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Compact Triple Notched Bandpass Filter Based on Multimode Resonator

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Abstract- This paper presents a novel approach to design a miniaturized ultra-wideband (UWB) microstrip bandpass filter (BPF) with triple notched bands using a multimode resonator (MMR). The MMR is integrated with folded high-impedance interdigital coupled-line structures, enabling the filter to achieve a UWB characteristic while offering independent control over the introduced notched bands to prevent interference with other operating systems. Additionally, the adoption of folded interdigital coupled-line structures significantly reduces the overall dimensions of the filter. The LC equivalent circuits and transfer function of the proposed MMR are extracted to analyze the behavior of the filter. To validate the design, a fabricated prototype of the proposed filter with triple notched bands at 5.4, 8.1, and 10.1 GHz, featuring attenuations exceeding -22 dB, is presented. The measured results demonstrate that the designed filter provides a passband ranging from 4.2 to 12 GHz, along with a wide rejection bandwidth of up to 20 GHz.

Index Terms- bandpass filter, multimode resonator, ultra-wideband, notch band, microstrip.

I. INTRODUCTION

High-performance UWB BPFs as an essential component in the modern UWB communication network have attracted much attention recently. Consequently, various methods have been published to develop UWB BPF by applying dual-stub-loaded resonator (DSLR) [1], stepped-impedance stubs [2, 3], interdigital structure [4], and a novel multimode resonator [5, 6]. However, UWB networks suffer from undesired radio signals caused by other existing communication systems like wireless local area networks (WLAN), etc. Thus, UWB BPFs with single/multiple-notched bands are recommended to eliminate the interfering signals [7-20]. The BPFs with a notched band using radial

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[7] and tapered impedance line [8] stub loaded resonator, multiple-mode resonator [9], and multi-layered structure [10] have been presented. To realize a wide upper stopband a ring resonator was presented in [11]. Using PIN diodes and varactors, a series of UWB bandpass filters with a controllable notch band was implemented in [12, 13]. However, all the above filters [7-13] address a single notched band within their passbands. This limitation restricts their ability to mitigate interference from multiple sources effectively.

Additionally, some of these approaches, such as the multi-layered structures employed in [11], and the utilization of active elements in [12, 13], introduce complexities in the design procedure, fabrication process, and power consumption, respectively. A compact E-shaped dual-notched BPF [14], a stepped impedance, and a radial stub loaded resonator [15] and right/left-handed stubs [16] have been proposed. However, these filters suffer from several drawbacks, such as the lack of control over the center frequencies of the notch bands and the limited upper stopbands. In [17], a wide rejection-band bandpass filter (BPF) was developed by cascading high-pass and low-pass filters. This approach aimed to achieve a wide upper stopband bandwidth; however, it resulted in an increased circuit size. Parallel U-shaped defected microstrip structure [18], triple-mode stepped impedance resonator [19], and integrated E- and T-shaped resonators into quarter wavelength short-circuited stubs [20] are utilized to generate triple notched bands. The reported performance of the filters in [18-20] indicates that they suffer from drawbacks such as poor return loss, high insertion loss, and occupying a large area. These limitations in performance and physical footprint can hinder their practical applicability and integration in compact electronic systems.

This paper presents a novel method for designing a miniaturized UWB BPF with triple-notched bands. The proposed design utilizes a new MMR that offers independent control over all the notched bands, allowing for effective rejection of interference signals within the passband region. The selected passband frequency ranges of 4.2 to 12 GHz is associated with specific applications and services, including microwave links, satellite communication, wireless broadband, and point-to-point communication, which allows for high-speed data transmission and long-range communication. Also, the chosen frequency bands were carefully selected to target common sources of interference and ensure effective communication within the desired UWB range. For example, the 5.4 GHz frequency band is often associated with Wi-Fi communication in the 5 GHz bands, which are widely used for wireless networking. By incorporating a notched band at 5.4 GHz, our design can effectively suppress interference from nearby Wi-Fi systems. Similarly, the 8.1 GHz frequency band is commonly used in radar systems for various applications, including weather radar, marine radar, and military radar. By incorporating a notched band at 8.1 GHz, our design can mitigate potential interference from radar signals. The 10.1 GHz frequency band is frequently employed in satellite communications for various purposes, including uplink and downlink transmissions. By incorporating a notched band at 10.1 GHz, our design can suppress interference from satellite communication systems.

