

Design of Compact Ultra-Wideband Filter with Triple Notch Bands Based on Cross-Shaped Anti-Shorted Coupled Lines

Hai-Hang Xu¹, Yu-Bo Liu¹, Li-Rong Qian¹, Cui-Ping Li¹,
Dan Li¹, Hong-Lang Li², and Li-Tian Wang^{1,*}

¹Tianjin Key Laboratory of Film Electronic and Communication Devices
School of Integrated Circuit Science and Engineering, Tianjin University of Technology, Tianjin 300384, China
²National Center for Nanoscience and Technology, Beijing 100190, China

ABSTRACT: In this paper, a compact ultra-wideband (UWB) bandpass filter (BPF) with triple-notch bands (TNBs) is proposed and demonstrated. We present a cross-shaped anti-shortened coupled-line structure employing a single coupled multi-mode resonator (MMR), whose resonant characteristics and intrinsic transmission zeros are investigated by employing the even-odd mode analysis method. In addition, the three notch bands are generated from the resonator's intrinsic transmission zeros without requiring any additional notch circuits. At the same time, their center frequencies can be quasi-independently controlled by properly adjusting the microstrip electrical lengths. For demonstration, the proposed filter is designed, fabricated, and measured. Simulated and measured results are in good agreement. The measured results agree well with theoretical predictions, which exhibit superior performance, such as triple-notch bands, high skirt selectivity, an ultra-wide passband from 2.8 to 12.5 GHz with a fractional bandwidth of 138%, a compact size of only 7.7 mm × 9.2 mm, and effective notched-band suppression levels.

1. INTRODUCTION

Ultra-wideband (UWB) bandpass filters (BPFs) are essential passive components in UWB front-ends, enabling high-speed data transmission and rapid system response through their ultra-wide bandwidth. The Federal Communications Commission (FCC) of the United States authorized the unlicensed use of the UWB spectrum from 3.1 to 10.6 GHz for short-range wireless communications [1]. UWB filter design has emerged as a critical research area. Unlike conventional wideband filters, UWB filters are characterized by an exceptionally large fractional bandwidth of approximately 109%. However, this ultra-wide passband inevitably overlaps with existing narrowband services, including C-band satellite communications, X-band radar, and WLAN signals, rendering UWB systems susceptible to severe narrowband interference [2]. To suppress such interference and improve the signal-to-noise ratio (SNR), integrating notch bands within the UWB passband has become a widely adopted strategy. Numerous UWB BPF designs with notch-band functionality have been reported, primarily employing multi-mode resonators (MMRs) [3], defected ground structures (DGSs) [4], and composite right/left-handed (CRLH) transmission lines [5]. While these approaches have successfully demonstrated single- or dual-notch-band (DNB) responses, they generally suffer from fundamental limitations: insufficient transmission zero sharpness [6–9], narrow upper stopbands [10], and the inability to support multiple independently tunable notch bands [3, 5].

The first MMR-based UWB filter achieving a fractional bandwidth of 100% was reported in 2005 [11], which established the foundation for subsequent wideband designs. Since then, numerous UWB filters employing techniques such as multi-stub-loaded lines, stepped-impedance resonators, and ring resonators have been developed [12, 13]. As the spectral environment grew more complex, the demand evolved from single-notch to double-notch-band (DNB) filters, and Ref. [14] provides a comprehensive review of DNB filter design and analysis. While the aforementioned filters can realize DNBs, the proliferation of 5G and other narrowband services has created an urgent demand for filters, supporting multiple notch bands, such as triple-notch bands (TNBs). However, many existing UWB filters achieve TNBs through the use of multiple resonant modes [15] or cascaded MMRs [16], which inevitably increase circuit size and complicate tuning process.

For instance, Wang et al. proposed a TNB UWB BPF using a triple-mode stepped-impedance resonator (SIR) with a DGS, achieving a fractional bandwidth of 114% but at the cost of a relatively large footprint (16 mm × 8 mm) and increased structural complexity due to external multi-mode resonators [17]. Similarly, Cao et al. presented a wide-stopband dual-notched UWB filter based on a novel CRLH-TL structure with out-of-band rejection exceeding 20 dB up to 28 GHz, yet it supports only dual notch bands without independent tunability [18]. Kalita et al. designed a compact UWB microstrip BPF on a low-cost FR4 substrate with a fractional bandwidth of 105.2%, but the absence of notch-band functionality leaves it vulnerable to narrowband interference [19]. These examples illustrate a persistent trade-off in existing designs: achieving multiple notch

* Corresponding author: Litian Wang (wanglitianrf@sina.com).

bands typically requires sacrificing either compactness, independent tunability, or skirt selectivity.

Among the unresolved challenges, most reported TNB filters still depend on cascaded resonators or external stub networks, leading to large circuit footprints and cumbersome tuning processes. Moreover, conventional external notch circuits introduce additional components that complicate the overall design and offer limited independent control over individual notch frequencies. Meanwhile, miniaturized alternatives often exhibit degraded skirt selectivity and insufficient notch depth owing to the reduced resonator quality factor. A compact UWB BPF architecture, which achieves triple-notch suppression through the resonator's intrinsic properties rather than through external networks, while maintaining largely independent notch tunability and steep skirt selectivity at both passband edges and notch frequencies, therefore remains highly desirable.

To address these challenges, this paper proposes a compact UWB BPF based on a single coupled MMR incorporating a cross-shaped anti-shortened coupled-line (ASCL) structure. The ASCL refers to a parallel coupled-line section, where the inner ends are shorted to ground through via holes while the outer ends remain open-circuited, a concept previously explored in dual-band designs [20]. Unlike conventional approaches that rely on external notch networks, all three notch bands originate from the resonator's intrinsic transmission zeros, thereby eliminating additional notch circuitry, while achieving sharp skirt selectivity. The stopband frequencies are largely decoupled by design: the first two notches are governed by the ASCL sections, whereas the third notch is primarily controlled by the center-loaded stub. This configuration enables largely independent tuning of the three notch bands with minimal impact on the overall passband response. The proposed architecture achieves an exceptionally compact size of 7.7 mm × 9.2 mm, which is significantly smaller than prior TNB UWB filters, while simultaneously realizing an ultra-wide passband with steep skirt selectivity at both passband edges and notch frequencies. The measured results of the fabricated prototype show good agreement with the full-wave EM simulation, validating the proposed compact design and its triple-notch filtering mechanism.

