Progress In Electromagnetics Research Letters, Vol. 73, 61–67, 2018

Super Compact Microstrip UWB BPF with Triple-Notched Bands

Jiewen Liu[1], Jing Lu[1, *], Zhouyan He[1], Ting Luo[1], Xinyang Ying[1], and Junding Zhao[2]

Abstract—A new super compact ultra-wideband (UWB) bandpass filter (BPF) with triple-notched bands is presented in this paper. Firstly, a new square ring quad-mode resonator (SRQMR) is employed to obtain the initial UWB BPF. Then, a triple-mode stepped impedance resonator (SIR) is inserted into the initial UWB BPF to achieve three desired notched bands. The proposed triple-mode SIR is found to have the advantages of introducing triple-notched bands and provide a higher degree of freedom to adjust the resonant frequencies. To validate the design concept, a new super compact UWB BPF with triple-notched bands respectively centered at frequencies of 3.7 GHz, 5.2 GHz and 7.8 GHz is designed and measured. The predicted results are compared with measured data, and good agreement is reported.

1. INTRODUCTION

Ultra-wideband (UWB) radio technology has been getting more and more popularity for high-speed wireless connectivity, since the Federal Communications Commission (FCC)'s decision to permit the unlicensed operation band from 3.1 GHz to 10.6 GHz in February 2002 [1]. These applications benefit from the unique features of low-power spectral density and consumption associated with UWB systems. The UWB bandpass filter (BPF), as one of the essential components of UWB systems, has gained much attention in recent years. There are many techniques presented to design UWB BPF. For example, quad-mode resonator (MMR) [2, 3], multilayer coupled structure [4, 5], and cascaded low-pass/high-pass filters [6] have been widely used to achieve UWB characteristics.

However, concurrently a rapidly increasing number of licensed narrow-band wireless devices are sharing their operating frequency bands with the existing allocated UWB spectrum: 3.1–10.6 GHz. These include 3.7 GHz WiMAX band, 5.2 GHz WLAN band, and 7.8 GHz satellite communication band systems. The overlaps of these bands with the UWB spectrum cause severe inband interference and negatively impact the performance of UWB systems, so a compact UWB BPF with multiple notched bands is urgently required to reject these undesired interfering signals [7–13]. Several structures have been studied in [7, 8], but only one notched band is created. The filter with dual notched bands is reported in [9, 10], based on a multi-layer structure that is hardly compatible with the existing microwave-integrated circuit. In [11, 12], the compact microstrip UWB BPF with triple notched bands is proposed; however, the reported design suffers from a large size.

Based on our previous work [13], a new super compact UWB BPF with three narrow notched bands is proposed. The basic UWB BPF is composed of a square ring structure and a quarter-wavelength short-circuited stub. Then, the triple-mode stepped impedance resonator (SIR) is inserted into the basic UWB BPF to achieve three desired notched bands. The properties of the proposed novel triple-mode stepped impedance resonator are analyzed theoretically, which has three resonance frequencies and a higher degree of adjusting freedom. To demonstrate a potential application of the proposed structure,

Received 8 November 2017, Accepted 1 February 2018, Scheduled 6 February 2018
* Corresponding author: Jing Lu (elejinglu@163.com).
[1] College of Science and Technology, Ningbo University, Ningbo 315211, China. [2] Nanjing Changfeng Aerospace Electronic Technology Co., Ltd., Nanjing 210094, China.

a new super compact UWB BPF with triple-notched bands respectively centered at frequencies of 3.7 GHz, 5.2 GHz and 7.8 GHz is designed and measured. The predicted results on S-parameters are compared with measured ones and good agreement is achieved. The designed topology and principle is very simple and efficient for filter synthesis. Moreover, the proposed new UWB BPF with triple notched bands structure is super compact.

Note that all of the numerical simulations and their optimizations reported in this paper were performed using the frequency domain ANSYS/ANSOFT high-frequency structure simulator (HFSS), version 13.0 [14].

2. UWB BANDPASS FILTER DESIGN

Figure 1 shows the layout of the proposed initial UWB BPF. The initial UWB BPF is composed of a square ring structure and an inserted quarter-wavelength short-circuited stub, i.e., square ring quad-mode resonator (SRQMR). The layout of the equivalent circuit of the SRQMR is shown in Fig. 2.

