LETTER

A compact tri-band microstrip filter with independently tunable passbands and high selectivity

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Abstract This paper presents a compact tunable tri-band filter with independently controlled passbands and high selectivity. The filter is comprised of three pairs of varactor-loaded $\lambda/4$ short-circuited resonators. Each passband of the filter can be independently tuned by varying the voltage applied to the corresponding resonators. In addition, a source-load coupling structure is employed to produce transmission zeros (TZs) achieving high selectivity. A prototype tunable tri-band microstrip filter is implemented. The experiment results show that the three passbands have tuning ranges of 0.81–0.99 GHz, 1.34–1.54 GHz, and 1.8–2.03 GHz, respectively.

Keywords: tri-band filter, microstrip filter, tunable filter

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

1. Introduction

As a result of increasing requirements of reconfigurable multiband communication systems, tunable planar band-pass filters (BPFs) have drawn a lot of attentions due to their potential of reducing the size, cost and complexity of RF front-ends [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. There have been lots of research attempts to design tunable dual-band filters [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. To further extend the tuning ranges of passband, a few research works have focused on tunable tri-band filters [24, 25]. However, the presented filters have either one tunable passband [24] or two tunable passbands [25] due to the modes of their multi-mode resonators cannot be controlled independently. The challenge for reaching three independently tunable passbands primarily lies in the implementation complexity of circuit and requirement of relatively large circuit size and number of tuning elements (if not impossible). In this paper, a simple approach to design compact tunable tri-band filter using varactor-loaded $\lambda/4$ short-circuited resonators is presented. The key features of the proposed filter are three independently controlled passbands and high frequency selectivity.

Fig. 1. (a) Schematic layout of the proposed tunable tri-band filter ($l_1 = 1.8$, $l_2 = 30.2$, $l_3 = 9.9$, $l_4 = 6$, $l_5 = 1.7$, $l_6 = 15.4$, $l_7 = 7.9$, $l_8 = 3$, $l_9 = 2.2$, $l_{10} = 7.4$, $l_{11} = 7.86$, $l_{12} = 3$, $l_{13} = 2.5$, $s_1 = 0.2$, $s_2 = 0.5$, $s_3 = 1.2$, $s_4 = 0.14$, $g_1 = 0.22$, $g_2 = 0.43$, $g_3 = 0.16$, $D = 0.6$, $D_1 = 2$, $D_2 = 1.8$, $D_3 = 2$, $W_0 = 1.5$, $W_1 = 0.8$, and $W_2 = 0.3$. unit: mm). (b) Implementation of the tunable capacitor C_{vi} ($i = 1, 2, 3$), where L_{choke} denotes an inductor for RF choke. (c) Photograph of the fabricated filter.

Fig. 2. (a) Equivalent circuit of the resonator. (b) Variation ranges of the resonators for the three passbands with $C_{v1} = C_{v2} = C_{v3} = C_v$ varying from 0.3 to 0.7 pF ($Y_1 = Y_2 = Y_3 = 0.016$ S, $L_1 = 47.9$, $L_2 = 28$, and $L_3 = 20.46$. unit: mm).

2. Filter design

Fig. 1(a) depicts the schematic layout of the proposed tunable microstrip tri-band filter. The filter consists of three pairs of $\lambda/4$ short-circuited resonators and common input and output feed lines. Each pair of resonators forms a passband and is folded for compactness. To control the center frequencies of the passbands, three pairs of tunable capacitors are attached at the open end of the corresponding resonators. The practical implementation of each tunable capacitor C_{vi} ($i = 1, 2, 3$) is demonstrated in Fig. 1(b),

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DOI: 10.1587/elex.16.20190589

Received September 15, 2019

Accepted October 17, 2019

Published November 8, 2019

Copied November 25, 2019

where C_{di} , C_{dci} , and V_i are varactor diode, DC block capacitor, and DC voltage, respectively. It should be mentioned that $C_{vi} = C_{di} \cdot C_{dci} / (C_{di} + C_{dci})$. The key features of the design are as follows. To enhance the selectivity, a source-load coupling structure is added between the feed lines to produce transmission zeros (TZs) in each passband. The source-load coupling line between the first and second pairs of resonators (denoted as Band 1 and Band 2) and the large separation between the second and the third pairs of resonators (denoted as Band 2 and Band 3) has helped to reduce the mutual interference between these three passbands. In addition, by adjusting the values of the bias voltages separately, the center frequencies of the three passbands can be controlled independently.

To analyze the proposed $\lambda/4$ resonator, the effects of microstrip line discontinuity is ignored. Fig. 2(a) shows the configuration of the resonator loaded with tunable capacitor C_{vi} , where Y_i and L_i denote the characteristic admittance and length of the resonator. The input admittance (Y_{in-i}) can be derived as

$$Y_{in-i} = j2\pi f_{0i} C_{vi} - jY_i \cot(\beta_i L_i) \quad (1)$$

where β_i is the propagation constant at the resonant frequency f_{0i} . With the resonance condition of $\text{Im}(Y_{in-i}) = 0$, the resonant frequency can be obtained as

$$f_{0i} C_{vi} \tan\left(\frac{2\pi f_{0i} L_i \sqrt{\epsilon_r}}{c}\right) = \frac{Y_i}{2\pi} \quad (2)$$

where ϵ_r and c mean relative permittivity constant and the speed of the light in free space. From (2), it is seen that by varying the C_{vi} , the resonant frequency of the resonator can be changed. Assuming $C_{v1} = C_{v2} = C_{v3} = C_v$, the variation ranges of the resonators for the three passbands with C_v varying from 0.3 to 0.7 pF are illustrated in Fig. 2(b).

