Progress In Electromagnetics Research C, Vol. 39, 1–10, 2013

A MINIATURIZED TRIPLE-BAND BRANCH-LINE COUPLER BASED ON SIMPLIFIED DUAL-COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE

Guo-Cheng Wu[1, *], Guang-Ming Wang[3], Li-Zhong Hu[2], Ya-Wei Wang[1], and Cang Liu[1]

[1]The No. 2 Team, Department of School of Air and Missile Defense, Air Force Engineering University, Xi'an, China

[2]The No. 1 Team, Department of School of Air and Missile Defense, Air Force Engineering University, Xi'an, China

[3]Laboratory of Microwave Technology, Department of School of Air and Missile Defense, Air Force Engineering University, Xi'an, China

Abstract—A miniaturized triple-band branch-line coupler based on the simplified dual-composite right/left-handed transmission line (S-D-CRLH-TL) is proposed in this paper. The electromagnetic characteristics of S-D-CRLH-TL are analyzed by the simulator and equivalent circuit model, and the results prove that there are three frequency points with phase of -90-degree in the passbands; this characteristic can be used to design triple-band quadrature microwave components. The proposed branch-line coupler is fabricated and measured, the measured and simulated results are in good agreement with each other, showing that the triple-band operating at 3.06 GHz, 4.00 GHz and 5.54 GHz, the useful bandwidths are 2.97 GHz–3.16 GHz, 3.82 GHz–4.12 GHz and 5.48 GHz–5.67 GHz. In addition, compared with the conventional branch-line coupler, the whole size of the proposed one is $17\,\text{mm}\times14.4\,\text{mm}$ ($0.173\lambda\times0.147\lambda$) ($\lambda$ is the wavelength in low frequency), it realizes a 73% size reduction. Moreover, compared with the triple-band branch-line coupler based on the double-Lorentz transmission line metamaterial, the proposed branch-line coupler is more effective in the situation, which is sensitive to phase-changing, as the sign of phase difference in the two outputs at the three frequency points keeps the same.

Received 8 March 2013, Accepted 1 April 2013, Scheduled 8 April 2013

* Corresponding author: Guo-Cheng Wu (wgc805735557@163.com).

1. INTRODUCTION

Recently, with the fast development of microwave wireless communication technology, the miniaturization and multiple bands of microwave components are becoming more and more important [1–25]. As an important microwave component, there are many methods applied to realize the miniaturization and multiple bands of branch-line coupler. In paper [2, 3], dual-band branch-line couplers are realized by adding the cross couple-lines to the parallel-lines and third branch-line in the coupler, but the size of these branch-line coupler is very large. In paper [4], the author applies the composite right/left-handed transmission lines (CRLH-TLs) based on complementary split ring resonator (CSRR) to design dual-band branch-line coupler, the dual-band and small size are realized. In paper [5], the structure of CRLH-TLs based on new technology of MIM (metal-insulator-metal) is used to design BLC, the small size is also realized, but the coupler based on CRLH-TLs cannot be used in the situation which is sensitive to phase-changing. In paper [6], a triple-band branch-line coupler is realized by using T-type and additional port impedance transformers, but it does not realize miniaturization. Paper [7] proposes a triple-band branch-line coupler by substituting the $\lambda/4$ transmission lines in the conventional branch-line coupler, however its complex structure is the biggest problem, in paper [16], the double-Lorentz transmission line metamaterial also can be used to design triple-band branch-line coupler, but the sign of phase difference in the two outputs at the triple-band do not keeps the same, and the designed branch-line coupler can not be used in the situation, which is sensitive to phase-changing.

In this paper, a novel simplified dual-composite right/left-handed transmission line (S-D-CRLH-TL) is proposed firstly. Then its electromagnetic characteristics are analysed by the simulator, and the equivalent circuit model is also provided. The results of the simulator and the equivalent circuit model are in good agreement, which prove that the equivalent circuit model is right. In the simulated results, there are three frequency points with phase of −90-degree in the passbands, and this characteristic has been applied in designing the triple-band branch-line coupler in this paper. Then, the proposed triple-band branch-line coupler is fabricated and measured, the measured and simulated results are in good agreement with each other, showing that the triple-band centre at 3.06 GHz, 4.00 GHz and 5.54 GHz, the useful bandwidths are 2.97 GHz–3.16 GHz, 3.82 GHz–4.12 GHz and 5.48 GHz–5.67 GHz. As the sign of phase difference in the two outputs at the triple-band keeps the same, the proposed branch-line coupler is more effective in the situation, which is sensitive to phase-changing. In addition, the whole size of the proposed branch-line coupler is 17 mm × 14.4 mm ($0.173\lambda \times 0.147\lambda$) ($\lambda$ is the wavelength in low frequency), it realizes a 73% size reduction in comparison with the conventional one.

