Progress In Electromagnetics Research Letters, Vol. 37, 189–197, 2013

A COMPACT TRI-BAND PASSBAND FILTER BASED ON THREE EMBEDDED BENDING STUB RESONATORS

Yatao Peng*, **Lijun Zhang, Yongqing Leng, and Jin Guan**

Department of Electronics System Technology, Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China

Abstract—A microstrip tri-band bandpass filter (BPF) based on three embedded bending stub resonators (EBSRs) is proposed in this paper. Three resonant paths that resonate at three different frequencies can achieve three passbands. The lumped circuit models of the proposed filter are given for designing. The filter is extremely compact, whose area is about $0.047\lambda_g \times 0.12\lambda_g$. There are two transmission zeros located between the first two passbands and a transmission zero between the second and third passbands, which results in good selectivity. For demonstrating the proposed filter structure, a filter at 0.9/2.14/3.6 GHz is designed and fabricated. The measured results are well agreed with simulated ones, which indicate the validity.

1. INTRODUCTION

In the recent years, with the development of multi-mode communication systems, multi-band BPF has become an important microwave device to meet the multi-signal processing occasions, which attracts more and more attention to proposed new structures for designing multi-band BPFs [1–6]. In the design of tri-band BPFs, it is pivotal to keep the circuit area compact while keeping the selectivity. In [7], a tri-band BPF was designed based on multi-section quarter-wavelength microstrip lines, which is not compact for the multiple lines. A dual-band stepped impedance resonator (SIR) and a singe-band unformed impedance resonator (UIR) were combined to achieve a tri-band BPF filter in [8]. By modifying the two-sections SIR to three-sections SIR, a tri-band BPF is designed in [9]. Moreover, the tri-band BPF is realized with higher modes of a single dual-mode resonator in [10]. In [11], a

Received 18 November 2012, Accepted 22 February 2013, Scheduled 26 February 2013
* Corresponding author: Yatao Peng (pengyatao@ime.ac.cn).

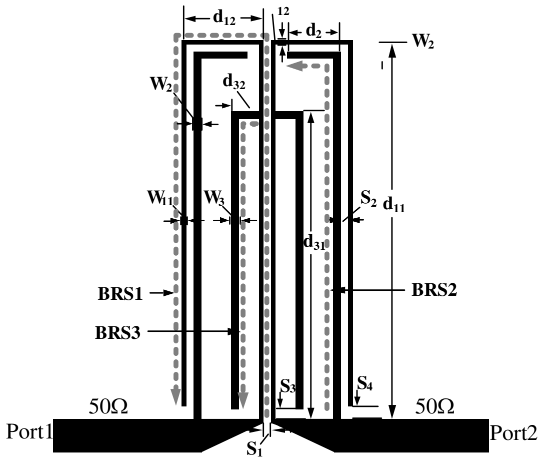

Figure 1. Configuration of the proposed filter.

new compact tri-band BPF based on three nested dual-mode defected ground structure resonators is devised. In [12], Doan et al. use square ring short stub loaded resonators to design a compact and high selectivity tri-band BPF. Nevertheless, it is still a challenge to design tri-band BPFs with both small area and high selectivity.

In this paper, an extra bending stub is added to two hook-shaped resonators [13], forming the proposed EBSR, to design the tri-band BPF. The three passband frequencies can be regulated to objective values by changing the dimensions of BSRs. This filter is planar and extremely compact, which simplifies the design and decreases the fabrication cost.

2. ANALYSIS OF THE PROPOSED FILTER

The configuration of the proposed filter is illustrated in Figure 1, which consists of two symmetrical parts. A single part consists of three bending stub resonators (BSRs), where BSR1 with length d_1, BSR2 with length d_2 and BSR3 with length d_3. BSR1 and BSR2 connect the $50\,\Omega$ feed lines directly (Port1/Port2), and BSR3 connects the appropriate position of BSR1. The tapered transmission lines (TTL) between the feed lines and BSR1s are applied for bettering the return loss.

The different parts of the proposed structure are illustrated in Figure 2. Figure 2(a) shows the structure without BSR2, and Figure 2(b) shows the structure with BSR3 removed, which is similar

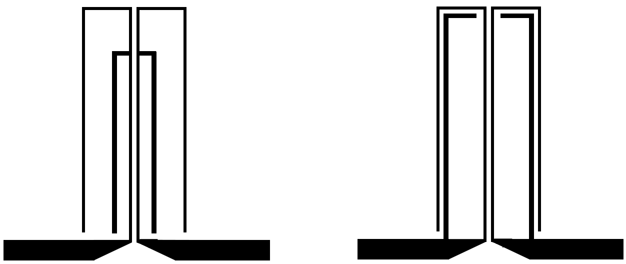

Figure 2. Different parts of the proposed filter structure, (a) BSR3 removed, (b) BSR2 removed.

