Progress In Electromagnetics Research C, Vol. 43, 79–91, 2013

COMPACT DIFFERENTIAL BANDPASS FILTER WITH IMPROVED IN-BAND COMMON-MODE SUPPRESSION WITH LOADED T-SHAPED RESONATORS

Hui Wang[1], Xuan Li[2], Wei Kang[1], Chen Tan[1], Wen Wu[1], and Guo Yang[1, *]

[1]Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing 210094, China

[2]Wireless R&D, Alcatel-Lucent Shanghai Bell, Nanjing 210037, China

Abstract—Compact symmetrical four-ports differential bandpass filters with good common-mode suppressions are proposed in this work. The presented filters are designed based on half-wavelength coupled resonators with compact size, good filtering responses for differential-mode, and wide common-mode suppression range. To further improve the common-mode performances within the differential-mode passband, T-shaped resonators are loaded at the center of the structure. It is noted that, the size of filter does not become larger with loaded T-shaped resonators. Both these two filters are centered at 1.8 GHz for Global System Mobile Communication (GSM) with 7.8% fractional bandwidth. For differential-mode, the insertion is less than -1.2 dB in the 3-dB passband and the matching is better than -20 dB. Good stopband characteristics are also obtained with more than -20 dB out-of-band attenuation from dc to 1.6 GHz in the lower stopband and from 2.0 to 4.8 GHz in the upper stopband. For common-mode, better than -15 dB suppression is achieved within dc to 6.2 GHz and with the help of the loaded T-shaped resonators, the rejection in the differential-mode passband is improved to be more than -40 dB. Theory analysis, simulation, and measurement show good agreement with each other.

Received 27 July 2013, Accepted 21 August 2013, Scheduled 28 August 2013

* Corresponding author: Guo Yang (yangguo110@vip.sina.com).

1. INTRODUCTION

Differential bandpass filters (BPFs) are one of the most essential components in the high speed wireless communication systems due to their high immunity to the environmental noise and low electromagnetic interference (EMI) to meet the prompt need in the development of balanced radio frequency (RF) front-end. Recently, many different differential BPFs with both differential-mode (DM) filtering responses and common-mode (CM) rejection have been demonstrated [1–24]. Conventional planar microstrip lines were employed in [1–3] for wideband differential BPFs design. In [4–6], ring resonators were analyzed and discussed for differential filters design. Ultra-wideband (UWB) differential BPFs based on transversal signal-interference concepts were fabricated in [7] and [8]. The passband with adjusted fractional bandwidth (FBW) of these filters can be achieved. Embedded [9] and integrated [10] passive device technology was introduced for miniaturization design of full differential BPFs. In [11–13], balanced coupled-resonators were demonstrated for implementation of differential BPFs. These filter showed stopband extension [11], good common-mode rejection ratio (CMRR) [12], and dual-band [13] performances. Analysis of balanced filters using composite right/left handed (CRLH) structures were presented in [14] and [15] while stepped-impedance slotline multiple-mode resonator [16] and stepped-impedance resonators (SIRs) [17–20] were introduced for differential BPFs applications. Novel UWB differential filters based on 180° phase shifter were fabricated in [21, 22], where π-network microstrip line structure was employed in [21] and double-sided parallel-strip line was used in [22]. To improve the performances of CM suppression, defected ground structures (DGS) were proposed in [23] and [24] for balanced BPFs implementations. However, the drawback was that the size was big and it would consume the available area in the ground plane.

This paper is focused on compact differential BPF design and improved CM rejection using loaded T-shaped resonators. Proposed basic compact differential filter, i.e., Filter A, is implemented using half-wavelength coupled resonators. As the circuit has twofold symmetry along the horizontal and vertical directions, the even-odd decomposition technique can be performed for the scattering analysis [25]. All the scattering parameters can be obtained and adjusted for DM and CM responses. The center frequency of Filter A is centered at 1.8 GHz for Global System Mobile Communication (GSM) with 7.8% fractional bandwidth (FBW). Meanwhile, wide out-of-band attenuation from dc to 1.6 GHz for lower stopband and from 2.0 to

4.8 GHz for upper stopband is implemented. The CM signals of Filter A can be rejected below −15 dB within dc-6.2 GHz, which shows very good CM responses. To further improve the in-band CM suppression, T-shaped resonators are loaded for Filter B construction. Due to the presence of T-shaped resonators, the balanced Filter B shows almost unchanged DM filtering responses and improved CM characteristics with more than −40 dB suppression. The proposed filters are analyzed by the equivalent circuit models, simulated by the full-wave simulators, and validated by the measurements. Good agreement between the theory analysis, simulations, and measurements is obtained.

