A Compact UWB Band-Pass Filter with Ultra-Narrow Tri-Notch-Band Characteristic

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Abstract **─** This paper proposes a novel approach for designing compact ultra-wideband (UWB) band-pass filter with a good tri-notch-band characteristic, which is obtained by using the ring-stub multimode resonator (MMR). The equivalent model of the filter is achieved by using odd/even excitation resonance condition. The characteristics of the designed filter are investigated and analyzed by means of IE3D. This filter is designed, analyzed, fabricated, and measured successfully. Experimental and numerical results show that the proposed filter, with compact size of 25×10 mm^2, has an impedance bandwidth range from 3 GHz to 10.6 GHz with the triple notch bands at 4.14 GHz, 6.1 GHz, and 7.1 GHz. The proposed filter can be incorporated into UWB radio systems in order to efficiently enhance the interference immunity from undesired signals.

Index Terms - Multimode resonator, notch band, RF identification (RFID) communication, ring-stub, and UWB filter.

I. INTRODUCTION

Since the Federal Communications Commission (FCC) released the frequency band from 3.1 GHz to 10.6 GHz for commercial ultra-wideband (UWB) communication applications in February 2002, the radio system has been receiving great attention from academic, governmental and industrial field [1]. An UWB band-pass filter (BPF) is one of the key passive components to realize a UWB radio system. Therefore, a number of demands have been placed on the design of BPFs with large fractional bandwidths (FBWs). Recently, many efficient methods and viable structures have been proposed to develop UWB various BPFs [2-5]. The typical structures, including a low and high-pass filter configuration [2], coplanar waveguide (CPW) forms [3], right/left-handed structure [4], multimode resonator (MMR) [5], have been proposed and investigated. Although, most of these UWB BPFs are suitable for practical use, they still have some drawbacks, such as smooth out-of-band rejection performance and complex structures.

In addition, the UWB frequency band overlaps with the existing narrowband communication systems, which means that those radio signals may interfere with UWB systems and vice versa. To reduce the potential interference, a compact communication system, which operates in UWB frequency band requires a small BPF with a notched band characteristic in order to avoid being interfered by the undesired radio signals. Recently, many methods have been investigated to design an UWB BPF with a notched band, such as embedded open-circuited stub [6], defected ground

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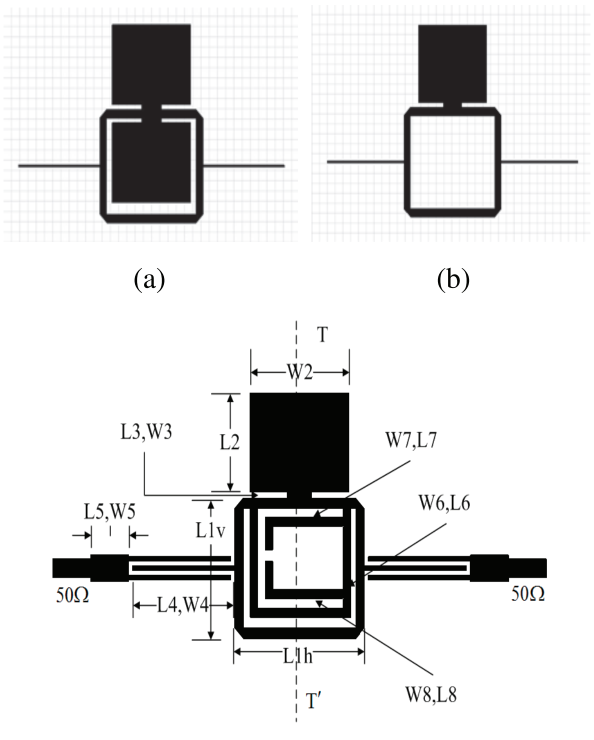
structures (DGS) [7], mismatch transmission line [8], parasitic coupled line [9] and E-shaped microstrip stepped impedance resonator (SIR) [10], which can effectively suppress undesired radio signals. Nevertheless, they are still large in size [6], not compatible with monolithic microwave integrated circuits (MMIC) [7], complex structure [8], and cannot provide multi-notch-band [6-10], such as tri-notch-band.

