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A Bandpass Filter with Triple-Narrow Notch Bands Based on Metamaterials SRR Configurations for UWB Applications

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***Abstract*-This paper presents a bandpass filter (BPF) with three narrow notched bands designed for ultra-wideband (UWB) applications. Initially, a basic UWB BPF is designed using a microstrip multimode resonator (MMR) with an open stepped impedance stub loaded at its center. Following that, the Split-Ring Resonator (SRR) is used to generate a triple narrow notched band, allowing undesired signals to be rejected. The frequency range is 2.81 GHz to 10.2 GHz. Beyond this range, there is a strong rejection. Notably, three narrowly notched bands at 5.29, 5.83, and 7.99 GHz are used to achieve in-band interference cancellation, with -3dB fractional bandwidths of 2.64%, 2.91%, and 1.77%, and rejection levels of -17.15 dB, -11.65 dB, and -11.56 dB, respectively. This filter simultaneously has three main advantages: it is simple, rejects unwanted signals within the bandwidth without affecting the adjacent signals, and achieved high selectivity, the simulation and measurement results show a good agreement, demonstrating effective filtering performance, with a compact dimension of 25.9 x 13.7 mm^2.**

***Index Terms-* Microstrip, Multimode Resonator, Notched, Split Ring Resonator, Band pass Filter.**

I. INTRODUCTION

Ultra-wideband (UWB) systems operate in the frequency range between 3.1 and 10.6 GHz. Until 2001, UWBs were mostly used for military purposes. Since 2002, however, [1] the Federal Communications Commission (FCC) has gradually allowed commercial use of this frequency spectrum. UWB connections have many attractive characteristics, such as very low power consumption, ability to pass through obstacles, good speed and accuracy. BPF integration is critical in UWB telecommunication systems, this enables the system to accept or reject specific frequencies[2]. As a result, considerable effort has been expended in proposing solutions for designing high-performance UWB BPF [3-9]. A demonstration of UWB BPF using a multiple-mode resonator (MMR) in [3]. While [4] presents an UWB BPF using a stub-loaded MMR. A dual-stub-loaded resonators (DSLR) was used in[5].In [6] the authors proposed UWB BPF using a stepped-impedance stub-loaded resonator (SISLR). Another technique was introduced in [7],built on a grounded square patch resonator. As for [8],it was demonstrated that a systematic approach for synthesizing the UWB filter responses employs low-pass and high-pass sections.[9]Presents a UWB BPF based on an asymmetric stepped impedance resonator (ASIR). The presence of in-band interference is another critical factor to consider when designing UWB bandpass filters (BPF). Other narrowband services, in particular, operate in the frequency bands used by UWB systems. These include Wi-Max operations at 3.6 GHz, WLAN operations at both 5.2 GHz, 5.8 GHz, and a communication allocation at 8 GHz for satellite use. To cancel this in-band interference, it is extremely necessary to design a UWB BPF with multiple notched bands. Various design methods were used to integrate notched bands within the UWB BPF [10-17].In [10-11]the stub loaded MMR was used, [10] Uses MMR with a single stub with only one notch width band where [11] Shorting Stub uses MMR Very complex design with via, [12-13] used shaped resonators;[12] used T and E-shaped resonators loaded with short-circuited stubs(Poor selectivity);[13] used E and C-shaped

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resonators(Complex design and large size);[14] and [15] used respectively defected ground structures (complex design with DGS) and Defected Microstrip Structure(Poor selectivity Via and DMS are used) in [16]using an open stub in an inverted T-Shaped Resonator(only one notch)in [17] modified genetic algorithms (MGA) are employed to design the main structure of the filter(Poor selectivity and via is used).

This article presents a new simple microstrip UWB BPF with triple narrow notch bands using metamaterial SRR. The design techniques are as follows: initially, a UWB BPF is designed using a stepped-impedance stub-loaded resonator (SISLR) that gives high selectivity of the filter, subsequently narrow stop-bands are formed by attaching the metamaterials SRR to the basic microstrip UWB BPF, which rejects undesired signals in the bandwidth without affecting adjacent signals. The proposed filter is realized and measured; and a good agreement is achieved between simulated and measured results.