To validate the design, the proposed filter was fabricated on Roger 5880 substrate with $\varepsilon r = 2.2$ and h = 20mil, achieving triple notched bands located at fz1 = 5.4 GHz, fz2 = 8.1 GHz, and fz3 = 10.1 GHz. The fabrication process ensures the practical implementation and functionality of the designed filter according to the specified requirements.

II. FILTER DESIGN AND CHARACTERISTIC

The structure of the proposed UWB BPF is illustrated in Fig. 1. The design incorporates a folded interdigital coupled-line section connected to a novel MMR. The MMR consists of a cross-shaped stub-loaded ring resonator and two pairs of stepped-impedance stubs. The folded coupled-line section on both sides enables the filter to achieve an ultra-wide rejection band. The folded coupled-line section on both sides leads to an ultra-wide rejection band. In Fig. 1, the larger pair of stepped-impedance stubs is responsible for creating a notched band at 5.4 GHz. The folded interdigital coupled lines play a crucial role in reducing the overall size of the filter while also generating a narrow-band notch at 8.1 GHz. The other notched band with center frequency at 10.1 GHz is excited due to a cross-shaped stub in the ring resonator. Additionally, the presence of a cross-shaped stub within the ring resonator contributes to the excitation of another notched band centered at 10.1 GHz. The combination of the folded interdigital coupled-line section and the unique features of the multimode resonator allows for effective rejection of unwanted signals within the specified frequency bands. The proposed design offers both size reduction and the ability to control and achieve multiple notched bands. Fig. 2 illustrates the S11 frequency responses and the resonance frequencies fz1, fz2, and fz3 as a function of different physical parameters. Fig. 2(b) demonstrates the impact of increasing parameter g3, which leads to a reduction in fz1 while keeping the other notched bands unchanged. This parameter adjustment allows for independent control over the location of the first notched band. Similarly, Fig. 2(c) depicts the effect of parameter g1 on fz2. By varying g1, the position of the second notched band can be manipulated while maintaining the other notched bands relatively constant. Furthermore, Fig. 2(d) illustrates how the value of parameter w3 influences the location of fz3, while the remaining notched bands remain mostly invariant. This characteristic provides the flexibility to individually tune and control the third notched band.

Consequently, the proposed design enables the independent tuning of three separate notched bands, empowering the filter to effectively reject unwanted signals from co-existing communication networks. The ability to adjust these parameters offers versatility in mitigating interference and tailoring the filter response according to specific application requirements.