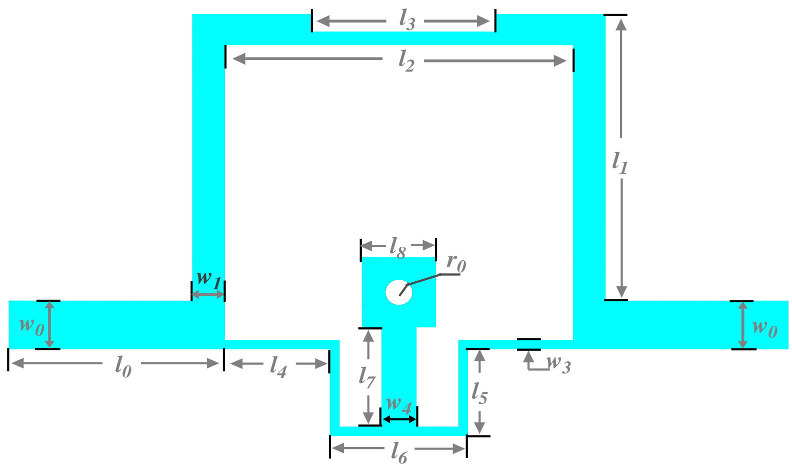

Figure 1. Schematic of the proposed initial UWB BPF.

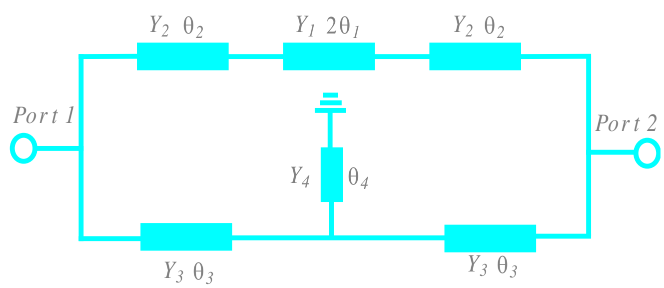

Figure 2. Schematic of the proposed SRQMR.

Since the resonator is symmetrical, the odd-even-mode method is implemented. The even- and odd-mode analysis method can be applied to the proposed initial UWB BPF using the symmetry characteristics of the novel structure. The simple schematic of the SRQMR is shown in Fig. 2, while the odd- and even-mode equivalent circuits are shown in Figs. 3(a) and (b).

From port 1 to port 2, two transmission paths with characteristic admittances Y_2 and Y_3 are introduced, and a shorted stub with characteristic admittance Y_4 and electrical length θ_4 is connected in the center of the second transmission path. The characteristic impedance at port 1 is $50\,\Omega$. When the even-/odd-mode signals are excited from ports 2 to 1, a virtual open/short appears along the centre of the square ring resonator. In the even mode, the stepped impedance stub is divided in half along

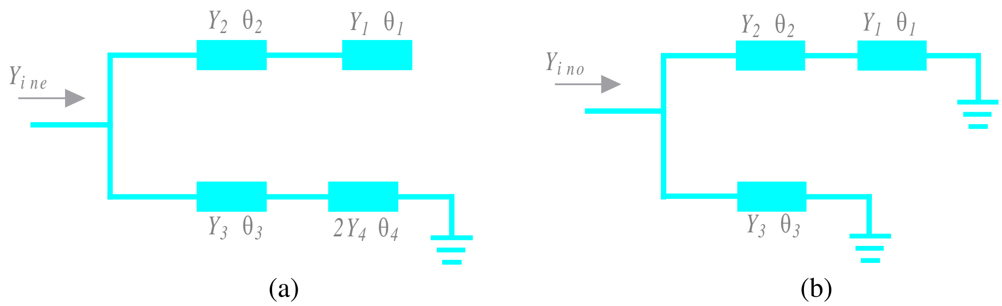

Figure 3. The equivalent circuit model of the proposed SRQMR. (a) Even mode circuit model. (b) Odd mode circuit model.

the plane of symmetry. In the odd mode, the plane of symmetry can be considered as a ground plane, with no current flows through the isolation resistor. The even/odd-mode input admittance Y_{ine}/Y_{ino} of Fig. 3 can be expressed as:

$$Y_{\text{ino}} = -jY_3 \cot\theta_3 - j\frac{Y_1 \cot\theta_3 - jY_2 \tan\theta_2}{Y_2 + Y_1 \cot\theta_1 \tan\theta_2} \tag{1}$$

$$Y_{ine} = jY_2 \frac{Y_1 \tan\theta_1 + Y_2 \tan\theta_2}{Y_2 \tan\theta_2 - Y_1 \tan\theta_1 \tan\theta_2} - jY_3 \frac{Y_4 \cot\theta_4 + 2Y_3 \tan\theta_3}{2Y_3 + Y_4 \cot\theta_4 \tan\theta_3} \tag{2}$$