2. DESIGN AND DISCUSSION OF FILTER A

As depicted in Fig. 1, Filter A, a compact differential BPF centered at 1.8 GHz for GSM systems, is proposed. The presented filter is composed of two main parts for DM filtering responses and CM suppression performances. The first part is half-wavelength resonator using microstrip lines and the second part is coupled open-ended lines which can provide electric coupling as a lumped capacitance in this design. As in Fig. 1, the circuit has twofold symmetry along the horizontal and vertical directions, the even-odd decomposition technique can be performed for the scattering analysis.

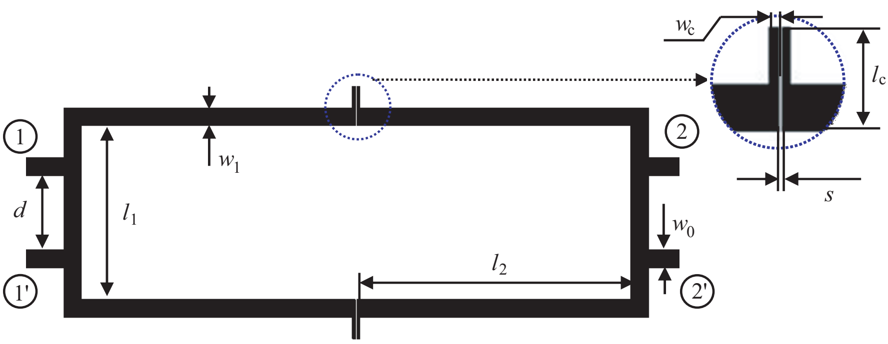

Figure 1. Configuration of Filter A.

Figure 2 shows the equivalent circuits of Filter A, where Z_1, Z_2, Z_3, θ_1, θ_2, and θ_3 are the characteristic impedances and electrical lengths of the half-wavelength resonator, and C is denoted as the equivalent capacitance of the coupled open-ended lines. When even-even, even-odd, odd-even, and odd-odd modes are excited, the symmetrical lines can be replaced as magnetic-magnetic, magnetic-electric, electric-magnetic, and electric-electric walls, respectively.

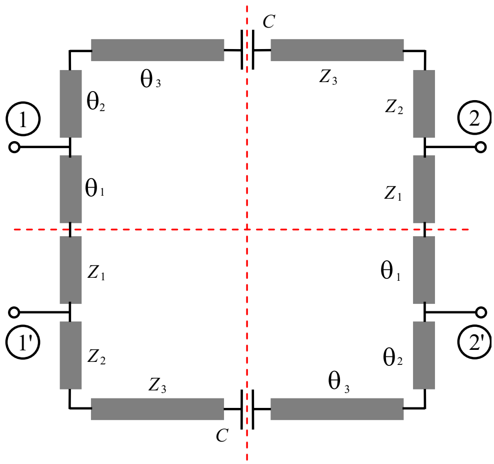

Figure 2. Equivalent circuit of the proposed compact differential BPF.

