A Compact Tunable Dual-band Bandpass Filter Using Varactor-loaded Step-impedance Resonators

Xiang Zhang, Chang Chen, Mingkang Li, Lingyun Zhou, and Bin Liu
Key Laboratory of Electromagnetic Space Information
Chinese Academy of Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China

Abstract— This paper presents a novel design of a compact tunable dual-band bandpass filter (BPF) using varactor-loaded step-impedance resonators(SIRs). The proposed filter structure offers the possibility of two tunable passbands. Compared to uniform impedance resonator (UIR), the SIR has more excellent performance such as compact size, and adjustable harmonic resonant frequency etc. The harmonic resonant frequency of SIR is determined by the length of SIR and the ratio of the two characteristic impedances. By choosing proper ratio of the two characteristic impedances, the length of SIR can be shorter than UIR with the same resonance frequency. So the proposed filter using varactor-loaded SIRs can be compact. Both theory and experiment are provided to validate the proposed filter. A prototype tunable dual-band filter is fabricated and measured. From the experimental results, the first passband center frequency tunable range is from 0.7 GHz to 1.2 GHz and the second passband center frequency tunable range is from 1.4 GHz to 2.15 GHz.

1. INTRODUCTION

Electronically tunable filters are essential microwave components for multiband communication systems due to their attractive features, i.e., miniaturizing the overall system size, reducing the system complexity and the cost in fabrication. To develop an electronically tunable filter, active tuning elements such as yittrium-iron-garnet (YIG), varactor diodes and RF MEMS need to be integrated within a passive filter. Although the YIG filters have large tuning range and small in-band insertion loss, their high power consumption, slow tuning rate, large size, and large weight block them from many applications in modern highly integrated communication systems. RF MEMS filters have the advantages of high Q-factor, low distortion levels and high linearity, but the fabricating cost is high. Recently, varactor diodes are widely used in the design of microstrip tunable bandpass filters due to their small size, high tuning speed, and low cost.

Several dual-band tunable filters using varactor didoes are developed [1–4]. In [1] and [3], the basic structure of dual-mode resonators consists of a uniform impedance transmission line and three varactor diodes. Compared to uniform impedance resonator (UIR), the SIR has more excellent performance such as compact size, and adjustable harmonic resonant frequency etc. There have been some tunable dual-band filters using SIRs. In [4], the varactor-loaded SIR is used in designing a tunable dual-band filter, but it only can tune the second passband while maintaining the first passband fixed.

In this paper, a compact tunable dual-band bandpass filter using varactor-loaded step-impedance resonators with controllable central frequencies of two passbands is presented. From theoretical even and odd-mode analysis, it is found that the two passbands can be tuned by varying the capacitances of varactor didoes. The resonant frequencies also depend on the length of SIR and the ratio of the two characteristic impedances. By properly selecting the ratio of the two characteristic impedances, the length of SIR can be shorter than UIR.

This paper is organized as follows. Firstly, the characteristics of proposed tunable SIRs are discussed. Secondly, the design and implementation of the filters along with the simulation and measurement results are described. Finally, conclusions are given.

2. CHARACTERISTICS OF VARACTOR-LOADED STEPPED-IMPEDANCE RESONATOR

Figure 1(a) shows the varactor-loaded stepped-impedance resonator. The basic structure is a symmetrical stepped-impedance resonator (a resonator with lines of two different characteristic impedance, Z_1 and Z_2) with three varactor diodes. Two varactor diodes are attached at the ends of the resonator and one varactor diode is placed at the center of the resonator. Since the structure is symmetrical, the even- and odd-mode analysis method is applicable to obtain the resonant frequencies.