2. ANALYSIS AND DESIGN METHODOLOGY

The ideal transmission-line model (TLM) of the proposed ultra-wideband bandpass filter with triple notch bands is shown in Fig. 1. The passive filtering structure is formed by a cross-shaped anti-shortened coupled-line architecture, which consists of parallel coupled lines (PCL), an anti-shortened parallel coupled-line (ASPCL) section, and a center-loaded shorted stub. The corresponding electrical lengths and characteristic admittances are denoted by θ_i (where $i = 1, 2, 3, 4, 5, 6$) and Y_j (for $j = 1, 2, 3, 4, 5, 6$), respectively. Additionally, to satisfy external coupling requirements, a lumped capacitor of C_1 is introduced within the feeding line. For simplicity, the admittances in the TLM are normalized as: $Y_2 = Y_4 = Y_6 = 2Y_1 = 2Y_3 = 2Y_5$. As shown in Fig. 1, the structure is symmetrical about the $A-A'$ plane.

When the proposed circuit is subjected to even-mode excitation, the symmetry plane behaves as a magnetic wall, yielding

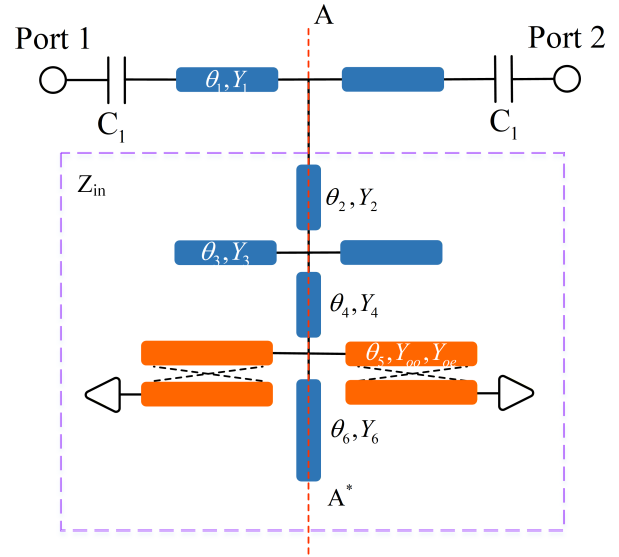


FIGURE 1. Ideal transmission-line model of triple-notch band UWB filter.

the even-mode equivalent circuit shown in Fig. 2(a). For the even-mode equivalent circuit, the resonance conditions are determined by setting the imaginary part of the input admittance to zero:

$$\text{Im}(Y_{in_even}) = 0 \quad (1)$$

where Y can be expressed as:

$$Y_{in_even} = Y \frac{jY \tan \theta_3 + Y_{inA} + jY \tan(\theta_1 + \theta_2)}{Y + Y_{inA} \tan(\theta_1 + \theta_2) - Y \tan(\theta_1 + \theta_2) \tan \theta_3} \quad (2)$$

in which the intermediate admittance terms are given by:

$$Y_{inA} = Y \frac{Y_{inB} + jY \tan \theta_4}{Y + jY_{inB} \tan \theta_4} \quad (3)$$

$$Y_{inB} = j \frac{2(Z_{oe} + Z_{oo})}{(Z_{oe} - Z_{oo})^2} \tan \theta_5 + j \frac{Z_{oe} + Z_{oo}}{2Z_{oe}Z_{oo}} \tan \theta_5 + jY \tan \theta_6 \quad (4)$$

Similarly, when the proposed circuit is subjected to odd-mode excitation, the symmetry plane acts as an electric wall, yielding the odd-mode equivalent circuit shown in Fig. 2(b). It can be seen from Fig. 2(b) that the odd-mode resonance condition is:

$$Y_{in_odd} = -jY \cot \theta_1 \quad (5)$$

Accordingly, the transmission coefficient S_{21} of the proposed structure can be calculated using Y_{in_even} and Y_{in_odd} :

$$S_{21} = \frac{(Y_{ino} - Y_{ine})Y_0}{(Y_{ine} + Y_0)(Y_{ino} + Y_0)} \quad (6)$$

where $Y_0 = 1/Z_0 = 0.02 \text{ S}$ is the port admittance. It follows from Eq. (6) that a transmission zero, and hence a notch band,

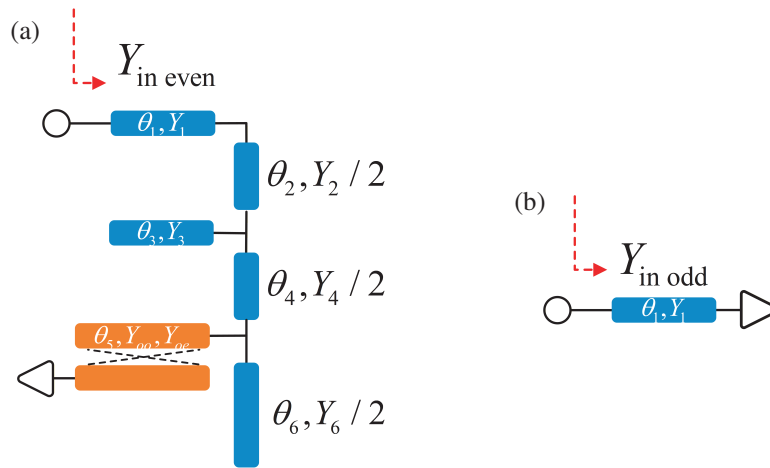


FIGURE 2. Triple-notch UWB filter. (a) Even mode equivalent circuit and (b) odd mode equivalent circuit.

