Compact balanced bandpass filter with the fractal defected structures

Sheng Zhang¹, Xue-Dong Fu¹, Jun-Jie Cheng¹, De-Qiang Cheng¹, Hai-Ting Wang¹, Fa-Lin Liu², and Li-Cun Bao³

¹ School of Information and Control Engineering, China University of Mining and Technology, Xu Zhou 221116, China
² Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei 230027, China
³ Zhuhai Century Dingli Polytron Technologies Inc, Zhuhai 519085, China

a) chengdq@cumt.edu.cn

Abstract: In this letter, the fractal defected structure (FDS) is firstly used to design miniaturized balanced bandpass filter (BPF). A novel quarter-mode substrate integrated waveguide resonator (QMSIWR) with etched symmetrical FDSs is presented, which has a lower resonate frequency (f₀) and acceptable unloaded quality (Qₜ₀) at TE₂₀₁ mode. Based on this novel resonator and eighth-mode substrate integrated waveguide resonator (EMSIWR) with etched the FDS, a compact balanced BPF with a reduced size over 72.5% is designed, which can implement one transmission zero (TZ) on each side of the differential-mode (DM) passband by using cross-coupling technology. Meanwhile, the common-mode (CM) signal is suppressed below −23.6 dB in the DM passband. The measured results agree well with the simulated ones.

Keywords: fractal defected structure (FDS), balanced BPF, cross-coupling, transmission zero (TZ)

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] W. Feng, et al.: “High selectivity wideband balanced filters with multiple transmission zeros,” IEEE Trans. Circuits Syst. II, Exp. Briefs 64 (2017) 1182 (DOI: 10.1109/TCSII.2015.2482398).
[2] K. Deng and Z. Chen: “Wideband balanced filters with wideband common mode suppression using coupled lines,” Prog. Electromagn. Res. Lett. 65 (2017) 49 (DOI: 10.2528/PIERL16111201).
[3] F. Bagci, et al.: “Compact balanced dual-band bandpass filter based on modified coupled-embedded resonators,” IEEE Microw. Wireless Compon. Lett. 27 (2017) 31 (DOI: 10.1109/LMWC.2016.2629962).
[4] D. Chen, et al.: “Differential bandpass filter on dual-mode ring resonator with slotline feeding scheme,” Electron. Lett. 51 (2015) 1512 (DOI: 10.1049/el.2015.1709).
[5] X. Xu, et al.: “A new approach to design differential-mode bandpass filters on...
SIW structure,” IEEE Microw. Wireless Compon. Lett. 23 (2013) 635 (DOI: 10.1109/LMWC.2013.2283859).

[6] M.-H. Ho and C.-S. Li: “Novel balanced BPF design using half-mode substrate integrated waveguide with common-mode suppression,” Microw. Opt. Technol. Lett. 55 (2013) 1112 (DOI: 10.1002/mop.27510).

[7] P. Li, et al.: “Design of compact bandpass filters using quarter-mode and eighth-mode SIW cavities,” IEEE Trans. Compon. Packag. Manuf. Technol. 7 (2017) 956 (DOI: 10.1109/TCPMT.2017.2677958).

[8] M. H. Ho and C. S. Li: “Novel balanced bandpass filters using substrate integrated half-mode waveguide,” IEEE Microw. Wireless Compon. Lett. 23 (2013) 78 (DOI: 10.1109/LMWC.2013.2238911).

[9] S. Zhang, et al.: “Quasi eighth-mode substrate integrated waveguide (SIW) fractal resonator filter utilizing gap coupling compensation,” Frequenz 70 (2016) 377 (DOI: 10.1515/freq-2015-0255).

[10] J. Ding, et al.: “W-band quasi-elliptical waveguide filter with cross-coupling and source-load coupling,” Electron. Lett. 52 (2016) 1960 (DOI: 10.1049/el.2016.3245).

1 Introduction

With the development of modern communication system, the balanced bandpass filter (BPF) is playing an increasingly important role because of its immunity to environmental noise and electromagnetic interference [1, 2, 3, 4]. Recently, the substrate integrated waveguide (SIW) has been gradually used in the balanced BPF design due to its high Q-factor, light weight, and simple fabrication process [5, 6, 7, 8]. In [5], an approach to design balanced BPF is presented based on the odd-symmetrical electric field distributions. And the proposed filter has better selectivity, but it has a larger size $1.88 \times 2.99 \lambda_{g}^{2}$. In order to reduce the size of balanced filter, half-mode SIW resonators (HMSIWR) [6], quarter-mode SIWR (QMSIWR) combined with eighth-mode SIWR (EMSIWR) [7] are proposed, respectively. Considering the demands of symmetrical frequency response, the selectivity of both filters are not satisfied due to no two transmission zeros (TZs). A further miniaturized filter [8] based on folded HMSIWRs is designed, but the fabrication process is complicated and costly.

