Progress In Electromagnetics Research Letters, Vol. 34, 65–74, 2012

DESIGN AND IMPLEMENTATION OF COMPACT HYBRID FOUR-MODE BANDPASS FILTER WITH MULTI-TRANSMISSION ZEROS

X. Guan*, X. Wang, B. Wang, Y. Yuan, and H. Liu

School of Information Engineering, East China Jiaotong University,
Nanchang 330013, China

Abstract—This paper presents a novel compact microstrip hybrid four-mode bandpass filter (BPF) with good selectivity and multi-transmission zeros. By adding an external resonator to a triple-mode stub-loaded resonator, four modes are generated in the desired passband and a hybrid four-mode BPF is implemented. Odd- and even-mode theory is introduced to investigate the mode characteristics of triple-mode resonator in detail. Circuit model and coupling matrix are built to further explain the proposed methodology. A microstrip BPF with central frequency of 3.4 GHz for wireless communication was designed and fabricated. Three transmission zeros are obtained at 3.2 GHz, 3.55 GHz and 3.73 GHz, which improve selectivity and out-of-band rejection of the filter. The measured results of the fabricated filter represent good in-band and sharp sideband characteristic, which match well with simulated results.

1. INTRODUCTION

Nowadays, with the expeditious popularization of satellite communication systems and mobile communication systems, the designs of filters have found an increasingly comprehensive application in wireless communication systems. As a consequence, the microstrip dual-mode or multimode filters have aroused more and more attention in virtue of their reductions in size compared with the conventional microstrip filters. The appearance of the first planar dual-mode BPF in 1972 was proposed by Wolff [1]. Dual mode characteristic is produced by introducing perturbation to a ring resonator to split two degenerated modes of the resonator. From then on, various dual-mode [2–5] and multimode [7–9] microstrip resonators and filters have been proposed. By

---

Received 15 July 2012, Accepted 16 August 2012, Scheduled 23 August 2012

* Corresponding author: Xuehui Guan (xuehuiguan@yahoo.com.cn).

loading a stub to a microstrip resonator, non-degenerated modes can be excited and dual-/multi-mode characteristics can be achieved [4, 5]. In [6] and [7], microstrip triple-mode filters were implemented by using a half-wavelength transmission line resonator with a couple of center symmetrical loaded stubs of different lengths or shapes. Microstrip triple-mode filters also can be realized by loading stubs to a loop [8] or adopting fractal defection in triangular patch [9]. Recently, hybrid multi-mode BPFs using associated resonators draw the interests of experts since it is easier to control the resonant modes of each resonators. In [10] and [11], extended doublet filters which consist of a doublet filter plus a grown resonator were proposed. The grown resonator is a half-wavelength resonator which couples to one mode of the dual-mode resonator. In [12], a hybrid multi-mode BPF was realized by associating the resonant mode of the SIW with the modes generated by stub-loaded triple mode resonator.

A microstrip hybrid four-mode BPF with three transmission zeros is proposed in this design. Four modes in the passband of the filter are created via associating a resonant mode produced by an external transmission line resonator with the original triple-mode generated by a stub-loaded resonator. The odd- and even-mode theory is applied to analyze the resonant characteristics of the triple-mode resonator and the coupling matrix is used to illustrate the design concepts. Finally, a four-mode BPF with good in-band and outof-band filtering performances is obtained. As compared to filters using single mode resonators, the filter that associates triple-mode resonator with single mode resonator is compact in size. The proposed BPF is simulated, implemented and measured, an excellent agreement is observed between simulated results and measured results.

2. FOUR-MODE RESONATOR DESIGN

As shown in Figure 1, the proposed four-mode microstrip BPF consists of a triple-mode stub-loaded resonator and a half-wavelength microstrip transmission line resonator. Thereinto, the triple mode resonator is realized by loading a couple of T-shaped stubs symmetrically at the center point of a transmission line. The configuration of the triple-mode microstrip resonator is presented in Figure 2. In order to obtain the resonant characteristics of the resonator, a 3D electromagnetic simulator Sonnet em is invoked by performing weak coupling. Figure 3 depicts the simulated frequency responses of the resonator against k and s, while L keeps unchanged. When k varies from 4.2 mm to 5.4 mm and the stub concurrently changes from 2.5 mm to 3.4 mm, resonant frequency of Mode-I shifts

