base design structure, the single-band filter is evolved into a triple-band filter, accompanied by an improvement in its loss characteristics. In multiband filter design, it is also essential to ensure adequate isolation between passbands to prevent information interference. This inter-band isolation is achieved by creating a high transmission loss at a frequency situated between the center frequencies of the passbands. In other words, the transmission loss, which is at a minimum at the passbands' center frequencies, reaches its maximum at the frequency designated for inter-band isolation.

In Fig. 3(a), to improve the frequency characteristics of the base design and move towards creating multiple passbands at specific frequency bands, the electromagnetic (EM) model architecture has undergone fundamental changes. These modifications were implemented to enhance the frequency response. In Fig. 3(a), the addition of resonators T1-T5 to the structure, together with significant alterations in the central section, has resulted in a very significant improvement in the frequency characteristics. These central alterations include introducing an air gap between the stubs and revising the dimensions of other parts of the base model, such as the transmission line and the side stubs, which have been relocated to the center.

The precise dimensions of the added resonators are as follows: Resonator T1 has a length L = 0.2 mm and width W = 2 mm; Resonator T2 has L = 0.2 mm and W = 1.5 mm; Resonator T3 has L = 0.36 mm and W = 1.25 mm; Resonator T4 has L = 3 mm and W = 5 mm; and Resonator T5 has L = 0.2 mm and W = 2 mm. Furthermore, the precise dimensions of the stubs in the final structure are: L1 = 1.98 mm, L2 = 6.87 mm, L3 = 0.75 mm, L4 = 1.25 mm, L5 = 5.57 mm, and W1 = 0.22 mm. Due to the symmetry of the final design, the dimensions of the stubs and added resonators are exactly replicated on the right side of the presented structure.

The frequency response of the enhanced design is presented in Fig. 3(b). The enhanced structure features three passbands with center frequencies at 5 GHz, 7.8 GHz, and 14.5 GHz. As shown in the frequency response, the passband frequency characteristics have improved compared to the base design. Specifically, the first, second, and third passbands exhibit insertion losses of 0.12 dB, 0.12 dB, and 0.7 dB, respectively. Their respective return losses are 55.8 dB, 22.4 dB, and 34.7 dB, and their bandwidths are 630 MHz, 1.06 GHz, and 570 MHz. Furthermore, to prevent information interference, adequate isolation has been achieved between the passbands. Between the first and second passbands at 7 GHz, an insertion loss of 42.4 dB is established, and between the second and third passbands at 12.5 GHz, an insertion loss of 38.9 dB is achieved.