We propose a novel approach for designing compact UWB band-pass filter with a good tri-notch-band characteristic in this paper. The proposed tri-notch-band characteristic is obtained by using the ring-stub multi-mode resonator (MMR), and the central frequencies of these notch bands are 4.14 GHz, 6.1 GHz, and 7.1 GHz, respectively, so that the designed UWB filter can be used for 3.5 GHz WiMAX, 5.5 GHz WLAN, and 6.8 GHz RFID communication applications. The middle ring-stub MMR is analyzed by using odd and even mode. By using this method, we can get the whole resonance condition of the MMR. Compared to the previous UWB notch-band filters in [7-12], the tri-notch-band realized in the proposed filter can be operated simultaneously. The performance of the filter is simulated by using the IE3D software and implemented on the substrate with a relative dielectric constant of 6.15 and a thickness of 0.635 mm. Simulated and measured results agree reasonably well.

II. FILTER GEOMETRY

The proposed BPF is a modified form of the UWB ring resonator BPF presented in [13]. The configuration of the prototype UWB filter in [13] is shown in Fig. 1 (a). Next, we construct a simplified filter, which is illustrated in Fig. 1 (b). Then, several folded stubs are inserted into the middle ring resonator of the simplified filter to generate the desired tri-notch-band characteristic, and the configuration of our proposed triple band-notched UWB filter is shown in Fig. 1 (c). This filter is printed on a RT/Duorid 6006 with a dielectric constant of 6.15 and a thickness of 0.635 mm. The proposed filter is composed of two inter-digital hairpin resonator units, a middle ring-stub MMR, folded stubs and two 50 Ω SIR-fed structures.

To simplify the analysis process, the odd-even-mode method is employed to analyze the proposed filter, which is also referred to the articles [14-15]. Figure 2 shows the equivalent transmission line model of the proposed UWB filter with triple notch bands. The proposed transmission-line circuit model shown in Fig. 2 can be illustrated in Fig. 3 by using the odd-even-mode method with T-T′ as the reference plane. Since $\theta_4 = \theta_1 + \theta_{1'} = \pi/4$, we use this known condition to simplify the designed filter structure.


(a) (b)

(c)

Fig. 1. Geometry of the proposed filter.

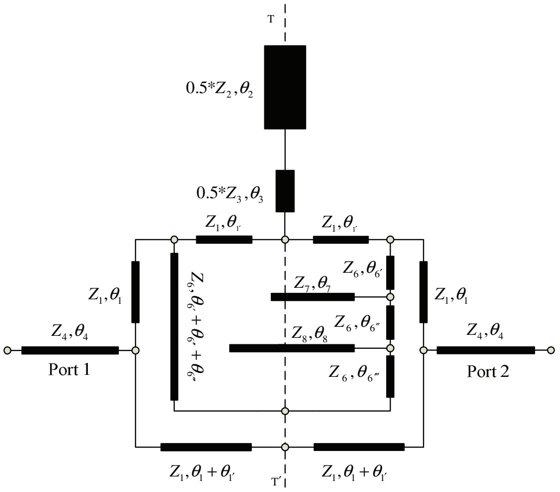
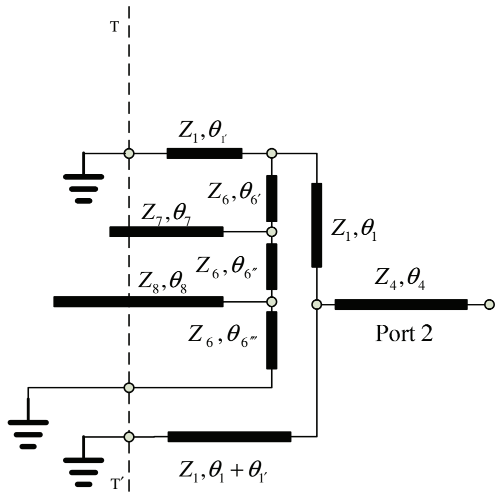
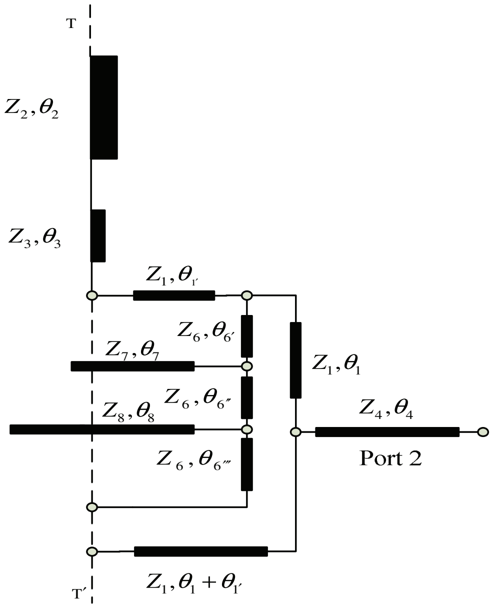


Fig. 2. Equivalent transmission line model of the proposed UWB filter.

