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COMPACT BANDPASS FILTER WITH WIDE UPPER-STOPBAND BASED ON SPIRAL-SHAPED RESONATORS AND SPUR-LINES

L. Ma, K. Song*, C. Zhuge, and Y. Fan

EHF Key Laboratory of Fundamental Science, School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

Abstract—A novel compact bandpass filter (BPF) with wide upper-stopband has been proposed in this paper. The structure is based on spiral-shaped resonators. Cross coupling is used to generate two transmission zeros at the lower and upper stopbands. Therefore, the out-of-band performance is improved. In addition, two spur-lines are adopted in the feed lines to reject the spurious response. The central frequency f_0 of this filter is at 2.45 GHz with a minimum insertion loss of less than 1 dB and a 3 dB bandwidth of 12.5%. Four transmission zeros are located at 2 GHz, 3 GHz, 5.5 GHz, and 8 GHz. The attenuation is greater than 20 dB in a wide upper stopband up to 9.8 GHz.

1. INTRODUCTION

Compact and high performance filters have been studied widely [1–19] as good and low cost filters are required in modern communication system. There are many ways to reduce the size of a filter, which includes slow-wave resonators [2], multi-layer circuit structure, multi-mode resonators [3], and substrates with high dielectric constant, etc.. Moreover, the bandpass filter with wide upper stopband is also necessary to reject out-of-band signals, and various approaches using slow-wave structure [4] and stepped-impedance resonator [6, 7] were presented to extend the stop-band.

In this paper, we proposed a wide upper-stopband filter with spur-lines. This compact filter is based on half-wavelength spiral resonators. The introduction of spur-lines can extend the stopband

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* Corresponding author: Kaijun Song (kjsong@ee.uestc.edu.cn).

effectively. Direct/Cross-coupled structure is used to improve the frequency selectivity in the passband.

2. STRUCTURE OF THE COMPACT BANDPASS FILTER BASED ON SPIRAL-SHAPED HALF-WAVELENGTH RESONATOR AND CROSS-COUPLED STRUCTURE

The spiral half-wave length ($\lambda/2$) resonator has compact size and can be used to design the compact filters, as shown in Figure 1. Base on this resonator, a simple symmetrical structure filter is proposed as shown in Figure 2. The physical length of the spiral shaped half-wavelength resonators are determined by the central frequency f_0. For half-wavelength resonators, harmonic frequencies occur in multiples frequency of f_0. With the introduction of spur-lines in the input and output feed lines, the adjacent spurious responses are suppressed so as to extend the upper-stopband bandwidth.

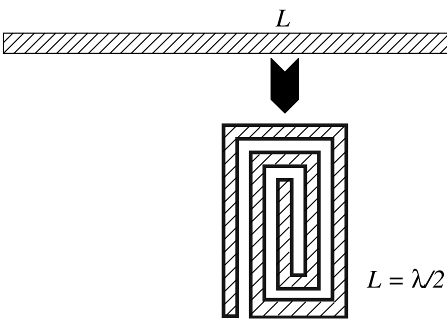

Figure 1. Structure of half-wavelength spiral resonator.

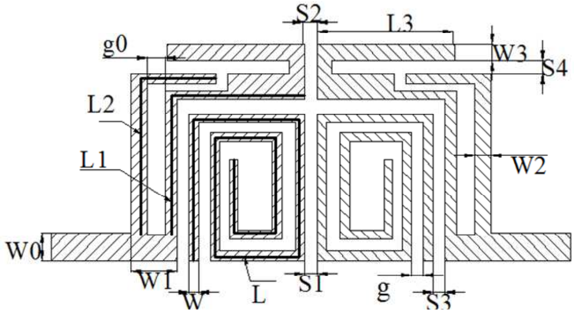

Figure 2. Structure of the presented compact bandpass filter.

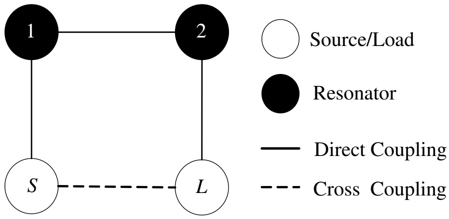

Figure 3. The coupling structure of the presented filter.

In addition, the cross-coupling structure between the input and output ports has also been used to generate additional transmission zeros within the stopband and to improve the frequency selectivity in the passband, as shown in Figure 2. Figure 3 shows the coupling structure of the presented compact bandpass filter with wide stopband. The direct/cross coupling mode included both electric and magnetic coupling [19]. Work in this paper mainly focused on a reciprocal network.