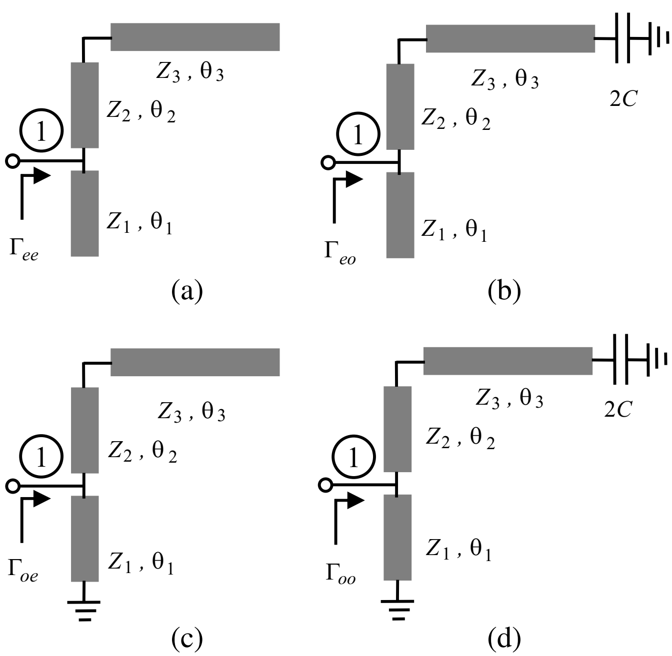

Figure 3. Quarter circuits of Filter A. (a) Even-even mode. (b) Even-odd mode. (c) Odd-even mode. (d) Odd-odd mode.

Thus, the circuit is divided into four different quarter circuits, as shown in Fig. 3. As seen from the figures, they are obtained by applying open- or short-circuited terminations on the horizontal and vertical planes of symmetry.

Firstly, the scattering parameters can be then found through the reflection coefficients of the four quarter circuits as

$$S_{11} = S_{22} = S_{33} = S_{44} = \frac{\Gamma_{ee} + \Gamma_{eo} + \Gamma_{oe} + \Gamma_{oo}}{4} \tag{1}$$

$$S_{21} = S_{12} = S_{43} = S_{34} = \frac{\Gamma_{ee} - \Gamma_{eo} + \Gamma_{oe} - \Gamma_{oo}}{4} \tag{2}$$

$$S_{31} = S_{42} = S_{13} = S_{24} = \frac{\Gamma_{ee} - \Gamma_{eo} - \Gamma_{oe} + \Gamma_{oo}}{4} \tag{3}$$

$$S_{41} = S_{32} = S_{23} = S_{14} = \frac{\Gamma_{ee} + \Gamma_{eo} - \Gamma_{oe} - \Gamma_{oo}}{4} \tag{4}$$

where Γ_{ee}, Γ_{ee}, Γ_{ee}, and Γ_{ee} are the reflection coefficients for the corresponding even-even, even-odd, odd-even, and odd-odd modes. And they can be calculated from the corresponding input port admittances as

$$\Gamma_{ij} = \frac{1 - y_{ij}}{1 + y_{ij}}, \quad \text{for } i, j = e \text{ or } o \tag{5}$$

with

$$y_{ee} = jy_1 \tan\theta_1 + jy_2 \tan(\theta_2 + \theta_3) \tag{6}$$

$$y_{eo} = jy_1 \tan\theta_1 + \frac{2j\omega C Z_2 + \tan(\theta_2 + \theta_3)}{Z_2 + 2j\omega C Z_2^2 \tan(\theta_2 + \theta_3)} \tag{7}$$

$$y_{oe} = -jy_1 \cot\theta_1 + jy_2 \tan(\theta_2 + \theta_3) \tag{8}$$

$$y_{oo} = -jy_1 t \cot\theta_1 + \frac{2j\omega C Z_2 + \tan(\theta_2 + \theta_3)}{Z_2 + 2j\omega C Z_2^2 \tan(\theta_2 + \theta_3)} \tag{9}$$

where $Z_2 = Z_3$ and $y_2 = 1/Z_2$ is considered in this design.

Secondly, the equivalent capacitance C of the coupled open-ended lines can also be solved as shown in Fig. 4, i.e., an equivalent circuit of LC-circuit model.

Figure 4(b) plots a T-network composed of three capacitances. The values of C_1 and C_2 can be calculated by

$$C_1 = -Z_{oo} \cot\theta_c \tag{10}$$

$$C_2 = -[(Z_{oe} - Z_{oo}) \cot\theta_c]/2 \tag{11}$$

where Z_{oe} and Z_{oo} are the even- and odd-mode characteristic impedances, and θ_c is the electrical length of the coupled open-ended lines. The equivalent capacitance is expressed as

$$C = \frac{1}{2} C_1 + C_2 \tag{12}$$

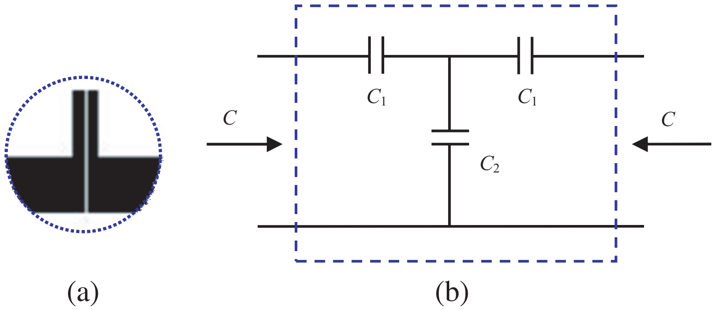

Figure 4. (a) Layout and (b) equivalent LC-circuit model of the coupled open-ended lines.