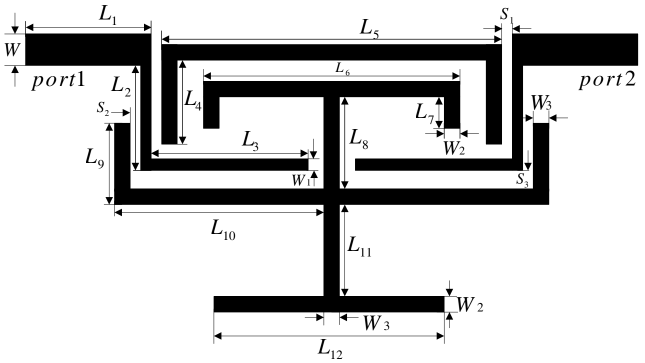


Figure 1. The layout of the proposed four-mode microstrip BPF.

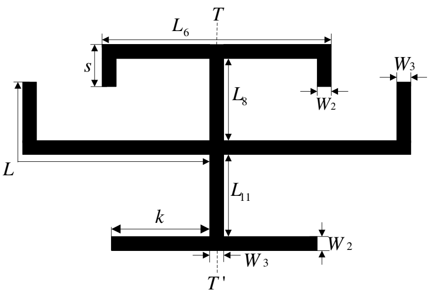


Figure 2. The configuration of the stub-loaded triple-mode resonator.

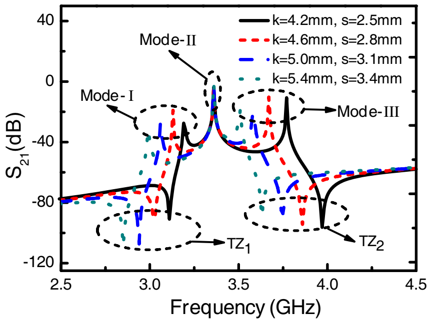
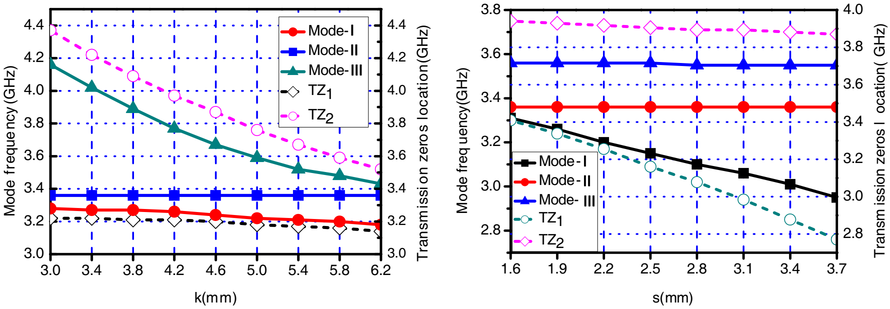


Figure 3. The simulated frequency responses of the triple-mode resonator versus k and s.

down, frequency of Mode-III shifts up, while resonant frequency of Mode-II remains nearly unchanged. Accordingly, the fixed mode f_2 is the odd mode of the triple-mode resonator, and the other changeable resonant modes are the even modes of the triple-mode resonator. In addition, the transmission zeros at the upper and lower stopband show variations with the changes of even modes. Figure 4(a) presents the simulated frequency responses of the resonator against k. When the length of k increasing from 3.0 mm to 6.2 mm. The third mode, that's one of even modes, shifts down to the odd-mode whilst the odd-mode and the other even mode are basically fixed. And the second transmission zero (TZ_2) moves downward while the transmission zero (TZ_1) near the first even-mode stays the same. So it is naturally concluded that the second even-mode and the second transmission



(a) (b)

Figure 4. Simulated frequency of resonant modes and transmission zeros versus (a) k with $s = 2.15\,\text{mm}$, and (b) s with $k = 5.15\,\text{mm}$.

zero are controlled by the lower stub. When s varies from 1.6 mm to 3.7 mm as shown in the Figure 4(b), the first even mode tends to shift downward, whereas the odd-mode and the second even-mode remain approximately constant. The transmission zero near the first even-mode TZ_1 moves downward with the increscent of stub length, but TZ_2 is unchanged.