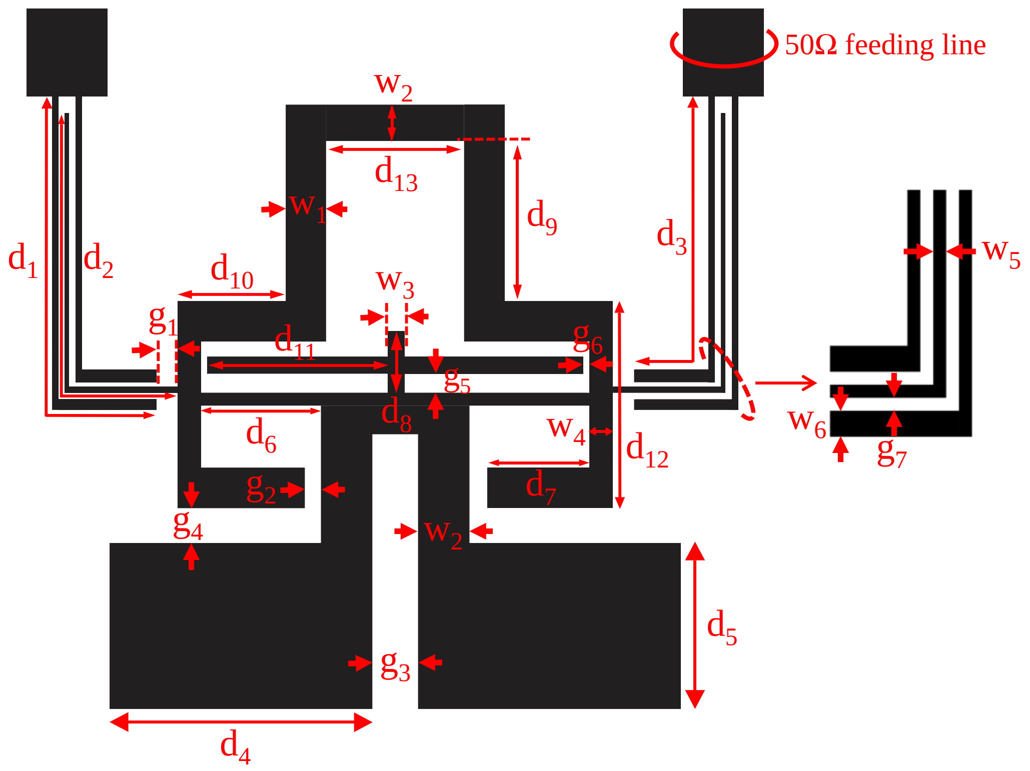
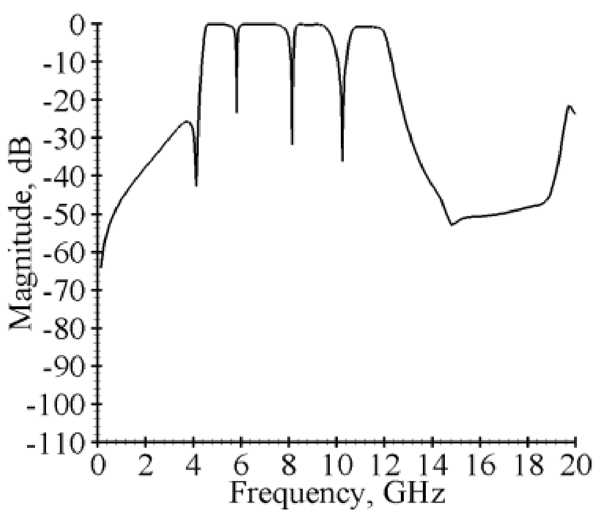
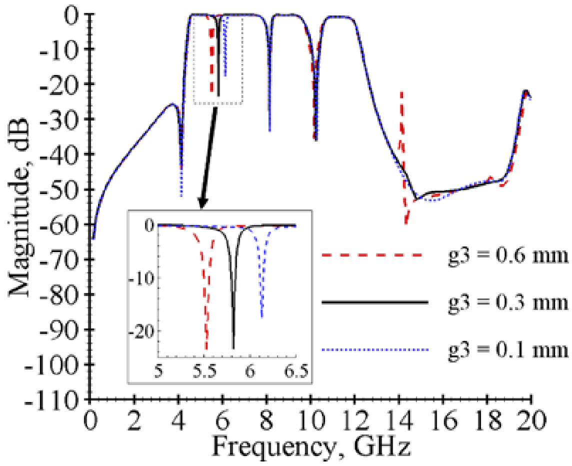


Fig. 1. Structre of the proposed UWB filter with triple-notched bands.



(a)



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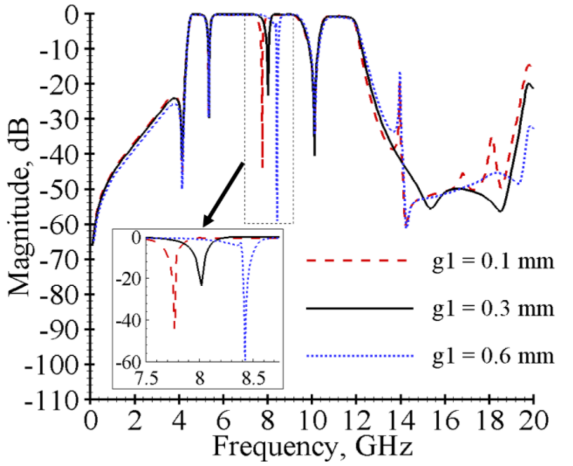
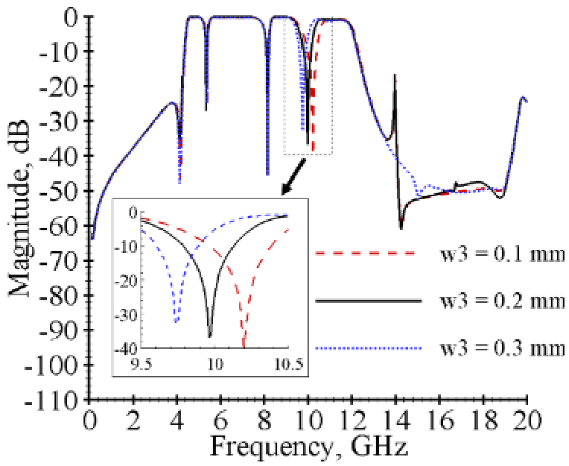


(c)



(d)

Fig. 2. Frequency responses of (a) proposed filter at resonant frequencies (b) fz1, (c) fz2, and (d) fz3 versus different physical parameters.