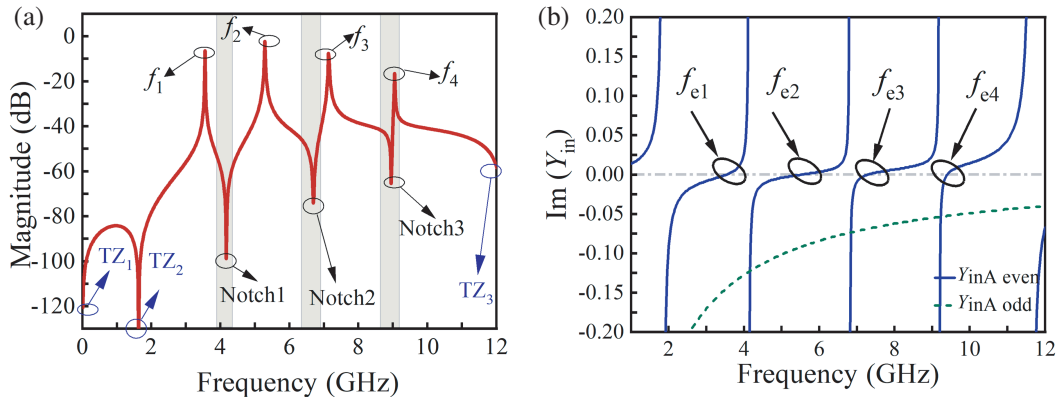


FIGURE 3. (a) Transmission coefficient $|S_{21}|$ of the weakly coupled UWB filter and (b) imaginary part of input admittances for even- and odd-mode excitations.

is produced when the transmission coefficient S_{21} approaches zero:

$$Y_{ino} = Y_{ine} \quad (7)$$

Subsequently, numerical solutions for the electrical lengths are obtained using MATLAB. The initial electrical lengths are set as $\theta_1 = \theta_2 = \theta_3 = \theta_5/2 = 60^\circ$, $\theta_4 = \theta_6 = 30^\circ$, with the reference frequency for electrical-length calculation taken as the UWB center frequency of 6.9 GHz.

Figure 3(a) shows four resonant peaks at frequencies f_1, f_2, f_3 , and f_4 . Among them, resonant peaks f_1 and f_4 collectively define the center frequency and bandwidth of the proposed filter. Meanwhile, resonance peaks f_2 and f_3 are interspersed with transmission zeros Notch1, Notch2, and Notch3, thereby forming three ultra-narrow stopbands. The pole and zero locations critically determine the skirt selectivity of the notch bands and the passband edges across the UWB spectrum. The simulated resonant peaks are consistent with the even-mode analytical solutions, as shown in Fig. 3(b), where all four peaks are attributed to even-mode excitation. This indicates that the transmission poles are generated by even-mode excitation.

Figure 4 shows the frequency response $|S_{21}|$ and input impedance of the cross-shaped anti-shortened coupled-line structure. It can be seen from Fig. 4 that three narrow notch

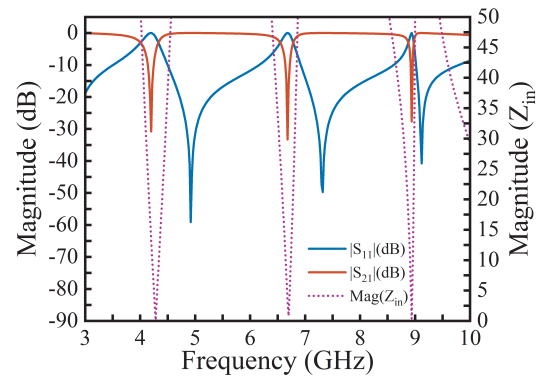


FIGURE 4. Input impedance of Z_{in} of cross shaped anti-shortened coupled lines versus $|S_{21}|$.

bands exist within the UWB passband. According to Eq. (7), a transmission zero and hence a notch band is produced when the even-mode and odd-mode input admittances satisfy $Y_{ine} = Y_{ino}$, which corresponds to a series resonance condition, where $Z_{in} = 0$. The three notch bands originate from the intrinsic transmission zeros of the single multi-mode resonator, without requiring any additional notch circuits. As illustrated in Fig. 3(b), all four resonant peaks (f_1 - f_4) are attributed to even-mode excitation, and transmission zeros

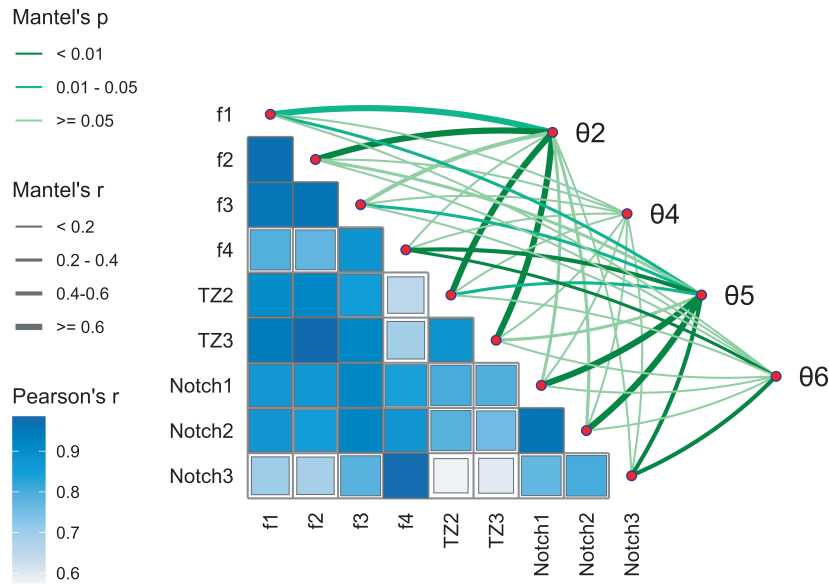


FIGURE 5. Sensitivity analysis of transmission zeros/poles to electrical lengths θ_2 , θ_4 , θ_5 and θ_6 .

Notch1, Notch2, and Notch3 are interspersed among these resonant peaks, forming three ultra-narrow stopbands with notch depths exceeding 30 dB. These zeros are located at 4.14, 6.7, and 8.96 GHz, falling within the 5G, C-band, and X-band frequency ranges, respectively.

Figure 5 presents the sensitivity analysis of the zero/pole locations to variations in θ_2 , θ_4 , θ_5 , and θ_6 . It can be observed from Fig. 5 that θ_2 dominantly controls the passband edge selectivity (TZ1/TZ2), with negligible effect on notch frequencies, while θ_4 , θ_5 and θ_6 are each closely associated with specific notch frequencies. The first two notch bands are mainly related to the parallel coupling line governed by θ_4 and θ_5 , while the third notch band can be independently controlled by θ_6 . This partially decoupled dependency among the electrical lengths provides the foundation for quasi-independent tuning of the three notch bands, which will be further elaborated in the subsequent design graphs.