3. ANALYSIS AND DESIGN OF FILTER

As is shown in Figure 2, Fifteen parameters (W, W_0, W_1, W_2, W_3, L, L_1, L_2, L_3, S_1, S_2, S_3, S_4, g, g_0) are used in the design of filter. However, the direct-coupling gaps width S_1, cross-coupling gap width S_2 and spur-lines length L_2 play a decisive role in the performance of filter since the coupling coefficient and second harmonic suppression are determined by S_1, S_2 and L_2 respectively. In addition, the value of W, L, g in spiral shaped resonators is extracted according to the central frequency f_0. W_0 and L_1 are decided by the input/output characteristic impedance (in this paper, $Z_0 = 50\,\Omega$). Details on how S_1, S_2 and L_2 influence the transmission responses of filter will be given in the following. The substrate for design was RF35 with thickness of 0.508 mm and $\varepsilon_r = 3.5$.

The coupling ratio between the two spiral-shaped resonators can be evaluated from S_1 by using the full-wave simulators. Two split mode frequencies (resonant peaks) are observable in Figure 4. These two split frequencies labeled as f_1 for the first peak and f_2 for the second peak. The coupling coefficient between two adjacent resonators can be calculated by [19]:

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$

$k = 0.11$, when $S_1 = 0.1\,\text{mm}$; $k = 0.072$, when $S_1 = 0.3\,\text{mm}$;

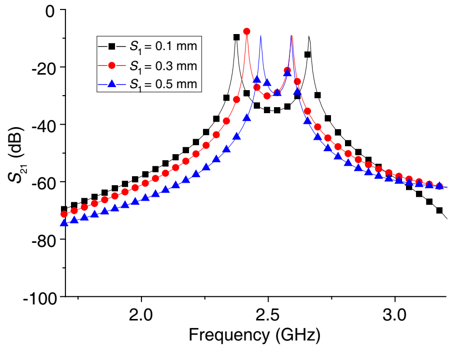

Figure 4. Frequency response of the proposed coupling structure. ($W = 0.5\,\text{mm}$, $L = 45\,\text{mm}$, $g = 0.5\,\text{mm}$.).

$k = 0.05$, when $S_1 = 0.5\,\text{mm}$.

Larger S_1 makes such two resonant peaks closer. It suggests that the electric coupling becomes weaker with the increase of S_1.

The external coupling Q_e can be calculated by [19]:

$$Q_e = \frac{2f_0}{\Delta f_{3\,\text{dB}}}$$

where f_0 is the resonant frequency and $\Delta f_{3\,\text{dB}}$ is the 3 dB bandwidth. In this paper, Q_e is about 20.

In order to investigate the relationship between coupling gap width S_1 and operating bandwidth, the transmission responses are given under four different coupling gaps S_1 between the two resonators with other parameters fixed, as shown in Figure 5. It can be seen from Figure 5 that the smaller S_1 is, the wider operating bandwidth is.

The performance in the passband of filter is controlled by the cross-coupling gap S_2 between source and load of the filter. Transmission responses are given under four different gaps S_2, as shown in Figure 6. The frequency selectivity in the passband will be better when S_2 decreases, while the performance in stopband will worsen when S_2 decreases. Then, a compromised size must be found in filter design.

Another fact is that the filter structure will cause a spurious response at the multiples of the central frequency f_0, which is at 5.7 GHz, as shown in Figure 6. By adjusting the spur-lines, the undesirable second harmonic can be rejected effectively, as shown in Figure 7. It can be seen that the transmission zero can be changed by adjusting the length L_2 of the spur-line. After appropriate design of the spur-line, the stop-band can be extended. Figure 8 shows the