III. MODEL ANALYSIS AND MEASURED RESULTS

Fig. 3(a) illustrates the configuration of the designed MMR. The proposed MMR exhibits a symmetrical structure, which allows for the representation of a half-equivalent LC circuit as depicted in Fig. 3(b). This circuit provides a simplified representation of the resonator and enables the calculation of the capacitor and inductor values. These values can be determined using formulas based on the low-high impedance lossless line and open-end principles [21]. By extracting transfer function in Equation (1) from the LC model, the filter can be analyzed, where r is a resistance corresponding to feeding lines in series with input and output terminal (r =50 Ω).

By setting the transfer function to zero, the resonance frequencies of the first and second notched bands can be obtained, as expressed in Equations (2) and (3) respectively. However, the equation governing the third notched band is complex and tedious to present here. To address this complexity, an equation based on the physical parameters is provided for the determination of the resonance frequency of the third notched band (fz3). This equation, denoted as Equation (4), allows for the adaptation of the position of the fz3 band primarily by varying the values of parameter w3. By manipulating the value of w3, one can observe a corresponding shift in fz3. For instance, when w3 varies between 0.1, 0.2, and 0.3 mm, the corresponding values of fz3 are 9.7, 9.9, and 10.1 GHz respectively, as demonstrated in Fig. 2(d).

$$\frac{vo}{vi}=\frac{r\left(2ab^2+s\left(b^2(2l_2+l_3+l_4)+2bl_2(l_2+l_3)s+{l_2}^2l_3s^2\right)\right)}{\begin{array}{c}2ab^2r+b(b(2l_2+l_3+l_4)r+2a(2(l_1+l_2)+l_3)(b+r)s+\\(b(4a(l_1+l_2)(l_1+l_2+l_3)+2bl_1(2l_2+l_3)+b(2(l_1+l_2)+l_3)l_4)+\\(2bl_2(2l_1+l_2)+2(a+b)(l_1+l_2)l_3+b(2(l_1+l_2)+l_3)l_4)r)s^2+\\2b(2l_1l_2(l_1+l_2)+l_1(l_1+2l_2)l_3+(l_1+l_2)(l_1+l_2+l_3)l_4)+\\(2a(l_1+l_2)^2l_3+l_3(l_2(2l_1+l_2)+(l_1+l_1)l_4)r)s^3+\\(l_1+l_2)l_3(2l_1l_2+(l_1+l_2)l_4)s^4\end{array}} \quad (1)$$

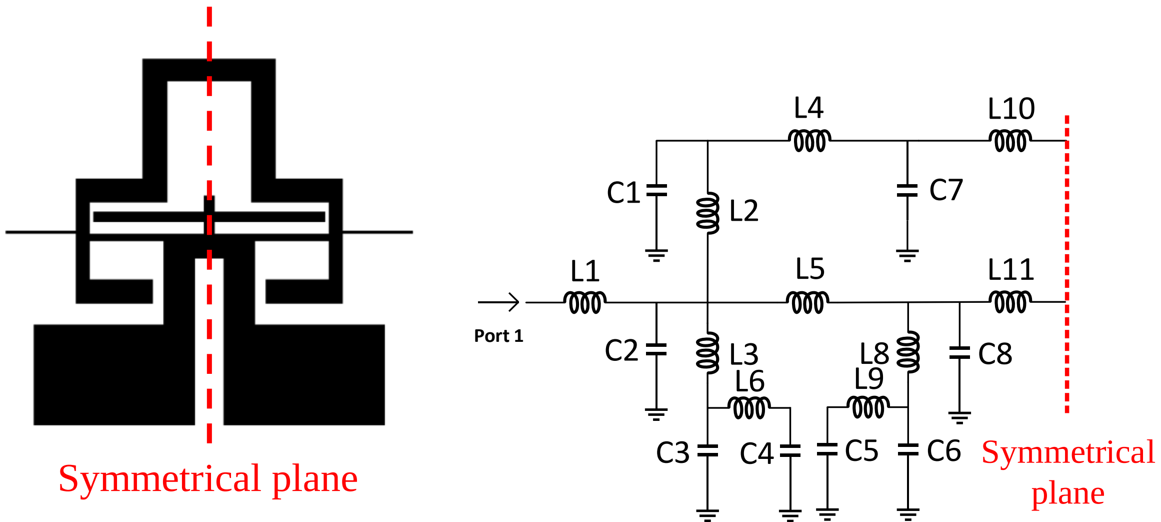
$$a=\frac{1+(c_2l_5+c_3(l_5+l_6)s^2+c_2c_3l_5l_6s^4}{\begin{array}{c}(s(c_1+c_2+c_3+(c_1(c_2+c_3)l_5+(c_1+c_2)c_3l_6)s^2+\\(c_1c_2c_3l_5l_6s^4)\end{array}}$$

