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A Novel Triple-Band Band-Pass Metamaterial Filter based on Modified Square Split Ring Resonators for Microwave Applications: Design and Analysis

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Abstract: In response to the growing demand for miniaturized electronic devices, this work presents a novel triple-band band-pass filter (TBBPF) design utilizing metamaterial design. The proposed filter comprises three split-ring resonators (SRRs) featuring identical modified square shapes but different dimensions, all printed on Rogers RT/Duroid 6002 substrates with a relative electrical permittivity of 2.94 and thickness of 1.52 mm. The compact filter design, occupying just 10×10 mm², is fed by two 5.25 mm microstrip lines matched at 50 Ω. Our simulation outcomes demonstrate exceptional performance across C-, X-, and Ku-bands, with distinct resonance frequencies at 6.06 GHz, 10.71 GHz, and 13.64 GHz, respectively. The filter exhibits remarkable electrical characteristics, including minimal insertion losses (IL <1.5 dB), optimal bandwidth distribution, and notably compact dimensions. These characteristics, combined with the filter's multi-band capabilities, make it particularly suitable for diverse applications in wireless communication systems, imaging technologies, and biomedical detection devices. The innovative design approach presented here addresses the contemporary challenges in RF/microwave system miniaturization while maintaining high-performance standards, offering a versatile solution for modern electronic systems requiring multi-band functionality.

Keywords: Bandwidth, Insertion losses, Metamaterial resonator, Triple-band, Versatile applications

Introduction

The rapid evolution of wireless communication systems has led to an unprecedented demand for compact, multi-functional microwave components, particularly in filtering technologies. Microwave filter design has undergone significant advancements in recent decades, driven by the increasing need for devices that can operate efficiently across multiple frequency bands while maintaining a minimal footprint. The selection of appropriate design methodologies and materials has become crucial in meeting these demanding specifications. Multi-band microwave filters have emerged as essential components in various applications, from sophisticated RADAR systems requiring precise signal processing capabilities (Han, 2023; Malki, 2023) to advanced sensor networks demanding high sensitivity and selectivity (Alnahwi, 2021). Their implementation spans diverse fields, including medical imaging (Tshibangu-Mbuebue, 2021; Liu, 2022), satellite communications (Akyildiz, 2019; Chhasatia, 2023; Nasser, 2023), and modern wireless devices operating across multiple frequency bands (Berka, 2018).

Recent years have witnessed significant advancements in multiband filter design, particularly in metamaterial-based approaches. (Berka et al., 2021) demonstrated a dual-band filter using coupled resonators achieving insertion losses below 1.2 dB at both 5.02 and 8.92 GHz bands. A notable breakthrough came from Choudhary and colleagues (Choudhary, 2018), who developed a modified CSRR structure at coplanar waveguide (CPW) ground plane investigated for designing of a dual-band bandpass filter with a minimum insertion loss of 0.5 and

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0.4 dB at 1.8 and 3.2 GHz, respectively. In Rouabhi (2022) an innovative approach using tapered split-ring resonators (TSRRs) was proposed for dual-bands while maintaining a compact footprint of 39.6×27.7 mm². The implementation of defected ground structures (DGS) by (Vali, 2024) resulted in enhanced stopband characteristics, albeit at the cost of increased circuit size. More recently, (Berka et al., 2024) demonstrated a compact dual-band filter using SIW structure, enabling dynamic frequency tuning across the C- and X- bands. Berka et al. (2022) advanced the field further with their metamaterial-inspired triple-band design based on (E-Z)-shaped resonators, achieving insertion losses below 1 dB across all three bands, though their structure required complex fabrication processes. Other works about metamaterial-based filters are reported in (Tan, 2024; Baghdad Bey, 2024; Li, 2022) for THz applications.

Drawing upon these developments and addressing current limitations, this work presents a novel triple-band band-pass microwave filter incorporating three modified square-shaped metamaterial resonators. The primary objective is to develop and analyze this structure that addresses the growing demand for miniaturized, high-performance RF components. Our design aims to achieve simultaneous operation across C-, X-, and Ku-bands while maintaining exceptional electrical characteristics and minimal footprint.