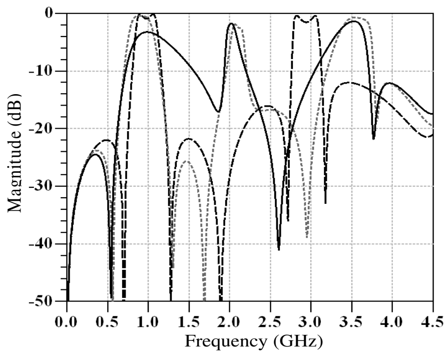

Figure 3. The comparison of the simulated $|S_{21}|$ for different structures (grey dot line: proposed filter structure; black solid line: Figure 2(a); black long dash line: Figure 2(b)).

to the structure proposed in [13]. The electromagnetic (EM) simulated results ($|S_{21}|$ versus frequency) of the structure in Figures 2(a) and (b) are depicted in Figure 3. It can be seen that the structure in Figure 2(a) has three poor performance passbands, located at almost the same frequencies as the configuration in Figure 1. There are only three transmission zeros (TZs) in the frequency response, and the first and third TZs are located at the same frequencies as the proposed tri-band BPF, which indicates that the coupled structure of the two symmetrical parts in Figure 2(a) is not enough for designing an acceptable tri-band BPF. The frequency response of the structure in Figure 2(b) has two passbands and five TZs, and the first passband is located at almost the same frequency as the tri-band passbands filter. Therefore, for the structure in Figure 2(b), when BSR2 is added and coupled to BSR1, another two TZs are produced which achieves a high selectivity and acceptable insert loss performance tri-band BPF. On the other hand, when BSR3 is added in the structure in Figure 2(b), a third different passband is introduced in the frequency response. Above all, thus the combination of structures in Figure 2(a) and Figure 2(b), namely three BSRs that embedded and coupled to each other, forms a tri-band BPF with high selectivity.

Based on the equivalent circuit models shown in [14], the equivalent lumped parameter circuit for the proposed structure is demonstrated in Figure 4, where C_{11}/L_{11} and C_{12}/L_{12} correspond to BSR1; C_2/L_2 corresponds to BSR2; C_3/L_3 corresponds to BSR3. Because the filter consists of two symmetrical parts, mutual inductance L_{M1}, L_{M2} and L_{M3} are introduced to denote the inductive couple between them. Additionally, C_0 is led to indicate the capacitive coupling. The other lumped parameters can be deduced from the discontinuities of the proposed structure. For the filter at 0.9/2.14/3.6 GHz, the lumped parameters are chosen as follows: $L_{a1} = L_{a4} = 0.05$, $L_{a2} = L_{a5} = 0.56$, $L_{a3} = L_{a6} = 0.02$, $L_{11} = L_{14} = 3.7$, $L_{12} = L_{15} = 1.58$, $L_2 = L_5 = 0.915$, $L_3 = L_6 = 0.92$, $L_{M1} = 1.11$, $L_{M2} = 0.24$, $L_{M3} = 0.9$ (all in nH), $C_{a1} = C_{a3} = 6.7$, $C_{a2} = C_{a4} = 3.62$, $C_0 = 3.8$, $C_{11} = C_{14} = 19.5$, $C_{12} = C_{15} = 9.3$, $C_2 = C_5 = 9.28$, $C_3 = C_6 = 7.5$ (all in pF). The geometric parameters of the proposed structure are set as: $W_{11} = W_{12} = 0.3$, $W_2 = 0.6$, $W_3 = 0.4$, $d_{11} = 24.5$, $d_{12} = 4.5$, $d_{21} = 3.5$, $d_{31} = 19.5$, $d_{33} = 2$, $S_1 = 0.28$, $S_2 = 0.22$, $S_3 = S_4 = 0.5$ (all in millimeter). The EM and equivalent circuit simulated results (S-parameters) are depicted in Figure 5. Considering the different characteristics between microstrip and lumped parameter circuit, the agreement between the two results is acceptable. Particularly, the TZs between the passbands are located at almost the same frequencies, and two transmission poles can be observed in every passband for both of the simulated