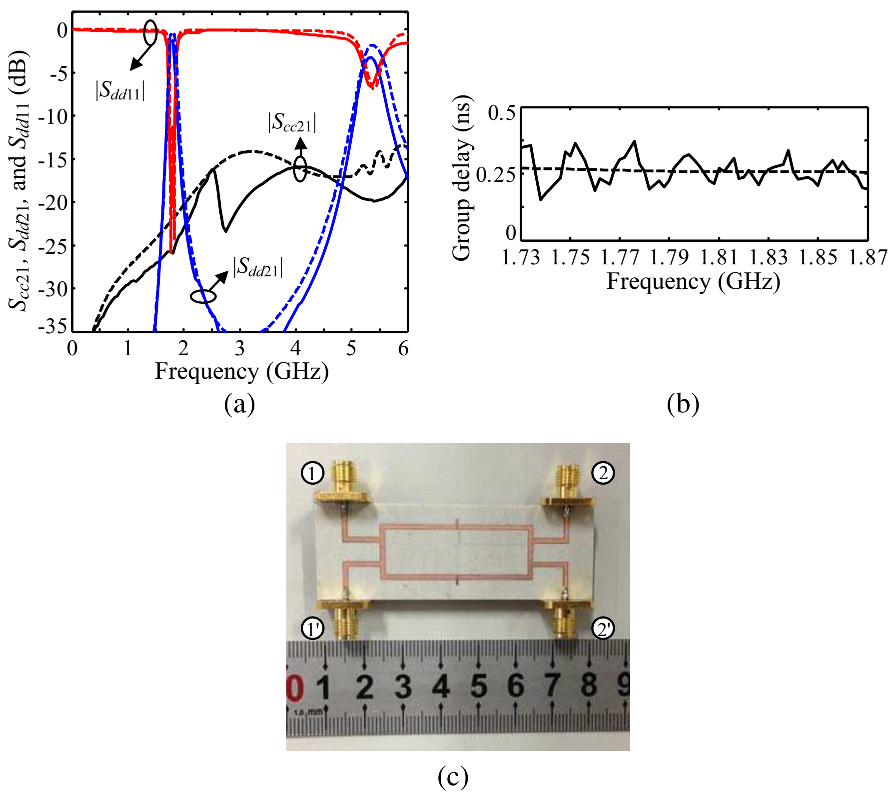

Figure 5. Simulated (dashed line) and measured (solid). (a) S-parameters, (b) group delay and (c) photo of Filter A.

Based on above analysis, the scattering parameters are all calculated and the DM and CM responses can be given by

$$S_{dd21} = (S_{21} - S_{41} - S_{23} + S_{43})/2 \tag{13}$$
$$S_{dd11} = (S_{11} - S_{31} - S_{13} + S_{33})/2 \tag{14}$$
$$S_{cc21} = (S_{21} + S_{41} + S_{23} + S_{43})/2 \tag{15}$$
$$S_{cc11} = (S_{11} + S_{31} + S_{13} + S_{33})/2. \tag{16}$$