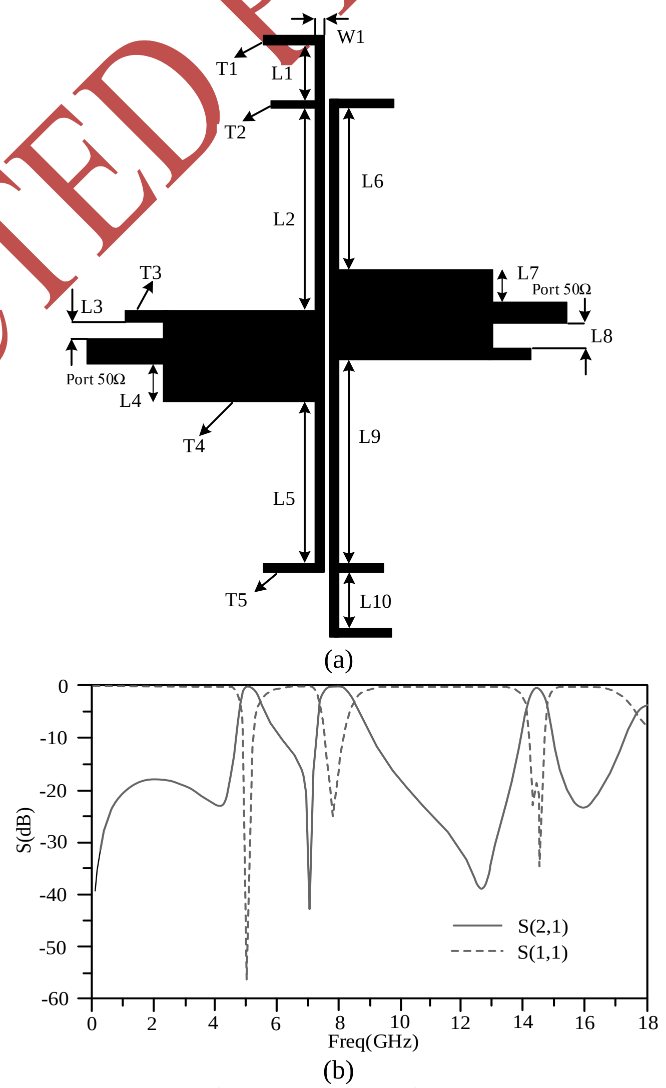


Fig. 3. (a) The enhanced filter structure evolved from the base structure through dimensional optimization and the addition of suitable resonators. (b) The frequency response resulting from the modifications applied to the base filter structure.

The final structure features three passbands with center frequencies of 5 GHz, 7.8 GHz, and 14.5 GHz, designed for applications in the C-band and Ku-band frequency ranges. The selected passbands offer significant practical applicability in modern communication and sensing systems. The 5 GHz band is widely utilized in Wireless Local Area Networks (WLANs) and Wi-Fi 6/6E, as well as in satellite communication downlinks. The 7.8 GHz band aligns with the frequency range commonly employed in satellite-based remote sensing, radar systems, and point-to-point microwave links. Meanwhile, the 14.5 GHz band falls within the Ku-band spectrum, which is extensively used for satellite uplinks, very small aperture terminal (VSAT) networks, and broadband communication services. Accordingly, the proposed structure is well-suited for integration into multi-band transceivers and reconfigurable RF front-end systems [26, 27]. In the enhanced structure, the passbands have evolved from a single to three passbands. Furthermore, for each passband, not only have the frequency characteristics, particularly the insertion loss and return loss, improved, but the loaded quality factor has also been enhanced for all three passbands.

IV. Fabricated Model

Fig. 4(a) presents the fabricated prototype alongside the measurement results compared with the simulation model results. As shown in Fig. 4(b), the measurement results of the fabricated prototype and the electromagnetic (EM) simulation model exhibit favorable agreement in terms of frequency characteristics, particularly the center frequency. The fabrication process of the triple-band bandpass filter utilized a Rogers 5880 substrate with a thickness of 15 mils, a low loss tangent of 0.0009, and a dielectric constant of 2.2. Table 1 provides and compares the precise results from the fabricated prototype and the electromagnetic (EM) simulation model. The fabricated filter was characterized using a network analyzer over the frequency range of 0 to 18 GHz, with a total of 800 measurement points to ensure sufficient frequency resolution.

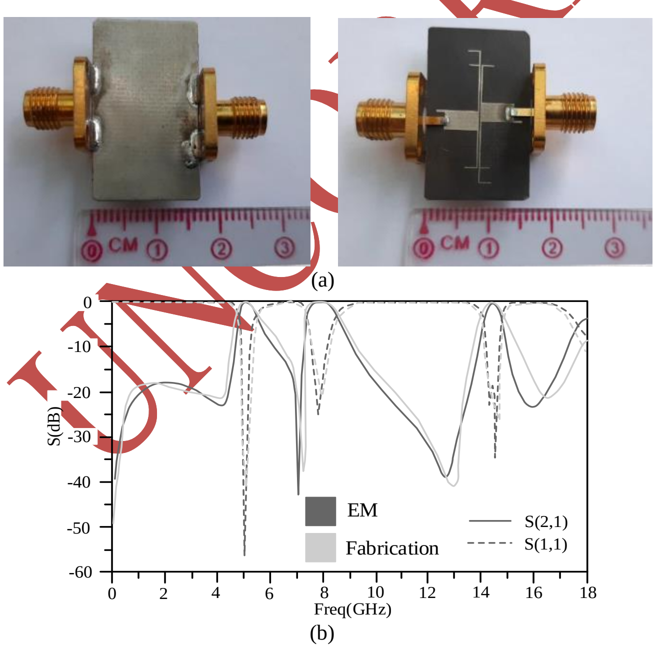


Fig. 4. (a) Fabricated prototype of the final designed filter. (b) Comparison of the frequency response between the fabricated prototype and the electromagnetic (EM) simulation model.