Given all that, the first and third resonant modes are even modes, yet the second resonant mode is odd mode. The first even mode and the transmission zero near it are determined by the upper stub. Similarly, the lower stub dominates the second even mode and the transmission zero in the neighborhood of it. Consequently, it is obviously validated that the central loaded-stubs just affect the characteristics of even-odds and the locations of two transmission zeros, and the odd mode is only in the control of the center transmission line, which hardly exercising influence on the even modes or two transmission zeros located at the sides of even modes.

To further probe deeply into the resonant characteristics of the triple-mode resonator, circuit models based on odd- and even-mode theory are set up due to the symmetric structure. For odd mode, there exists a short-circuit plane along the vertical symmetry plane TT' of the structure, which will act as a perfect electrical wall, and its equivalent circuit is shown in Figure 5. The central location of the resonator corresponds to a short circuit for odd modes, and the triple-mode resonator works like a uniform impedance resonator (UIR). Its resonant frequencies are determined by [13]

$$f_{odd} = \frac{(2n-1)c}{L\sqrt{\varepsilon_{eff}}} \tag{1}$$

where $L = L_9 + L_{10} - W_3$, $n = 1, 2, 3, \ldots,$ c is the velocity of light in the

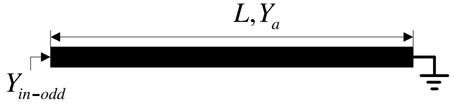


Figure 5. Equivalent circuit at odd mode.

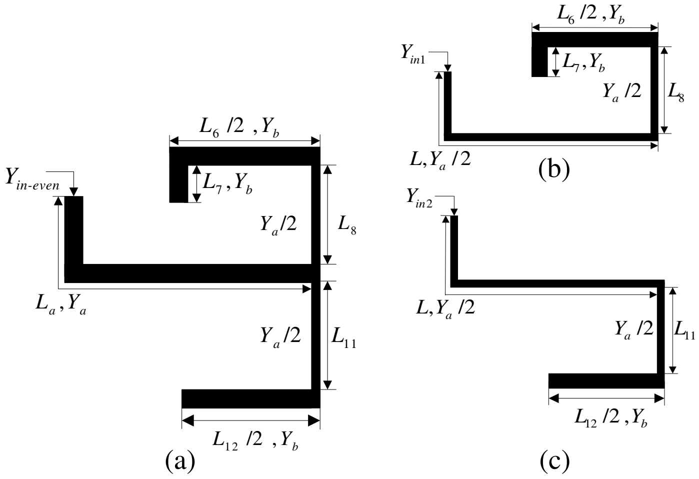


Figure 6. Equivalent circuits models at even modes.

free-space, and ε_{eff} is the effective dielectric constant of the substrate. From the equation, it's evidently verified the odd modes are dominated by the length of center transmission line, changing the parameters of the loaded stubs will not influence the resonant characteristics of odd modes.

For the dual case, when the circuit is excited by even-mode, the symmetry plane TT' can be seemed as a magnetic wall and it will act as an open end. The overall circuit model of even-mode is shown in Figure 6(a), even-mode frequencies are split into two different frequencies, as presented in Figure 6(b) and Figure 6(c), respectively. The microstrip resonator is open-circuited at the center plane TT'. For the special condition, i.e., $Y_a = 2Y_b$, the even-mode resonant frequencies can be described by

$$f_{even1} = \frac{nc}{(L_6 + 2L_7 + 2L_8 + 2L)\sqrt{\varepsilon_{eff}}} \tag{2}$$

$$f_{even2} = \frac{nc}{(L_{12} + 2L_{11} + 2L)\sqrt{\varepsilon_{eff}}} \tag{3}$$

On the ground of the formulas above, varying the length of the upper stub (L_6, L_7) and lower stub (L_{12}) can have a strong impact on the resonant frequencies of the even-modes f_{even1} and f_{even2} respectively. Nevertheless the odd mode of the resonator remains basically unchanged. As a consequence, the odd-mode is under the command of the center transmission line, and the loaded stubs mainly control the changes of even modes