II. BASIC UWB FILTER DESIGN

As shown in Fig. 1(a), the UWB BPF is composed with a microstrip-line multiple-mode resonator (MMR). This MMR is a low-impedance half-wavelength line section ($L_1 = \lambda g/2$, λg refers to the guided-wavelength at 6.85 GHz) in the middle, connected on both sides by greater impedance quarter-wavelength line sections ($L_2 = \lambda_g/4$).And loaded at the center with a stepped-impedance open stub(SIS)[3]-[6]-[18]-[19].The latter was folded into the design to reduce the size of the structure. The inter-digital coupled lines are used to release a good coupling at the desired bandwidths. The suggested updated MMR has a symmetrical structure Fig. 1(a). Odd- and even-mode analysis can be used to describe it. Figs. 1(b) and 1(c), the input admittances for each resonance are expressed as follows:

$$Y_{in\,odd} = Y_1 \frac{Y_{in\,o1} + jY_1 \tan\theta_1}{Y_1 + jY_{in\,o1}\tan\theta_1} \quad ,Y_{in\,o1} = \frac{Y_2}{j\tan\theta} \tag{1}$$

$$Y_{in\,even} = Y_1 \frac{Y_{in\,e1} + jY_1 \tan\theta_1}{Y_1 + jY_{in\,e1}\tan\theta_1} \tag{2}$$

$$Y_{in\,e1} = Y_2 \frac{Y_{in\,e2} + jY_2 \tan\theta_2}{Y_2 + jY_{in\,e2}\tan\theta_2} \tag{3}$$

$$Y_{in\,e2} = Y_3 \frac{Y_{in\,e3} + jY_3 \tan\theta_3}{Y_3 + jY_{in\,e3}\tan\theta_3} \tag{4}$$

$$Y_{in\,e3} = jY_4 \tan\theta_4 \tag{5}$$

where Y_i and θ_i indicate respectively the characteristic admittance and the electric length of the microstrip line i.

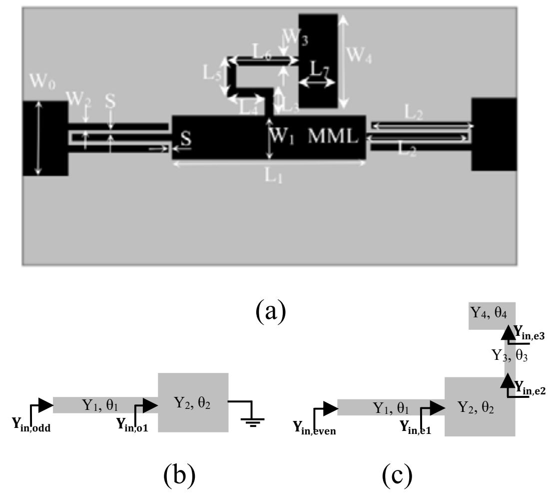

Fig.1. (a) Structure of UWB filter basic, (b)odd-mode equivalent circuit of the resonator(b) Even-modeequivalent circuit of the resonator

The resonance conditions of odd and even mode, respectively, are: $\mathrm{Y_{in\,odd}} = 0$(tow frequencies) and $\mathrm{Y_{in\,even}} = 0$(thry frequencies), and the transmission zero condition is obtained when $\mathrm{Y_{in\,odd}}= \mathrm{Y_{in\,even}}$,this condition is fulfilled only if $\mathrm{Y_{in\,e2}} \rightarrow \infty$ which gives tow transmission zero.

To simplify the design of proposed structure, we start by designing a filter without SIS ($\theta_3 = \theta_4 = 0$) and ($\theta_1 = \theta_2$), in the next stage and by tuning admittances ratio(Y_1/Y_2) of the MML we get a UWB BPF with two resonances in odd mode and one in even mode, as shown in Fig. 2 in the case of MML without SIS for weak coupling. Enhancing the coupling improves the filter response as shown in Fig. 2 in the case of MML without SIS for strong coupling. then the insertion of the SIS into the center of the MMR, and by tuning his parameters, that introduced two additional resonant at even modes (Equation 2)

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and a pair of transmission zeros located on each side of this bandwidth, as shown in Fig. 2 in the case of MML with SIS for weak coupling.