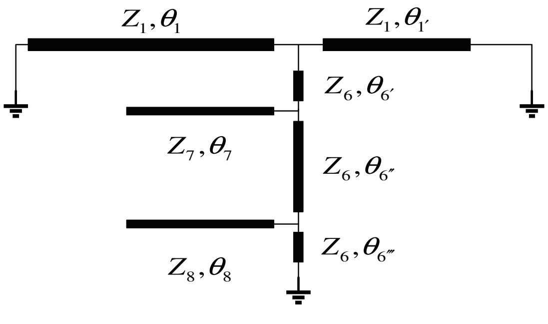


(a) odd-mode

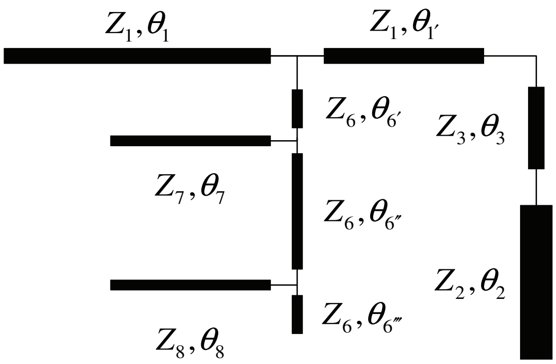


(b) even-mode

Fig. 3. Equivalent transmission line model of the proposed UWB filter with odd/even modes.



(a) odd-mode



(b) even-mode

Fig. 4. Simplified equivalent transmission line model of the proposed UWB filter for odd and even modes.

The equivalent transmission line model of the proposed UWB filter shown in Fig. 3 is simplified and shown in Fig. 4. The input admittance Y_{inodd} of the odd-mode resonator and Y_{ineven} of the even-mode resonator are expressed as follows,

$$Y_{inodd}=\frac{\dfrac{\tan\theta_1}{Z_1}+\dfrac{\dfrac{\tan\theta_{6'}}{Z_6}+\Delta}{1-Z_6\tan\theta_{6'}\Delta}+\dfrac{\cot\theta_{1'}}{Z_1}}{1-Z_1\tan\theta_1\left(\dfrac{\dfrac{\tan\theta_{6'}}{Z_6}+\Delta}{1-Z_6\tan\theta_{6'}\Delta}+\dfrac{\cot\theta_{1'}}{Z_1}\right)} \tag{1}$$

where

$$\Delta=\left[\frac{\tan\theta_7}{Z_7}+\frac{\left(\dfrac{\tan\theta_{6''}}{Z_6}+\dfrac{\cot\theta_{6'''}}{Z_6}-\dfrac{\tan\theta_8}{Z_8}\right)}{1-Z_6\tan\theta_{6''}\left(\dfrac{\cot\theta_{6'''}}{Z_6}-\dfrac{\tan\theta_8}{Z_8}\right)}\right].$$

The resonance condition can be achieved at $R_{inodd} = 0$ then we have,

$$1-Z_1\tan\theta_1\left(\frac{\dfrac{\tan\theta_{6'}}{Z_6}+\Delta}{1-Z_6\tan\theta_{6'}\Delta}+\frac{\cot\theta_{1'}}{Z_1}\right)=0.$$

Because $\theta_{6'}$ is very small, then $\theta_{6'}\to 0$ and $\tan\theta_{6'}\to 0$. So the resonance condition can be simplified as,

$$1-Z_1\tan\theta_1\left(\Delta+\frac{\cot\theta_{1'}}{Z_1}\right)=0\cdot$$

Furthermore, $\theta_{1'}\approx\theta_1$, $\theta_{6''}\approx 2\theta_{6'''}$. Thus, the resonance condition can be simplified as, $\tan\theta_7=0$ and $\tan\theta_{6''}+\cot\theta_{6'''}-\tan\theta_8=0$. Thus, we have,

$$Y_{ineven}=\frac{\dfrac{\tan\theta_1}{Z_1}+\Psi}{1-\tan\theta_1 Z_1\Psi} \tag{2}$$

