Novel Varactor-Tuned Balanced Bandpass Filter with Continuously High Common-Mode Suppression

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Abstract **─** In this letter, a novel balanced varactor-tuned bandpass filter (BPF) designed by using the half-wavelength microstrip resonators is proposed. The frequency-tuning mechanism of the resonator is analytically investigated for designing the proposed balanced BPF. By adding a tunable capacitor to the center of the resonator, it is noted that the common mode can be suppressed to a great extent in the frequency-tuning range of the differential-mode passband. Also, it has no effect on the differential-mode response. For demonstration, a balanced BPF is designed and fabricated. The simulated and measured results with good agreement show that the center frequency of the differential-mode passband can be tuned from 0.725 GHz to 0.811 GHz, while the common-mode suppression in this frequency range is always more than 25 dB.

Index Terms – Balanced bandpass filter (BPF), common-mode suppression, half-wavelength resonator, and tunable filter.

I. INTRODUCTION

Balanced technologies are becoming more and more attractive in the designs of RF/microwave circuits and systems because of their many advantages such as superior response performance, noise immunity and harmonic suppression. Many reports presented the effort [1-6], which was paid to achieve the desired bandpass response in differential operation and to decrease the level of common-mode noise in balanced bandpass filters (BPFs). Some of the common-mode suppression methods such as coupled-line and multi-section resonators, double-sided parallel-strip line (DSPSL), and coupled stepped-impedance resonators were reported in [1-6]. However, all of the designed filters were not tunable.

Tunable resonators and BPFs are in great demand by the current and emerging reconfigurable communication systems. The half-wavelength ($\lambda_g/2$) resonator has been widely studied for designing tunable circuits [7, 8]. Since the differential-mode frequency response of the $\lambda_g/2$ resonator corresponds to the fundamental resonance, it is highly suitable for applications in balanced tunable BPF [7]. In this case, the conventional methods can be utilized for analyzing the differential- and common-mode responses.

In this paper, the tunable $\lambda_g/2$ resonator is investigated for designing a balanced BPF. By adding a few tunable capacitors to the ends and center of the $\lambda_g/2$ resonator, the proposed BPF can be made not only tunable in its differential-mode passbands, but it has also attained high common-mode suppression in the frequency range of its differential-mode passbands. Simulated and measured results show that the center frequency of the differential-mode passband can be tuned from 0.725 GHz to 0.811 GHz, and the common-mode suppression in this frequency range is always greater than 25 dB. The input 1 dB compression point (P_{in-1dB}) and the input third-order intercept point (IIP_3) of the balanced tunable BPF are found to be 16 dBm and 26 dBm, respectively.

II. BALANCED TUNABLE BANDPASS FILTER

Figure 1 shows the configuration of the proposed balanced tunable BPF. It is composed of a pair of coupled tunable $\lambda_g/2$ resonator with loaded tunable admittances, as shown in Fig. 2 (a),

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which are realized by a combination of a varactor D_i and a DC block capacitor C_i in series (where i = 1 or 2). As compared with the design in [7], the topology of the proposed BPF has a much simpler configuration, especially in the feeding scheme at the two differential ports. To simplify the analysis, the employed varactor D_i can be represented by a tunable capacitor C_{ti} and a resistance r_i in series. As a result, the loaded admittances at the center and the two ends of the $\lambda_g/2$ resonator can be obtained using,

$$Y_i = \frac{j\omega C_{ti}}{jr_i\omega C_{ti} + 1}. \tag{1}$$

In this design, the end-loaded Y_1 is used to tune the differential-mode resonant frequency f_0^d of the resonator for designing the tunable differential-mode passband of the proposed BPF. The central-loaded Y_2 is used to change the common-mode frequency response, and to ensure that the common-mode suppression in the differential passband is continuously high.

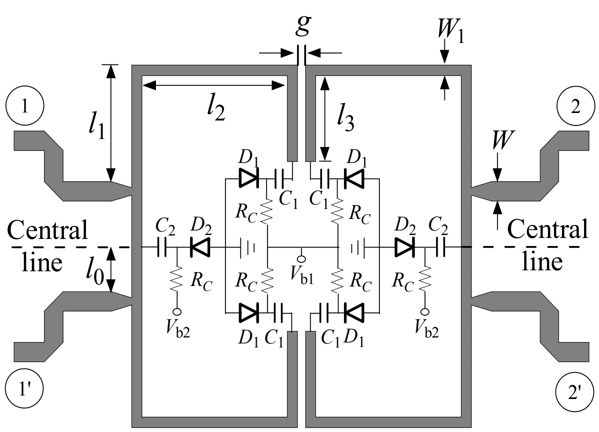

Fig. 1. Configuration of the proposed balanced varactor-tuned BPF using $\lambda_g/2$ resonators.