A compact differential filter is fabricated on RO4003 with dielectric constant of 3.38, thickness of 0.508 mm, and loss tangent of 0.0027 to validate the theory and discussion. The dimensions shown in Fig. 1 are $w_0 = w_1 = 1.17$ mm, $w_c = 0.2$ mm, $l_1 = 11.3$ mm, $l_2 = 17.8$ mm, $l_c = 2.6$ mm, $d = 4.8$ mm, and $s = 0.1$ mm. The simulated and measured results and a photography of Filter A are plotted in Fig. 5. For DM, the center frequency is set at 1.8 GHz for GPS systems with 7.8% FBW and the insertion loss is less than -1.2 dB with more than -20 dB matching. Better than -20 dB out-of-band attenuations are obtained from dc to 1.6 GHz in the lower stopband and from 2.0 to 4.8 GHz in the upper stopband. Flat group delay in the passband is also obtained as shown in Fig. 5(b). For CM, the rejection is as good as more than -15 dB from dc to 6.2 GHz, which indicates wide suppression characteristic. Total size of Filter A is only $16.5 \times 38.5\,\text{mm}^2$ ($0.059\lambda_0^2$, where λ_0 is the wavelength at the center frequency). The simulations and measurements show very good agreement, as shown in Fig. 5.

3. DESIGN AND DISCUSSION OF FILTER B

Filter A exhibits good DM filtering responses and wideband CM rejection. However, the suppression level of the CM in the region of interest is very limited. Thus, another compact differential BPF named Filter B with further rejected CM signals by loaded T-shaped resonator is designed as shown in Fig. 6.

For DM operation, the symmetric plane TT' becomes a perfect electric wall, and the equivalent half circuit will be the same as the DM mode of Filter A. For CM, a perfect magnetic wall will be replaced, and the even-/odd-mode circuits of that are drawn in Fig. 7. The input admittances of even-/odd-mode equivalent circuits of CM half circuit of Filter B can be written as

$$Y_{ine} = jy_2 \tan(\theta_2 + \theta_3) + \frac{Z_1 + jZ_t \tan\theta_1}{Z_1 Z_t + jZ_1^2 \tan\theta_1} \tag{17}$$

$$Y_{ino} = \frac{2j\omega C Z_2 + \tan(\theta_2 + \theta_3)}{Z_2 + 2j\omega C Z_2^2 \tan(\theta_2 + \theta_3)} + \frac{Z_1 + jZ_t \tan\theta_1}{Z_1 Z_t + jZ_1^2 \tan\theta_1} \tag{18}$$

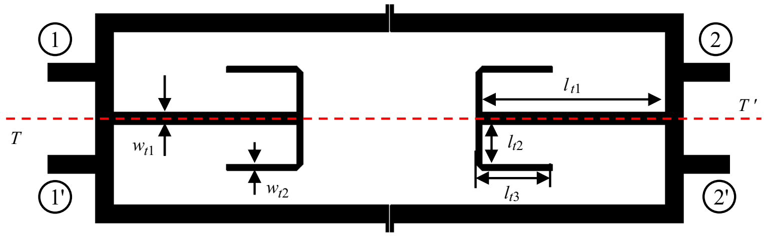

Figure 6. Configuration of Filter B.

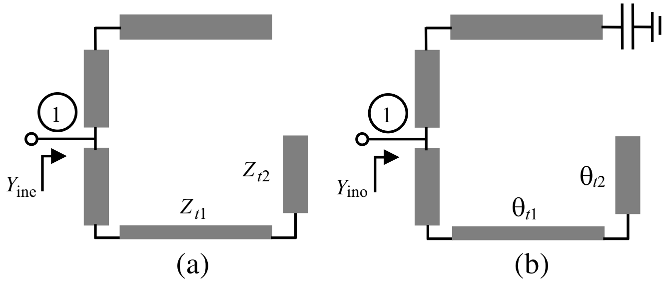

Figure 7. (a) Even-mode and (b) odd-mode equivalent circuits of CM half circuit of Filter B.

with

$$Z_t = Z_{t1} \frac{Z_{t2} + jZ_{t1} \tan \theta_{t1}}{Z_{t1} + Z_{t2} \tan \theta_{t1} \cot \theta_{t2}} \tag{19}$$

Obviously, one more transmission zero is obtained for CM suppression when the condition $Y_{ine} = Y_{ino}$ is considered. Fig. 8 plots the variations of the zero created by the loaded T-shaped resonator for CM performance, in which (a) is the relationship between the position of the zero and the length of the T-shaped resonator when Z_{t1} and Z_{t2} are equal, and (b) is the changes of the CM rejection level with different impedances of the resonator with fixed physical length.