As analyzed in [2], due to the symmetry of the square ring resonator, the resonance frequencies can be calculated when $Y_{ine}/Y_{ino} = 0$ from the one end of the even- and odd-mode circuit. Hence, it cannot solve the expressions for the two pairs of resonance modes directly. Thus, another two odd mode resonator frequencies f_{odd1} ($\theta_1 = 120°$, $4f_0/3$) and f_{odd2} ($\theta_1 = 180°$, $2f_0$) can be realized. As we can see, the bandwidth of the UWB BPF decreases as Y_3 increases, and increases as f_0, θ_4, Y_4 increase. In this way, the bandwidth for the passband of the UWB BPF with the SRQMR can be conveniently controlled by varying the characteristic matrix Y_3, Y_4 and θ_4 when Y_1, Y_2 and θ_1, θ_2 are fixed. Therefore, by properly tuning the dimensions of the SRQMR, a new super compact microstrip UWB BPF can be achieved with the desired bandwidth.

To illustrate the design theory, the proposed UWB BPF is fabricated using Rogers 4350B with a thickness of 0.508 mm, relative dielectric constant of 3.45 and loss tangent of 0.009. The simulated scattering parameters are recorded in Fig. 4. It can be seen that the proposed UWB BPF has an insertion loss better than 0.5 dB from 2.52 to 10.54 GHz. The return loss is under -20 dB over the most part of

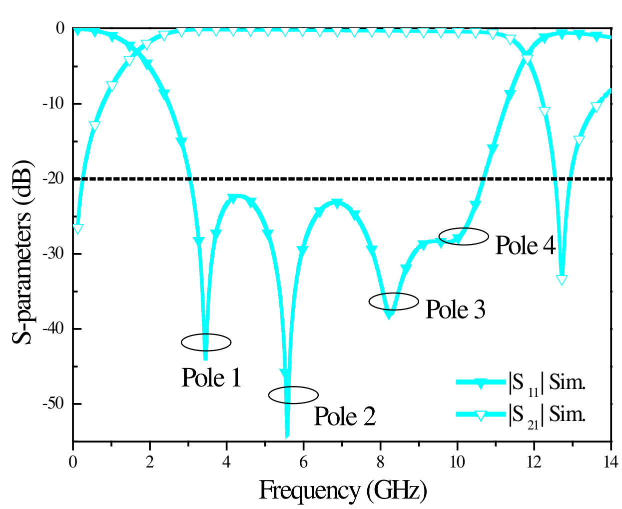

Figure 4. Simulated performance of the proposed initial UWB BPF.

the passband. In addition, four poles are located in the pass band, i.e., quad-mode resonator. All the dimensions are selected as follows: $l_0 = 4.7$ mm, $l_1 = 6.6$ mm, $l_2 = 7.6$ mm, $l_3 = 4.0$ mm, $l_4 = 2.2$ mm, $l_5 = 2.0$ mm, $l_6 = 3.0$ mm, $l_7 = 2.3$ mm, $l_8 = 1.6$ mm, $w_0 = 1.1$ mm, $w_1 = 0.7$ mm, $w_2 = 0.7$ mm, $w_3 = 0.1$ mm, $w_4 = 0.7$ mm, $r_0 = 0.3$ mm. The size of the whole circuit is only 16.6 mm × 11.8 mm.

3. TRIPLE-MODE SIR ANALYSIS

Figure 5(a) shows the geometry of the proposed triple-mode SIR. It consists of two half-wavelength SIRs and two short-circuited stubs on its center plane. Since the resonator is symmetrical to the T-T' plane, the odd-even-mode method is implemented. For odd-mode excitation, the equivalent circuit is one quarter-wavelength resonator with one end grounded, as shown in Fig. 5(b). From the resonance condition of $Y_{ino} = 0$, the odd-mode resonant frequency can be deduced as:

$$f_{ino} = \frac{c}{4L_1\sqrt{\varepsilon_{eff}}} \tag{3}$$

where f_{ino} is the center frequency of the notch band, ε_{eff} the effective dielectric constant, and c the light speed in free space.