Specifically, we focus on implementing three modified square-shaped split-ring resonators (SRRs) with distinct dimensions, strategically designed to resonate at 5.28 GHz, 9.14 GHz, and 14.32 GHz. The proposed filter targets insertion losses below 0.5 dB across all three bands, a significant improvement over existing designs. A key goal is to achieve these performance metrics while maintaining an ultra-compact form factor of just 10×10 mm², utilizing Rogers RT/Duroid 6002 substrate material. The design methodology emphasizes optimizing the coupling mechanism between resonators through carefully positioned 50 Ω matched microstrip feed lines measuring 5.25 mm. This research seeks to demonstrate that superior multi-band performance can be achieved without compromising device miniaturization, making it particularly suitable for emerging wireless communication systems, advanced imaging applications, and next-generation biomedical detection devices.

Design and Materials

Unit Cell Design

The split ring metamaterial resonator is a microwave structure with a magnetic activity that has unusual physical characteristics. The first proposed SRR is the circular-shaped resonator formed by two internal and external rings (Marquez, 2002). For our unit cell, we have chosen a modified square shape with sixslots for the two rings and one arm. The chosen dimensions for our cell are in the millimeter scale to have frequency responses in the microwave bands. The proposed metamaterial resonator of the basic cell is shown in Figure 1.

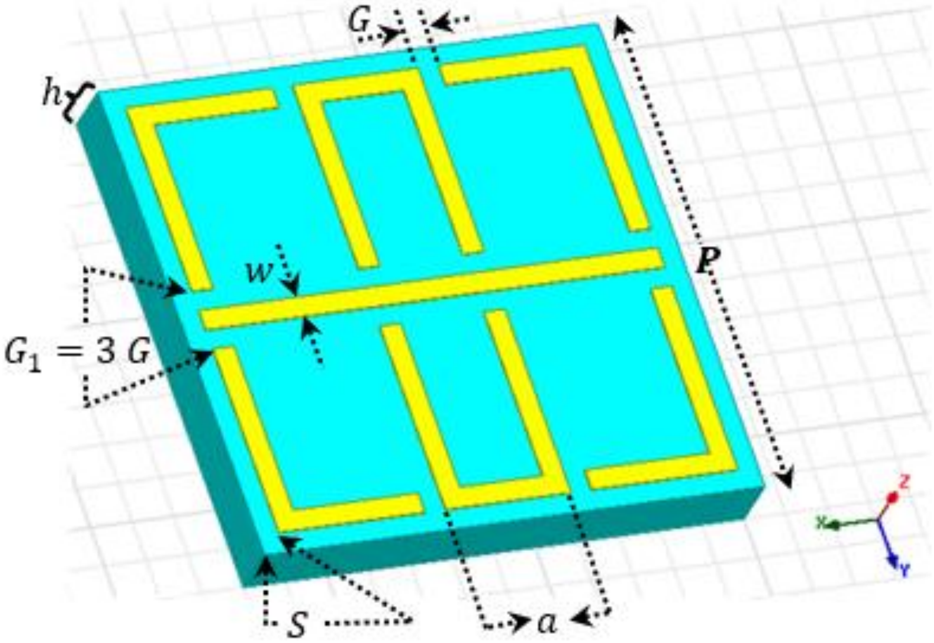


Figure 1. Geometric layout of the proposed metamaterial unit cell.

The unit cell dimensions are summarized in Table 1.

Table 1. Various parameters of the unit cell

Parameter	Value (mm)	Parameter	Value (mm)
a	3	G_1	1.5
G	0.5	S	0.5
w	0.5	P	12

Filter Configuration

The proposed TBBPF is formed by two metamaterial resonators previously studied for the unit cell. The used resonators are identical with the same dimensions mentioned in Table 1. Our TBBPF is fed by two microstrip lines of length $L_f = L_{eff_1} + L_{eff_2} + L_{eff_3} = 24.5$ mm each; these lines are coupled to the proposed resonators by a spacing e =0.5 mm. All the components making up the filter are printed on the upper face of the chosen substrate. The proposed filter which has the surface formed by the two sides (X, Y) is shown in Figure 2.