2. ANALYSIS OF THE S-D-CRLH-TL

Figure 1 is the geometry structure and equivalent circuit model of the S-D-CRLH-TL proposed in this paper, The unit structure is designed on a substrate with relative dielectric constant 2.65 and thickness 0.8 mm. In the circuit model, where the L_1 is models the main transmission line inductance, the L_R is realized by the narrow microstrip lines paralleled with the structure of spiral inter-digital, the L_L models the left-handed inductance realized by the stub line, the C_L represents the coupling of the structures of spiral inter-digital and the C_1 and L_2 are realized by the self-coupling of the structures of spiral inter-digital.

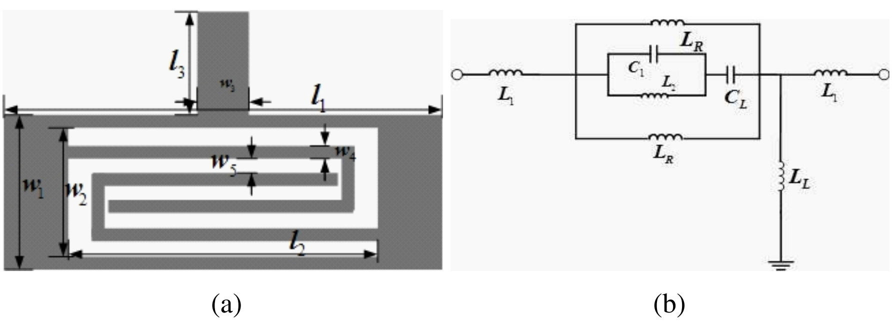


Figure 1. Geometry structure and equivalent circuit model of S-D-CRLH-TL. (a) Geometry structure. (b) Equivalent circuit model.

Compared with the conventional D-CRLH-TL, the proposed S-D-CRLH-TL does not have the right-handed capacitance (C_R), so the stopband between the first right-handed passband and the left-handed passband of the conventional D-CRLH-TL is destroyed, a passband between the two transmission zeros is engendered, and because of this, the dispersion diagram will change as shown in Figure 2.

In Figure 2, we can see that a new passband is engendered, and the electromagnetic characteristics of the S-D-CRLH-TL in other frequency keep the same with the D-CRLH-TL.

In order to obtain good performances such as low insertion losses in the bandwidth of interest and sharpened rejection out of band, the physical dimensions of the S-D-CRLH-TL are optimized and the detailed dimensions are: $l_1 = 10\,\text{mm}$, $l_2 = 7\,\text{mm}$, $l_3 = 3\,\text{mm}$, $w_1 = 2.2\,\text{mm}$, $w_2 = 1.8\,\text{mm}$, $w_3 = 1.2\,\text{mm}$, $w_4 = 0.2\,\text{mm}$, $w_5 = 0.2\,\text{mm}$. The simulated results are shown in Figure 3. We can see that there are three frequency points with phase of -90-degree, and all these three frequency points are in the passband.

Figure 1(b) is the equivalent circuit model of the proposed S-D-CRLH-TL. When $L_1 = 0.19\,\text{nH}$, $L_2 = 0.45\,\text{nH}$, $L_R = 12.22\,\text{nH}$, $C_1 = 2.32\,\text{pF}$, $C_L = 5.28\,\text{pF}$, the results of the equivalent circuit model are shown in Figure 4.

From Figures 3 and 4, we can see that the results of the simulator and the equivalent circuit model are in good agreement with each other, proving that the circuit model is right.

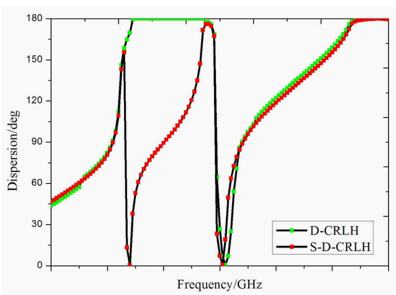


Figure 2. The dispersion diagrams of D-CRLH and S-D-CRLH-TL.