The parameters of the SISLR (MML+SIS) are tuned to produce the five resonant modes. and a pair of transmission zeros (ftz1 and ftz2) to realize the UWB passband bandwidth [6] .The S-parameter of a two-port network may be calculated using the formulas 6 and 7 [20].

Using a substrate with a thickness of 1.524 mm and a relative permittivity of 3.55, this filter was optimized and simulated using a 3D electromagnetic simulator tool. Table 1 shows the optimized design parameters of the basic filter.

$$S_{11} = \frac{Y_{in\ odd}Y_{in\ even} - Y_0^2}{(Y_{in\ odd} + Y_0)(Y_{in\ even} + Y_0)} \quad (6)$$

$$S_{21} = \frac{Y_{in\ odd}Y_0 - Y_{in\ even}Y_0}{(Y_{in\ odd} + Y_0)(Y_{in\ even} + Y_0)} \quad (7)$$

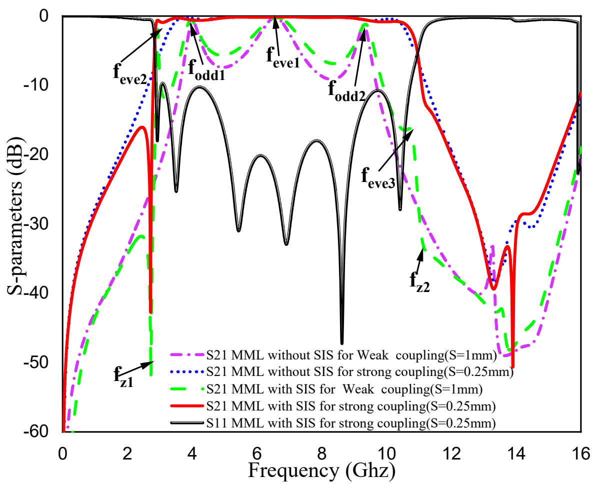

Fig.2.Simulated S21 of the filter with and without a SIS structure for weak and strong coupling.

Table 1 Optimized parameters of the basic filter.

Parameter	L_1	W_1	L_2	W_2	L_3	L_4	L_5
Value(mm)	12.24	2.5	6.65	0.34	1.4	2	2.4
Parameter	L_6	W_3	L_7	W_4	S	W_0	
Value(mm)	3.4	0.2	2	5.7	0.2	3.38	

As shown in Fig. 2 in the case of MML with SIS for strong coupling, the reached performances are acceptable, namely, the fractional bandwidth (FBW) is 116.3% around the central frequency of 6.82 GHz and a pair of transmission zeros on each side of this bandwidth. (2.71 GHz and 11.25 GHz), As a result, a clear cutoff is achieved, ensuring considerable out-of-band rejection. In addition, over the entire bandwidth, S_{11} not exceeding -14 dB is maintained.

III.PARAMETRIC INVESTIGATION ON THE NOTCH PERFORMANCE

The notched band can be achieved by coupling the SRR to the main structure of the filter Fig. 3. In this section, we will observe the impact of each of its parameters, namely, L_r, W_r, g_r, and S, on the overall response of the filter.

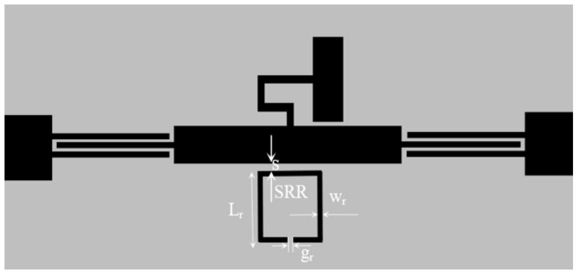

Fig.3.Illustrates the basic structure of the filter with different SRR parameters

Fig. 4 shows the effects of parameter L_r on the notch. It can be seen from this figure that when L_r increases from 3.31 mm to 4.6 mm, the resonance frequency decreases from 8.4 GHz to 5.7 GHz.

