Compact Tunable Balanced Dual-band Bandpass Filter Using Tri-Stub Loaded Resonator

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Abstract. This letter proposes a tunable balanced dual-band bandpass filter (BPF) with high common-mode (CM) suppression based on tri-stub loaded resonator (TSLR). Two TSLRs terminated with varactor diodes are employed to obtain the tunable second differential-mode (DM) passband, which is independent of the first one. For validation, a tunable balanced dual-band BPF is designed, fabricated and measured that achieve the continuous frequency-tuning range of the second DM passband from 5.968 to 6.368 GHz with constant 3dB fractional bandwidth (FBW) of 6.8% ± 0.17% and CM rejection levels of over 30 dB. The measured results agree well with the simulated ones.

1. Introduction

Due to the growing demand of anti-environmental noise and electromagnetic interference, balanced circuits have been widely noticed. As an important part of the RF system front end, the research of balanced filter with high differential-mode (DM) filtering responses and good anti-noise interference has caught much attention. Recent research are committed to developing single-band balanced bandpass filter (BPF) with common-mode (CM) suppression¹² and wide stopband³. In order to cater to the demand of multi-band system, balanced dual-band BPF⁴⁷ is of the essence in the communication system. In [4], a balanced dual-band BPF based on two stepped-impedance resonator (SIR) and two uniform-impedance resonator (UIR) was proposed, which has the low CM suppression and large insertion loss (IL). In [5], a balanced dual-band BPF using substrate integrated waveguide (SIW) cavity with high CM suppression and low IL was presented, while the size is large.

The electrically tunable filter plays a significant role in communication system, which can reduce the size, thereby realizing miniaturization and low lost. A compact tunable balanced BPF based on novel multi-mode resonator was presented in [8], however possessing low CM suppression. A tunable balanced dual-band BPF using the defected ground structure (DGS) was proposed in [9], yet the CM suppression is still large.

In this letter, a balanced dual-band BPF based on tri-stub loaded resonator (TSLR) with the first tunable passband and the second fixed one is proposed, analyzed under DM and CM excitation to obtain its resonant frequencies. Varactor diodes are terminated on the open-stub of TSLR to tune the second DM passband while independent of the first one. A good agreement between simulated and measured results is realized.
2. Resonant characteristics of TSLR

The equivalent circuit of proposed dual-mode TSLR is shown in figure 1(a). Since this resonator is symmetrical along the T-T' plane, under DM excitation, the symmetrical line can be regarded as an electrical wall (or a short-circuit), the equivalent circuit of DM is depicted in figure 1(b).

For simplicity, assuming the input admittance of the stub loaded with capacitor \( C_v \) is \( Y_{1d} \). The input admittance of port \( P_1 \) under DM excitation is

\[
Y_{in}^{dd} = j\omega C_v + Y_1 + \frac{jY_1 \tan \theta_2 + Y_{1d}}{jY_1 \tan \theta_2 + Y_1} \tag{1}
\]

where

\[
Y_{1d} = jY_1 \left( \frac{\tan \theta_1 + \tan \theta_2}{1 - \tan \theta_1 \tan \theta_2} - \cot \theta_1 \right) \tag{2}
\]

\( \theta = \beta L_i \). The resonant condition under DM excitation can be derived by

\[
Y_{in}^{dd} = 0 \tag{3}
\]

Thus, for the expected resonant frequency, the value of the capacitor \( C_v \) can be deduced as

\[
C_v = \frac{Y_1 jY_{1dd} - Y_1 \tan \theta_{4dd}}{\omega_{dd} jY_1 - Y_{1dd} \tan \theta_{4dd}} \tag{4}
\]

where

\[
Y_{1dd} = jY_1 \left( \frac{\tan \theta_{1dd} + \tan \theta_{2dd}}{1 - \tan \theta_{1dd} \tan \theta_{2dd}} - \cot \theta_{3dd} \right) \tag{5}
\]

\( \theta_{3dd} \) is the electrical length for the resonant frequency \( \omega_{3dd} \).

Similarly, when applying CM excitation, the symmetrical plane can be known as a magnetic wall (or an open-circuit), subsequently the circuit is divided into two halves along the plane and the obtained equivalent circuit is shown in figure 1(c). Assuming the input admittance of the stub loaded with capacitor \( C_v \) is \( Y_{1c} \). The input admittance of port \( P_1 \) under CM excitation is given by

\[
Y_{in}^{cc} = j\omega C_v + Y_1 + \frac{jY_1 \tan \theta_3 + Y_{1c}}{jY_1 \tan \theta_3 + Y_1} \tag{6}
\]

where

\[
Y_{1c} = jY_1 \left( \frac{\tan \theta_1 + \tan \theta_2 + \tan \theta_3 + \tan \theta_4}{1 - \tan \theta_1 \tan \theta_2 - 1 - \tan \theta_3 \tan \theta_4} \right) \tag{7}
\]

The resonant condition under CM excitation can be derived by

\[
Y_{in}^{cc} = 0 \tag{8}
\]

Hence, the value of the capacitor \( C_v \) can be deduced as

\[
C_v = \frac{Y_1 jY_{1cc} - Y_1 \tan \theta_{4cc}}{\omega_{cc} jY_1 - Y_{1cc} \tan \theta_{4cc}} \tag{9}
\]

where

\[
Y_{1cc} = jY_1 \left( \frac{\tan \theta_{1cc} + \tan \theta_{2cc} + \tan \theta_{3cc} + \tan \theta_{4cc}}{1 - \tan \theta_{1cc} \tan \theta_{2cc} + 1 - \tan \theta_{3cc} \tan \theta_{4cc}} \right) \tag{10}
\]