where

$$\Psi=\frac{\dfrac{\tan\theta_{6'}}{Z_6}+\dfrac{\tan\theta_7}{Z_7}+\dfrac{\left(\dfrac{\tan\theta_{6''}}{Z_6}+\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}{1-Z_6\tan\theta_{6'}\left(\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}}{1-Z_6\tan\theta_{6'}\left[\dfrac{\tan\theta_7}{Z_7}+\dfrac{\left(\dfrac{\tan\theta_{6''}}{Z_6}+\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}{1-Z_6\tan\theta_{6''}\left(\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}\right]}+$$

$$\frac{\dfrac{\tan\theta_{1'}}{Z_1}+\left(\dfrac{\dfrac{\tan\theta_3}{Z_3}+\dfrac{\tan\theta_2}{Z_2}}{1-\dfrac{Z_3}{Z_2}\tan\theta_3\tan\theta_2}\right)}{1-\tan\theta_{1'}Z_1\left(\dfrac{\dfrac{\tan\theta_3}{Z_3}+\dfrac{\tan\theta_2}{Z_2}}{1-\dfrac{Z_3}{Z_2}\tan\theta_3\tan\theta_2}\right)}.$$

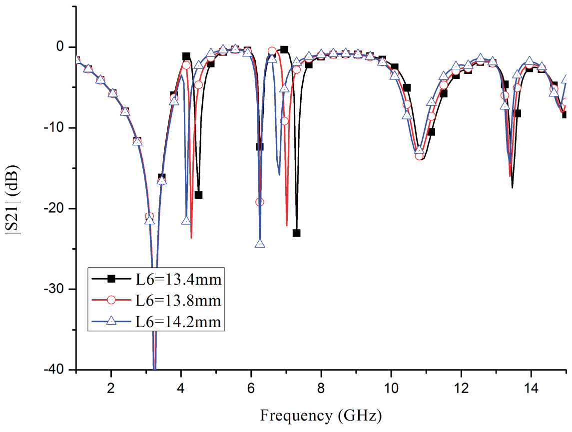
The resonance condition can be achieved at Y_{ineven} = 0. Because $\theta_{6'}$ is very small, then $\theta_{6'}\to 0$ and $\tan\theta_{6'}\to 0$. Ψ can be simplified as,

$$\Psi=\frac{\tan\theta_7}{Z_7}+\frac{\left(\dfrac{\tan\theta_{6''}}{Z_6}+\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}{1-Z_6\tan\theta_{6''}\left(\dfrac{\tan\theta_{6'''}}{Z_6}+\dfrac{\tan\theta_8}{Z_8}\right)}$$

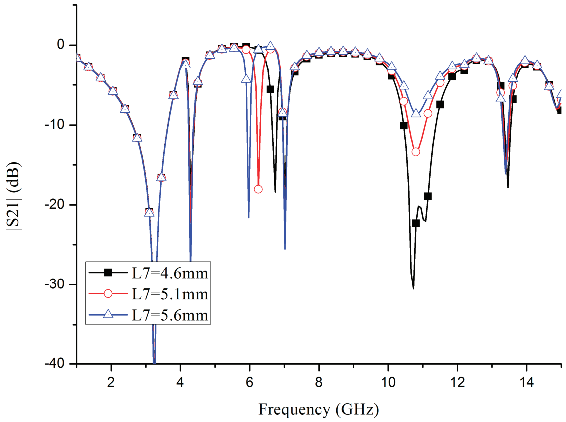
$$+\frac{\dfrac{\tan\theta_{1'}}{Z_1}+\left(\dfrac{\dfrac{\tan\theta_3}{Z_3}+\dfrac{\tan\theta_2}{Z_2}}{1-\dfrac{Z_3}{Z_2}\tan\theta_3\tan\theta_2}\right)}{1-\tan\theta_{1'}Z_1\left(\dfrac{\dfrac{\tan\theta_3}{Z_3}+\dfrac{\tan\theta_2}{Z_2}}{1-\dfrac{Z_3}{Z_2}\tan\theta_3\tan\theta_2}\right)}.$$

Here, $\theta_{6''}\approx 2\theta_{6'''}\to\pi$, then we have $\theta_{6'''}\to\dfrac{\pi}{2}$ and $\tan\theta_{6'''}\to\infty$. In this case, $Y_{ineven}=0$ is impossible. So the resonance condition is $\tan\theta_7=0$ and $\tan\theta_{6''}+\cot\theta_{6'''}-\tan\theta_8=0$. Above all, L7 is designed to control the center frequency of one notch band independently and L8/L6 are designed to adjust the center frequencies of the others notched bands.

