Balanced tri-band bandpass filter using sext-mode stepped-impedance square ring loaded resonators

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Abstract: In this letter, a novel balanced tri-band bandpass filter (BPF) is developed by using the proposed sext-mode stepped-impedance square ring loaded resonators (SI-SRLR). The new SI-SRLR has six resonant modes, including three differential-modes (DMs) and three common modes (CMs). The operating mechanisms of these resonances are explored by the even-/odd-mode method and simulation techniques. Three DMs of the proposed resonator are used to build the triple DM passbands. The appropriately admittance ratio $K$ of SI-SRLR is chosen to inhibit the CM signal in within three DM passbands. Moreover, three T-shaped stubs are loaded to enhance the CM suppression. Finally, a balanced tri-band BPF with compact size and high selectivity is designed, fabricated, and measured. The measurements are in good agreement with the simulated results, which verifies well the proposed structure and design method.

Keywords: balanced bandpass filter (BPF), sext-mode, stepped-impedance square ring loaded resonator (SI-SRLR), tri-band

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

References

[1] S. Zhang, \textit{et al.}: “Compact differential bandpass filter using one-sixth mode and novel one-third mode triangular SIW resonators,” IEICE Electron. Express \textbf{15} (2018) 20180044 (DOI: 10.1587/elex.15.20180044).

[2] C.-H. Lee, \textit{et al.}: “Balanced dual-band BPF with stub-loaded SIRs for common-mode suppression,” IEEE Microw. Wireless Compon. Lett. \textbf{20} (2010) 70 (DOI: 10.1109/LMWC.2009.2038433).

[3] Y.-H. Cho and S.-W. Yun: “Design of balanced dual-band bandpass filters using asymmetrical coupled lines,” IEEE Trans. Microw. Theory Techn. \textbf{61}
1 Introduction

Recently, balanced multiband bandpass filters (BPFs) have attracted more attention due to their high immunity for environmental noise, as compared to the single-ended BPFs [1]. To support dual-band operation, many balanced dual-band BPFs based on different types of structures, such as stepped-impedance resonators [2], coupled lines [3], and stub-loaded resonators [4], have been developed in past few years. But for tri-band operation, only five works until now are reported in public [5, 6, 7, 8, 9]. Multi-stub-loaded resonators are used to construct the tri-band balanced BPFs in [5] and [6]. To improve the suppression of common-mode (CM) noise, a balanced stepped-impedance microstrip-slotline transition structure [7] or a slotline coupled-feed structure [8] is employed to suppress the CM, while the three differential-mode (DM) passbands are built by the coupled complementary split ring resonators and three pairs of half-wavelength resonators, respectively. In [9], a balanced tri-band BPF has been achieved based on the octo-section stepped-impedance ring resonators. However, these designs suffer from large circuit size [5, 6], large insertion loss [8], or difficulty in controlling the bandwidth [7, 9]. In all, the study on balanced tri-band BPFs is in progress, but still limited.

In this letter, a new sext-mode stepped-impedance square ring loaded resonator (SI-SRLR) is proposed, and a high-performance balanced tri-band BPF is developed. Resonant characteristics of the proposed SI-SRLR are analyzed by both theoretical and parametric studies. Three T-shaped stubs are loaded at the sym-
metric plane of SI-SRLR to misalign the two CM resonances for enhancing the suppression of CM noises. Finally, a compact balanced tri-band BPF based on two coupled SI-SRLRs is designed and experimented.

2 Analysis of sext-mode SI-SRLR

Fig. 1a depicts the transmission line model (TLM) of the proposed sext-mode SI-SRLR. The TLM consists of eight transmission line sections, with corresponding electrical lengths and characteristic admittances as \( Y_1, Y_2, Y_3, Y_4 \), respectively. Compared with the presented quadruple-mode SI-SRLR in [10], the proposed new SI-SRLR has two additional open-circuited stubs that loaded at upper two corners of square ring. Thus, two more resonances, total six resonant modes, are obtained. As conducted in [10], the even- and odd-mode method is used to analysis the symmetrical SI-SRLR. Under the even-/odd-mode excitation (with respective to CM case and DM case), the symmetrical plane (red dashed line) of the circuit behaves as a perfect magnetic wall or electric wall, respectively, and the DM and CM bisection of the SI-SRLR are shown in Fig. 1b and Fig. 1c, respectively. Herein, \( Y_1 = Y_2 = Y_4 \) is assumed for simplification, and define \( K = Y_1 / Y_3 \). Following the transmission line theory, the resonant condition can be written as

\[
\text{DM Case: } \text{Im}(Y_L + Y_{DR}^R) = 0, \quad \text{CM Case: } \text{Im}(Y_L + Y_{CM}^R) = 0,
\]

where \( Y_L, Y_{DR}^R, \) and \( Y_{CM}^R \) are the input admittances of the corresponding TL counterparts, as denoted in Fig. 1b and 1c and given by

\[
Y_{DR}^R = j Y_1 \left[ \frac{\tan \theta_1 + K \tan \theta_4 - K \cot \theta_2}{K + K^2 \cot \theta_2 \tan \theta_3 - K^2 \tan \theta_2 \tan \theta_4} - \cot \theta_2 \right],
\]
\[
Y_{CM}^R = j Y_1 \left[ \frac{\tan \theta_1 + K \tan \theta_3 + K \tan \theta_4}{K + K^2 \tan \theta_2 \tan \theta_3 + K^2 \tan \theta_3 \tan \theta_4} + \tan \theta_2 \right].
\]