$$b=\frac{1+\left(c_5l_7+c_6(l_7+l_8)\right)s^2+c_5c_6l_7l_8s^4}{\begin{array}{c}s(c_4+c_5+c_6+(c_4(c_5+c_6)l_7+(c_4+c_5)c_6l_8)s^2+\\(c_4c_5c_6l_7l_8s^4)\end{array}}$$

$$f_{z1}=-\frac{1}{8\pi}\sqrt{\frac{-c_4c6(l_7+l_8)-c_5(c_4l_7+c6l_8)+\sqrt{-4c_4c_5c6(c_4+c_5+c6)l_7l_8+(c_4(c_5+c6)l_7+(c_4+c_5)c6l_8)^2}}{c_4c5c6l_7l_8}} \quad (2)$$

$$f_{z2}=\frac{5\sqrt{-\frac{1}{c5l7+c6(l7+l8)+\sqrt{-4c5c6l7l8+(c5l7+c6(l7+l8))^2}}}}{4\pi\sqrt{2}} \quad (3)$$

$$f_{z3} = 9.7 + 1.425 \times \left|\frac{w_3 - 0.3}{2}\right| - \left|\frac{(w_3 - 0.3)^2}{2}\right| - \left|\frac{(w_3 - 0.3)^4}{2}\right| \tag{4}$$

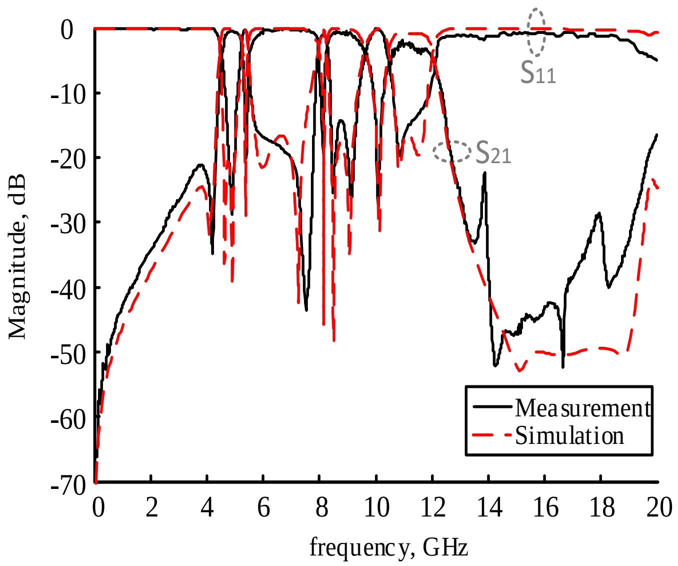


(a) (b)

Fig. 3. (a) Structure of the proposed MMR and (b) LC model.

In this paper, the filter dimensions are fixed as follows: d1 = 7.3 mm, d2 = 6.9 mm, d3 = 6.4 mm, d4 = 4.6 mm, d5 = 2.9 mm, d6 = 2.1 mm, d7 = 1.8 mm, d8 = 1.1 mm, d9 = 2.8 mm, d10 = 1.9 mm, d11 = 3.15 mm, d12 = 3.6 mm, d13 = 2.4, w1 = 0.7 mm, w2 = 0.65 mm, w3 = 0.3 mm, w4 = 0.4 mm, w5 = 0.1 mm, w6 = 0.2 mm, g1 = 0.4 mm, g2 = 0.2 mm, g3 = 0.8 mm, g4 = 0.6 mm, g5 = 0.35 mm, g6 = 0.1 mm, g7 = 0.1 mm.