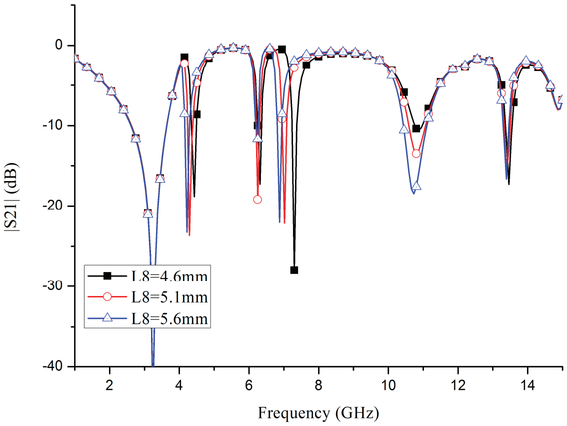
The frequency characteristics of the ring-stub multi-mode resonator are simulated by using IE3D as shown in Fig. 5. f_L , f_M and f_U denote the central frequencies of the lower, middle, and upper notched bands, respectively. It can be seen from Fig. 5 (a) that L6 has important effects on f_L and f_U while f_M remains constant. It can be seen from Fig. 5 (b) that L7 changes the center frequency of f_M . With the increase of L7, the center frequency of the middle notch band moves to the lower frequency. So, we can control the middle notch band by adjusting the dimension of L7. According to the Fig. 5 (c), we can see that L8 has important effect on f_U , which changes dramatically by tuning L8. Based on the discussions above, firstly f_L was designed by tuning the structure parameters (such as L6 and L8), and then f_M was designed by, adjusting L7. Finally, f_U was chosen by adjusting L6 and L8. The required three resonant frequencies of the notched bands can be simultaneously obtained by choosing the proper dimensions of the middle ring-stub multi-mode resonator and the stubs.



(a) Variation of insertion loss with parameter L6.



(b) Variation of insertion loss with parameter L7.



(c) Variation of insertion loss with parameter L8.

Fig. 5. Simulated insertion loss of the proposed asymmetric structure for varying parameters.

III. RESULTS AND DISCUSSION

In this paper, geometric parameters of the filter were adjusted and optimized by means of IE3D. Optimal parameters of the tri-notch-band UWB filter are listed in Table I. To verify the effectiveness of the proposed filter, the filter with tri-notch-band is fabricated and measured. The fabricated filter is shown in Fig. 6. The performance of the proposed filter is measured by using Anristu 37347D vector network analyzer. Figures 7 and 8 demonstrate the frequency responses of proposed tri-notch-band UWB band-pass filter. Here, only S11 is adopted to analyze the proposed filter since the size of this filter is very small. The measured results agree well with the simulated results which help to verify the accuracy of the simulation. The differences between the simulated and measured values may be due to the errors of the manufactured filter. The fabricated filter has a measured pass-band from 3 GHz to 10.6 GHz, while the center frequencies of the notched bands are 4.14 GHz, 6.1 GHz, and 7.1 GHz. The group delays are shown in Fig. 9, 0.2 ns and 0.6 ns at the mid-band frequency of lower pass-band and at the mid-band frequency of upper pass-band, respectively. It should be noted that the ring-stub MMR can generate three notched band at the desired frequency with no significant influence on the wide pass-band performance of the filter. In a word, the proposed UWB BPF has a good tri-notch-band characteristic for implementing the functions of UWB radio system.

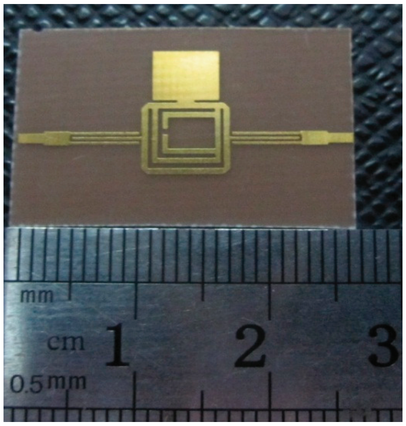


Fig. 6. The photo of the proposed tri-notch band UWB filter.