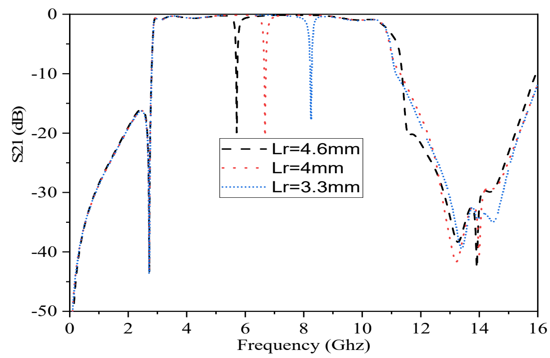

Fig.4. S_{21} of the filter with SRR for various L_r values.

The effect of the parameter W_r on the notch performances, namely, the resonant frequency of the notch (N-f), the 3dB FBW of the notch (N-FBW), and the notch attenuation (N-At), is shown in Fig. 5(a). It can be seen that increasing W_r from 0.2 to 1 mm reduces the notch's resonance frequency from 5.7 to 5.52 GHz as well as the 3 dB notch FBW from 2.27% to 2% but increases the attenuation from -19.9 to -18.2 dB.

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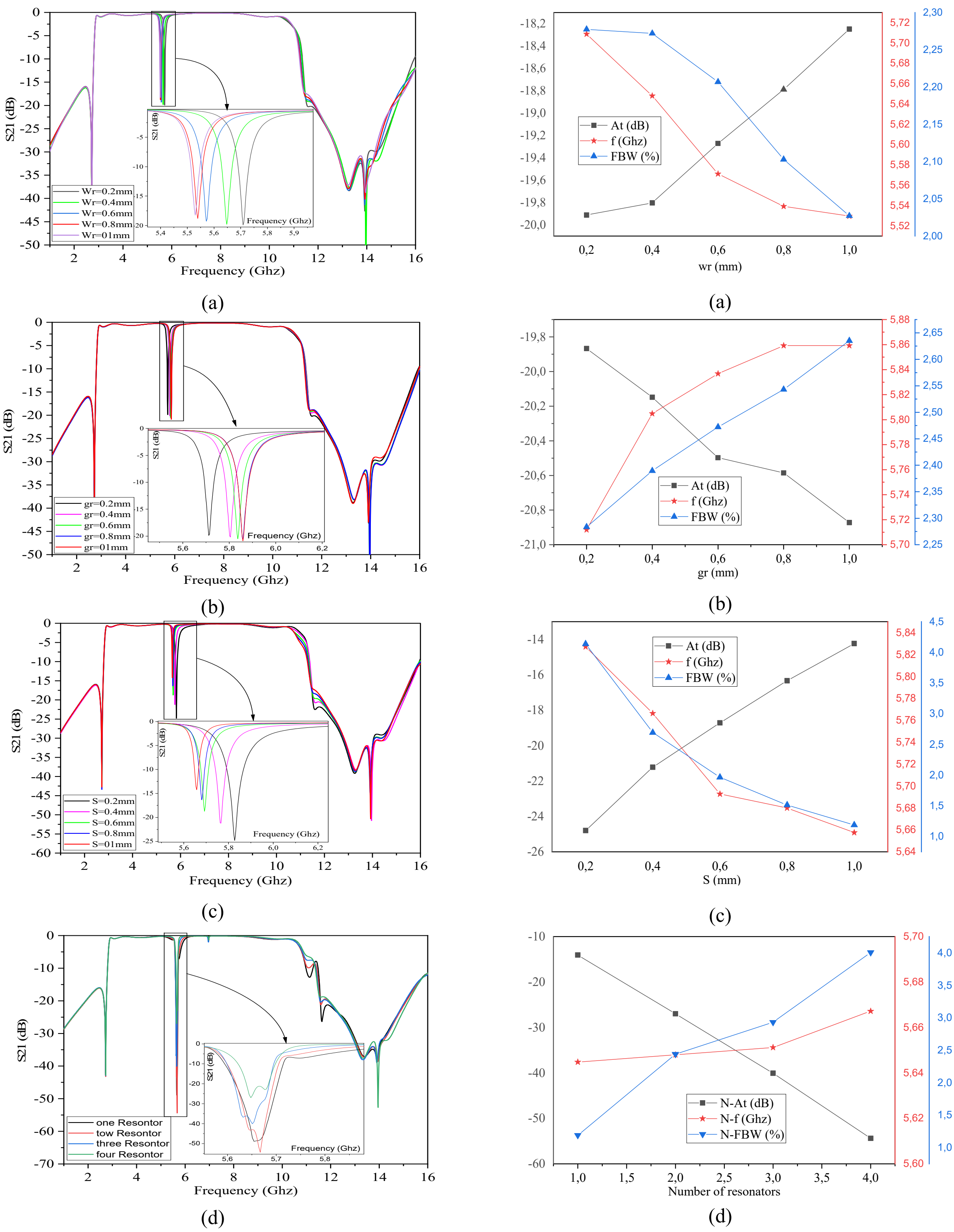