The equivalent LC values of proposed filter are L1 = 4.77 nH, L2 = 1.24 nH, L3 = 0.93 nH, L4 = 0.89 nH, L5 = 0.37 nH, L6 = 1.53 nH, L7 = 0.6 nH, L8 = 0.3 nH, C1 = 0.159 pF, C2 = 0.18 pF, C3 = 0.06 pF, C4 = 0.166 pF, C5 = 0.37 pF, C6 = 0.476pF.



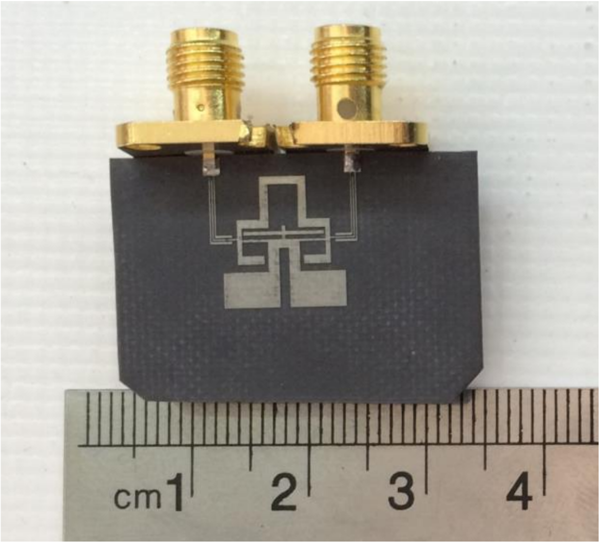


Fig. 4: (a) Designed filter S-parameters. (b) Fabricated filter.

The simulated and experimental results exhibit a satisfactory level of similarity, as demonstrated in Fig. 4(a). A photograph of the fabricated BPF is provided in Fig. 4(b). The designed BPF features a passband ranging from 4.2 to 12 GHz, characterized by low insertion loss below 0.8 dB. Notably, the filter incorporates three notched bands with significant suppressions exceeding -22 dB, located at 5.4 GHz, 8.1 GHz, and 10.1 GHz. Furthermore, the proposed UWB BPF demonstrates an extended upper stopband reaching up to 20 GHz.

TABLE I. Proposed Filter versus Previous Designs

Ref.	NB@ (GHz)	Roll-off rate	RL (dB)	US (GHz)	Circuit Size (λg × λg)
[1]	-	34	14.3	18	0.51 × 0.33
[5]	5.5	135	5	16	0.74 × 0.88
[9]	5.3/7.8	27	6	30	1.02× 0.54
[10]	5.2/5.8/8.0	34	12	17	0.63 × 0.36
[11]	5.2/5.85/8.0	10	10	20	0.7 × 0.45
This Work	5.4/8.1/10.1	135	16	20	0.45 × 0.39

NB: Notch-band; ζ: Roll-off rate; RL: Return loss; US: Upper-stopband with 20dB; λg is the free space wavelength at 8.1 GHz

It is worth mentioning that the degradation of measured insertion loss, especially at higher frequencies, is primarily attributed to the effects of the SMA connectors. The choice of connectors becomes critical as the frequency increases, and the use of high-performance connectors would have been preferable. Furthermore, the use of a proper metal box or shielded enclosure can minimize the effects of connectors and external interference, resulting in a more accurate measurement environment. Additionally, the effects of connectors can be mitigated by designing and employing appropriate calibration kits to compensate for any inherent losses introduced by the connectors. To emphasize the advantages of the designed circuit, a comparison with recently published UWB BPFs is presented in Table I. This comparison highlights the superior performance and unique features offered by the proposed design, further establishing its contribution to the field of UWB filtering.

IV. CONCLUSION

This paper introduces a novel structure for achieving a compact ultra-wideband (UWB) bandpass filter with triple notched bands. The proposed design utilizes a folded interdigital coupled-line section connected to a multimode resonator, allowing for independent control of the notched bands. This enables the filter to effectively reject unwanted signals from co-existing communication networks. To validate the performance of the proposed design, a UWB bandpass filter with triple notched bands centered at 5.4, 8.1, and 10.1 GHz is fabricated. Experimental results demonstrate that the filter exhibits a sharp skirt, excellent passband performance, and a wide upper stopband. These characteristics make it well-suited for applications in modern UWB wireless technology.

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