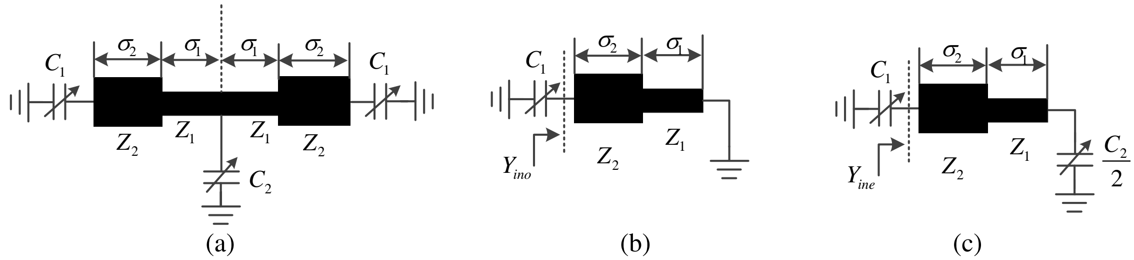

Figure 1: (a) Basic structure of the proposed resonator. (b) Odd-mode excitation equivalent circuit. (c) Even-mode excitation equivalent circuit.

When the odd-mode excitation is applied to the ends of the proposed resonator, there is a voltage null along the symmetry plane. Under the odd-mode excitation, it can be represented by the half circuit as shown in Fig. 1(b). The odd-mode input admittance is given as follows:

$$Y_{ino} = j\left(wC_1 + Y_2\frac{Y_2\tan\theta_1\tan\theta_2 - Y_1}{Y_2\tan\theta_1 + Y_1\tan\theta_2}\right) \tag{1}$$

where C_1 is the capacitance of the varactor diode connected at the end of the line, $Y_2 = 1/Z_2$ and θ_2 are the characteristic admittance and electric length of the outer line, $Y_1 = 1/Z_1$ and θ_1 are the characteristic admittance and electric length of the inner line. From the resonance condition of $\mathrm{Im}[Y_{ino}] = 0$, the odd-mode resonant frequency can be determined as follows:

$$2\pi f_{odd}C_1\cdot Y_1\cdot\tan\left(\frac{2\pi f_{odd}L_2}{v_p}\right)+Y_2\tan\left(\frac{2\pi f_{odd}L_1}{v_p}\right)\left(2\pi f_{odd}C_1 + Y_2\tan\left(\frac{2\pi f_{odd}L_1}{v_p}\right)\right) = Y_1Y_2 \tag{2}$$

where v_p is the phase velocity. The fundamental odd-mode resonant frequency can be used as the first passband frequency. From (2), it is concluded that the odd-mode resonant frequency depends on the capacitance of the varactor diode connected at the ends of the transmission line. Therefore, the change of the bias voltage on both end varactor diodes will result in the change of passband frequencies, enabling the tunability of the first passband frequency. Moreover, the odd-mode resonant frequencies are not affected by the varactor diode connected at the center of the transmission line.

For the even-mode excitation, there is no current flowing through the center of the transmission line. Under the even-mode condition, the proposed resonator can be represented by the equivalent half circuit shown in Fig. 1(c) . The even-mode input admittance is given as follows:

$$Y_{ine} = j\left(wC_1 - Y_2\frac{2Y_1(Y_1\tan\theta_1 + Y_2\tan\theta_2) + wC_2(Y_1 - Y_2\tan\theta_1\tan\theta_2)}{2Y_1(Y_2 - Y_1\tan\theta_1\tan\theta_2) - wC_2(Y_2\tan\theta_1 + Y_1\tan\theta_2)}\right) \tag{3}$$

where C_2 is the capacitance of the varactor diode connected at the center of the transmission line. For the resonance condition , the even-mode resonant frequency can be determined as follows:

$$2\pi f_{even}C_1 - Y_2\frac{\left[\begin{array}{l}2Y_1\Big(Y_1\tan(\frac{2\pi f_{even}L_1}{v_p})+Y_2\tan(\frac{2\pi f_{even}L_2}{v_p})\Big)\\ +2\pi f_{even}C_2\Big(Y_1-Y_2\tan(\frac{2\pi f_{even}L_1}{v_p})\tan(\frac{2\pi f_{even}L_2}{v_p})\Big)\end{array}\right]}{\left[\begin{array}{l}2Y_1\Big(Y_2-Y_1\tan(\frac{2\pi f_{even}L_1}{v_p})\tan(\frac{2\pi f_{even}L_2}{v_p})\Big)\\ -2\pi f_{even}C_2\Big(Y_2\tan(\frac{2\pi f_{even}L_1}{v_p})+Y_1\tan(\frac{2\pi f_{even}L_2}{v_p})\Big)\end{array}\right]} = 0 \tag{4}$$