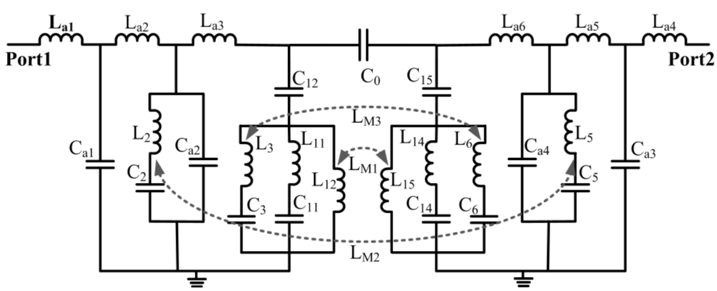

Figure 4. The equivalent lumped parameter circuit for the proposed filter.

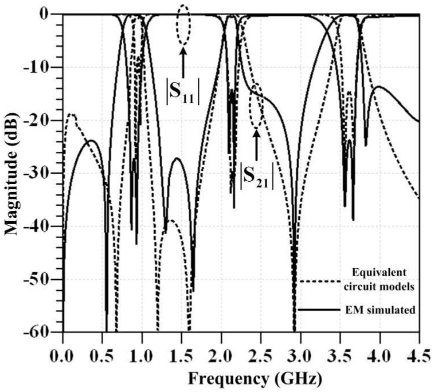

Figure 5. S-parameter comparison for simulation and equivalent circuit.

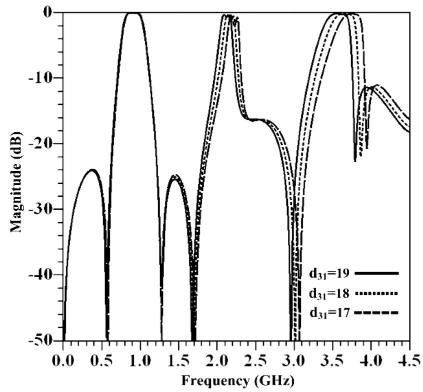

Figure 6. Operating frequencies against different d_{31} (unit: mm).

results. Based on the lumped parameter circuit model, we can conclude that three different passbands of the proposed structure are corresponding to three shunt LC resonators that resonate at different frequencies. The equivalent circuit lumped parameters are related to the geometry dimensions, thus the frequency response of the filter can be adjusted conveniently by the dimensions of the BSRs. And the original dimension of the three bending stub resonator paths are chosen close to a quarter-wavelength at the centre frequencies of the three passbands respectively.

The simulated transmission responses versus various d_{31} are illustrated in Figure 6. We can see that d_{31} has a significant effect on the transmission performance in the second and third operating bands. The upper two passbands decrease with increasing d_{31}, while the first passband almost keeps the same. Figure 7 demonstrates the operating frequency of the proposed filter versus length of BSR3 (d_{32}). When decreasing d_{32}, the second passband frequency increases, but the first and third ones rarely change, which can be utilized to control the second passband independently. Figure 8 plots the simulated frequency response results with different values of W_{11}. It can be seen that W_{11} has a significant effects on the first two passbands but hardly influences the third passband, and W_{11} is set as 0.3 mm here for good transmission around 0.9 GHz and 2.14 GHz. The coupling between the symmetric parts can be easily adjusted by the gap (S_1) that can be used to adjusted the bandwidths of the passbands [13]. In summary, the transmission responses of the filter can be tuned relatively independently by the parameters of the structure.

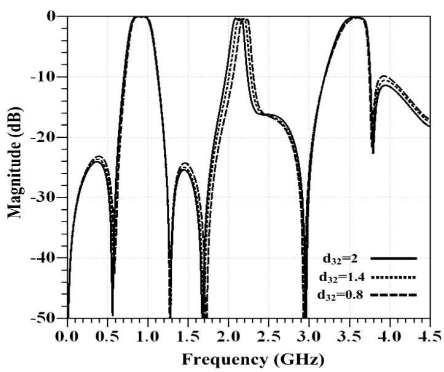

Figure 7. Operating frequencies against different d_{32} (unit: mm).

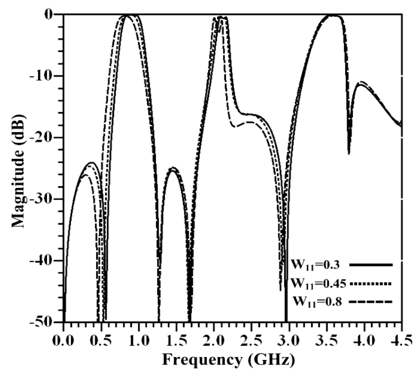

Figure 8. Operating frequencies against different W_{11} (unit: mm).