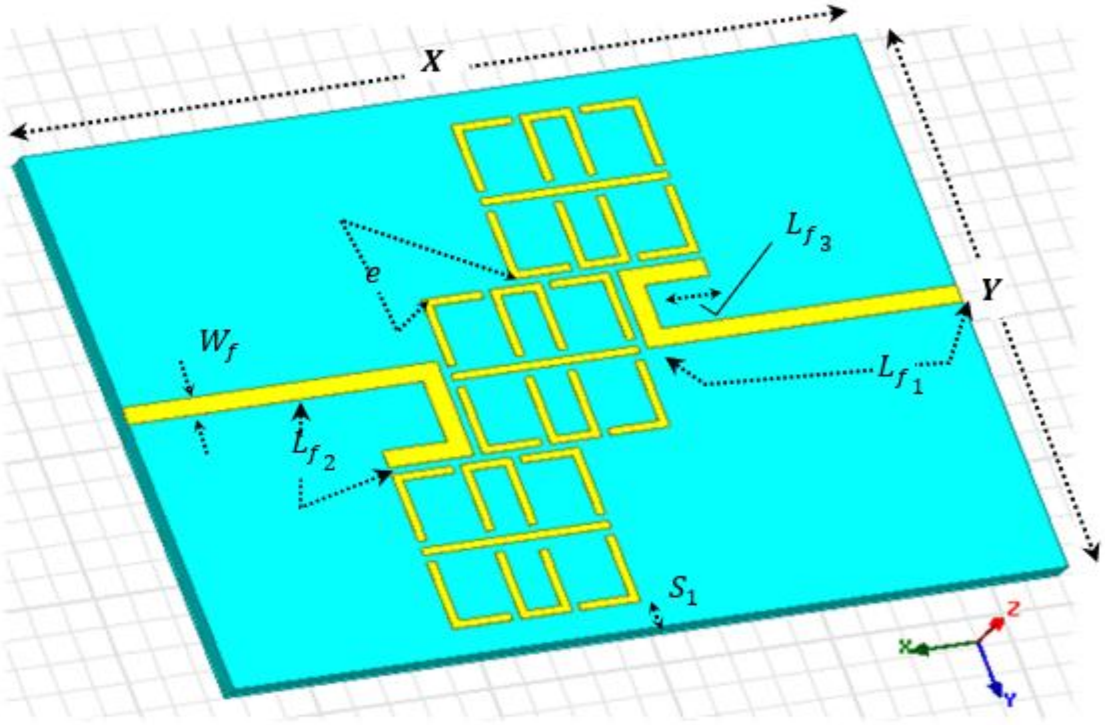


Figure 2. Proposed TBBPF with the three SRRs.

The dimensions of the elements constituting the filter are summarized in Table 2.For these values, the filter has the dimensions (X =41 mm, $Y = 37$ mm).

Table 2. Various parameters of the proposed filter

Parameter	Value (mm)	Parameter	Value (mm)
L_{eff_1}	14.5	S_1	2
L_{eff_2}	5.5	S_2	6.4
L_{eff_3}	4.5	e	0.5

Results and Discussion

Functional Behaviour of the Proposed Unit Cell

Leave On the substrate of RT/Duroid 6002 of physical characteristics (ε_r =2.94 and $tg\delta = 0.0012$) and thickness of 1.52 mm, the slotted square patch is printed for both inner and outer rings with a thickness (t = 0.035 mm). Figure 3 represents the frequency response of the proposed unit cell for a period of 12 mm.

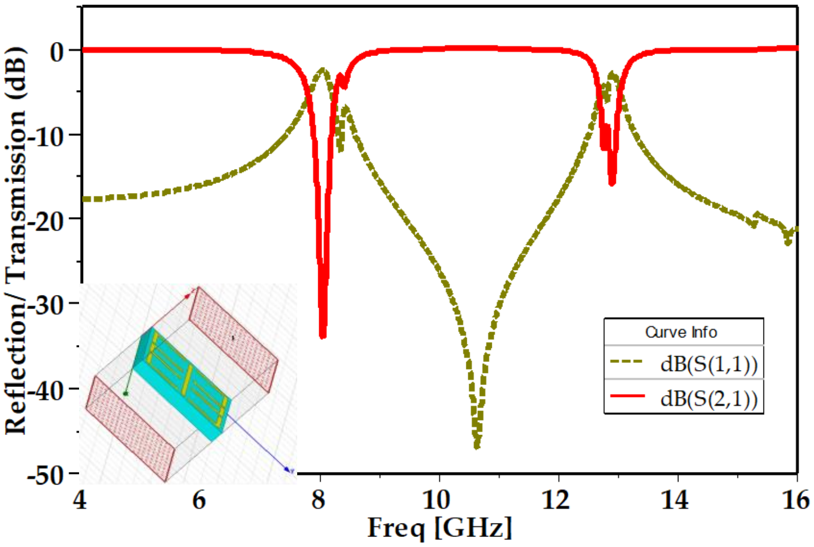


Figure 3. Frequency feature of the proposed SRR unit cell.