Fig.5. The influence of parameters (a) W_r, (b) g_r, (c) S, and (d) Number of SRR on notch performance

Fig.5(b) shows that increasing gr from 0.2 to 1 mm, the resonance frequency of the notch increases from 5.71 to 5.86 GHz, the 3 dB FBW increases from 2.28 % to 2.63%, and the attenuation decreases from -19.86 to -20.87 dB.

As for Fig.5(c), raising the gap (S) from 0.2 to 1 mm leads to a lower resonance frequency from 5.82 to 5.65 GHz and a 3 dB FBW from 4.13% to 1.18%, but increases the attenuation of the notch from -24.79 to -14.23 dB.

Another relevant parameter is the number of resonators. As shown in Fig. 5(d), when the number of resonators increases from one to four, the 3 dB FBW increases from 1.19% to 4%, and the notch depth decreases from -14 to -54.39 dB with negligible effect some at the resonant frequency.

The optimal parameters of the suggested UWB BPF with triple narrow notch bands with high performance based on this study are presented in Fig.6, and the final values are details in Table 2. The overall filter size is 25.9mm x 13.7mm.

Table 2. Optimized parameters of the filter.

Parameter	L_{r1}	L_{r2}	L_{r3}	W_{r1}	W_{r2}
Value(mm)	5	4.55	3.41	0.25	0.25
Parameter	W_{r3}	g_{r1}	g_{r2}	g_{r3}	S_1
Value(mm)	0.25	0.25	0.25	0.25	1.35
Parameter	S_2	S_3	d_1	d_2	d_3
Value(mm)	1.39	1.25	16.31	16.4	2.95

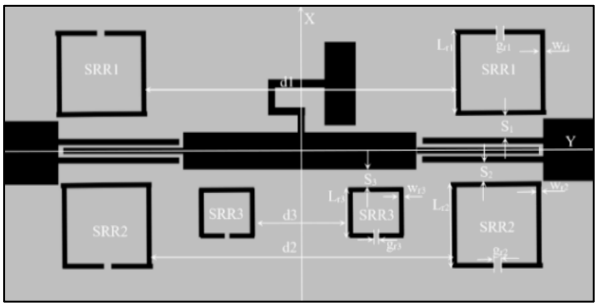

Fig. 6. Structure of the proposed UWB filter

IV. EQUIVALENT CIRCUIT OF THE FILTER

To investigate the behavior of the suggested filter, an equivalent circuit is studied. In the first step, the designed filter without stepped-impedance open stub is presented in Fig.7(a) (simple structure with microstrip model). The equivalent RLC circuit of this filter is shown in Fig.7(b). From the response of this filter by lines-microstrip model (S_{21} Fig.7(c)), it can be concluded that the proposed filter behaves like a 3rd-order Chebyshev filter and has a symmetrical structure with one resonant frequency $f_0 = f(L_1, C_1)$in the even mode and two resonant frequency in odd mode f_1 and $f_2 = (L_1, C_1, L_2, C_2)$,we can see that L_1, C_1 they describe the filter center frequency and L_2, C_2 describe the width of that bandwidth. The lumped components are optimized and tuned using Advanced Design System software to obtain the band pass characteristic. The simulated S-parameter of the microstrip-lines model and the equivalent circuit model are compared, as shown in Fig.7(c).

According to the comparative study, the given circuit is applicable to the filter structure. Indeed, the circuit parameters achieved are summarized in Table 3:

Table 3. Optimized lumped components of simple structure of the filter.