3. TRI-BAND BANDPASS FILTER RESULTS AND ANALYSIS

To verify the proposed filter structure, a tri-band BPF at 0.9/2.14/3.6 GHz is designed and fabricated. A photograph of the filter is shown in Figure 9, where the dielectric substrate is Taconic TLX-8 with dielectric constant 2.55, thickness 0.787 mm, and loss tangent 0.002 at 10 GHz. After optimizing by the EM simulator, the dimensions for this tri-band BPF are set as follows: $W_{11} = W_{12} = 0.3$, $W_2 = 0.6$, $W_3 = 0.4$, $d_{11} = 24.5$, $d_{12} = 4.5$, $d_{21} = 3.5$, $d_{31} = 19.5$, $d_{33} = 2$, $S_1 = 0.28$, $S_2 = 0.22$, $S_3 = S_4 = 0.5$ (all in millimeter). The whole area of the filter is about $10 \times 25\,\text{mm}^2$. Its simulated and measured results (obtained by Agilent N5230A network analyzer) are shown in Figure 10, which show excellent agreement. Three good passbands are obtained distinctly. For the first passband, from 0.7 to 1.0 GHz, the insert loss (IL) is less than 0.6 dB, and the return loss (RL) is greater than 17 dB. For the second passband (from 2 to 2.2 GHz), the measured IL is less than 1.85 dB, and RL is greater than 15 dB. Within the third passband (between 3.5 and 3.7 GHz), the measured IL is better than 1.8 dB, and RL is better than 21 dB. Five transmission zeros located at 0.6\1.3\1.67\2.9\3.9 GHz are obtained, which enhances the isolation. The proposed tri-band bandpass filter is compared with some filters in [1–5], and their respective performances are tabulated in Table 1. It can be concluded that this filter has the advantage of compact size and high selectivity. The small discrepancies are mainly attributed to the tolerance in fabrication (0.015 mm) and implementation.

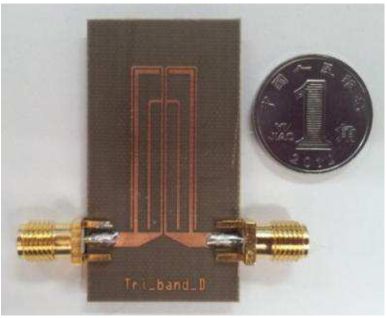

Figure 9. Photograph of the fabricated proposed filter.

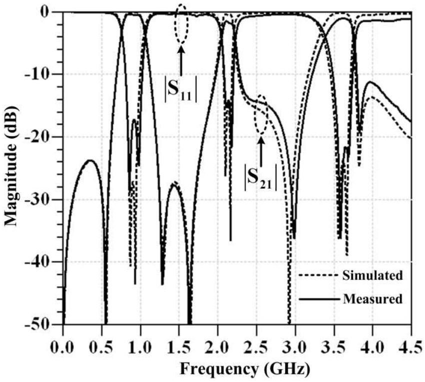

Figure 10. Simulated and measured S-parameters of the tri-band BPF.

Table 1. Comparison with other designs.

Ref.	Freqs (GHz)	RBW (%)	Area ($\lambda_g \times \lambda_g$)	TZs (GHz)
[1]	1.57/2.24/5.2	8.2/10/7.3	0.18×0.2	3.84/5.0
[2]	2.4/3.5/5.25	2.0/3.0/3.0	0.28×0.3	2.2/2.7/3.7/4.6/5.6
[3]	1.57/2.45/3.5	12.5/8/6	0.25×0.36	1.4/2/2.1/2.8/3.3/3.9
[4]	2.37/4.83/7.3	7.1/7.1/5.6	0.36×0.36	1.7/2.45/4.5/5.4/7.3/8.1
[5]	1.59/1.8/2.44	6.6/4.4/3.8	0.14×0.16	1.68/1.71/1.94/2.33/2.6
This work	0.9/2.14/3.6	18/9.3/11.1	0.047×0.12	0.56/1.2/1.67/2.9/3.8

λ_g is the guided wavelength at the centre frequency of the first passband. Freqs represents the three passbands frequencies. RWB is the relative bandwidth.