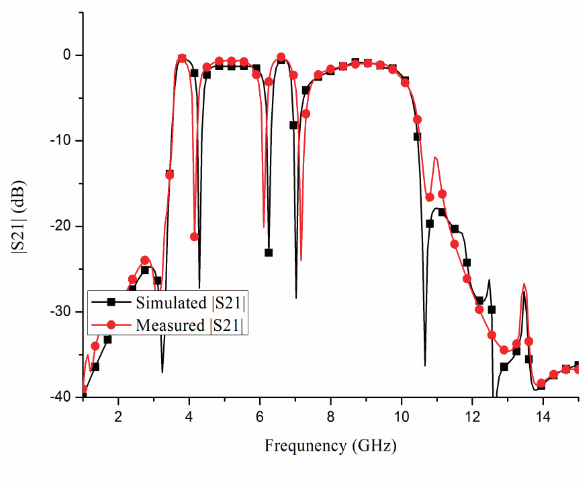


Fig. 7. Comparison between simulated and measured results for |S21| of the fabricated filter.

Table I: Dimensions of the proposed tri-notch band UWB filter.

Dimensions of the proposed tri-band filter (unit: mm)			
PARAMETER	SIZE	PARAMETER	SIZE
L1v	5.12	W1	0.46
L1h	5.92	W2	5.2
L2	4.25	W3	1.3
L3	0.25	W4	0.11
L4	5.39	W5	1.15
L5	2	W6	0.4
L6	3.8	W7	0.4
L7	5.1	W8	0.4
L8	5.1		

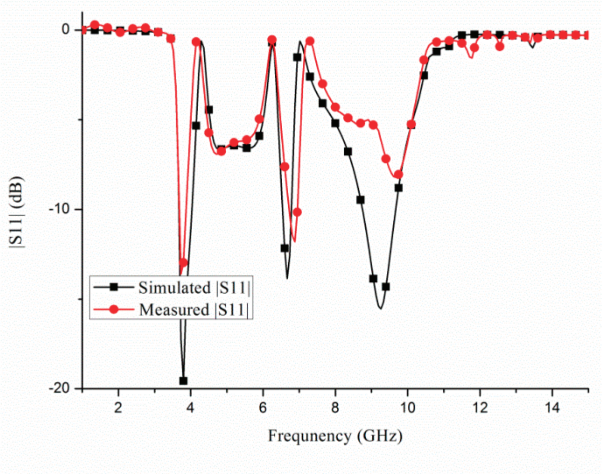


Fig. 8. Comparison between simulated and measured results for |S11| of the fabricated filter.

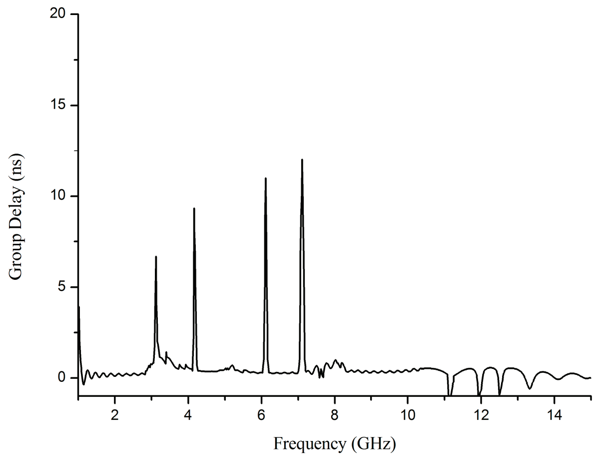


Fig. 9. Group delay of the fabricated filter.

IV. CONCLUSION

In this article, a compact UWB band-pass filter with an ultra-narrow tri-notch-band characteristic has been developed and manufactured. Inserting ring-stub MMR to the original UWB BPF leads to blocking undesired existing radio signals. The ring-stub multi-mode resonator can generate three narrow notched bands corresponding to the undesired radio signal frequencies with no significant influence on the wide pass-band performance of the filter. The measured results show that the proposed filter can cover the entire UWB band with three notch bands. The proposed filter is promising for using in UWB systems due to its simple structure, compact size, and excellent performance.

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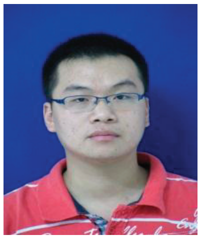

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