\( \theta_{4cc} \) is the electrical length for the resonant frequency \( \omega_{4cc} \). As can be seen in the equation (4) and (9), reasonably changing the capacitor \( C_v \) can tune the DM and CM resonant frequency.
As can be seen in equation (4) and (5), the DM resonant frequencies are basically independent of open-stub with length of $L_5$. For demonstration, EM simulation software HFSS was utilized to conduct the experiment, as shown in figure 2. It is apparently seen that CM resonant frequencies decrease with $L_5$ increasing, while DM resonant frequencies are not affected. Therefore, both the equations and simulation illustrate that CM resonant frequencies can be independently tuned without influencing DM ones. Furthermore, the effects of other vital parameters are considered. As can be seen from figure 3(a), both the DM and CM resonant frequencies vary with $L_3$. In addition, it is noted from figure 3(b) that the second passbands of both DM and CM response can be controlled by $L_4$ but independently from the first ones. Therefore, through appropriately adjusting $L_4$, frequencies of the second passband, both DM and CM response, can be tuned independently. Besides, by reasonably regulating the dimensions of TSLR, the CM response can be shifted away from the DM one, thus realizing good CM suppression.

**Figure 1.** (a) Transmission line model of the proposed dual-mode TSLR. (b) DM equivalent circuit. (c) CM equivalent circuit.

**Figure 2.** Resonant frequency of dual-mode TSLR versus open-stub with length of $L_5$. 
3. Fabrication and measurement

The configuration and the coupling scheme of the proposed tunable balanced dual-band filter are shown in figure 4. According to the design method above and then fine-tuned design by EM simulator, the final optimized sizes of the structure are as follows: \( L_0 = 5 \) mm, \( L_{01} = 3.7 \) mm, \( L_1 = 15.2 \) mm, \( L_2 = 2.3 \) mm, \( L_3 = 4 \) mm, \( L_4 = 3.5 \) mm, \( L_5 = 11.8 \) mm, \( L_{001} = 10.2 \) mm, \( L_{0002} = 3 \) mm, \( W_{01} = 2.3 \) mm, \( W_1 = 0.5 \) mm, \( W_2 = 0.5 \) mm, \( W_3 = 0.5 \) mm, \( W_4 = 0.7 \) mm, \( W_5 = 0.8 \) mm, \( S_1 = 0.13 \) mm, \( S_2 = 0.3 \) mm, \( S_3 = 0.6 \) mm, \( C = 100 \) pF (0402), \( R_b = 10 \) k\( \Omega \) (0402).

The proposed filter was fabricated on a RT/Duriod 5880 substrate with the layer thickness of 0.787 mm and the relative permittivity of 2.2. The photograph of the fabricated tunable balanced dual-band BPF is shown in figure 5, its overall size is 33.6 mm \( \times \) 17.0 mm, and is about 0.36\( \lambda_g \times 0.18\lambda_g \) (where \( \lambda_g \) is the guided wavelength at the center frequency of the first passband). The diameter of the via-hole is 0.05 mm. The Silicon varactor MACOM MA46H120 with tuning range of 0.1-0.14 pF was applied to tune the frequency of the second DM passband.

The tunable balanced dual-band BPF is simulated and measured by using HFSS and Agilent N5244A, respectively. Figure 6 depicts the measured and simulated results with good agreement. For DM, when applying bias voltage from 18 V to 30 V, it is noticed that the tuning range of the second passband is 5.968-6.368 GHz with 3-dB FBW of 6.8\% \pm 0.17\%, the measured return loss (RL) within the passband is greater than 10.1 dB and the minimum IL is 1.01 dB. Meanwhile, the first passband is fixed at 2.428 GHz with RL better than 10.3 dB, 3-dB FBW of 15.2\% and the minimum IL is 1.71 dB. For CM, the measured IL of the first and second passband are greater than 40 dB and 30 dB, respectively.

Comparisons between the proposed tunable balanced dual-band BPF with the other presented works are given in Table 1, it is noted that the presented tunable dual-band BPF has wider frequency-tuning range, lower IL and better CM suppression.
Figure 5. Photograph of the fabricated tunable balanced dual-band BPF.

Figure 6. Measured and simulated S parameters of tunable balanced dual-band BPF.

Table 1. Comparisons with other works.

| Ref.  | $f_1/f_2$ (GHz) | 3-dB FBW (%) | IL (dB)       | Size ($\lambda_g\times\lambda_g$) | CM suppression (dB) |
|-------|----------------|--------------|---------------|----------------------------------|---------------------|
| [9]   | 1.25-1.52/3.65 | 5.9-5.6/6.4  | 1.45-4.21/1.51 | 0.42×0.14                        | >16                 |
| [10]  | 2.0-2.18       | 115.5-16.1   | 0.78-1.18     | 1.23×1.23                        | >14                 |
| [11]  | 0.805-0.87/2.4 | 6.5/3        | 1.1-2.8/2.9   | 0.33×0.35                        | >30                 |
| This work | 2.42/5.968-6.368 | 15.2/6.8±0.17 | 1.71/1.01-2.36 | 0.36×0.18                        | >40/>30             |

4. Conclusion
In this paper, a tunable balanced dual-band BPF using TSLR is designed, analyzed and demonstrated carefully. The filter realized the continuous frequency-tuning range of the second DM passband from 5.968 to 6.368 GHz with constant 3dB FBW of 6.8% ± 0.17% and CM rejection levels of over 30 dB for both passbands. The measured results suggest that the proposed tunable BPF has the merits of compact size, low IL and good anti-CM response. At the same time, frequencies of the second DM passband can be tuned independently from the first one. The filter is expected to apply in the multi-standard communication system.

5. References
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