Parameter	$L_1 = L_3$	$C_1 = C_3$	L_2	C_2
Value	1.07nH	0.76pF	1.30nH	0.63pF

In the second stage, an equivalent to an order 5 elliptical filter is produced by introducing a stepped-impedance open stub (refer to Fig. 8(a)), as shown in Fig. 8(b). The filter must be optimized and adjusted in order to obtain symmetry

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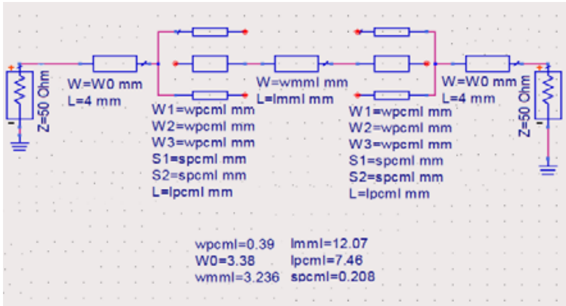
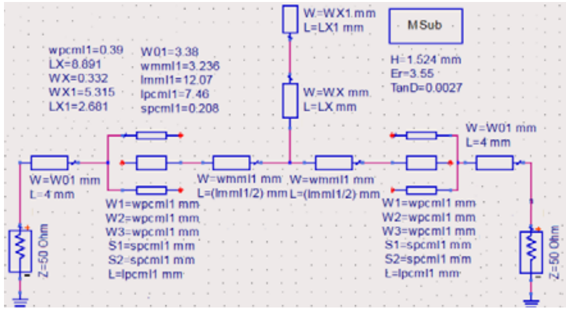
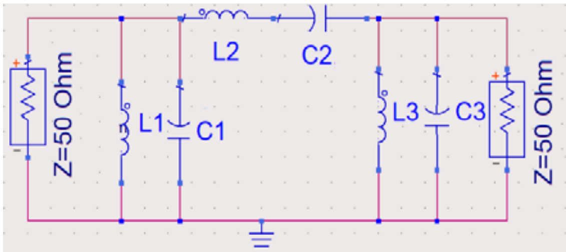


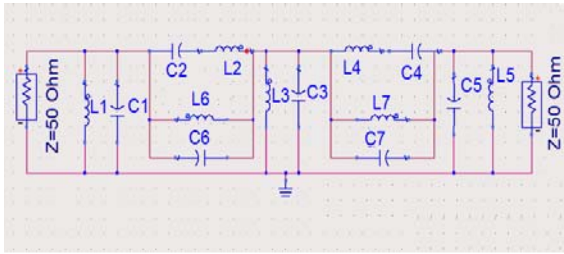
(a)



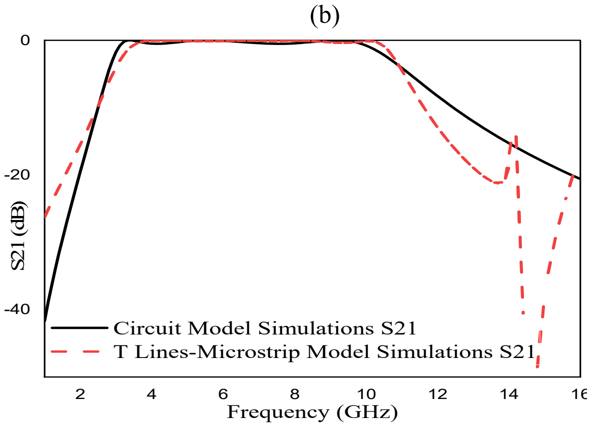
(a)



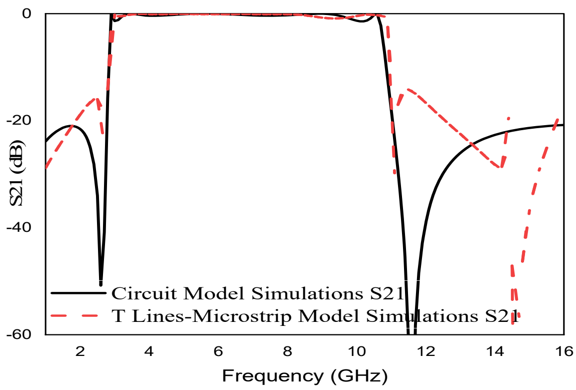
(b)



(b)



(c)



(c)

Fig. 7. (a) Simple structure of the filter by TLines-Microstrip model (b) by RLC circuit and (c) Comparative S parameter between a and b

Fig. 8. (a) Structure of the filter with SISLR by TLines-Microstrip model (b) by RLC circuit and (c) Comparative S parameter between a and

The MMR profile dimensions, which are the approximate equivalent function of the inductances (L_1, L_2, L_3,L_4, and L_5) and capacitances (C_1, C_2, C_3, C_4, and C_5),determine the band pass width of the filter. The parallel resonant circuits (L_6, C_6 and L_7, C_7) are the estimated stepped-impedance open stub.