Thus, both the center frequency of the zero and the rejection level for CM suppression can be controlled by adjusting the length and width of the loaded T-shaped resonators. Based on this analysis, Filter B is designed, fabricated on RO4003, and measured. The dimensions of Filter B are $l_c = 1.8$ mm, $l_{t1} = 12$ mm, $l_{t2} = 2.6$ mm, $l_{t3} = 5$ mm, $w_{t1} = 0.8$ mm, and $w_{t2} = 0.4$ mm, and the other dimensions are same as what of Filter A.

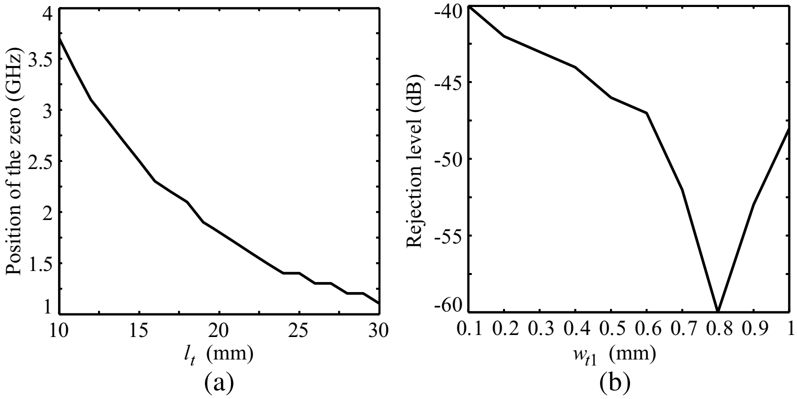

Figure 8. Variation of (a) zero position with length of the T-shaped resonator ($l_t = l_{t1} + l_{t2} + l_{t3}$) and (b) rejection level with width of the stubs of the resonator ($l_t = 20$ mm and $w_{t1} = 2w_{t2}$).

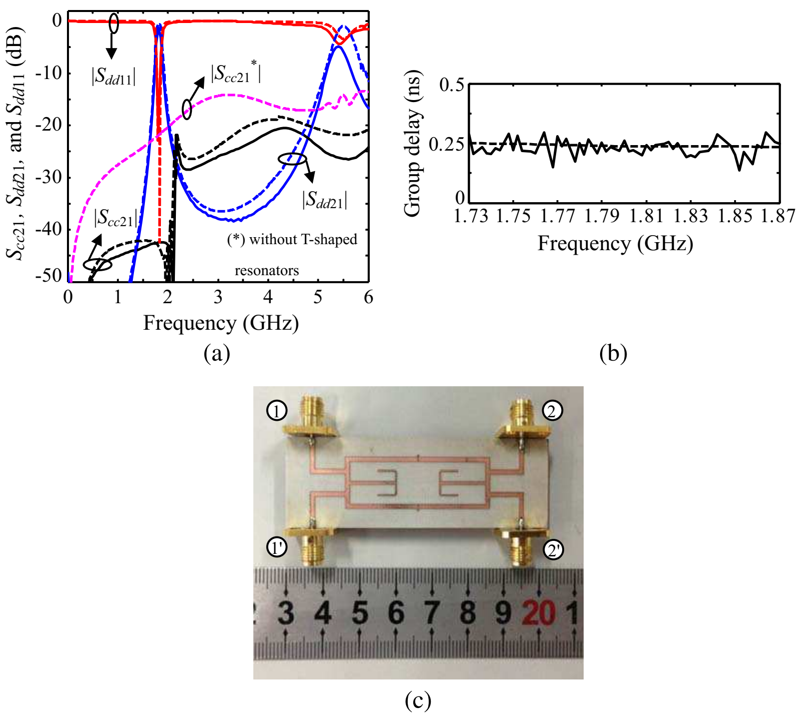

Figure 9. Simulated (dashed line) and measured (solid). (a) S-parameters, (b) group delay and (c) photo of Filter B.

The simulated and measured results and a photo of Filter B are shown in Fig. 9. For DM, filtering responses are almost unchanged with loaded T-shaped resonators. That is because the DM half circuits of Filter A and Filter B are the same with each other. For CM, the rejection is better than −20 dB (measured results) from dc to 6 GHz within a very wide range. Moreover, the in-band (around 1.8 GHz) suppression is much improved to be more than −40 dB, which shows very good attenuation characteristic with about −20 dB improvement. The total size of Filter B is as compact as that of Filter A, i.e., $0.059\lambda_0^2$ although the T-shaped resonators are loaded and the performances are much improved. Table 1 is the comparison between the proposed differential BPFs between the reported ones.