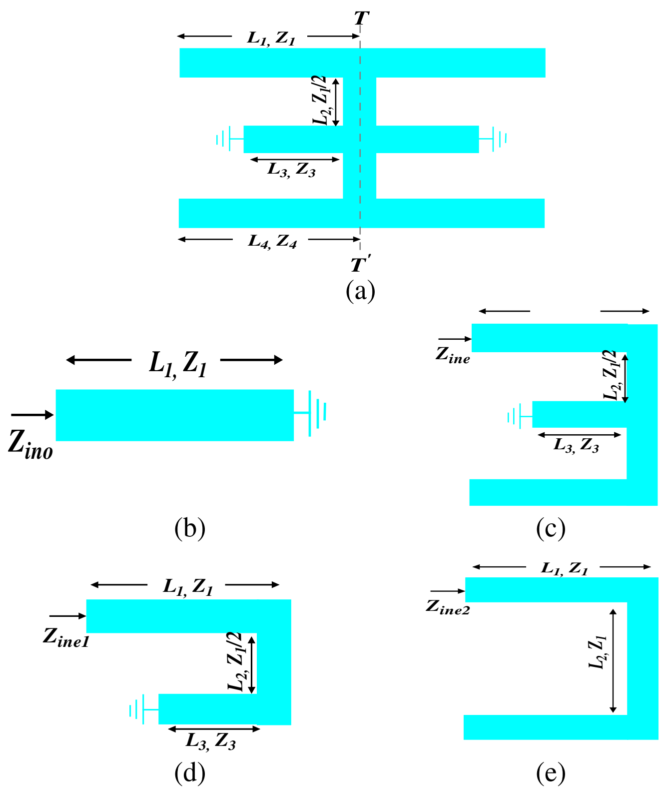

Figure 5. (a) Configuration of the proposed novel triple-mode SIR. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit. (d) Path I of Even-mode equivalent circuit. (e) Path II of Even-mode equivalent circuit.

For even-mode excitation, the equivalent circuit is shown in Fig. 5(c), which contains two resonant circuits: a quarter-wave-length resonator and a half-wavelength resonator, as shown in Figs. 5(d) and (e). The even-mode resonant frequencies can be determined as follows:

$$f_{ine1} = \frac{c}{4(L_1 + L_2 + L_3)\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$f_{ine2} = \frac{c}{(2L_1 + 2L_2 + 2L_4)\sqrt{\varepsilon_{eff}}} \tag{5}$$

where $Z_1 = Z_3 = Z_4$ assumed for simplicity. The resonance frequencies can be determined by the electrical length.

The triple-mode SIR can result in triple band-stop performance when being placed next to the microstrip line, and it can be equivalent to three shunt-connected series resonance circuits. The triple-mode SIR can result in triple band-stop (i.e., the triple notched-bands) performance when being placed next to the microstrip line, and it can be equivalent to three shunt-connected series resonance circuits, as shown in Fig. 6. In this paper, the coupled triple-mode SIR dimensions are selected as follows: $w_{e1} = 0.3\,\text{mm}$, $w_{e2} = 0.4\,\text{mm}$, $w_{e3} = 1.1\,\text{mm}$, $w_{e4} = 0.1\,\text{mm}$, $l_{e1} = 2.3\,\text{mm}$, $l_{e2} = 1.6\,\text{mm}$, $l_{e3} = 1.5\,\text{mm}$.

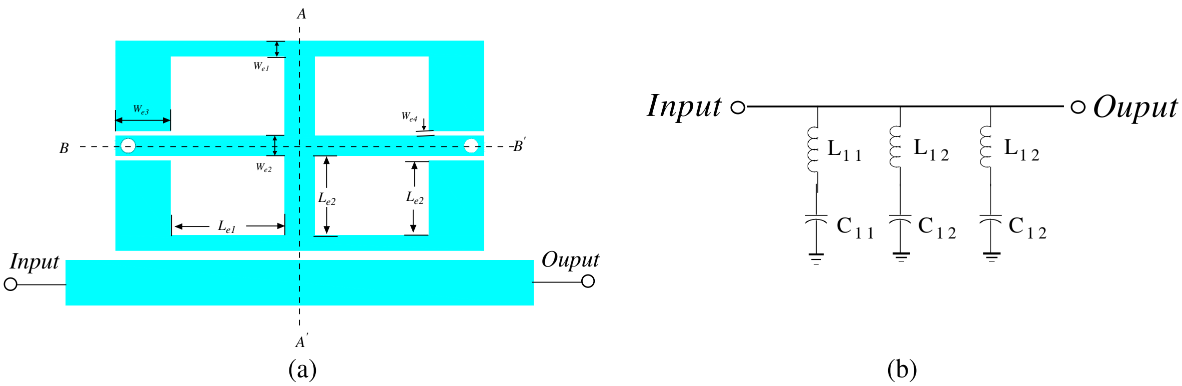

Figure 6. Geometry and equivalent circuit of the proposed coupled triple-mode SIR.