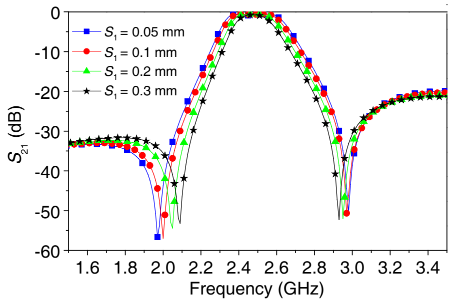

Figure 5. The transmission response S_{21} with varying S_1. ($W = 0.5\,\mathrm{mm}$, $W_0 = 1.11\,\mathrm{mm}$, $W_1 = 0.6\,\mathrm{mm}$, $W_2 = 0.15\,\mathrm{mm}$, $W_3 = 0.5\,\mathrm{mm}$, $L = 20\,\mathrm{mm}$, $L_1 = 10\,\mathrm{mm}$, $L_2 = 7\,\mathrm{mm}$, $L_3 = 4\,\mathrm{mm}$, $S_2 = 0.3\,\mathrm{mm}$, $S_3 = 0.1\,\mathrm{mm}$, $S_4 = 0.4\,\mathrm{mm}$, $g = 0.5\,\mathrm{mm}$, $g_0 = 0.1\,\mathrm{mm}$.).

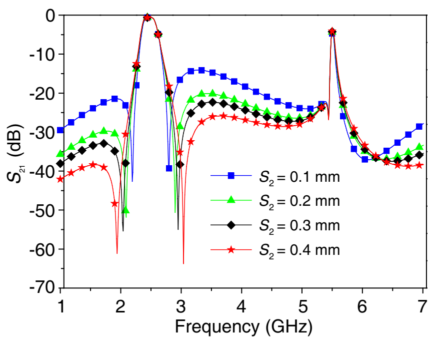

Figure 6. The transmission response S_{21} with various S_2. ($W = 0.5\,\mathrm{mm}$, $W_0 = 1.11\,\mathrm{mm}$, $W_1 = 0.6\,\mathrm{mm}$, $W_2 = 0.15\,\mathrm{mm}$, $W_3 = 0.5\,\mathrm{mm}$, $L = 20\,\mathrm{mm}$, $L_1 = 10\,\mathrm{mm}$, $L_3 = 4\,\mathrm{mm}$, $S_1 = 0.2\,\mathrm{mm}$, $S_3 = 0.1\,\mathrm{mm}$, $S_4 = 0.4\,\mathrm{mm}$, $g = 0.5\,\mathrm{mm}$, $g_0 = 0.1\,\mathrm{mm}$.).

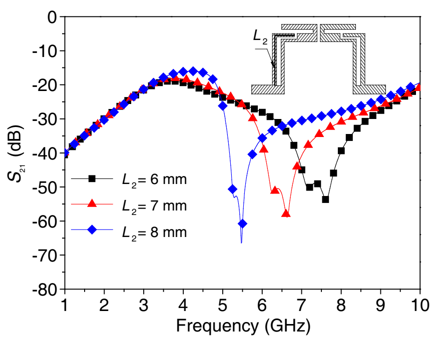

Figure 7. The transmission response with varying spur-line L_2. ($W_0 = 1.11\,\mathrm{mm}$, $W_1 = 0.6\,\mathrm{mm}$, $W_2 = 0.15\,\mathrm{mm}$, $W_3 = 0.5\,\mathrm{mm}$, $L_1 = 10\,\mathrm{mm}$, $L_3 = 4\,\mathrm{mm}$, $S_4 = 0.4\,\mathrm{mm}$, $g_0 = 0.1\,\mathrm{mm}$.).

comparison of with and without the spur-line. Obviously, a wider upper-stopband has been achieved in the proposed design.

With central frequency $f_0 = 2.45\,\mathrm{GHz}$, BW $= 300\,\mathrm{MHz}$ and characteristic impedance $Z_0 = 50\,\Omega$ I/O ports, the choice of initial parameters for the proposed filter are given in the following:

$W_0 = 1.11\,\mathrm{mm}$, $W_1 = 0.5\,\mathrm{mm}$, $W_2 = 0.2\,\mathrm{mm}$, $W_3 = 0.5\,\mathrm{mm}$, $W = 0.5\,\mathrm{mm}$, $L = 50\,\mathrm{mm}$, $L_1 = 10\,\mathrm{mm}$, $L_2 = 6\,\mathrm{mm}$, $L_3 = 4\,\mathrm{mm}$,

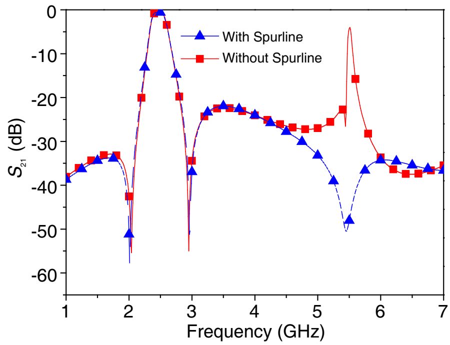

Figure 8. The transmission response within and without spur-line. ($W = 0.5$ mm, $W_0 = 1.11$ mm, $W_1 = 0.6$ mm, $W_2 = 0.15$ mm, $W_3 = 0.5$ mm, $L = 20$ mm, $L_1 = 10$ mm, $L_2 = 7$ mm, $L_3 = 4$ mm, $S_1 = 0.2$ mm, $S_3 = 0.1$ mm, $S_4 = 0.4$ mm, $g = 0.5$ mm, $g_0 = 0.1$ mm.).