4. CONCLUSION

A novel structure for designing tri-band passband filters is proposed in this article. The circuit consists of two mutual coupling symmetrical parts consist with three embedded bending stub resonators, which achieves three good performance passbands. The circuit area of the filter is about $0.047\lambda_g \times 0.12\lambda_g$ which is significantly smaller than the other filters of the same type. Five transmission zeros are obtained in the frequency response, which led to excellent isolation. An experimental filter (0.9/2.14/3.6 GHz) is designed and fabricated, and good agreements between measured and simulated results verify the design concept. This filter is planar in structure, which simplifies the design and decreases the fabrication cost. This structure has potential to be applied to various communication systems.

REFERENCES

1. Zhao, L.-P., X.-W. Dai, Z.-X. Chen, and C.-H. Liang, "Novel design of dual-mode dual-band bandpass filter with triangular resonators," *Progress In Electromagnetics Research*, Vol. 77, 417–424, 2007.
2. Chen, Z.-X., X.-W. Dai, and C.-H. Liang, "Novel dual-mode dual-band bandpass filter using double square-loop structure," *Progress In Electromagnetics Research*, Vol. 77, 409–416, 2007.
3. Castaldi, G., V. Fiumara, and I. Gallina, "An exact synthesis method for dual-band Chebyshev impedance transformers," *Progress In Electromagnetics Research*, Vol. 86, 305–319, 2008.
4. Wu, Y., Y. Liu, and S. Li, "Dual-band modified Wilkinson power divider without transmission line stubs and reactive components," *Progress In Electromagnetics Research*, Vol. 96, 9–20, 2009.
5. Wang, J., H. Ning, Q. Xiong, M. Li, and L.-F. Mao, "A novel miniaturized dual-band bandstop filter using dual-plane defected structures," *Progress In Electromagnetics Research*, Vol. 134, 397–417, 2013.
6. Panda, J. R. and R. S. Kshetrimayum, "A printed 2.4 GHz/5.8 GHz dual-band monopole antenna with a protruding stub in the ground plane for WLAN and RFID applications," *Progress In Electromagnetics Research*, Vol. 117, 425–434, 2011.
7. Lee, C.-H., C.-I. G. Hsu, and H.-K. J. huang, "Design of a new tri-band microstrip BPF using combined quarter-wavelength SIRs," *IEEE Microw. Wireless Compon. Lett.*, Vol. 16 , No. 11, 594–596, 2006.
8. Chen, F. C. and Q. X. Chu, "Design of compact tri-band bandpass filters using assembled resonators," *IEEE Microw. Theory Tech.*, Vol. 57, No. 1, 165–171, 2009.
9. Hsu, C.-I. G., C.-H. Lee, and Y.-H. Hsieh, "Tri-band bandpass filter with sharp passband skirts designed using tri-section SIRs," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, No. 1, 19–21, 2008.
10. Luo, S., L. Zhu, and S. Sun, "Compact dual-mode triple-band bandpass filters using three pairs of degenerate modes in a ring resonator," *IEEE Trans. Microw. Theory Tech.*, Vol. 59, No. 5, 1222–1229, 2011.
11. Wang, L. and B.-R. Guan, "Compact and high selectivity tri-band BPF using nested DDGSRs," *Electron. Lett.*, Vol. 48, No. 7, 378–379, 2012.
12. Doan, M. T., W.Q. Che, and W.J. Feng, "Tri-band bandpass filter

using square ring short stub loaded resonators," *Electron. Lett.*, Vol. 48, No. 2, 106–107, 2012.

13. Zhang, Z., et al., "Design of a compact dual-band bandpass filter using opposite hook-shaped resonator," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No. 7, 359–361, 2011.
14. Wadell, B. C., *Transmission Line Design Handbook*, Artech House, Inc., Norwood, MA, 1991.
15. Liu, Y., W.-B. Dou, and Y.-J. Zhao, "A tri-band bandpass filter realized using tri-mode T-shape branches," *Progress In Electromagnetics Research*, Vol. 105, 425–444, 2010.
16. Chen, W.-Y., M.-H. Weng, and S.-J. Chang, "A new tri-band bandpass filter for GSM, WIMAX and ultra-wideband responses by using asymmetric stepped impedance," *Progress In Electromagnetics Research*, Vol. 124, 365–381, 2012.
17. Wu, M.-S., Y.-Z. Chueh, J.-C. Yeh, and S.-G. Mao, "Synthesis of triple-band and quad band bandpass -filters using lumped-element coplanar waveguide resonators," *Progress In Electromagnetics Research B*, Vol. 13, 433–451, 2009.