Figure 6 presents the sensitivity analysis of the transmission zeros, transmission poles, and loaded quality factor Q_L to the electrical lengths θ_2 , θ_4 , θ_5 , and θ_6 . In Fig. 6(a), as θ_2 increases from 130° to 160° , the transmission zeros TZ1 and TZ2 shift slowly toward lower frequencies while the three notch bands Notch1, Notch2, and Notch3 remain almost unchanged, indicating that θ_2 has negligible influence on the notch center frequencies. Meanwhile, the loaded quality factor Q_L increases monotonically with θ_2 , demonstrating that θ_2 serves as a core parameter for tuning the coupling strength without disturbing the notch positions. The relative fractional bandwidth (FBW) and loaded quality factor Q_L of the proposed filter can be extracted as:

$$Q_L = \frac{f_0}{\Delta f_{3\text{ dB}}} \quad (8)$$

$$\text{FBW} = \frac{\Delta f_{3\text{ dB}}}{f_0} \times 100\% \quad (9)$$

where f_0 is the filter center frequency, and $\Delta f_{3\text{ dB}}$ is the 3-dB absolute bandwidth.

Figures 6(b) and 6(c) illustrate the sensitivity of the first two notch bands to θ_4 and θ_5 , respectively. It can be observed that both θ_4 and θ_5 are capable of adjusting Notch1 and Notch2, while Notch3, TZ1 and TZ2 remain unaffected in both cases. However, θ_5 exhibits a more pronounced effect on the notch frequencies than θ_4 , suggesting that θ_5 serves as the dominant tuning parameter for the first two notch bands, and θ_4 provides supplementary fine-tuning capability.

In Fig. 6(d), as θ_6 increases from 150° to 200° , only Notch3 exhibits a pronounced downward frequency shift, whereas Notch1, Notch2, TZ1, and TZ2 maintain constant frequencies, validating that θ_6 solely regulates the third notch band. These results collectively demonstrate that the three notch bands can be largely independently tuned by θ_4 , θ_5 , and θ_6 , respectively, which is the key mechanism enabling the independent tunability of the proposed triple-notch UWB BPF.

Figure 7(a) investigates the positions of Notch1 and Notch2, which vary with changes in θ_4 and θ_5 . By appropriately selecting the values of θ_4 and θ_5 , the first notch band can be tuned from 3.85 GHz to 5.15 GHz, and the second from 6.1 GHz to 8.6 GHz. Fig. 7(b) further explores the detailed trends of the proposed BPF fractional bandwidth with respect to the electrical lengths θ_4 and θ_5 . It can be observed from Fig. 7(b) that adjusting θ_4 and θ_5 does not significantly alter the filter performance over a wide range, which validates the largely independent tunability of the first two notch bands without degrading the overall passband response.

Figure 8(a) shows the transmission coefficient $|S_{21}|$ as a function of the coupling coefficient k . It can be observed that the second notch band is predominantly affected by the coupling gap g and shifts toward lower frequencies as g increases. Apart from a slight influence on the first notch, changes in k do not significantly alter the filter's passband characteristics or the

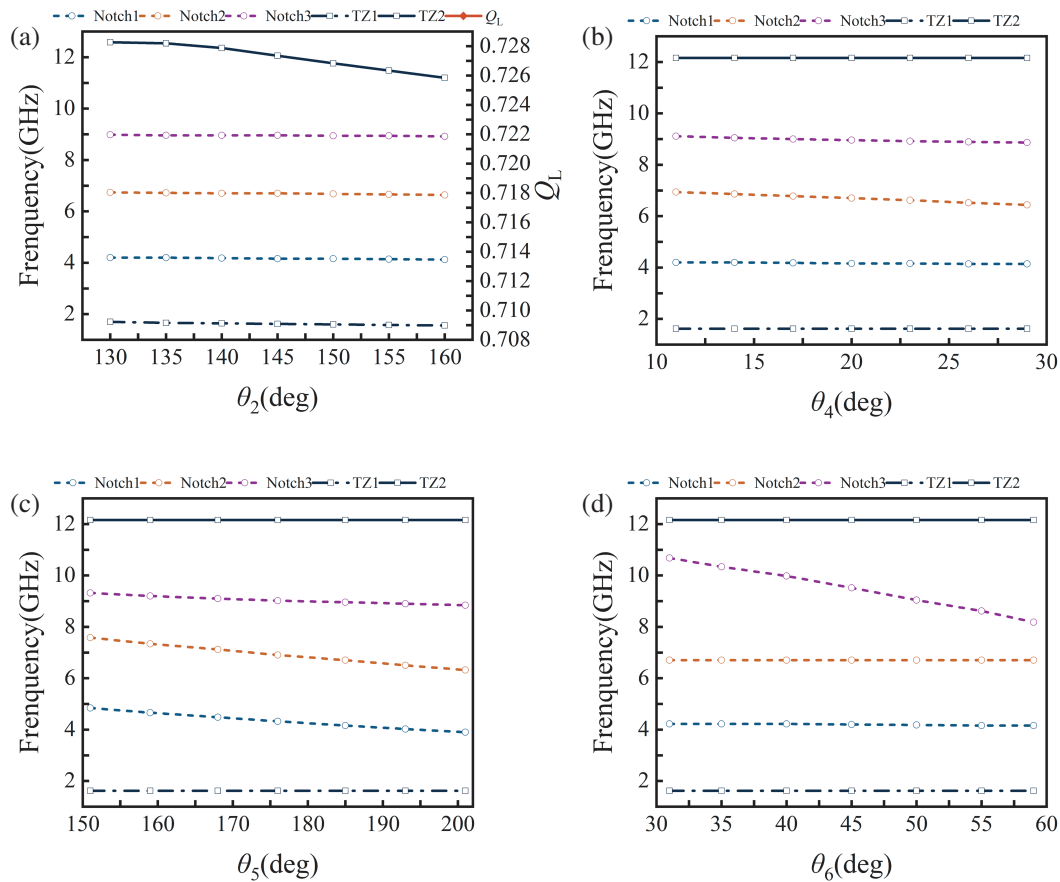


FIGURE 6. Design graph of the TPs and TZs versus varied parameters of (a) θ_2 , (b) θ_4 , (c) θ_5 , and (d) θ_6 .