In Figure 3 we observe the reflection and transmission of the proposed unit cell which represents a stop-band behavior at the resonances of 8.43 and 12.92 GHz for the transmissions of −33.51 and −15.69 dB, respectively. Depending on the characteristics simulated previously, we can obtain the effective permeability of the proposed resonator. The following relationship can determine this permeability (Hannan, 2020).

$$\mu_{eff}(f) = \frac{2}{jkh}\frac{1-v_1}{1+v_1} \tag{1}$$

With,

$$v_1 = S_{21} - S_{11} \tag{2}$$

Where S_{11} and S_{21} represent the reflection and transmission coefficients, respectively and$k$ is the ratio of frequency ω to the speed of lightc_0. It comes,

$$\mu_{eff}(f) = \mu'_{eff} - j\mu''_{eff} = \frac{2}{jkh}\frac{1 - S_{21}(f) + S_{11}(f)}{\left(1 + S_{21}(f) - S_{11}(f)\right)} \tag{3}$$

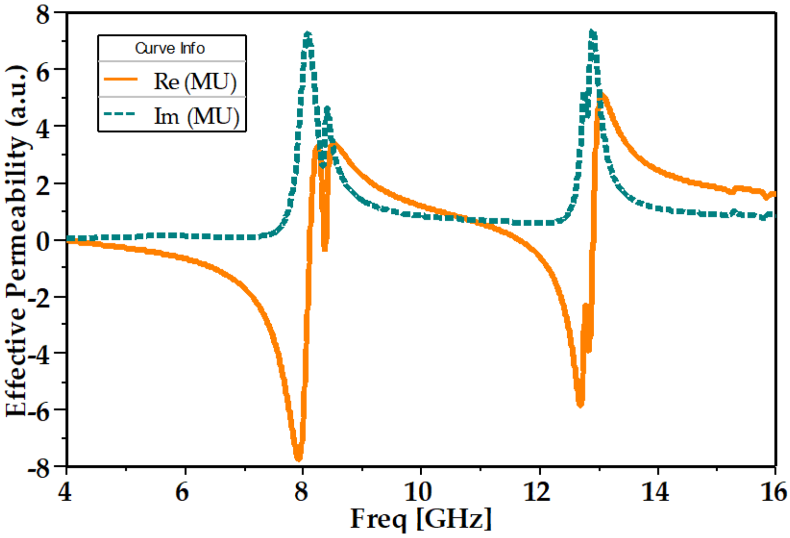


Figure 4. Characteristics of effective permeability.

The frequency characteristics of the effective permeability of the unit cell are shown in Figure 4.We observe two different characteristics around the two resonances (at 8.43 and 12.92 GHz) of the unit cell whose imaginary part is positive over the entire frequency range. Around the first resonance, it is remarkable that the real part of the permeability changes its sign from −7.71 to 3.14. Around the second resonance of the base cell, the real part of the permeability changes its sign from −13.07 to 5.05.

TBBPF Response

Upon the necessary simulations, the spectral response of the filter is represented in Figure5.