The fundamental even-mode resonant frequency can be utilized as the second passband frequency. From (4), it is observed that the even-mode resonant frequency depends on C_1 and C_2. Thus, the change of the bias voltages applied to all of the varactor diodes will also result in the change of passband frequencies, enabling the tunability of the second passband frequency.

According to the analysis above, the odd- and even-mode resonant frequencies are affected by the length of SIR and the ratio of the two characteristic impedances (Y_1/Y_2). By choosing proper ratio of the two characteristic impedances, the length of SIR can be shorter than UIR with the same resonance frequency. Therefore, the tunable dual-band filter can be designed with compact size using varactor-loaded SIRs.

3. FILTER DESIGN AND IMPLEMENTION

To verify the analytical analysis of the proposed resonators, a tunable dual-band BPF is designed, simulated and measured. The filter is fabricated with a substrate with a relative dielectric constant of 2.2 and thickness of 31 mil.

Figure 2(a) depicts the configuration of the second-order microstrip tunable dual-band filter. In the proposed filter, four varactors are attached at the ends of the two microstrip lines and two varactor diodes are attached at the center of the two microstrip lines. The resonators are folded in order to reduce the size, forming open loops. The varactor diodes are SMV1233-079LF from Skyworks Solutions Inc. The input/output lines are tapped at the resonators. Two capacitors are attached in the feeding lines, functioning as a dc block. Another two dc block capacitors are attached at the center of line. The simulation was accomplished by using Ansoft's HFSSv14. The parameters are chosen as follows: $W_1 = 0.9\,\text{mm}$, $W_2 = 2.4\,\text{mm}$, $W_3 = 2.4\,\text{mm}$, $L_1 = 12.1\,\text{mm}$, $L_2 = 5.5\,\text{mm}$, $L_3 = 22.9\,\text{mm}$, $L_4 = 7\,\text{mm}$, $g = 0.15\,\text{mm}$, $C_{\text{dc1}} = 20\,\text{pF}$ and $C_{\text{dc2}} = 3.9\,\text{pF}$. The fabricated two-port filter is finally measured using the Rohde & Schwarz ZNB 20 vector network analyzer, as shown in Fig.2 (b).

Figure 3 shows the simulation and measurement results of the tunable dual-band filter for several typical bias voltages. The measurement results agree well with the simulation results. The first passband center frequency tunable range measured is from 0.7 GHz to 1.2 GHz with the 3-dB fractional bandwidth of 11.29%–14.77% and the second passband center frequency tunable range measured is from 1.4 GHz to 2.15 GHz with the 3-dB fractional bandwidth of 8%–9.38%.

The return loss is better than 10 dB in the overall tuning range of both passbands, as shown in Fig. 3(a). The insertion loss of the first passband varies from 1.54 dB to 3.86 dB, while the insertion