Owing to self-similarity and space filling of the fractal defected structure (FDS), it has been widely used in many microwave fields. But it is seldom introduced in filter design [9], especially in balanced BPF. In [9], an improved EMSIWR with etched FDS is proposed, which has a lower resonate frequency ($f_{0}$) and satisfied unloaded quality ($Q_u$). For its asymmetry, the improved EMSIWR cannot be independently used to design balanced BPF. But it can be reformative part of a balanced BPF to further reduce its size.

In this letter, a novel QMSIWR with etched symmetrical FDSs is proposed firstly. Compared with the conventional QMSIWR, this novel resonator has a lower $f_{0}$ and satisfied $Q_u$ to suppress CM signals. The novel QMSIWR and the improved EMSIWR [9] could be innovatively combined together to design miniaturized balanced BPF. Based on this idea, a compact balanced BPF using cross-coupling technology is designed and optimized. One TZ is generated on each side of the DM
passband, which improves its selectivity greatly. Compared with the filter in [5],
the filter size is reduced over 72.5%. Meanwhile, the proposed balanced BPF can
achieve high CM suppression in the DM passband. The measured results are in
good agreement with the simulated ones.

2 Novel quarter-mode SIWR (QMSIWR)

The electric field distribution in the square SIWR is shown in Fig. 1(a). By cutting
along the perfect magnetic walls (the dotted lines), QMSIWR and EMSIWR can be
obtained with the electric field distribution almost unchanged, which are shown in
Fig. 1(b) and (c), respectively. When the electric field distribution in the SIWR is
odd-symmetric, the electrical field is in the statuses of out-of-phase under CM
operation and in-phase under DM operation [5]. So the QMSIWR at the $TE_{201}$
mode can be used to suppress CM signals and transmit DM signals, as shown in
Fig. 1(d).

![Electric field distribution](image)

**Fig. 1.** The electric field distribution. (a) square SIWR (b, d) QMSIWR (c) EMSIWR

The proposed novel QMSIWR is shown in Fig. 2, and the symmetrical
isosceles right angled triangular FDSs are etched on the upper metallic layer. With
a increased, the electric field is gradually weakened in the central part of the
resonator, and it is gradually concentrated on the two open magnetic walls. The
electric field is slightly changed with different FDSs. However, its odd-symmetric
characteristic is almost unchanged. So the novel QMSIWR can be used to design
balanced BPF. The surface current at $TE_{201}$ mode is disturbed by FDSs, as shown in
Fig. 3(a) and (b). In the central part of the resonator, the current flows downward
rather than directly to the right part. Thus the equivalent electrical length of
QMSIWR is increased, which results in lower $f_0$ at $TE_{201}$ mode. The novel
resonator is simulated on 0.65 mm-thick RT/Duroid6006 with $\varepsilon_r = 6.15$ and
$\tan \delta = 0.0019$. Table I depicts the influence of different length $a$ on $f_0$ and $Q_a$
with the size of QMSIWR ($c = 17$ mm) unchanged, where the $k$ is the decreasing
percent of $f_0$. When $a$ is increased, the $f_0$ and $Q_a$ are both decreased. Length
$a = 4.5$ mm is chosen in this letter. In this case, the $f_0$ is 8.61 GHz reducing about
20.8%. Meanwhile, compared with the microstrip structure, the $Q_a$ is higher than
142, which is still acceptable for filter design.

![Electric field distribution](image)
3 Design of balanced BPF

In order to obtain a sharp cutoff skirt under DM operation, two TZs should be introduced on both sides of the passband. The most effective way to generate TZ is cross-coupling technology [10]. Because of the extra two open sides for the novel QMSIWR, this resonator has more flexibilities to implement diverse coupling topology structures. A compact balanced BPF based on two novel QMSIWRs (R2, R3) and four improved EMSIWRs [9] (R1, R1’, R4 and R4’) is designed and optimized by utilizing cross-coupling technology, which is shown in Fig. 4(a) and (b). The dotted lines indicate the main coupling path, which is implemented by two different negative coupling forms. One negative coupling form is the gap coupling between the cascaded R1 and R2, and it is same with R3 and R4. Another form is achieved between R2 and R3 by two reverse S-shape slots etched on the top and bottom of the resonators. The solid lines indicate the second coupling path, which is implemented by the positive coupling between R1 and R4.