Table 1. Comparison with the reported differential BPFs.

Ref.	f_0 (GHz)	3 dB FBW	Insertion Loss (dB)
Filter A	1.8	7.8%	−1.2
Filter B	1.8	7.8%	−1.1
[1]	6.5	119%	−0.8
[11]	1.025	11.5%	−3.88
[13]	1.835	7%	−2.2
[17]	2.44	16.7%	−1.78
Ref.	Return Loss (dB)	CM Rejection [dB (GHz–GHz)]	Size (λ_0^2)
Filter A	−20	> 15 (0–6.2)	0.059
Filter B	−20	> 20 (0–6)	0.059
[1]	−14	> 9.6 (2.6–12)	0.245
[11]	−20	> 30 (0–5)	0.079
[13]	−15	> 20 (0–3.5)	0.053
[17]	−13	> 27 (1–8)	0.156

To clarify the proposed differential BPFs design, the design procedure can be summarized as follows:

1) The DM and CM circuits can be obtained easily using the proposed filter structures due to the quarter equivalent circuits of both Filter A and Filter B as shown in Fig. 3.
2) The basic performances of Filter A can be analyzed and calculated by Eqs. (1)–(16).

3) Using Eqs. (17)–(19), the location of zeros can be adjusted by the length of l_t, as shown in Fig. 8(a). And the varied characteristic impedances of Z_{t1} and Z_{t2} can be used to control the rejection level of CM, as shown in Fig. 8(b).
4) The final dimensions can be obtained by using some microwave simulators although the open ends and cross sections will affect the practical electrical lengths of the resonator.

4. CONCLUSION

Compact differential BPFs, Filter A and Filter B, are designed, fabricated, measured, and discussed in this work. Very good DM filtering responses including good insertion and return losses, wide out-of-band attenuation range in both lower and upper stopbands, and sharp skirt are obtained. Meanwhile, compared with Filter A, the CM performance of Filter B is much improved to have more than -40 dB rejection within the DM passband based on the T-shaped resonators, indicating potential applications in the GSM communication systems.

REFERENCES

1. Wu, X. H. and Q. X. Chu, "Compact differential ultra-wideband bandpass filter with common-mode suppression," *IEEE Microw. Wireless Compon. Lett.,* Vol. 22, No. 9, 456–458, 2012.
2. Lim, T. B. and L. Zhu, "Highly selective differential-mode wideband bandpass filter for UWB application," *IEEE Microw. Wireless Compon. Lett.,* Vol. 21, No. 3, 133–135, 2011.
3. Lim, T. B. and L. Zhu, "A differential-mode wideband bandpass filter on microstrip line for UWB application," *IEEE Microw. Wireless Compon. Lett.,* Vol. 19, No. 10, 632–634, 2009.
4. Feng, W. J., W. Q. Che, Y. L. Ma, and Q. Xue, "Compact wideband differential bandpass filters using half-wavelength ring resonator," *IEEE Microw. Wireless Compon. Lett.,* Vol. 23, No. 2, 81–83, 2013.
5. Lee. C. H., C. I. G. Hsu, H. H. Chen, and Y. S. Lin, "Balanced single- and dual-band BPFs using ring resonators," *Progress In Electromagnetics Research*, Vol. 116, 333–346, 2011.
6. Wang, H., W. Kang, G. Yang, and W. Wu, "A wideband differential bandpass filter based on T-shaped stubs and single ring resonator," *Progress In Electromagnetics Research Letters*, Vol. 40, 39–48, 2013.