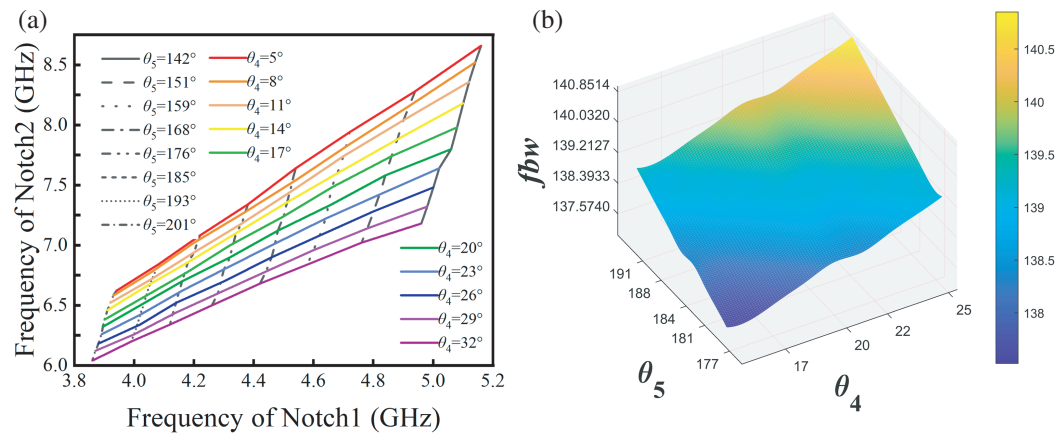


FIGURE 7. (a) Design graph of the first notch band and the second notch band versus variation of θ_4 and θ_5 and (b) design graph of FBW versus variation of θ_4 and θ_5 .

third notch. The corresponding values of k are 0.80, 0.66, 0.54, and 0.45, which correspond to coupling gaps of 0.1, 0.2, 0.3, and 0.4 mm, respectively. Fig. 8(b) demonstrates the transmission coefficient $|S_{21}|$ versus the electrical length θ_6 . The third notch region exhibits a significant response to θ_6 , shifting from 7.9 GHz to 10.4 GHz as θ_6 increases from 28° to 52° . Variations in θ_6 have negligible effects on other notch bands and the overall transmission characteristics. These results further confirm that the first two notch bands are governed by the coupling pa-

rameters, and the third notch band is independently controlled by θ_6 , validating the decoupled tuning mechanism of the proposed design.

Figure 9(a) shows the loaded quality factor Q_L as a function of C_1 . It can be observed that Q_L stabilizes when C_1 is approximately 2.5 pF or larger. Fig. 9(b) demonstrates Q_L versus the transmission line impedance Z_2 , indicating that Q_L also varies with Z_2 . Therefore, both C_1 and Z_2 can serve as effective tuning parameters to adjust the Q_L of the proposed filter. Con-

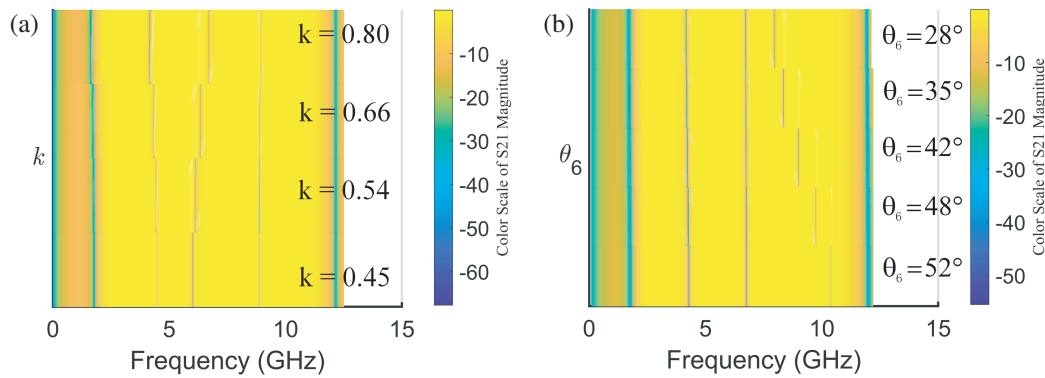


FIGURE 8. $|S_{21}|$ spectrograms: (a) Sweeping coupling coefficient k for Notch1&2 and (b) sweeping electrical length θ_6 .

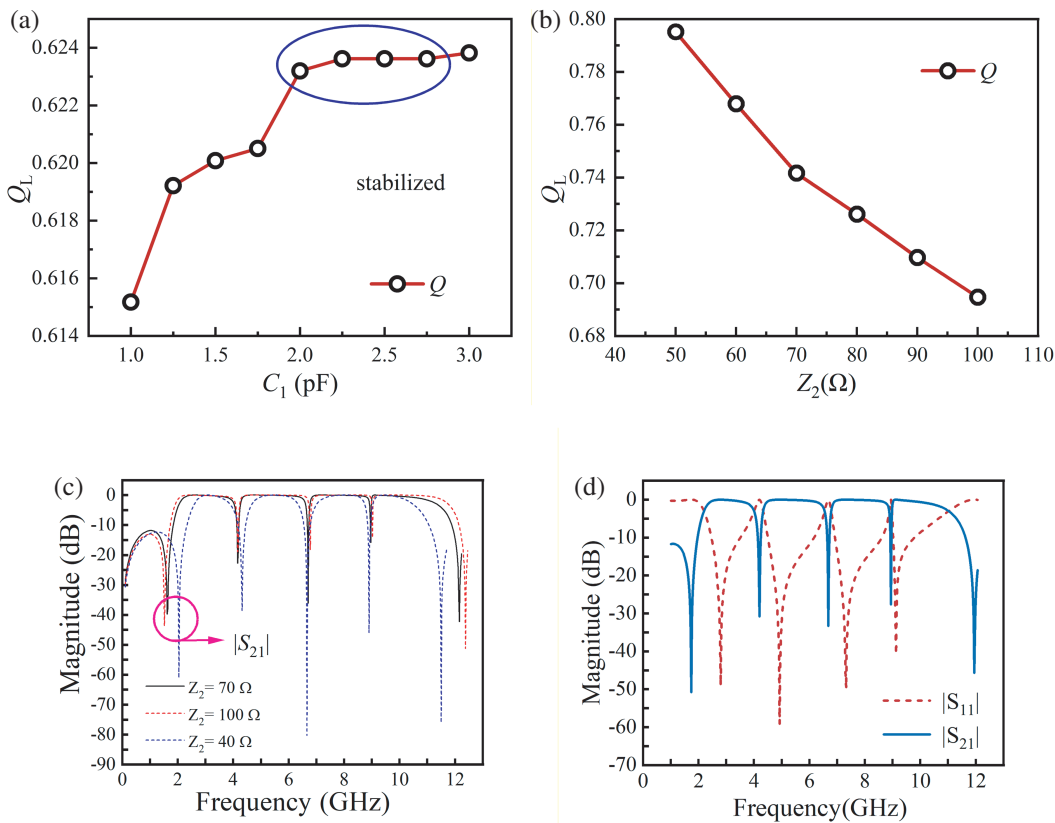


FIGURE 9. (a) Extracted Q_L against variation value of C_1 , (b) extracted Q_L against variation value of Z_2 , (c) $|S_{21}|$ frequency responses under different characteristic impedances Z_2 , and (d) circuit simulation and theoretical results.