3. MATRIX OF THE FOUR-MODE RESONATOR

The coupling scheme of the hybrid four-mode filter is presented in Figure 7, and it consists of four modes, i.e., two even modes and two odd modes. There is no coupling between these modes and they are all coupled to the source and the load. Commonly, the coupling between even modes and input or output is all positive, while there is positive coupling between odd modes and input port, negative coupling between odd modes and output port. Therefore, the corresponding coupling matrix of the coupling scheme is given by

$$M = \begin{bmatrix} 0 & M_{S1} & M_{S2} & M_{S3} & M_{S4} & 0 \\ M_{1S} & M_{11} & 0 & 0 & 0 & M_{1L} \\ M_{2S} & 0 & M_{22} & 0 & 0 & M_{2L} \\ M_{3S} & 0 & 0 & M_{33} & 0 & M_{3L} \\ M_{4S} & 0 & 0 & 0 & M_{44} & M_{4L} \\ 0 & M_{L1} & M_{L2} & M_{L3} & M_{L4} & 0 \end{bmatrix} \qquad (4)$$

Due to the symmetrical geometry of the proposed resonator, the coupling coefficients agree with $M_{S1} = -M_{1L}$, $M_{S2} = M_{2L}$, $M_{S3} = M_{3L}$ and $M_{S4} = -M_{4L}$. The coupling between source and load is very weak, and that can be neglected. Therefore, the generalized coupling matrix for the proposed BPF with central frequency of 3.4 GHz can be obtained in (5) on the basis of the approach of synthesis in [14]. The synthesized scatting characteristics of the proposed filter are shown in

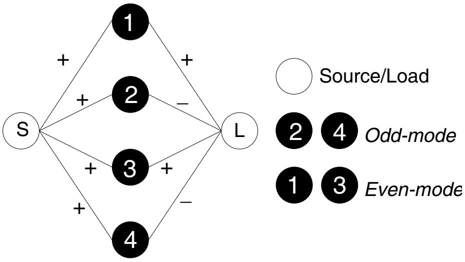


Figure 7. The coupling scheme of four-mode filter.

Figure 8.

$$M=\begin{bmatrix} 0 & 0.3208 & 0.2593 & 0.5459 & 0.7511 & 0 \\ 0.3208 & 1.2595 & 0 & 0 & 0 & 0.3208 \\ 0.2593 & 0 & -1.1638 & 0 & 0 & -0.2593 \\ 0.5459 & 0 & 0 & -0.1004 & 0 & 0.5459 \\ 0.7511 & 0 & 0 & 0 & 0.5656 & -0.7511 \\ 0 & 0.3208 & -0.2533 & 0.5459 & -0.75111 & 0 \end{bmatrix} \qquad (5)$$

Three transmission zeros are created in this proposed design. As previously mentioned, two transmission zeros are created by the triple-mode resonator, i.e., one is produced by the upper stub of the triple-mode resonator, the other is under the control of the lower stub of the triple-mode resonator. Besides, an additional transmission zero is generated by introducing external transmission line. Figure 9 depicts the comparison of frequency responses between four-mode BPF and triple-mode resonator. When introducing the microstrip resonator to the triple-mode resonator, a transmission zero is generated at 3.55 GHz, while the other two transmission zeros remain unchanged. Thus, the transmission zeros TZ_1 (located at 3.2 GHz) and TZ_2 (located at 3.73 GHz) are created by the upper stub and lower stub of the triple-mode resonator, respectively. The introduction of an external resonator adds a signal path which will interact with the path of the triple-mode resonator, and then a transmission zero TZ_3 (located at 3.55 GHz) is created. The appearance of the transmission zero improves the selectivity of the filter to a great extend, and this concept can be widely used to design multi-mode filter with high selectivity.

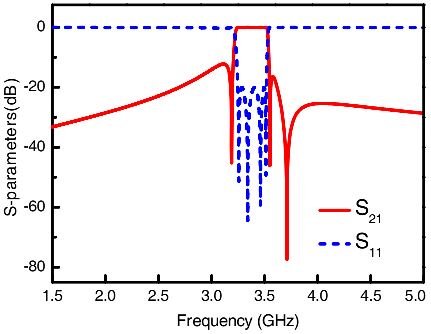


Figure 8. Synthesized theory results of the proposed filter.