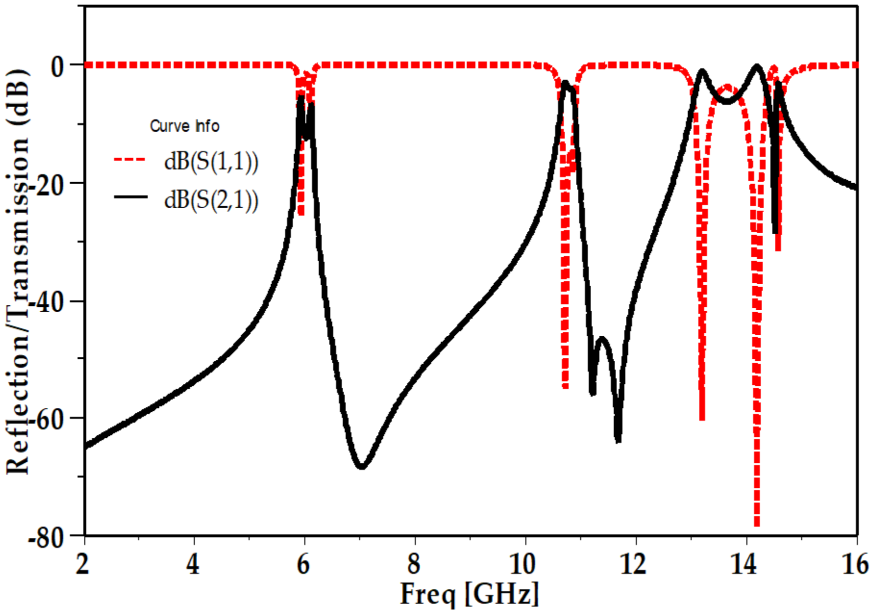
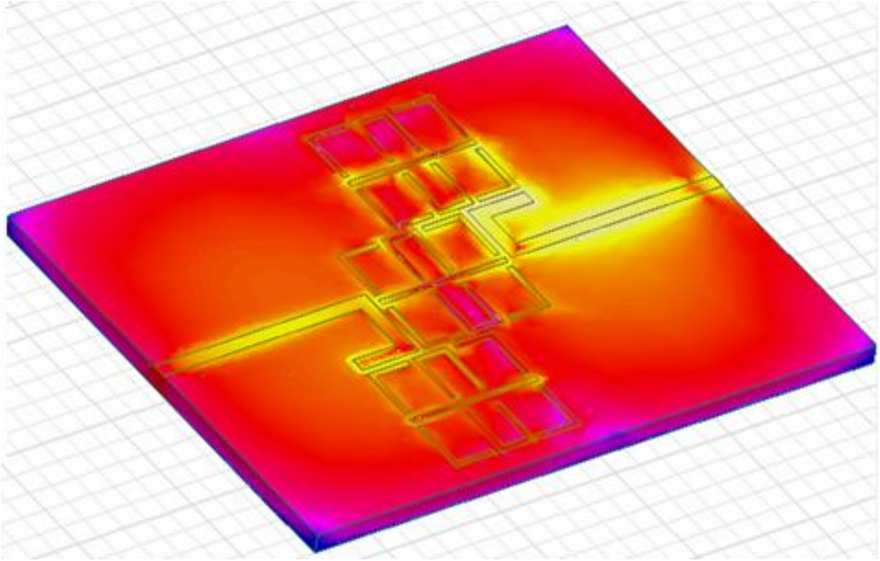
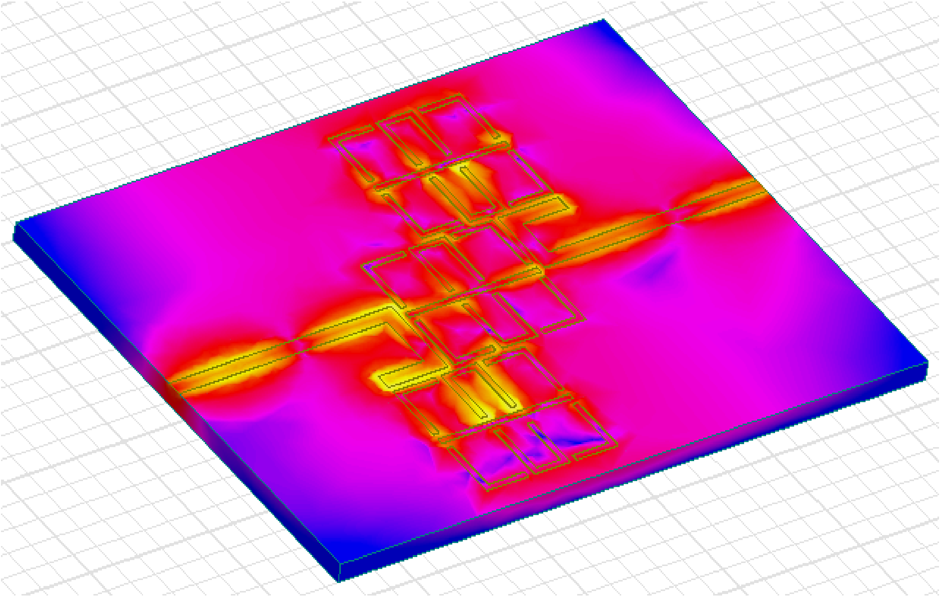


Figure 5. Reflection and transmission of the proposed filter.