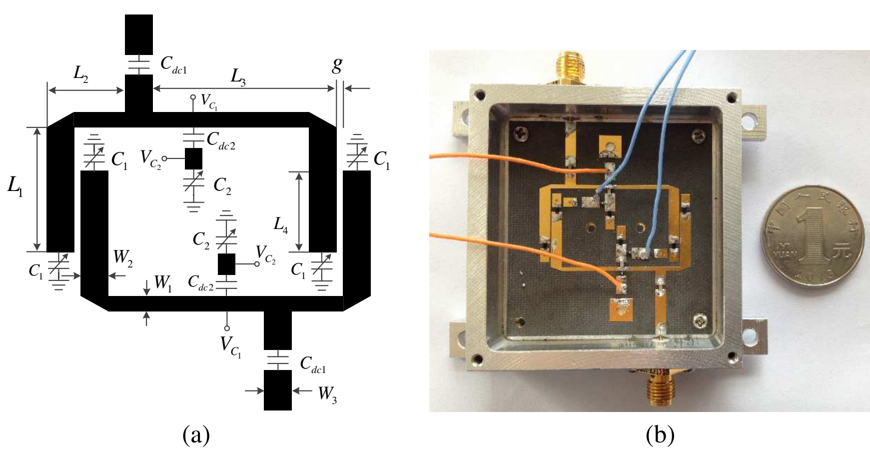

Figure 2: (a) Configuration of the proposed filter. (b) Photograph of the fabricated tunable dual-band filter.

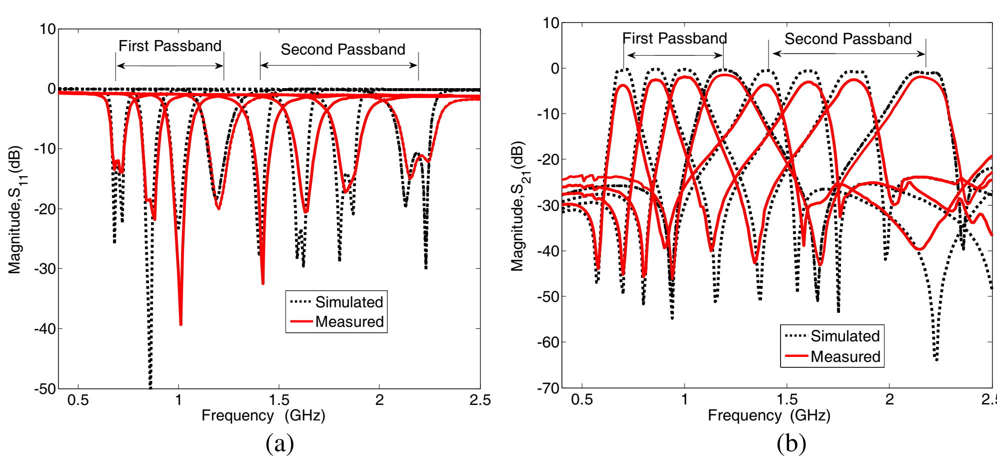

Figure 3: Simulation and measurement results (a) S_{11}-magnitude, (b) S_{21}-magnitude. Reverse-bias voltage variation: $V_{\text{C1}} = 0 \sim 7\,\text{V}$ and $V_{C2} = 1\,\text{V} \sim 15\,\text{V}$.

loss of the second passband varies from 1.93 dB to 3.63 dB, as shown in Fig. 3(b). However, there exist some discrepancies between the simulated and measured results, and these are mainly caused by the approximate SPICE model of the used varactor diodes and other unwanted parasitic effects, including parasitic capacitance caused by wielding and the bias circuit in practical circuits. The size of the main structure is about 19 mm × 33.35 mm. The size of the proposed tunable dual-band filter using SIRs decrease 22% compared to the tunable dual-band filter using UIRs in [1].

4. CONCLUSION

In this paper, a compact dual-band microstrip filter has been investigated and designed. The dual-mode step-impedance resonator with the loaded varactor diodes is proposed an analyzed. Compared to uniform impedance resonator (UIR), the SIR has more excellent performance such as compact size, and adjustable harmonic resonance frequency etc. Therefore, by using varactor-loaded SIRs, the tunable dual-band filter can be designed with compact size. And a two-pole dual-band filter with two tunable passbands is fabricated. The experimental results are in good agreement with the theoretical predictions. The first passband center frequency tunable range is from 0.7 GHz to 1.2 GHz with the 3-dB fractional bandwidth of 11.29%–14.77% and the second passband center frequency tunable range is from 1.4 GHz to 2.15 GHz with the 3-dB fractional bandwidth of 8%–9.38%. The size of the proposed tunable dual-band filter using SIRs decrease 22% compared to the tunable dual-band filter using UIRs.

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