4. EXPERIMENTAL RESULTS

Finally, the designed UWB BPF is measured with an Agilent N5244A vector network analyzer. Fig. 7 shows the schematic view of the UWB BPF with triple-notched bands. The overall size is only about $11.8\,\text{mm} \times 16.6\,\text{mm}$. Fig. 8 shows the comparison between the simulated and measured results. It can be seen that the designed UWB BPF has a passband from 1.7 GHz–11.9 GHz. The return loss is under 20 dB over the most part of the passband. The three notched bands realized high selectivity with 3 dB FBW of 5.4%, 4.4% and 2.7%, respectively. The attenuation is better than $-13\,\text{dB}$ at the center frequencies 3.7 GHz, 5.2 GHz, and 7.8 GHz. The minor discrepancy between simulation and measurement results

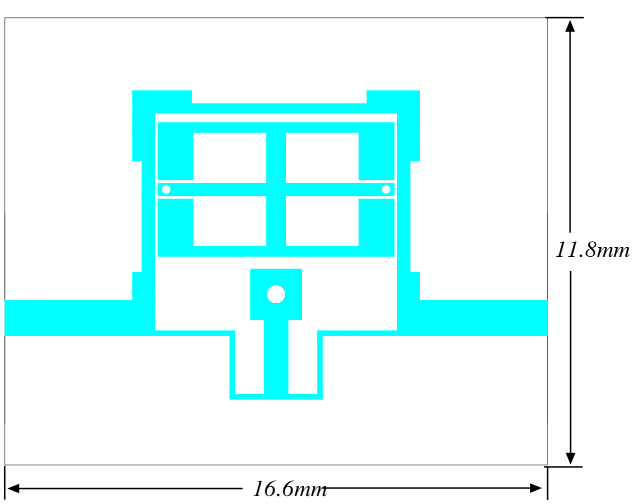

Figure 7. Schematic view of the UWB BPF with triple-notched bands.

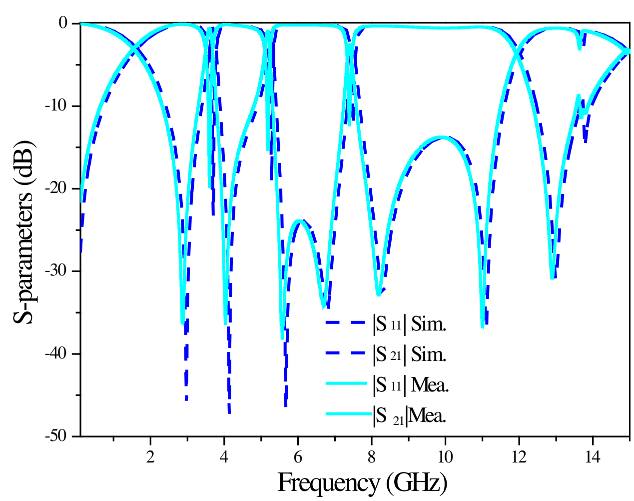

Figure 8. Simulated and measured S-parameters of the designed UWB BPF.

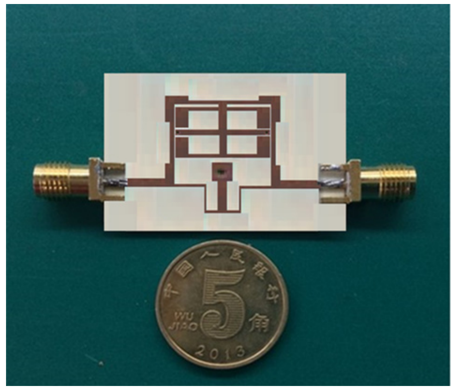

Figure 9. Photograph of the fabricated UWB filter.

Table 1. Comparisons with other proposed UWB BPF with notched band.