TABLE I
Comparison of Results Between the Fabricated Prototype and the Electromagnetic (EM) Simulation Model

Parameter	First / Second / Third Passbands (GHz)	3-dB FBW (%)	IL (dB)	RL (dB)	ISO ($Iso_{1,2}$ / $Iso_{2,3}$ dB)
Simulation Model (EM)	5, 7.8, 14.5	12.6, 12.9, 3.9	0.1, 0.1, 0.7	55.8, 22.4, 34.7	42.4, 38.9
Fabricated Prototype Results	5, 7.8, 14.5	11.8, 12.5, 3.7	0.6, 0.7, 1.4	41.2, 21, 25.1	38.6, 41.4

A key observation from measuring the parameters of the fabricated prototype, compared to the electromagnetic (EM) simulation model, is the precise alignment of the frequency characteristics. These include the center frequency, bandwidth, insertion loss, and return loss. While the losses of the fabricated prototype and the simulation model inherently differ, the center frequencies of the passbands demonstrate accurate alignment with each other. Furthermore, the fabricated prototype delivers satisfactory results in terms of the loaded quality factor (Q_L) criterion. Table 2 presents and compares the measurement results of the fabricated model with those of the simulation model.

TABLE II
Comparison of the Quality Factor Between the Fabricated Prototype and the Electromagnetic (EM) Simulation Model

C_F (GHz)	5	7.8	14.5
Simulation Model Q_L	7.9	7.35	25.4
Fabricated Prototype Q_L	8.4	7.9	26.3

Another criterion for which the fabricated prototype yields favorable results is the inter-band isolation, which prevents information interference. The isolation between adjacent passbands is realized by creating a high insertion loss at a frequency positioned between them. Stated differently, whereas the insertion loss within the passbands, especially at the center frequency of each passband, where the ideal insertion loss value is near zero, must be maintained at a minimal level, the insertion loss at the designated isolation frequency attains its maximum value. The fundamental purpose of employing this technique in multi-band filter designs is to prevent mutual interference of information transmitted within contiguous passbands. In this research, given that the fabricated prototype is a triple-band filter, it exhibits two isolation bands: the first between the initial and second passbands, and the second between the second and third passbands. Table 3 presents and compares the measurement results of the fabricated model with those of the simulation model.

TABLE III
Comparison of Isolation Between the Fabricated Prototype and the Electromagnetic (EM) Simulation Model

Parameter	$ISO_{1,2}$ (dB)	$ISO_{2,3}$ (dB)
Simulation Model	42.4	38.9
Fabricated Prototype	38.6	41.4

TABLE IV
Comparison of the Results of the Proposed Filter with Several References

Ref.	First / Second / Third Passbands (GHz)	3-dB FBW (%)	IL (dB)	RL (dB)	ISO ($Iso_{1,2}$ / $Iso_{2,3}$ dB)	Circuit Size (λ_g^2)
[2]	1.93, 2.6, 3.9	3, 11, 5	1.5, 0.6, 1.83	20, 20, 15	25, 27	0.54 × 0.77
[5]	1.575, 2.4, 3.45	15, 6, 7	0.7, 1.14, 0.3	18, 22.3, 17	40, 38	0.44 × 0.56
[15]	1.93, 3.52, 5.11	11.8, 19.22, 8.8	0.66, 0.7, 0.94	22, 25, 15	25, 40	0.17 × 0.13
[17]	1.9, 3.58, 5.75	17.5, 12.8, 2.9	0.25, 0.37, 0.9	33.2, 15.7, 21.9	30, 28	0.29 × 0.17
[18]	1.37, 2.43, 3.53	4.4, 5.2, 9.7	1.7, 1.8, 2.5	20, 15, 15	30, 56	0.13 × 0.26
[19]	1.7, 3.5, 5.8	22.9, 16.9, 8.52	0.55, 0.99, 1.2	13, 14, 20	45, 55	0.168 × 0.183
[20]	1.82, 2.3, 44.49	7, 9.7, 4.1	1.5, 0.93, 1.17	12, 15, 12	45, 60	0.24 × 2.0
[21]	1.37, 2.2, 43.53	4.4, 5.2, 9.7	1.7, 1.8, 2.5	20, 15, 15	32, 60	0.26 × 0.13
[22]	1.7, 2.7, 4.5	7,20, 3	1.82, 1.87, 3.4	17.2, 16, 19.8	45, 48	0.35 × 0.28
[23]	6.9, 10.1, 13.3	7.6, 12.2, 7.4	0.8, 0.9, 2	20, 21, 22.1	38, 65	1.29 × 1.62
[24]	2.12, 2.79, 4.185	5.4, 7.6, 3.5	1.57, 1.43, 1.72	18.57, 23.85, 18.33	30, 33	0.0175
[25]	2.4, 3.9, 5.0	7.5, 7.0, 1.8	1.2, 1.6, 2.3	25, 22, 21	56, 52	0.46 × 0.36
This Work	**5, 7.8, 14.5**	**11.8, 12.5, 3.7**	**0.6, 0.7, 1.4**	**41.2, 21, 25.1**	**38.6, 41.4**	**0.041 × 0.014**