The circuit parameters optimized are summarized in table4

Table 4. Optimized lumped components of the filter.

Parameter	L_1/L_5	C_1/C_5	L_2/L_4	C_2/C_4
Value	1.945nH	0.419pF	0.590nH	1.380pF
Parameter	L_6/L_7	C_6/C_7	L_3	C_3
Value	1.565nH	0.536pF	1.759nH	0.463Pf

Fig.8(c) depicts a comparison of the simulated S-parameters for the Microstrip-Lines model with the corresponding circuit model. The observed circuit is appropriate for the filter structure based on the comparison study

V. RESULTS AND DISCUSSION

The suggested UWB BPF with three narrow notch bands has been validated experimentally. It was manufactured on a Rogers's 4003C substrate with a 1.524 mm thickness, a relative permittivity of 3.55, and a dissipation factor of 0.0027. Fig.9 presents a photograph of the manufactured filter. The S-parameter was measured using a PNA Network Analyzer (N5224A). a good agreement was achieved between simulated and measured results, as seen in Fig. 10 and 11. The measured bandwidth is from 2.81 to 10.2 GHz, and a wide upper-stopband up to 16 GHz with a -10-dB attenuation is realized. The return loss(S_{11}) is not greater than -14 dB over the greater part of the passband (VSWR< 1.5). Very high in-ban interference cancellation was achieved thanks to the narrow-notched bands occurring at the frequencies of 5.29 GHz, 5.83 GHz, and 7.99 GHz and having 3 dB N-FBW of 2.64%, 2.91%, and 1.77%, as well as rejection levels of -17.15 dB, -11.65 dB, and -11.56 dB, respectively. Also, the measured group delay has a maximum deviation of 0.5 ns in the passband, as seen in Fig. 12. As a result, the desired passband has an excellent linear phase response, avoiding any signal distortion when the filter is integrated into a UWB front-end. The small mismatch between simulation and measurement could be explained by the limited resolution of measurement, the fabrication error process, and the soldering process of the SMA connectors.