![Fig. 2](image1.png)

**Fig. 2.** The electric field distributions in novel QMSIWR at $TE_{201}$ mode with different $a$. (a) $a = 2$ mm (b) $a = 3$ mm (c) $a = 4.5$ mm

![Fig. 3](image2.png)

**Fig. 3.** Surface current distribution of QMSIWR at $TE_{201}$ mode. (a) Without FDSs (b) With FDSs

| $a$ (mm) | $f_0$ (GHz) | $k$ | $Q_u$ |
|---------|-------------|-----|-------|
| 0       | 10.87       | 0   | 220   |
| 0.5     | 10.53       | 3.1%| 214   |
| 1       | 10.48       | 3.6%| 206   |
| 1.5     | 10.39       | 4.4%| 196   |
| 2       | 10.12       | 6.9%| 184   |
| 2.5     | 9.85        | 9.4%| 176   |
| 3       | 9.56        | 12.1%| 167 |
| 3.5     | 9.28        | 14.6%| 158 |
| 4       | 8.92        | 17.9%| 150 |
| 4.5     | 8.61        | 20.8%| 142 |
| 5       | 8.33        | 23.4%| 126 |

**Table 1.** Different $f_0$ and $Q_u$ for different length $a$

© IEICE 2018
DOI: 10.1587/elex.15.20180518
Received May 20, 2018
Accepted June 26, 2018
Publicized July 11, 2018
Copyedited August 10, 2018
Due to the symmetrical property of the proposed filter, a perfect electric wall would appear along the symmetrical plane under DM operation. The half bisection topology is shown in Fig. 5. On the left side of passband, the phase change of the main path is $+90^\circ + 90^\circ + 90^\circ + 90^\circ + 90^\circ = -90^\circ$, and the phase change of the second path is $+90^\circ - 90^\circ + 90^\circ = +90^\circ$. The phase of the two paths is opposite, so the cross-coupling is achieved, which could introduce one TZ. Similar to the left, one TZ is generated on the right side of passband.

The final optimized dimensions are shown as follows (all in mm): $w_{SO} = 1$, $a = 4.5$, $b = 1.14$, $a_1 = 13.8$, $b_1 = 8.2$, $c = 16$, $b_2 = 8$, $a_3 = 4.3$, $b_3 = 1.33$, $e = 1.3$, $g = 0.2$, $g_1 = 0.3$, $l_1 = 1.34$, $l_2 = 0.93$, $l_3 = 3.4$, $l_4 = 4$, $l_5 = 1.5$, $l_6 = 1.2$, $l_7 = 1$, $d = 0.5$, $d_1 = 0.4$, $s = 0.8$.

The measured results are shown in Fig. 6, which agree well with the simulated ones, and the fabricated filter size is $1.12 \times 1.39\lambda_g^2$. The measured passband is centered at 8.45 GHz with a 3-dB bandwidth of 147 MHz under DM operation. Within the DM passband, the minimum $|S_{dd21}|$ is 2.32 dB, and the $|S_{dd11}|$ is higher than 20.2 dB. The radiation loss of the eight FDSs and the parasitic effect of SMA cause the $|S_{dd21}|$ a little larger than the filter in [5]. Two TZs can be observed at 8.23 GHz and 8.97 GHz with attenuation of 21.3 dB and 40.6 dB, respectively. Meanwhile, the measured $|S_{cc11}|$ is less than 0.5 dB from 7.2 GHz to 9.8 GHz under CM operation, and the CM suppression level is higher than 23.6 dB in the DM passband.

Comparisons between the proposed filter and previous SIW balanced BPFs are shown in Table II, where the CF is the central frequency. Compared with the proposed filters in [5], this filter size is reduced over 72.5%. Compared with the proposed filters in [6, 7], this filter has better selectivity. So the proposed filter has smaller size and better selectivity concurrently.
4 Conclusion

In this letter, a novel QMSIWR with etched FDSs is proposed firstly. Compared with the traditional QMSIWR, it keeps odd-symmetric characteristic unchanged, while it has a lower $f_0$ at $TE_{201}$ mode. Then a balanced BPF based on improved EMSIWR and novel QMSIWR is proposed, which has excellent DM selectivity, good CM suppression. More importantly, compared with the conventional SIWR filter, this filter size reduces over 72.5%. In short, the FDS can be used to further miniaturized the size of balanced BPF.

Acknowledgments

This work is supported by the Fundamental Research Funds for the Central Universities (No. 2014ZDPY32).