Table IV presents the measurement results of the fabricated sample alongside the findings of similar studies conducted in recent years. A comparison of these results based on frequency characteristics and dimensions indicates the relative desirability of the outcomes obtained in the present study.

V. Conclusion

In this research, a triple-band wideband bandpass filter has been meticulously designed and presented through a precise process. The core design methodology is based on establishing an initial base structure and subsequently enhancing it by selecting suitable resonators and optimizing their characteristic parameters. During this process, by implementing fundamental modifications to the base structure, adding resonators T1 through T5 to the architecture, and optimizing the parameters of each resonator, the initial design, which was a single-band filter, has been evolved into a triple-band filter. In addition to creating the second and third passbands with desirable frequency characteristics, the final designed structure benefits from adequate inter-band isolation. Specifically, the isolation between the first and second passbands is 38.6 dB, and between the second and third passbands is 41.4 dB, which constitutes a highly favorable outcome. Furthermore, another performance index evaluated in this study is the loaded quality factor. In the final design, the triple-band filter possesses three quality factors for the first, second, and third passbands, with calculated values of 8.4, 7.9, and 26.3, respectively. The final results demonstrate the high performance and efficacy of the designed filter.

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BIOGRAPHIES

Morteza Khajavi received the B.Eng. and M.Eng. degrees in Electronics Engineering from Jundi-Shapur University of Technology, Dezful, Iran, in 2017 and 2019, respectively. He is currently working toward the Ph.D. degree in Electrical Engineering at Shahid Chamran University of Ahvaz, Ahvaz, Iran. His research interests include analog and radio-frequency (RF) circuit design.

Ebrahim Farshidi (corresponding author) was born in Shoushtar, Iran, in 1973. He received the B.Sc. degree in 1995 from Amir Kabir University of Technology, Tehran, Iran, the M.Sc. degree in 1997 from Sharif University of Technology, Tehran, Iran and the Ph.D. degree in 2008 from IUT, Esfahan, Iran, all in electronic engineering. He worked for Karun Pulp and Paper Company during 1997–2002. From 2002 he has been with Shahid Chamran University, Ahvaz, Iran, where he is currently Professor of Electrical Engineering Department. His areas of interest include current-mode circuits design, and data converters. He is author of more than 85 technical papers in electronics.

Mohammad Soroosh received BEng degree from Isfahan University of Technology at Isfahan in 2000 and MEng and PhD degrees from Tarbiat Modares University at Tehran in 2003 and 2009, respectively, all in electronics. He joined Iran Telecommunication Research Center, Tehran in 2003 where he was a researcher at optical communication group. Currently, he is a professor of electronics at Shahid Chamran University of Ahvaz. His expertise is further evidenced by his selection as a top 2% scientist in 2023, 2024 and 2025. His research interests are in modeling and simulation of photonic and optoelectronic devices.

Shahrzad Ajabi received the B.Sc. degree from Sharif University of Technology, Tehran, Iran, in 1998, and M.Sc. degree from Tarbiat Modares University, Tehran, Iran, in 2002, both in telecommunication engineering. She joined the Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Iran, in 2018, as an assistant professor. His research interests include analog and RF circuits