A. Different-mode analysis

Figure 2 (b) shows the differential-mode equivalent circuit of the tunable $\lambda_g/2$ resonator, where the central line in Fig. 1 is replaced by a short-circuited plane [8]. The central-loaded Y_2 has no effect on the differential-mode response. The differential-mode input admittance Y_{in}^d can be expressed as,

$$Y_{in}^d = -j\frac{Y_c}{\tan\theta} + Y_1 \tag{2}$$

where Y_c is the characteristic admittance, and θ is the electrical length of the transmission line. The resonant condition is that the imaginary part of Y_{in}^d is equal to 0, namely, Im{ Y_{in}^d } = 0, the expression of f_0^d can then be obtained as

$$f_0^d = \frac{Y_c}{2\pi C_{t1}(\tan\theta - jr_1 Y_c)}. \tag{3}$$

In this case, it is reasonable to assume $r_1 = 0$, and then it is obvious that f_0^d shifts down as C_{t1} is increased.

B. Common-mode analysis

Figure 2 (c) shows the common-mode equivalent circuit of the tunable $\lambda_g/2$ resonator, and the common-mode input admittance Y_{in}^c can be expressed as,

$$Y_{in}^c = Y_1 + Y_c\frac{Y_2/2 + jY_c\tan\theta}{Y_c + jY_2\tan\theta/2}. \tag{4}$$

Substituting equation (1) into equation (4) while assuming $r_1 = 0$,

$$\begin{aligned} Y_{in}^c = {} & j\omega C_{t1} + \frac{Y_c}{m}\times\{2Y_c r_2\omega^2 C_{t2}^2(1+\tan^2\theta) \\ & + j[2Y_c\omega C_{t2}(1-\tan^2\theta) \\ & + (4Y_c^2 r_2^2\omega^2 C_{t2}^2 + 4Y_c^2 - \omega^2 C_{t2}^2)\tan\theta]\} \end{aligned}, \tag{5a}$$

$$m = (2Y_2 - \omega C_{t2}\tan\theta)^2 + (2Y_2 r_2\omega C_{t2})^2. \tag{5b}$$

The common-mode unloaded quality factor Q_u^c can be obtained by

$$Q_u^c = \left| \frac{1}{r_2}\left(\frac{\cos(2\theta)}{\omega C_{t2}} + \frac{m\omega C_{t1} + 4Y_c^3\tan\theta}{2Y_c^2(1+\tan^2\theta)\omega^2 C_{t2}^2} - \frac{\sin(2\theta)}{4Y_c} \right) + Y_c r_2\sin(2\theta) \right|. \tag{6}$$

From equations (3) and (6), as C_{t1} is increased, f_0^d decreases; while Q_u^c increases when C_{t2} is fixed. Therefore, in the design of balanced tunable BPF, it is predictable that the suppression of dynamical common-mode can become a problematic issue when differential-mode passband is frequency agile. To solve this problem, C_{t2} should be made variable to maintain Q_u^c at a low value so that the common-mode can be always highly suppressed in the tunable differential-mode passband. For demonstration, the BPF is designed on an FR4 substrate with ε_r = 4.6 and h = 1.0 mm, and the two varactors are 1SV277 (D_1) and 1SV232 (D_2) from Toshiba, Tokyo, Japan with two capacitors: C_1 = 1.5 pF and C_2 = 20 pF. The dimensions of the filter are: w_1 = 0.7 mm, l_0 = 4.33 mm, l_1 = 11.13 mm, l_2 = 15 mm, l_3 = 8.5 mm, g = 0.4 mm, and w = 1.84 mm is the width of the 50 Ω microstrip line.

As can be seen from the simulated results in Fig. 3, the utilization of Y_2 can decrease the Q_u^c value of the resonator, and the common-mode suppression of the balanced BPF in Fig. 1 is enhanced significantly (about 10 dB). However, as V_{b1} is decreased, i.e., C_{t1} is increased, the differential-mode passband shifts down, and the common-mode suppression gradually deteriorates when V_{b2} is fixed (C_{t2} is fixed). In the process of decreasing V_{b1} from 9 V to 0 V, the high common-mode suppression can be maintained by decreasing V_{b2} from 7 V to 4.2 V, as shown in Fig. 3.

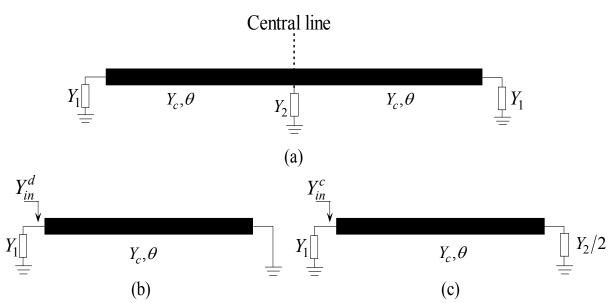

Fig. 2. (a) Equivalent model of the $\lambda_g/2$ resonator with loaded Y_1 and Y_2, (b) differential-mode equivalent circuit, and (c) common-mode equivalent circuit.