Thus, the DM resonant frequencies and CM resonant frequencies can be found by solving (1) and (2). It is obvious that all of resonances can be varied by changing...
the electrical lengths and the admittance ratio $K$. As studied in [11], both the DM bisection and CM bisection of SI-SRLR behave as a triple-mode stub-loaded resonator. Three DM resonances and three CM resonances are denoted as $f_{d1}$, $f_{d2}$, $f_{d3}$, and $f_{c1}$, $f_{c2}$, $f_{c3}$, respectively. The typical frequency responses of the SI-SRLR obtained by using the ADS simulator and *sonnet* em simulator are drawn in Fig. 2. In the simulation, $\theta_1$, $\theta_2$, $\theta_3$, and $\theta_4$ are chosen as 48°, 53°, 37°, and 34°, respectively, at 1.9 GHz. $Y_1 = 0.01 \, \text{S}$ and $K = 0.42$ are used. Based on the given electrical parameters, the microstrip line model of SI-SRLR with the optimized geometrical dimensions is obtained and shown the inserted configuration in Fig. 2. The used substrate is Roger RO4003C with $\varepsilon_r$ of 3.38 and thickness of 0.813 mm.

As expected, six resonances are clearly observed in Fig. 2 and the EM simulation matches well with the TLM result. In addition, it is found from the simulation that the frequency separations of between $f_{d1}$ and $f_{d2}$ and between $f_{c3}$ and $f_{d3}$ can be adjusted by changing $K$. We define $\Delta_1 = |f_{d2} - f_{c1}|$ and $\Delta_2 = |f_{d3} - f_{c3}|$, indicating the frequency separation between two pairs of the tightly adjacent DM and CM resonances. Fig. 3 shows the variation of $\Delta_1$ and $\Delta_2$ against the $K$. It is seen that $\Delta_1$ decreases while $\Delta_2$ increases with enlarged $K$. When $K = 4.2$, a balanced frequency separation of two pairs resonances is obtained, as indicated the red point P in Fig. 3. It is a key point to achieve the desirable CM suppression both in the second and third DM passbands simultaneously.

### 3 Design of the balanced tri-band BPF

Based on sext-mode SI-SRLR, a compact balanced tri-band BPF with three DM passbands centered at 1.9 GHz, 3.35 GHz, and 5.8 GHz, respectively, is designed.
The configuration of the filter is given in Fig. 4a. Four open-circuited stubs as well as the center lines of SI-SRLR are folded inner or meandered for compact size. Fig. 4b presents the coupling scheme of the BPF under DM excitation. There are three coupling paths, each path forms one DM passband. To obtained the required coupling coefficients of three passbands, the geometrical parameters $L_{12}$, $L_{33}$, and $C_d$ are determined by simulated extraction. On the other hand, two high-impedance microstrip lines, act as the feeding line structures, with dimension $L_{f1}$, $L_{f2}$, $w_f$, and $g$ are tuned to meet the demanded external quality factors.

Moreover, three T-shaped stubs are loaded at the center of both two coupled SI-SRLRs to shift their CM resonances without affecting DM resonances, as shown in Fig. 4a. Then, the CM coupling between two coupled SI-SRLRs will be weaken, and the CM transmission will be reduced. With the help of the parameterization and optimization tools of Sonnet, the dimensions of the designed filter are finally determined as follows: $L_{11} = 8.15$, $L_{12} = 3.55$, $L_2 = 9$, $L_{31} = 3.35$, $L_{32} = 3.3$, $L_{33} = 3.2$, $L_{f1} = 9.3$, $L_{f2} = 4.2$, $S_{l1} = 0.65$, $S_{l2} = 3.5$, $S_{l3} = 2.4$, $S_{l4} = 2$, $S_{l5} = 2.6$, $w_1 = 0.45$, $w_2 = 2.3$, $w_f = 0.2$, $g = 0.2$, and $C_d = 0.3$ (unit: mm).

4 Results and discussion

To verify the above design, the filter shown in Fig. 4a is fabricated, and its photograph is given in Fig. 5a. The overall size is $19.1 \, \text{mm} \times 23.4 \, \text{mm} \ (0.19\lambda g \times 0.23\lambda g)$, where $\lambda g$ is the guided wavelength at 1.9 GHz. The measurement is executed on a four-port vector network analyzer, Agilent E5071C.

The simulated results and measured results are illustrated in Fig. 5b. The solid lines indicate the simulation and the dashed lines represent the measurement, and they are agree reasonably with each other. For DM response, the measured three passbands are centered at 1.92 GHz, 3.34 GHz, and 5.84 GHz, with a 3-dB fractional bandwidth of 4.74%, 8.61%, and 2.78%, respectively. The measured minimum in-band insertion losses are 0.94 dB, 1.21 dB, and 1.93 dB at the three passbands, respectively. Five transmission zeros (TZs, TZ$_1$–TZ$_5$) generated by SI-SRLR and signal cancellation between two coupling paths improves the selectively of DM passbands. For CM response, the measured minimum CM insertion losses within the three DM passbands are 54 dB, 27 dB, and 32 dB,
respectively, which shows a good CM suppression within DM passbands. Besides, Table I gives a comparison of the proposed balanced tri-band BPF with other reference works. It is seen that the implemented balanced tri-band BPF has merits like the flatness of DM passbands, high selectivity, and compact circuit size.

### 5 Conclusion

A new sext-mode SI-SRLR is proposed to develop a high-performance balanced tri-band BPF in this letter. The admittance ratio $K$ of SI-SRLR can be adjusted to obtain a balanced frequency separations of two pairs of DM and CM resonances, which is important to prevent the CM interference within the DM passbands. Furthermore, stub-loading technique is used to enhance the CM suppression and the generated multiple TZs improve significantly the selectivity of DM passbands. With the features of compactness, steep sideband, and desired CM suppression, the designed filter is attractive for balanced multiband wireless applications.

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