Using the above resonator, a tunable tri-band filter was implemented on a 0.508-mm RT/Duriod 5880 substrate with relative dielectric constant of 2.2. The filter was firstly designed with fixed center frequencies and 3-dB fractional bandwidths (FBWs), i.e., $f_1 = 1$ GHz, $f_2 = 1.5$ GHz, $f_3 = 1.99$ GHz, $\text{FBW}_1 = 9.4\%$, $\text{FBW}_2 = 6\%$, and $\text{FBW}_3 = 4.2\%$. The initially designed passband return losses for the three passbands are 14 dB, 15 dB, and 13 dB, respectively. Using the filter design approach described in [26], the coupling coefficients and external quality factors are $K_1 = 0.089$, $K_2 = 0.051$, $K_3 = 0.033$, $Q_{e1} = 13.1$, $Q_{e2} = 28.4$, and $Q_{e3} = 38.5$. Referring to Fig. 1(a), the coupling coefficients are determined by the sizes of coupling gaps (s_1, s_2, s_3) and coupling lengths (l_4, l_8, l_{12}) between resonators. The external quality factors are determined by the sizes of coupling gaps (g_1, g_2, g_3) between resonators and feed lines. To achieve the tunable characteristics, two types of varactor diodes from Skyworks are employed to control the three passbands. The varactor C_{d1} (shown in Fig. 1(b)) is realized by varactor diode SMV2020-079LF (0.35–3.2 pF, 20–0 V bias) [27]. The C_{d2} and C_{d3} are varactor diode SMV1405-079LF (0.63–2.67 pF, 30–0 V bias) [28]. The DC block capacitors C_{dc1} , C_{dc2} , and C_{dc3} are 2.2 pF (GRM1885C1H2R2WA01), 1.2 pF (GRM1885C1H1R2WA01), and 0.8 pF (GRM1885C1HR80WA01) from Murata Corporation

Fig. 3. Simulated and measured S-parameters of independently tunable passbands. (a) First passband. (b) Second passband. (c) Third passband.

Table I. Comparison with other tunable multi-band microstrip filters.

Ref	TR* (GHz)	IL (dB)	Num. of TZs	Num. of Passbands	NICP*
[23]	1.25–1.36 2.10–2.31	1.46–4.3 3.10–4.85	5	2	2
[24]	1.6–2.55 3.5 4.4	4.7–3.3 1.7 3.2	4	3	1
[25]	1.24–1.50 1.8 2.26–2.80	3.9–4.3 – 1.9–3.5	4	3	2
This work	0.81–0.99 1.34–1.54 1.80–2.03	3.64–2.13 3.4–2.14 4.01–2.87	6	3	3

*TR: Passband tuning range; NICP: Number of independently controlled passbands.

[29]. In addition, the RF choke L_{choke} is a 100 nH (LQG18HNR10J00) Murata inductor [30]. The design and optimisation of the filter were done by co-simulation between full-wave electromagnetic (EM) simulator HFSS and ADS. The optimized critical dimensions of the filter are shown in the caption of Fig. 1. The photograph of the fabricated filter with bias circuits is shown in Fig. 1(c).

3. Experimental results

The measurement of the tunable filter was performed by using an Agilent E8363B vector network analyser. Fig. 3(a)–(c) show the simulated and measured S-parameters of the independently tunable passbands. As shown in Fig. 3, the tuning ranges of the first, second, and third passbands are 0.81–0.99 GHz, 1.34–1.54 GHz, and 1.8–2.03 GHz with FBWs of 7.9–8.8%, 4.8–5.3%, and 3.5–4.1%, respectively. Within these tuning states, the insertion losses (ILs) of the three passbands are 3.64–2.13 dB, 3.4–2.14 dB, 4.01–2.87 dB, respectively. The return losses of the three passbands over the whole tuning ranges are greater than 11 dB. Very importantly, it is evident that the tuning of one passband has almost no effect on the other two bands. There are some small discrepancies between the simulated and measured results. These are most likely due to the fabrication tolerance and the parasitic effect of varactor diodes and their biasing circuits. Besides, excluding feed lines, the normalized size of the filter is approximately $0.12\lambda_g \times 0.16\lambda_g$, where λ_g is the waveguide length at 0.81 GHz. Table I gives a comparison between this work and several reported works. The presented design in this work offers more TZs within the stopband achieving high selectivity and enables three passbands being independently tunable.

4. Conclusion

A compact varactor-tuned tri-band filter using varactor-loaded $\lambda/4$ resonators has been presented. The filter offers independently tunable tri-band characteristics with high selectivity. The presented filter can be a good candidate for modern and future wireless communication systems.

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