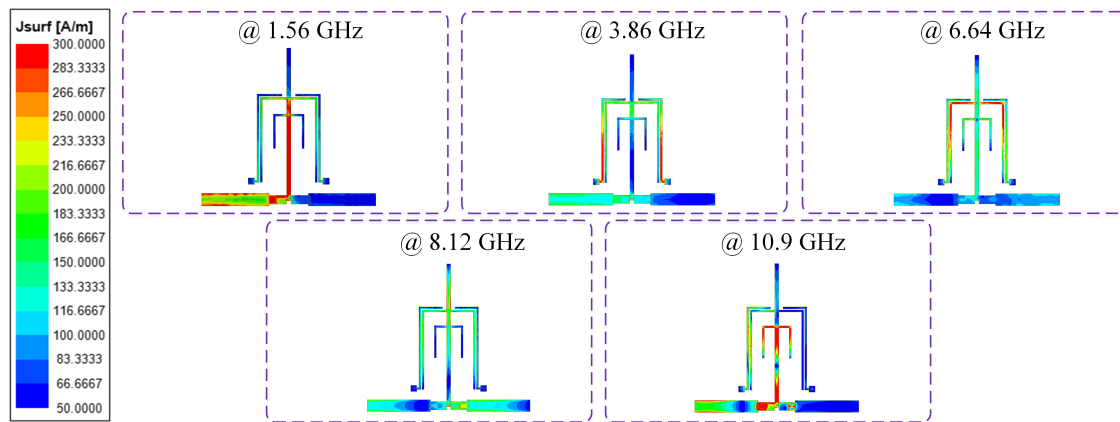
sidering the passband characteristics over a reasonable range of loaded quality factor values and aiming for effective lower stop-band suppression, a final capacitance of 2 pF is selected based on the results shown in Fig. 9(a). Fig. 9(c) illustrates the transmission coefficient $|S_{21}|$ under different values of Z_2 . It can be observed that a lower impedance Z_2 enables the filter to attain a larger bandwidth. Notably, variations in Z_2 do not shift the positions of the three notch bands, but only affect the locations of TZ1 and TZ2 at the passband edges, further confirming that the bandwidth and notch frequencies can be independently managed. Fig. 9(d) presents the optimized full-band scattering parameters $|S_{11}|$ and $|S_{21}|$ of the proposed filter, which demon-

strates an ultra-wide passband from 2.8 to 12.5 GHz with triple notch bands centered at 4.16, 6.48, and 8.21 GHz. The ideal TLM predicts a preliminary passband with a relative bandwidth of 138%, which covers both the 5G band and the FCC-defined UWB frequency band.

Table 1 summarizes the optimized circuit parameters of the proposed transmission-line model. The initial electrical lengths were set with the UWB center frequency of 6.9 GHz as reference and subsequently optimized using the design graphs in Figs. 5–9. Notably, θ_1 is significantly shortened from 60° to 12° to satisfy the input matching condition at the lower pass-band edge, and θ_2 and θ_5 are extended to 99° and 168° to en-

TABLE 1. Ideal transmission-line model parameters of the proposed UWB BPF.

Parameter	Initial value	Optimized value	Physical dimension (mm)
θ_1	60°	12°	$L_1 = 0.95, W_1 = 0.2$
θ_2	60°	99°	$L_2 = 7.475, W_2 = 0.4$
θ_3	60°	55°	$L_3 = 4.325, W_3 = 0.2$
θ_4	30°	20°	$L_4 = 1.525, W_4 = 0.4$
θ_5	120°	168°	$L_5 = 10.225, W_5 = 0.2, g = 0.1$
θ_6	30°	60°	$L_6 = 4.475, W_6 = 0.4$
Z_1, Z_3	—	107 Ω	$W = 0.2$
Z_2, Z_4, Z_6	—	83 Ω	$W = 0.4$
Z_5 (coupled line)	—	$Z_E = 150.4 \Omega, Z_O = 50.0 \Omega$	$W = 0.2, g = 0.1$

**FIGURE 10.** The current distributions for the proposed notched-band BPF at the frequencies of 1.56, 3.86, 6.64, 8.12, and 10.9 GHz.

hance the coupling strength and sharpen the skirt selectivity. The parallel coupled-line section (θ_5) is characterized by even-/odd-mode impedances $Z_E = 150.4 \Omega$ and $Z_O = 50.0 \Omega$ for $W = 0.2$ mm and $g = 0.1$ mm.

Figure 10 portrays the surface current density distribution at five characteristic frequencies. At the two transmission zeros TZ1 (1.56 GHz) and TZ2 (10.9 GHz), current concentrates along the main coupled-line path, indicating that passband edge selectivity is governed by the overall resonator structure. At Notch1 (3.86 GHz) and Notch2 (6.64 GHz), current accumulates predominantly in the ASCL sections, confirming that the first two notch bands are controlled by coupling parameters. At Notch3 (8.12 GHz), current is mainly distributed on the center-loaded shorted stub, validating that the third notch is independently governed by θ_6 . These current distributions corroborate the $Z_{in} = 0$ series resonance condition derived from the even-odd mode analysis in Fig. 4 and Eq. (7), where the three notch bands correspond to the frequencies at which the input impedance crosses zero.