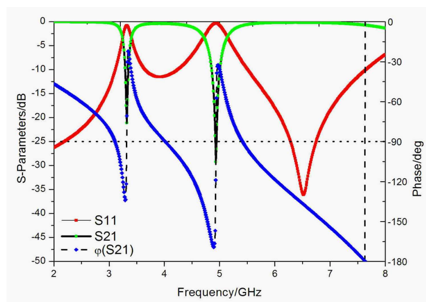


Figure 3. S-parameters and phase of S-D-CRLH-TL by simulator.

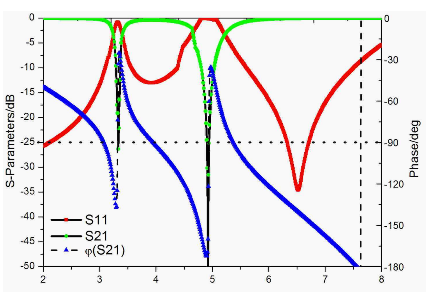


Figure 4. S-parameters and phase of S-D-CRLH-TL by equivalent circuit model.

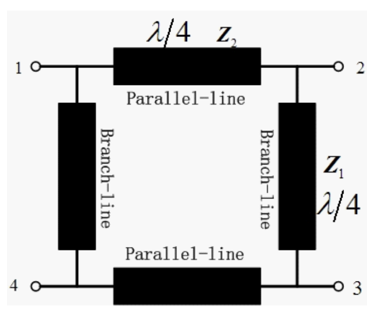


Figure 5. The conventional structure of branch-line coupler.

3. DESIGN OF THE TRIPLE-BAND BRANCH-LINE COUPLER

3.1. Unit Cells of S-D-CRLH-TL with Different Physical Dimensions

Figure 5 is the structure of conventional branch-line coupler, which is consisted of two parallel-lines and two branch-lines. According to the designing method proposed in paper [8], the electrical length of branch-line and parallel-line is 90-degree, $Z_1 = 50\,\Omega$, $Z_2 = 35\,\Omega$, so the width of branch-line is 2.2 mm, and parallel-line is 3.5 mm.

In order to make sure the electromagnetic characteristics of the S-D-CRLH-TL unit cells with different width keep the same, other physical dimensions of this structure should be change. It is known that the three frequency points with −90-degree phase shift of the $50\,\Omega$ transmission line are 3.08 GHz, 4.02 GHz and 5.50 GHz, then, the required $35\,\Omega$ transmission line is designed through similar procedures. The geometrical parameters of the $50\,\Omega$ and $35\,\Omega$ transmission lines are shown in Table 1. The comparison results of these two unit cells are shown in Figure 6.

In Figure 6, the results indicate that there are three frequency points with phase of −90-degree in the passbands. The proposed prototype can be treated as the $50\,\Omega$ and $35\,\Omega$ transmission lines with

Table 1. The physical dimensions of two unit cells (mm).

	l_1	l_2	l_3	w_1	w_2	w_3	w_4	w_5
unit1	10	7	3	2.2	1.8	1.2	0.2	0.2
unit2	10	7	3	3.5	2.7	1.2	0.3	0.3

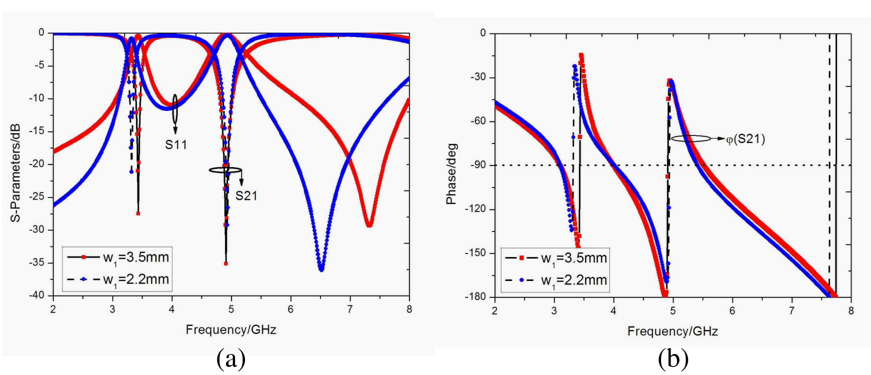


Figure 6. Comparison of two unit cells with different width. (a) S-parameters. (b) Phase of S_{21}.