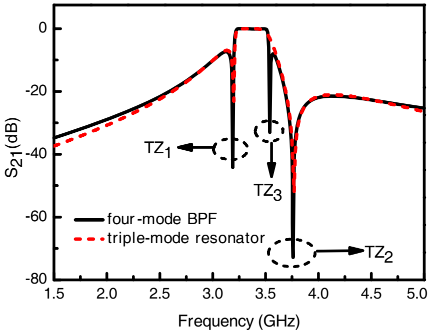


Figure 9. The comparison of frequency responses between four-mode BPF and triple-mode resonator.

4. EXPERIMENTAL RESULTS

Hinging on the above-discussed theories, a four-mode microwave bandpass filter with central frequency of 3.4 GHz, bandwidth of 9.4%, and equal ripple of 0.05 dB in passband is designed. A substrate Rogers TMM4 with a relative permittivity of 4.5, loss tangent of 0.002, and a thickness of 0.8 mm is used in the design. Figure 10 presents a photograph of the fabricated circuit. The size of proposed four-mode resonator is around 19.8 mm × 11 mm ($0.41\lambda g \times 0.23\lambda g$, where λg is the guided wavelength of 50 Ω microstrip line on the substrate at the center frequency of 3.4 GHz). A comparison between the simulated and experimental frequency responses of the proposed four-mode BPF is shown in Figure 11. The agreement is good with the exception of a frequency shift which occurs between the simulated and measured responses. Such a frequency shift is observed in most previous literatures, and is mainly caused by the deviation of dielectric constant between the nominal and its real values, and by the fabrication error of the filter. The simulated results illustrate that the proposed filter has a 3 dB-bandwidth from 3.21 GHz to 3.53 GHz and the return loss within the passband is larger than 22 dB. Three transmission zeros are clearly observed at about 3.2 GHz, 3.55 GHz and 3.73 GHz, respectively, which provide a better cutoff response in the stopband and improve the selectivity of the filter. The measured insertion loss is larger than 1.02 dB in the passband, which is mainly owing to the dielectric losses of the substrate. Three transmission zeros are observed in the measured results which proves the feasibility of this design. And the measured results, showing good in-band and out-of-band filtering performances, match well with the simulated

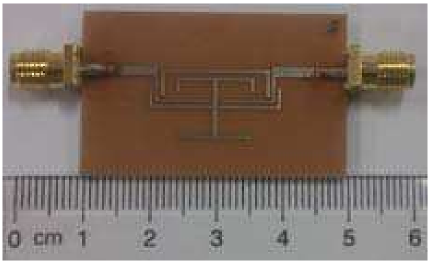


Figure 10. A photograph of the fabricated filter.

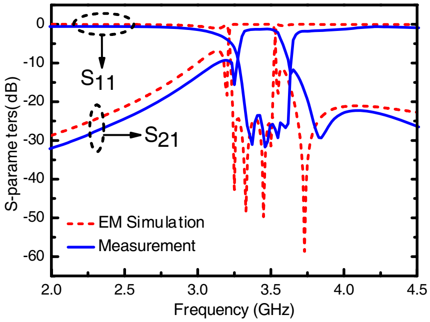


Figure 11. Comparison between simulated and measured results of the proposed filter.

results. Achieved parameters depicted in Figure 1 are: $L_1 = 11.4\,\mathrm{mm}$, $L_2 = 4\,\mathrm{mm}$, $L_3 = 5.6\,\mathrm{mm}$, $L_4 = 3.7\,\mathrm{mm}$, $L_5 = 16.4\,\mathrm{mm}$, $L_6 = 11.6\,\mathrm{mm}$, $L_7 = 1.75\,\mathrm{mm}$, $L_8 = 3.65\,\mathrm{mm}$, $L_9 = 3.15\,\mathrm{mm}$, $L_{10} = 9.65\,\mathrm{mm}$, $L_{11} = 4.1\,\mathrm{mm}$, $L_{12} = 10.8\,\mathrm{mm}$, $W = 1.5\,\mathrm{mm}$, $W_1 = 0.4\,\mathrm{mm}$, $W_2 = 0.5\,\mathrm{mm}$, $S_1 = S_2 = 0.4\,\mathrm{mm}$, and $S_3 = 0.3\,\mathrm{mm}$.