The three notch bands can be largely independently tuned through distinct structural parameters, as validated by the parametric studies in Figs. 6–8. The first two notch bands are governed by the parallel coupled-line sections, where θ_5 serves as the dominant tuning parameter and θ_4 provides supplementary fine-tuning (Figs. 6(b) and 6(c)). By appropriately selecting the

values of θ_4 and θ_5 , Notch1 can be tuned over 3.85–5.15 GHz and Notch2 over 6.1–8.6 GHz, while the fractional bandwidth remains largely unaffected (Figs. 7(a) and 7(b)). In addition, the coupling coefficient k predominantly modulates the second notch band while exerting a slight influence on the first notch band, without significantly altering the third notch band or the overall passband response (Fig. 8(a)). The third notch band is independently controlled by the center-loaded shorted stub through θ_6 , which acts as an independent resonant element decoupled from the coupled-line sections. As demonstrated in Fig. 6(d) and Fig. 8(b), increasing θ_6 shifts Notch3 from 7.9 GHz to 10.4 GHz, whereas Notch1, Notch2, TZ1, and TZ2 remain at their respective frequencies.

The generalized design procedure of the proposed filter is illustrated in Fig. 11. The detailed design steps are summarized as follows:

Step I: The initial electrical lengths $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$, and θ_6 are ascertained based on the ideal transmission line model. For the sake of simplicity, these parameters are normalized, with the reference frequency taken as the UWB center frequency of 6.9 GHz.

Step II: The transmission zeros are synthesized by satisfying the input impedance conditions through the even- and odd-mode equivalent circuits shown in Fig. 2. The resonance

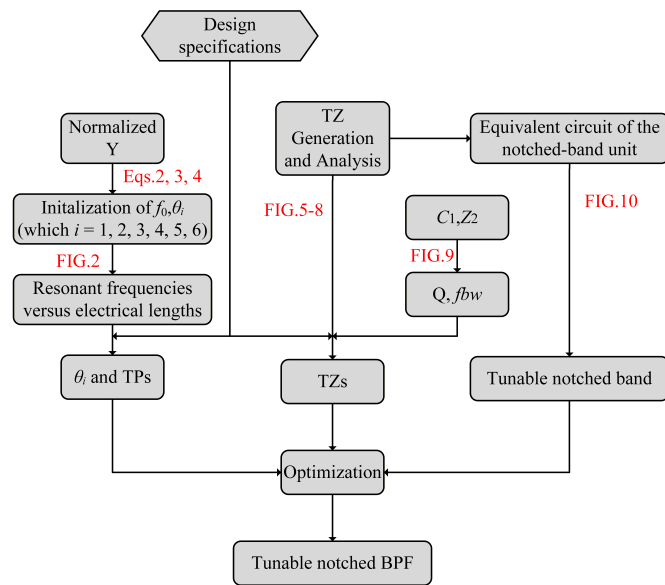


FIGURE 11. The design flowchart of the proposed BPF.

conditions are analyzed to determine the pole and zero distributions.

Step III: The positions of the three notch bands are independently controlled by adjusting the electrical lengths θ_4 , θ_5 , and θ_6 , utilizing the design graphs depicted in Figs. 5, 6, 7, and 8.

Step IV: The loaded quality factor Q_L and the FBW is optimized by selecting appropriate values of C_1 and Z_2 , as illustrated in Fig. 9.

Step V: The design parameters are optimized using a full-wave electromagnetic simulator. The final miniaturized physical dimensions are achieved by meandering the transmission lines and miniaturizing the layout to obtain a compact footprint of $7.7 \text{ mm} \times 9.2 \text{ mm}$.

3. FABRICATION AND MEASUREMENT

In this section, a prototype BPF is implemented to verify the design approach. To validate the feasibility of the design scheme, the proposed BPF is fabricated on the Rogers 4003C substrate with a dielectric constant ϵ_r of 3.55, substrate thickness h of 20 mil, metal layer thickness t of 0.035 mm, and loss tangent $\tan \delta$ of 0.0027. An embedded lumped capacitor element of 2 pF is introduced within the feeding line to satisfy external coupling requirements. The detailed structural parameters are as follows: $L_1 = 0.95$, $L_2 = 7.475$, $L_3 = 4.325$, $L_4 = 1.525$, $L_5 = 10.225$, $L_6 = 4.475$, $W_1 = W_3 = W_5 = 0.2$, $W_2 = W_4 = W_6 = 0.4$, and $g = 0.1$ (unit: mm). The layout of the proposed BPF is precisely determined by using full-wave EM solver optimization, as depicted in Fig. 12. The final circuit size is $7.7 \text{ mm} \times 9.2 \text{ mm}$, excluding the feeding lines.

Once the SMA connectors were soldered, the assembly was complete. Fig. 13 shows the photograph of the fabricated prototype UWB BPF. An Anritsu MS4644A vector network an-

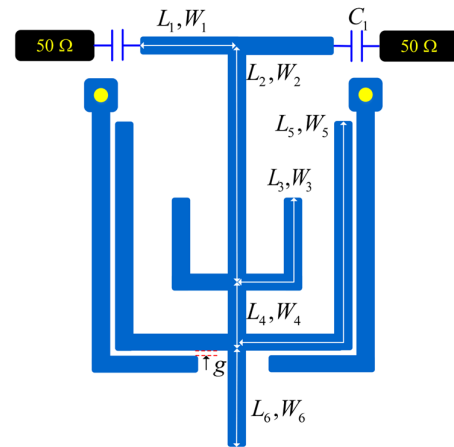


FIGURE 12. Geometrical configuration of the proposed BPF.

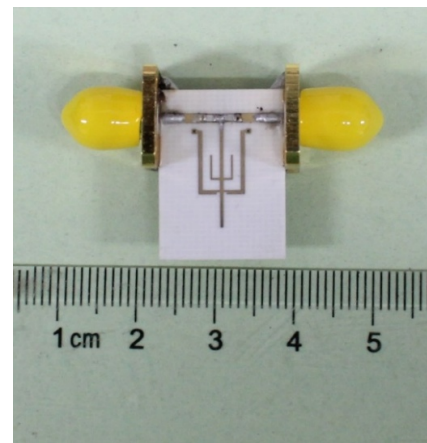


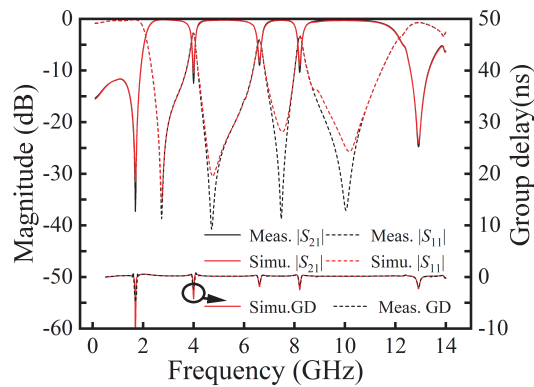
FIGURE 13. The photograph of the fabricated notched band BPF.