90-degree phase shift, and based on the above two transmission lines, the branch-line coupler is convenient to synthesize. Besides, compared with the double-Lorentz transmission line proposed in paper [16], the phase of the three frequency points of S-D-CRLH-TL keep the same, and it is more suitable in designing the microwave components, which are sensitive to phase-changing.

3.2. Design of the Proposed Triple-band Branch-line Coupler

Figure 7 shows the structure of the proposed triple-band branch-line coupler. The unit cells of S-D-CRLH-TL are embedded into the branch-lines and parallel-lines. By using the optimization in Ansoft HFSS, when $W = L = 10\,\text{mm}$, the performances of this proposed branch-line coupler are the best.

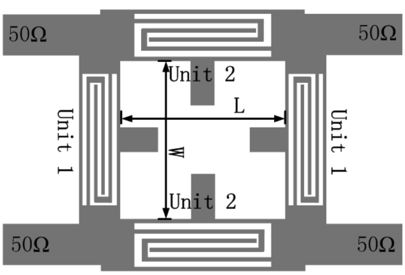


Figure 7. Structure of the proposed branch-line coupler.

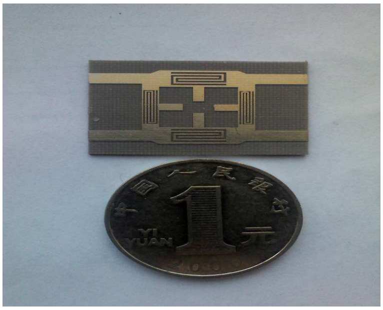
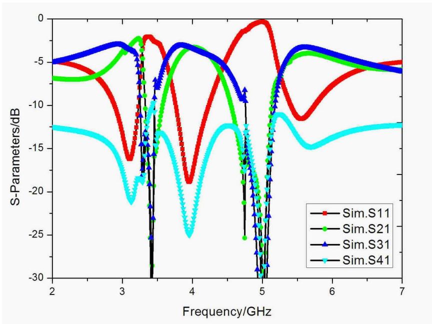


Figure 8. The photograph of the fabricated triple-band branch-line coupler.

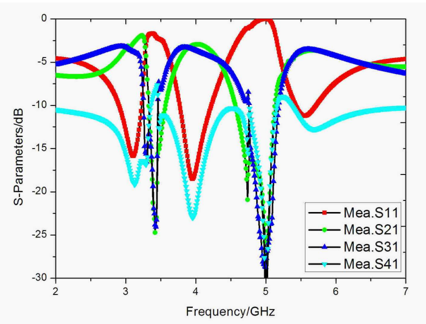
4. MEASURED RESULTS AND DISCUSSIONS

Figure 8 is a photograph of the fabricated triple-band branch-line coupler. The measured and simulated results are shown in Figure 9.

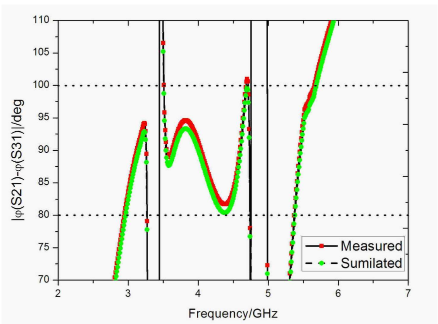
Figure 9 shows that the measured and simulated results are in good agreement with each other, the triple-band operating at 3.06 GHz, 4.00 GHz and 5.54 GHz, as shown in Table 2, the first operating frequency is 3.06 GHz, the useful bandwidth is 2.97 GHz–3.16 GHz, the relative is 6.2%, in this band, the return loss is less than $-12\,\text{dB}$, the phase difference is from 80-degree to 94-degree, the performance is very good; the second frequency is 4.00 GHz, the bandwidth is 0.3 GHz, it also has a good performance; the third frequency is 5.54 GHz, it has a very narrow bandwidth, the relative is only 3.4%. The isolation



(a)



(b)



(c)

Figure 9. Measured and simulated results. (a) Simulated S-parameters. (b) Measured S-parameters. (c) Phase difference of S_{21} and S_{31}.