5. CONCLUSIONS

A novel compact microstrip four-mode bandpass filter is proposed in this paper. Four modes are realized by parallel integration of a triple-mode resonator and a transmission line resonator. Besides, the odd- and even-mode theory and coupling matrix are established to further explain the proposed design. Three transmission zeros which are generated near the either passband verge guarantee high selectivity of the filter. This kind of filters introduced in this article has great advantages, such as compact size and high selectivity, over the conventional filters, and can be used in the future microwave circuits.

ACKNOWLEDGMENT

This work is supported by the NSFC of China (No. 61061001, No. 61161005), Open Fund from State Key Laboratory of Millimeter Waves (K201210), and Foundation of Jiangxi Educational Committee (GJJ11437).

REFERENCES

1. Wolff, I., “Microstrip bandpass filter using degenerate modes of a microstrip ring resonator,” *Electronics Letters*, Vol. 8, No. 12, 302–303, 1972.
2. Zhao, L.-P., X. Zhai, B. Wu, T. Su, W. Xue, and C.-H. Liang, “Novel design of dual-mode bandpass filter using rectangle structure,” *Progress In Electromagnetics Research B*, Vol. 3, 131–141, 2008.
3. Athukorala, L. and D. Budimir, “Design of open-loop dual-mode microstrip filters,” *Progress In Electromagnetics Research Letters*, Vol. 19, 179–185, 2010.
4. Deng, H.-W., Y.-J. Zhao, X.-S. Zhang, L. Zhang, and W. Zhao, “Compact dual-mode open stub-loaded resonator and BPF,” *Progress In Electromagnetics Research Letters*, Vol. 14, 119–125, 2010.

5. Guan, X., B. Wang, X. Y. Wang, S. Wang, and H. Liu, "A novel dual-mode bandpass filter using stub-loaded defected ground open-loop resonator," *Progress In Electromagnetics Research Letters*, Vol. 26, 31–37, 2011.
6. Shen, W., X.-W. Sun, and W.-Y. Yin, "A novel microstrip filter using three-mode stepped impedance resonator (TSIR)," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 12, 774–776, 2009.
7. Zhang, L., Z. Yu, and S. Mo, "Novel planar multimode bandpass filters with radial-line stubs," *Progress In Electromagnetics Research*, Vol. 101, 33–42, 2010.
8. Mo, S.-G., Z.-Y. Yu, and L. Zhang, "Design of triple-mode bandpass filter using improved hexagonal loop resonator," *Progress In Electromagnetics Research*, Vol. 96, 117–125, 2009.
9. Xiao, J.-K., Q.-X. Chu, and S. Zhang, "Novel microstrip triangular resonator bandpass filter with transmission zeros and wide bands using fractal-shaped defection," *Progress In Electromagnetics Research*, Vol. 77, 343–356, 2007.
10. Amari, S. and U. Rosenberg, "New building blocks for modular design of elliptic and self-equalized filters," *IEEE Trans. Microw. Theory Tech.*, Vol. 52, No. 2, 721–736, 2004.
11. Liao, C.-K., P.-L. Chi, and C.-Y. Chang, "Microstrip realization of generalized Chebyshev filters with box-like coupling schemes," *IEEE Trans. Microw. Theory Tech.*, Vol. 55, No. 1, 147–153, 2007.
12. Shen, W., W. Y. Yin, X. W. Sun, and J. F. Mao, "Compact substrate integrated waveguide (SIW) transversal filter with triple-mode microstrip resonator," *Proceedings of Asia-Pacific Microwave Conference*, 1875–1878, 2010.
13. Zhang, X. Y., J.-X. Chen, Q. Xue, and S. M. Li, "Dual-band bandpass filters using stub-loaded resonators," *IEEE Microw. Wireless Compon. Lett.*, Vol. 17, No. 8, 583–585, 2007.
14. Amari, S., U. Rosenberg, and J. Bornemann, "Adaptive synthesis and design of resonator filters with source/load-multiresonator coupling," *IEEE Trans. Microwave Theory and Tech.*, Vol. 50, No. 8, 1969–1977, 2002.