$S_1 = 0.15$ mm, $S_2 = 0.2$ m, $S_3 = 0.2$ mm, $S_4 = 0.3$ mm, $g = 0.5$ mm, $g_0 = 0.2$ mm.

4. SIMULATED AND MEASURED RESULTS

Based on the above analysis, a compact bandpass filter with wide upper-stopband performance has been designed. Electromagnetic simulation tools (IE3D) is utilized in the process of design, simulation, and optimization. The final dimensions of the filter are: $W = 0.5$ mm, $W_0 = 1.11$ mm, $W_1 = 0.6$ mm, $W_2 = 0.15$ mm, $W_3 = 0.5$ mm, $L = 40$ mm, $L_1 = 10$ mm, $L_2 = 7$ mm, $L_3 = 4$ mm, $S_1 = 0.2$ mm, $S_2 = 0.3$ m, $S_3 = 0.1$ mm, $S_4 = 0.4$ mm, $g = 0.5$ mm, $g_0 = 0.1$ mm. The substrate for fabrication was RF35 with thickness of 0.508 mm and a relative dielectric constant of 3.5. The fabricated filter is shown in Figure 9. Although a low dielectric constant has been used, the filter is quite compact with a size of 9.5 mm $\times$ 8.6 mm.

The fabricated filter is measured with Agilent 8757D scalar network analyzer. The simulated and measured results are in reasonable agreement with each other. As is shown in Figure 10, the measured insertion and loss and return loss are about 1 dB and 18 dB with a 3 dB bandwidth of 12.5% at 2.45 GHz. In addition, the designed bandpass filter has four transmission zeros at 2 GHz, 3 GHz, 5.5 GHz, and 8 GHz. The attenuation greater than 20 dB in the upper stopband is up to 9.8 GHz. A comparison is carried out with other filters from the aspects of insertion loss, passband return loss, stopband rejection and size in Table 1.

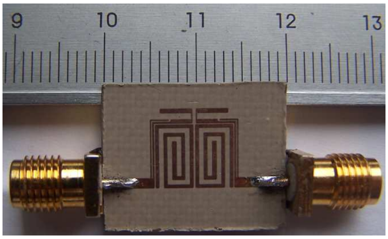

Figure 9. Fabricated compact bandpass filter.

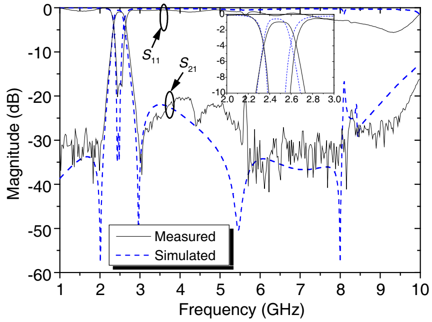

Figure 10. Simulated and measured results of the fabricated filter.

Table 1. Comparison with other filters.

Contents / References	Insertion loss	Return loss	Stopband		Size
			bandwidth	rejection	
Reference [17]	1.9 dB	16.5 dB	5.5-12 GHz	> 15 dB	$0.54\lambda \times 0.43\lambda$ ($f_0 = 5.04$ GHz)
Reference [18]	3 dB	15 dB	2.2-8 GHz	> 17 dB	$0.14\lambda \times 0.1\lambda$ ($f_0 = 1.51$ GHz)
Reference [8]	2.52 dB	22 dB	2.5-4.7 GHz	> 10 dB	$0.33\lambda \times 0.09\lambda$ ($f_0 = 2.40$ GHz)
This wok	1.5 dB	18 dB	2.8-9.8 GHz	> 20 dB	$0.08\lambda \times 0.07\lambda$ ($f_0 = 2.45$ GHz)

5. CONCLUSION

In this paper, a compact filter with wide upper stopband using spiral-shaped resonator and spur-line has been proposed, designed, fabricated and measured. By using spiral shaped resonator and cross-coupling, the compact and low loss filter is realized. The spur-line structure suppressed the spurious responses and extended the stopband. Simulated and measured results show reasonable agreement.