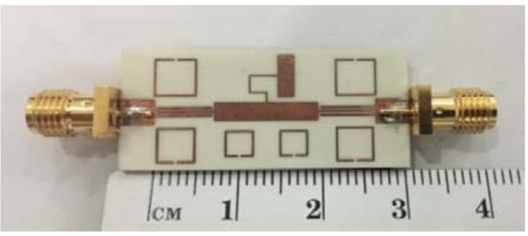


Fig. 9. Photographs of the UWB BPF with triple narrow notch bands

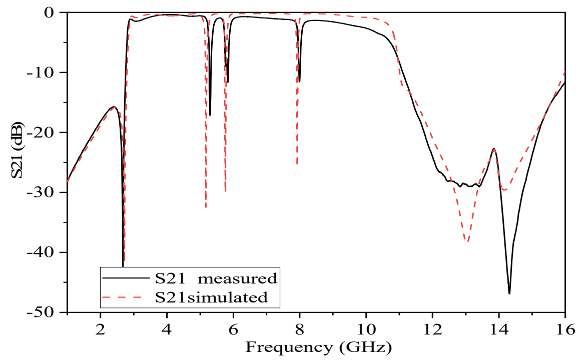


Fig. 10. Comparison between simulated and measured S21

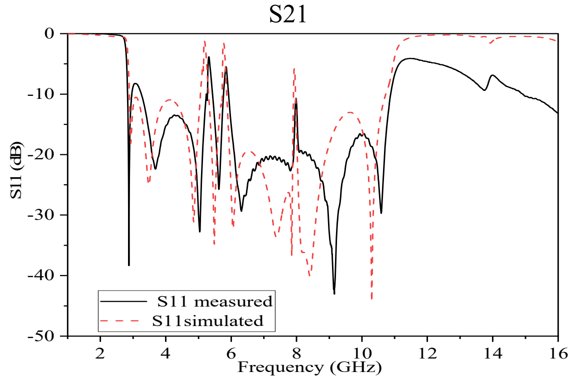


Fig. 11. Comparison between simulated and measured S11

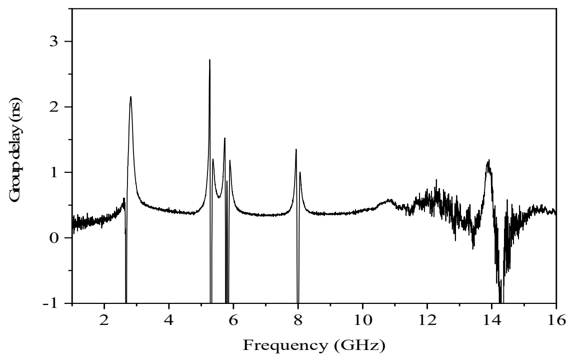


Fig. 12. Measured group delay

Table 5 summarizes the comparisons with other studies on the same topic. It could be observed that the proposed filter achieves competitive performance. With a very simple structure without Via, defected ground, high selectivity, compact size, and an extremely narrow notch band, which allowed to reject undesirable signals without affecting adjacent signals.

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Table 5. A comparison between the proposed design and recently published works.

Ref	ε_r /Size (mm)	-3dB FBW(%)/f0(GHz)	selectivity	VSWR	Notches Freq. (GHz)/ Attenuation(dB).	-3dB FBW(%)of each Notch	Nbr of notches
[12]	3.66/34X12	116/6.7	poor	< 1.7	3.3 /5.1 /8.3>15	24.24/12.06/ 7.8	3
[13]	2.33/32.4X26.7	109.9/6.85	good	< 1.8	3.6/5.3/8.4>16	7.58/4.88/2.83	3
[14]	2.65/30X16	118/6.9	good	< 1.9	5.3/7.8>20	10.56/11.02	2
[15]	4.4/30X10	104.9/7.15	poor	< 1.6	4.6/5.6/8.0/>15	1.96/1.75/1.12	3
[17]	3.38/NA	109.6/7.14	poor	< 1.6	4.5/5.9/8.0>NA	5.3/2.8/3.3	3
[21]	2.2/30X32	109.8/6.84	poor	< 1.6	7.2>20	4.72	1
[22]	2.2/ 32 X10	123.9/6.62	poor	<1.4	3.5/7.5>17	15.91/09.63	2
[23]	2.2/32.3X13	98.5/6.7	medium	< 1.8	5.2>22.7	21.15	1
[24]	2.65/35.4X28	111.42/7	medium	< 1.7	5.8/8.7>14	2.6/3.4	2
[25]	3.38/24.7X12	108.2/7.06	poor	< 1.6	5.9/8>17	4.6/3	2
[26]	3.48/30X15	124.8/6.65	good	< 1.6	5.4/9.43>20	16.6/13.15	2
[27]	2.2/31X20	123.28/7.3	medium	< 1.8	3.6/5.9/8.0>10	2.9/3.7/2.3	3
[28]	3.55/34.4x11.8	116.12/7.07	medium	< 1.7	5.8/8.1>NA	13.8/14.2	2
This work	3.55/25.9X13.7	113.36/6.51	good	< 1.5	5.29/5.83/7.99 >11.5	2.64/2.91/1.77	3

NA: not available

VI. CONCLUSION

A highly competitive ultra-wide-band bandpass filter with triple narrow notch bands was designed, fabricated, and measured. By coupling the basic UWB BPF to the SRR, the filter has a 7.38 GHz bandwidth and a fractional bandwidth of 113% while rejecting undesirable WLAN bands (5.29 and 5.83 GHz) and communication by satellite (7.99 GHz), respectively, with extremely narrow notch bands of 2.64%, 2.91%, and 1.77%. This was done without affecting adjacent signals in these bands. With all these performances, the proposed filter is desirable in ultra-wide band applications.

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