7. Zhu, H. T., W. J. Feng, W. Q. Che, and Q. Xue, "Ultra-wideband differential bandpass filter based on transversal signal-interference concept," *Electron. Lett.*, Vol. 47, No. 18, 1033–1035, 2011.
8. Shi, S. Y., W. W. Choi, W. Q. Che, K. W. Tam, and Q. Xue, "Ultra-wideband differential bandpass filter with narrow notched band and improved common-mode suppression by DGS," *IEEE Microw. Wireless Compon. Lett.,* Vol. 22, No. 4, 185–187, 2012.
9. Wu, S. M., C. T. Kuo, P. Y. Lyu, Y. L. Shen, and C. I. Chien, "Miniaturization design of full differential bandpass filter with coupled resonators using embedded passive device technology," *Progress In Electromagnetics Research*, Vol. 121, 365–379, 2011.
10. Wu, S. M., C. T. Kuo, and C. H. Chen, "Very compact full differential bandpass filter with transformer integrated using integrated passive device technology," *Progress In Electromagnetics Research*, Vol. 113, 251–267, 2011.
11. Wu. C. H., C. H. Wang, and C. H. Chen, "Balanced coupled-resonator bandpass filters using multisection resonators for common-mode suppression and stopband extension," *IEEE Trans. Microwave Theory & Tech.*, Vol. 55, No. 8, 17561763, 2007.
12. Wu, C. H., C. H. Wang, and C. H. Chen, "Novel balanced coupled-line bandpass filters with common-mode noise suppression," *IEEE Trans. Microwave Theory & Tech.,* Vol. 55, No. 2, 287–295, 2007.
13. Shi, J. and Q. Xue, "Balanced bandpass filters using center-loaded half-wavelength resonators," *IEEE Trans. Microwave Theory & Tech.,* Vol. 58, No. 4, 970–977, 2010.
14. Niu, J. X. and X. L. Zhou, "Analysis of balanced composite right/left handed structure based on different dimensions of complementary split ring resonators," *Progress In Electromagnetics Research*, Vol. 74, 341–351, 2007.
15. Kim, Y. and S. Sim, "Symmetric coupled composite right-/left-handed transmission line in common-/differential-mode operation," *Progress In Electromagnetics Research Letters*, Vol. 40, 1–8, 2013.
16. Lee, C. H., C. I. G. Hsu, and C. J. Chen, "Band-notched balanced UWB BPF with stepped-impedance slotline multi-mode resonator," *IEEE Microw. Wireless Compon. Lett.,* Vol. 22, No. 4, 182–184, 2012.
17. Shi, J. and Q. Xue, "Novel balanced dual-band bandpass filter using coupled stepped-impedance resonators," *IEEE Microw. Wireless Compon. Lett.,* Vol. 20, No. 1, 19–21, 2010.

18. Lin, S. C. and C. Y, Yeh, "Stopband-extenede balanced filters using both $\lambda/4$ and $\lambda/2$ SIRs with common-mode suppression and improved passband selectivity," *Progress In Electromagnetics Research*, Vol. 128, 215–228, 2012.
19. Cho, Y. H. and S. W. Yun, "Design of balanced dual-band bandpass filters using asymmetrical coupled lines," *IEEE Trans. Microwave Theory & Tech.,* Vol. 61, No. 8, 2814–2820, 2013.
20. Lee, C. H., C. I. G. Hsu, and C. C. Hsu, "Balanced dual-band BPF with stub-loaded SIRs for common-mode suppression," *IEEE Microw. Wireless Compon. Lett.,* Vol. 20, No. 2, 70–72, 2010.
21. Wang, X. H., H. L. Zhang, and B. Z. Wang, "A novel ultra-wideband differential filter based on microstrip line structures," *IEEE Microw. Wireless Compon. Lett.,* Vol. 23, No. 3, 128–130, 2013.
22. Wang, X. H., Q. Xue, and W. W. Choi, "A novel ultra-wideband differential filter based on double-sided parallel-strip line," *IEEE Microw. Wireless Compon. Lett.,* Vol. 20, No. 8, 471–473, 2010.
23. Xia, B., L. S. Wu, and J. F. Mao, "An ultra-wideband balanced bandpass filter based on defected ground structures," *Progress In Electromagnetics Research C*, Vol. 25, 133–144, 2012.
24. Fernandez-Prieto, A., J. Martel, F. Medina, F. Mesa, S. Qian, J. S. Hong, J. Naqui, and F. Martin, "Dual-band differential filter using broadband common-mode rejection artificial transmission line," *Progress In Electromagnetics Research*, Vol. 139, 779–797, 2013.
25. Reed, J. and G. J. Wheeler, "A method of analysis of symmetrical four-port networks," *IRE Trans. Microwave Theory & Tech.,* Vol. 4, No. 4, 246–252, 1956.