alyzer was used to test the assembled filter. Before measurement, a full two-port SOLT (Short-Open-Load-Thru) calibration was performed using the standard calibration kit over the frequency range of 100 MHz to 20 GHz. The measured results demonstrate an ultra-wide passband from 2.8 to 12.5 GHz, in good agreement with the full-wave EM simulation. The ideal TLM predicts notch depths exceeding 30 dB, while the EM simulation of the compact bent layout shows approximately 10–12 dB corresponding to a degradation of roughly 18–20 dB in notch depth. This degradation is primarily attributed to parasitic cross-coupling between non-parallel segments introduced by layout bending, which effectively lowers the resonator's unloaded Q-factor at notch frequencies. Despite this reduction, the notch depths remain well above the minimum required for practical narrowband interference suppression, demonstrating that the notch depth trade-off is fully justified by the compact footprint of $7.7 \text{ mm} \times 9.2 \text{ mm}$. The simulated in-band insertion loss remains below 0.12 dB, whereas the measured passband loss is subject to additional connector and fabrication tolerances. As depicted in Fig. 14, the measured results agree reasonably well with the bent-layout EM simulation, validating the proposed design methodology. The filter exhibits an ultra-wideband response with triple notched bands at 4.16, 6.48, and 8.21 GHz, corresponding to the 5G, C-band, and X-band satel-

TABLE 2. Comparison with the reported UWB BPFs.

Ref.	TZs at PBE		Notch band (GHz)/ attenuation (dB)	IL (dB)	Size (mm)	FBW	IT	RC	NM	GD (ns)
[7]	×	×	5.2/5.8/8.0, > 10	—	27 × 15	119%	✓	TMSIR	External TMSIR coupling	< 1
[8]	×	×	5.2/5.8/6.8, > 15	0.6	18.5 × 18	99%	✓	MMR	TMSIR/interdigital coupling	< 1
[16]	✓	✓	4.4/5.5/7.6, > 15	0.9	34 × 11	106%	✓	MMR	MMR multimode resonance	0.25–0.45
[17]	✓	✓	4.4/5.3/8.2, > 15	—	16 × 8	114%	×	DGS	Dual SIRs on SCRLH-TL	< 1
[21]	✓	✓	2.9/5.7/6.4, > 10	—	13 × 12	83%	✓	SLRR/DGS	SSLSIRs embedded in SLRR	0.7–5
[22]	✓	✓	5.2/5.9/7.9, > 15	1.5	34 × 11.7	108.5%	✓	SIR	Stub tuning, ICL	0.1–0.45
[23]	✓	✓	5.1/6.0/8.0, > 10	1	30 × 11	127%	✓	TSIR	External TSIR coupling	—
This work	✓	✓	4.2/6.5/8.2, > 10	0.12	7.7 × 9.2	138%	✓	MMR	Intrinsic TZs	0.13–0.5

PBE = Passband Edges; IL = Insertion Loss; FBW = Fractional Bandwidth; IT = Independent Tunability; RC = Resonator Configuration; NM = Notch Mechanism; GD = Group Delay

**FIGURE 14.** Comparison of simulated and measured results of TNBs UWB filter, including S -parameter magnitudes and group delay (GD).

lite signals, respectively. The measured notch depths are 10.23, 9.31, and 10.26 dB, respectively, slightly exceeding the EM-simulated values and confirming effective suppression at the targeted interference bands. The measured group delay varies from 0.13 to 0.5 ns within the passband, exhibiting a relatively flat response that confirms good phase linearity suitable for UWB pulse transmission. At the three notch frequencies, the group delay exhibits sharp peaks, which is expected due to the steep transmission zeros at these frequencies. The measured group delay is in good agreement with the simulated results, further validating the accuracy of the proposed design.

To further evaluate the proposed filter, a comprehensive comparison with recently reported triple-notch UWB BPFs is provided in Table 2. The proposed design exhibits the following distinct advantages. In terms of resonator configuration, a single coupled multi-mode resonator is employed instead of multiple cascaded resonators or external stub networks, resulting in the smallest circuit footprint of $7.7 \times 9.2 \text{ mm}^2$. Regarding the notch-generation mechanism, all three notch bands originate from the intrinsic transmission zeros of the single resonator without any additional notch circuitry, which is fundamentally different from conventional designs that rely on external coupling, embedded stubs, or defected ground structures. The proposed filter achieves a low insertion loss, effective notch sup-

pression exceeding 10 dB, and a return loss above 10 dB across the passband, which are comparable to or better than reported designs. Furthermore, the measured group delay remains below 1 ns within the passband, confirming good phase linearity. Combined with the widest fractional bandwidth of 138% and the triple independently tunable notch bands, the proposed design demonstrates clear advantages over previously reported triple-notch UWB filters.

4. CONCLUSION

In this paper, a compact UWB BPF with triple largely independently tunable notch bands is proposed and validated. Based on the odd-even-mode analysis method, the resonant characteristics of the cross-shaped anti-shortened coupled-line resonator are investigated. Due to the intrinsic transmission zeros of the single multi-mode resonator, three notch bands are constructed to suppress narrowband interference without additional notch circuitry. Furthermore, the positions of the three notch bands can be largely independently controlled by adjusting the electrical lengths θ_4 , θ_5 and θ_6 . The loaded quality factor Q_L and the FBW can be managed by selecting appropriate values of C_1 and Z_2 . The fabricated prototype achieves an ultra-wide passband from 2.8 to 12.5 GHz with triple notch bands centered at 4.16, 6.48, and 8.21 GHz, while maintaining a compact footprint of only $7.7 \text{ mm} \times 9.2 \text{ mm}$. Compared with the reported TNB UWB filters, the proposed design exhibits a smaller circuit footprint and a wider fractional bandwidth of 138%. The measurement results are in good agreement with the theoretical predictions. It is foreseen that this compact triple-notch UWB BPF will be widely applicable in future UWB front-end systems.

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