Table 2. The performances of the three bands ($\Delta S_{21} = ||S_{21}| - 3\,\text{dB}|$, $\Delta S_{31} = ||S_{31}| - 3\,\text{dB}|$, $\Delta\varphi = ||\varphi(S_{21}) - \varphi(S_{31})| - 90°|$).

f/GHz	$S_{11} < -10\,\text{dB}$	$\Delta S_{21} < 1\,\text{dB}$ & $\Delta S_{31} < 1\,\text{dB}$
3.06 GHz	2.81 GHz–3.21 GHz	2.96 GHz–3.16 GHz
4.00 GHz	3.73 GHz–4.13 GHz	3.82 GHz–4.12 GHz
5.54 GHz	5.35 GHz–5.67 GHz	5.48 GHz–5.89 GHz
f/GHz	$\Delta\varphi < 10°$	useable
3.06 GHz	2.97 GHz–3.26 GHz	2.97 GHz–3.16 GHz
4.00 GHz	3.51 GHz–4.31 GHz	3.82 GHz–4.12 GHz
5.54 GHz	5.38 GHz–5.68 GHz	5.48 GHz–5.67 GHz

of this designed branch-line coupler is also great, it is less than $-12.5\,\text{dB}$, especially in the first and second operating band, it reaches to $-20\,\text{dB}$. This proposed branch-line coupler not only has good triple-band performances, but also is more effective in the situation which is sensitive to phase-changing, as the sign of phase difference in the two outputs at the three frequencies keeps the same. In addition, the whole size of this triple-band branch-line coupler is 17 mm × 14.4 mm ($0.173\lambda \times 0.147\lambda$) ($\lambda$ is the wavelength in low frequency), it realizes a 73% size reduction in comparison with the conventional branch-line coupler.

5. CONCLUSION

A novel miniaturized triple-band branch-line coupler based on S-D-CRLH-TL is proposed in this paper. The electromagnetic characteristics of S-D-CRLH-TL are analyzed by the simulator and equivalent circuit model, and the characteristic of three frequencies with phase of -90° is proved. Then, the proposed branch-line coupler is designed, fabricated and measured. The measured and simulated results are in good agreement, showing that the triple-band operating at 3.06 GHz, 4.00 GHz and 5.54 GHz, the useful bandwidths are 2.97 GHz–3.16 GHz, 3.82 GHz–4.12 GHz and 5.48 GHz–5.67 GHz, this designed coupler has good triple-band performances. In addition, this coupler not only is effective in the situation, which is sensitive to phase-changing, but also can realize a 73% size reduction in comparison with the conventional one.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 60971118).

REFERENCES

1. Lin, F., Q.-X. Chu, and Z. Lin, "A novel tri-band branch-line coupler with three controllable operating frequencies," *IEEE Microwave and Wireless Component Letters*, Vol. 20, No. 12, 666–668, 2010.
2. Zhang, H. and K. J. Chen, "A stub tapped branch line coupler for dual-band operations," *IEEE Microwave and Wireless Component Letters*, Vol. 17, No. 2, 106–108, 2007.
3. Cheng, K. K. M. and F. L. Wong, "A novel approach to the design and implementation of dual-band compact planar 90° branch-line coupler," *IEEE Trans. Microw. Theory Tech.*, Vol. 52, No. 11, 2458–2463, 2004.