Ref.	Circuit dimension	Pass band (GHz)	Insertion loss (dB)	Notch frequency (GHz)/	Circuit size (λg: at 6.85 GHz)
[7]	2-D	$3.7 \sim 11.6$	0.45	7.0	0.46×0.34
[8]	2-D	$3.6 \sim 10.2$	0.6	5.6	0.81×0.17
[9]	3-D	$2.6 \sim 10.6$	0.75	6.4/8.0	1.36×0.32
[10]	3-D	$3.1 \sim 14$	1.5	5.5/8.0	0.65×0.55
[11]	2-D	$2.8 \sim 11.0$	1.0	5.2/5.9/8.0	1.16×0.68
[12]	2-D	$3.0 \sim 10.2$	0.7	3.6/5.8/8.0	0.63×0.36
[13]	2-D	$3.2 \sim 10.9$	0.5	5.9/8.0	0.63×0.36
This work	2-D	$1.8 \sim 11.8$	0.4	3.7/5.2/7.8	0.43×0.35

is mainly due to the reflections from the SMA connectors and the finite substrate. Fig. 9 shows a photograph of the fabricated UWB filter. Comparisons with other reported UWB BPFs with notched bands are listed in Table 1 and demonstrate that the proposed filter has good characteristics and a small size.

5. CONCLUSION

A new super compact UWB BPF has been designed and measured. Three desired notched bands with sharp rejection are achieved by inserting a novel triple-mode SIR into the initial UWB BPF. With good passband characteristics and super compact size, the proposed filter is attractive for UWB wireless systems.

ACKNOWLEDGMENT

This work was supported by Natural Science Foundation of Ningbo under Grant No. 2017A610127, and Zhejiang Provincial Department of Education research plan No. Y201430481.

REFERENCES

1. FCC, Revision of Part 15 of the Commission's Rules Regarding Ultra-wide-band Transmission System, Tech. Rep., ET-Docket, 98–153, 2002.
2. Zhu, L., S. Sun, and W. Menzel, "Ultra-wideband (UWB) bandpass filters using multiple-mode resonator," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 11, 796–798, 2005.

3. Qiang, L., Y.-J. Zhao, Q. Sun, W. Zhao, and B. Liu, "A compact UWB HMSIW bandpass filter based on complementary split-ring resonators," *Progress In Electromagnetics Research*, Vol. 11, 237–243, 2009.
4. Packiaraj, D., K. J. Vinoy, and A. T. Kalghatgi, "Analysis and design of two layered ultra wide band filter," *Journal of Electromagnetic Waves and Applications*, Vol. 23, Nos. 8–9, 1235–1243, 2009.
5. Wang, H., L. Zhu, and W. Menzel, "Ultra-wideband bandpass filter with hybrid microstrip/CPW structure," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 12, 844–846, 2005.
6. Comez-Garcia, R. and J. I. Alonso, "Systematic method for the exact synthesis of ultra-wideband filtering responses using high-pass and low-pass sections," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 10, 3751–3764, 2006.
7. Pirani. S., J. Nournia, and C. Ghobadi, "Band-notched UWB BPF design using parasitic coupled line," *IEEE Microw. Wireless Compon. Lett.*, Vol. 20, No. 8, 444–446, 2010.
8. Wong, S. W. and L. Zhu, "Implementation of compact UWB bandpass filter with a notch-band," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, No. 1, 10–12, 2008.
9. Hao, Z.-C. and J.-S. Hong, "Compact UWB filter with double notch-bands using multilayer LCP technology," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 8, 500–502, 2009.
10. Hsiao, P.-Y. and R.-M. Weng, "Compact tri-layer ultra-wideband bandpass filter with dual notch bands," *Progress In Electromagnetics Research*, Vol. 106, 49–60, 2010.
11. Wei, F., Q. Y. Wu, X. W. Shi, and L. Chen, "Compact UWB BPF with triple-notched bands based on stub loaded resonator," *IET Electron. Lett.*, Vol. 49, No. 2, 124–126, 2013.
12. Zhao, J.-D., J.-P. Wang, and J.-L. Li, "Compact UWB bandpass filter with triple notched bands using parallel U-shaped defected microstrip structure," *IET Electron. Lett.*, Vol. 50, No. 2, 89–91, 2014.
13. Zhao, J.-D., J.-P. Wang, and J.-L. Li, "Compact microstrip UWB bandpass filter with dual notched bands using E-shaped resonator," *IEEE Microw. Wireless Compon. Lett.*, Vol. 23, No. 12, 638–640, 2013.
14. NSYS Corp. ANSYS/ANSOFT, 2012, High Frequency Structure Simulator (HFSS), Ver. 13.0., [Online], available: http://www.ansoft.com.