ACKNOWLEDGMENT

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REFERENCES

1. Song, K. and Q. Xue, "Inductance-loaded Y-shaped resonators and their applications to filters," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 4, 978–984, 2010.
2. Pistono, E., M. Robert, and L. Duvillaret, "Compact fixed and tune-all bandpass filters based on coupled slow-wave resonators," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 6, 2790–2799, 2006.
3. Song, K. and Q. Xue, "Novel broadband bandpass filters using Y-shaped dual-mode microstrip resonators," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 9, 548–550, 2009.
4. Hong, J.-S. and M. J. Lancaster, "Theory and experiment of novel microwave slow-wave open-loop resonator filters," *IEEE Trans. Microw. Theory Tech.*, Vol. 45, No. 12, 2358–2365, Dec. 1997.
5. Song, K. and Q. Xue, "Asymmetric dual-line coupling structure for multiple-notch implementation in UWB bandpass filters," *Electron. Lett.*, Vol. 46, No. 20, 1388–1390, 2010.
6. Hsu, C. L. and J. T. Kuo, "A two-stage SIR bandpass filter with an ultra-wide upper rejection band," *IEEE Microw. Wireless Compon. Lett.*, Vol. 7, No. 1, 34–36, 2007.
7. Chen, Y. M., S. F. Chang, C. C. Chang, and T. J. Hung, "Design of stepped-impedance combline bandpass filter with symmetric insertion-loss response and wide stopband range," *IEEE Trans. Microw. Theory Tech.*, Vol. 55, No. 10, 2191–2198, 2007.
8. Deng, P.-H. and P.-T. Chiu, "New bandpass filter using half-wavelength and branch-line resonators," *Progress In Electromagnetics Research C*, Vol. 16, 241–249, 2010.
9. Dai, G. and M. Xia, "Novel miniaturized bandpass filter using spiral-shaped resonators and window feed structures," *Progress In Electromagnetics Research*, Vol. 100, 235–243, 2010.
10. Song, K. and Q. Xue, "Compact ultra-wideband (UWB) bandpass filters with multiple notched bands," *IEEE Microw. Wireless Compon. Lett.*, Vol. 20, No. 8, 447–449, 2010.
11. Wang, R., L.-S. Wu, and X.-L. Zhou, "Compact folded substrate integrated waveguide cavities and bandpass filter," *Progress In Electromagnetics Research*, Vol. 84, 135–147, 2008.
12. Li, L., H. Liu, and B. Teng, "Novel microstrip lowpass filter using stepped impedance resonator and spurline resonator," *Microwave and Optical Technology Letters*, Vol. 51, No. 1, 196–197, 2009.

13. Chu, Q.-X. and H. Wang, "A compact open loop filter with mixed electric and magnetic coupling," *IEEE Trans. Microw. Theory Tech.*, Vol. 56, No. 2, 431–439, 2008.
14. Wu, H.-W., S.-K. Liu, M.-H. Weng, and C.-H. Hung, "Compact microstrip bandpass filter with multispurious suppression," *Progress In Electromagnetics Research*, Vol. 107, 21–30, 2010.
15. Song, K. and Y. Fan, "Compact ultra-wideband bandpass filter using dual-line coupling structure," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 1, 30–32, 2009.
16. Yang, R.-Y., H. Kuan, C.-Y. Hung, and C.-S. Ye, "Design of dual-band bandpass filters using a dual feeding structure and embedded uniform impedance resonators," *Progress In Electromagnetics Research*, Vol. 105, 93–102, 2010.
17. Wu, L.-S., J.-F. Mao, W. Shen, and W.-Y. Yin, "An extended doublet bandpass filter implemented with microstrip resonator and substrate integrated waveguide cavity," *Proceedings of Asia-pacific Microwave Conference 2010 WE4B-2*, 2010.
18. Peng, L., C.-L. Ruan, and C.-Y. Ding, "Miniature filter based on metamaterials with transmission zeros and wider upper-stopband performance," *3rd IEEE International Symposium Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, 2009.
19. Hong, J. S. and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, Chapter 8, 235–271, Wiley, New York, 2001.