4. Bonache, J., G. Sisó, M. Gil, A. Iniesta, J. Garcíarincón, and F. Martín, "Application of composite right/left-handed (CRLH) transmission lines based on complementary split ring resonators (CSRRs) to the design of dual-band microwave components," *IEEE Microwave and Wireless Component Letters*, Vol. 18, No. 8, 524–526, 2008.
5. Nguyen, H. V. and C. Caloz, "Dual-band CRLH branch-line coupler in MIM technology," *Microwave and Optical Technology Letters*, Vol. 48, No. 11, 2331–2333, 2006.
6. Lin, Y.-L., T.-Y. Huang, T.-M. Shen, C.-C. Chen, and R.-B. Wu, "Design of compact triple-band branch-line coupler with three arbitrary operating frequencies," *Asia-Pacific Microwave Conference*, 25–28, 2011.
7. Liou, C.-Y., M.-S. Wu, J.-C. Yeh, Y.-Z. Chueh, and S.-G. Mao, "A novel triple-band microstrip branch-line coupler with arbitrary operating frequencies," *IEEE Microwave and Wireless Component Letters*, Vol. 19, No. 11, 683–685, Nov. 2009.
8. Xu, H.-X., G.-M. Wang, X. Chen, and T.-P. Li, "Broadband balun using fully artificial fractal-shaped composite right/left-handed transmission line," *IEEE Microwave and Wireless Components Letters*, Vol. 22, No. 1, 16–18, 2012.
9. Yu, A., F. Yang, and A. Z. Elsherbeni, "A dual band circularly polarized ring antenna based on composite right and left handed metamaterials," *Progress In Electromagnetics Research*, Vol. 78, 73–81, 2008.
10. Dong, Y. D., H. Toyao, and T. Itoh, "Design and characterization of miniaturized patch antennas loaded with complementary split-ring resonators," *IEEE Trans. on Antennas and Propag.*, Vol. 60, 772–785, 2012.
11. Jin, P. and R. W. Ziolkowski, "Multi-frequency, linear and circular polarized, metamaterial-inspired, near field resonant parasitic antennas," *IEEE Trans. on Antennas and Propag.*, Vol. 59, 1446–1459, 2011.
12. Xu, H.-X., G.-M. Wang, and J.-Q. Gong, "Compact dual-band zeroth-order resonance antenna," *Chinese Physics Letters*, Vol. 29, 014101, 2012.
13. Hsu, C.-L., C.-W. Chang, and J.-T. Kuo, "Design of dual-band microstrip rat race coupler with circuit miniaturization," *IEEE MTT-S Int. Microw. Symp. Dig.*, 177–180, Honolulu, HI, 2007.
14. Xu, H.-X., G.-M. Wang, J.-G. Liang, and T.-P. Li, "A compact microstrip diplexer using composite right/left-handed transmission line with enhanced harmonic suppression," *Microwave Jour-*

nal, Vol. 54, No. 11, 112–120, 2011.

15. Cao, W.-Q., B.-N. Zhang, T.-B. Yu, A. J. Liu, S.-J. Zhao, D.-S. Guo, and Z.-D. Song, "Single-feed dual-band dual-mode and dual-polarized microstrip antenna based on metamaterial structure," *Journal of Electromagnetic Waves and Applications*, Vol. 25, No. 13, 1909–1919, 2011.
16. Rennings, A., T. Liebig, C. Caloz, and I. Wolff, "Double-Lorentz transmission line metamaterial and its application to tri-band devices," *IEEE/MTT-S Microwave Symposium*, 1427–1430, Honolulu, 2007.
17. Wu, G.-C., G.-M. Wang, T. Li, and C. Zhou, "Novel dual-composite right/left-handed transmission line and its application to bandstop filter," *Progress In Electromagnetics Research Letters*, Vol. 37, 29–35, 2013.
18. Chiou, Y.-C. and J.-Y. Kuo, "Planar multiband bandpass filter with multimode stepped-impedance resonators," *Progress In Electromagnetic Research*, Vol. 114, 129–144, 2011.
19. Li, B., X. Wu, and W. Wu, "A miniaturized branch-line coupler with wideband harmonics suppression," *Progress In Electromagnetics Research Letters*, Vol. 17, 181–189, 2010.
20. Xu, H.-X., G.-M. Wang, and J.-G. Liang, "Novel CRLH TL metamaterial and compact microstrip branch-line coupler application," *Progress In Electromagnetics Research C*, Vol. 20, 173–186, 2011.
21. Kuo, J.-T. and C.-H. Tsai, "Generalized synthesis of rat race ring coupler and its application to circuit miniaturization," *Progress In Electromagnetics Research*, Vol. 108, 51–64, 2010.
22. Lu, K., G.-M. Wang, C.-X. Zhang, and Y.-W. Wang, "Design of miniaturized branch-line coupler based on novel spiral-based resonators," *Journal of Electromagnetic Waves and Applications*, Vol. 25, No. 16, 2244–2253, 2011.
23. Dai, G. and M. Xia, "Novel miniaturized bandpass filters using spiral-shaped resonators and window feed structures," *Progress In Electromagnetics Research*, Vol. 100, 235–243, 2010.
24. Wang, Y. X., "Microstrip cross-coupled tri-section stepped impedance bandpass filter with wide stop-band performance," *Journal of Electromagnetic Waves and Applications*, Vol. 23, Nos. 2–3, 289–296, 2009.
25. Huang, C.-Y., M.-H. Weng, C.-S. Ye, and Y.-X. Xu, "High band isolation and wide stopband diplexer using dual-mode stepped impendence resonators," *Progress In Electromagnetics Research*, Vol. 100, 299–308, 2010.