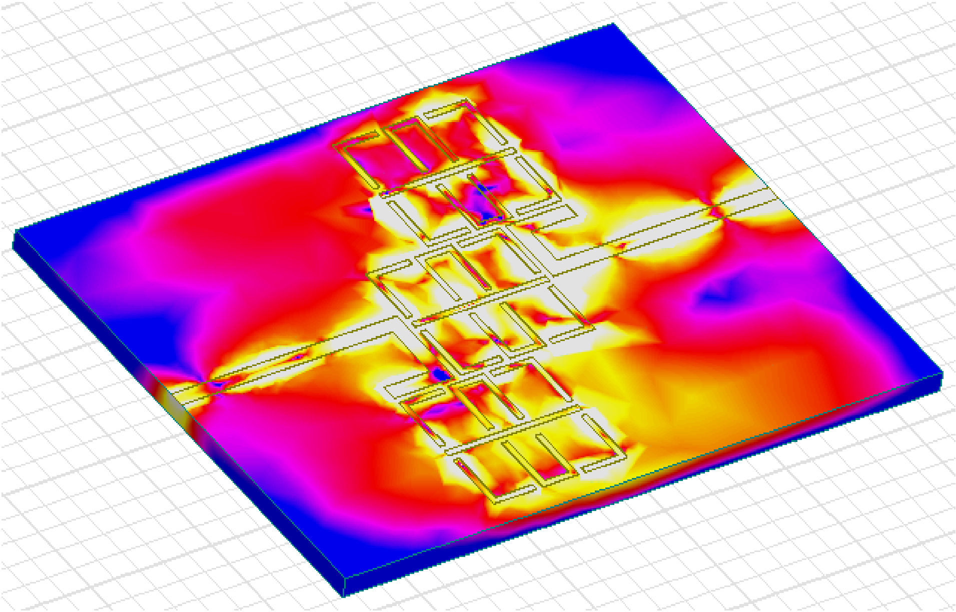
Figure 5 represents the reflection and transmission coefficients of the filter for the proposed configuration. This figure shows that the filter has a band-pass behavior for three different bands. The three resonances are obtained at 6.06, 10.71 and 13.64 GHz, respectively. Moreover, the proposed TBBPF represents a good adaptation for weak insertion losses (*IL* <1.5 dB). Also, the filter bandwidths are estimated at 280, 416 and 725 MHz, respectively. To better explain the behavior of the filter, we represent the distribution of the electric field on the structure for the three resonances.



(a)



(b)



(c)

Figure 6. Electric field distribution at (a) 6.06 GHz, (b) 10.71 and (c) 13.64 GHz.

Figure 6 shows the distribution of the electric field on the filter at 6.06, 10.71 and 13.64 GHz, respectively. We note that the electric field is distributed over the feed lines and the two metamaterial resonators SRRs, which justify the transfer of electromagnetic power at the resonance thus indicated.

Conclusion

This work has successfully demonstrated the design and analysis of a novel triple-band bandpass filter based on metamaterial resonators, achieving exceptional performance across C-, X-, and Ku-bands. The proposed filter, utilizing three modified square-shaped split-ring resonators (SRRs), exhibited distinct resonance frequencies at 6.06 GHz, 10.71 GHz, and 13.64 GHz with remarkably low insertion losses below 1.5 dB. The filter's design, implemented on Rogers RT/Duroid 6002 substrate, demonstrated optimal bandwidth distribution of 280 MHz, 416 MHz, and 725 MHz for the respective bands. The electric field distribution analysis confirmed efficient electromagnetic power transfer at all three resonance frequencies, validating the filter's operational effectiveness. The compact dimensions of the filter, combined with its multi-band capabilities and superior electrical characteristics, make it particularly well-suited for various applications in modern wireless communication systems, imaging technologies, and biomedical detection devices. These results represent a significant advancement in RF/microwave filter design, successfully addressing the growing demand for miniaturized, high-performance components in contemporary electronic systems requiring multi-band functionality.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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