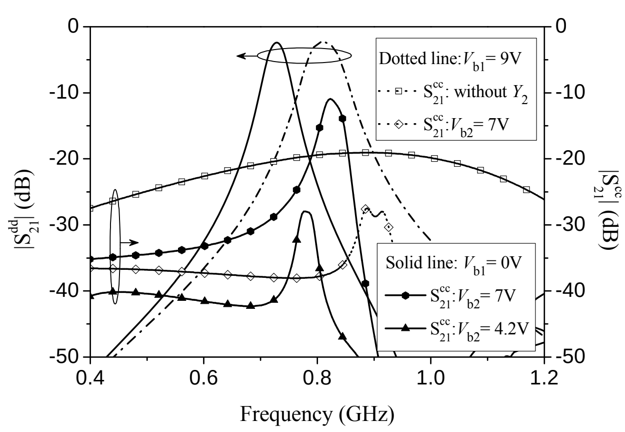

Fig. 3. The simulated results of the BPF shown in Fig. 1.

III. SIMULATED AND MEASURED RESULTS

Figure 4 shows the photo of the fabricated balanced tunable BPF, while Figs. 5 and 6 show the simulated and measured differential- and common-mode frequency responses of the balanced tunable BPF. The simulation and measurement resukts are accomplished using ADS software and network analyzer N5230C (both from Agilent). The analyzer is able to measure the two-port differential- and common-mode S-parameters directly. The center frequency of the differential passband shifts down from 0.811 GHz to 0.725 GHz as V_{b1} is decreased from 9 V to 0 V, and the insertion loss of the passband is always less than 3 dB in the entire frequency-tuning range. Meanwhile, the common-mode suppression in the differential passband can be kept greater than 25 dB by tuning V_{b2}. When V_{b1} = 6 V and V_{b2} = 5.4 V, the measured $P_{in\text{-}1dB}$ and IIP_3 are 16 dBm and 26 dBm, respectively, as shown in Fig. 7. As compared with the single-ended tunable BPFs in [9-12], the nonlinear performance of the proposed balanced tunable BPF is found to be more attractive and desirable, as shown in Table 1.

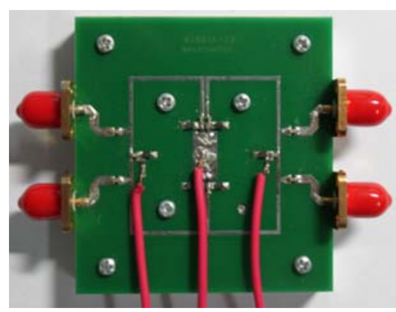

Fig. 4. Photo of the fabricated tunable balanced BPF.

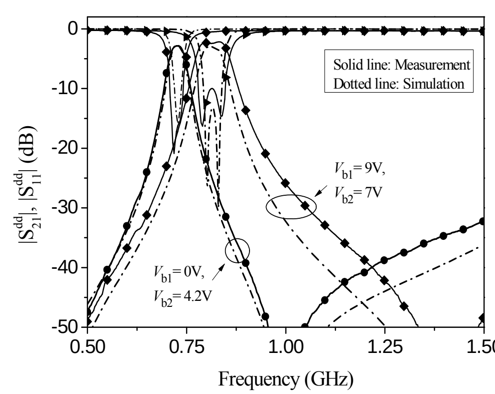

Fig. 5. Measured and simulated differential-mode responses.

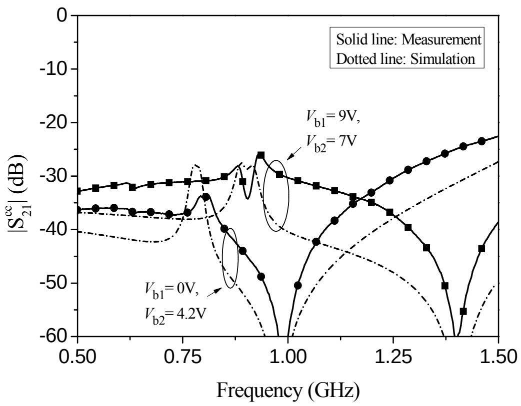

Fig. 6. Measured and simulated common-mode responses.

Table 1: Performance comparison with single-ended tunable BPFs.

Performance	$P_{in\text{-}1dB}$	IIP_3
Ref [9]	NA	10.4 dBm
Ref [10]	9 dBm	14dBm
Ref [11]	NA	15 dBm
Ref [12]	NA	19 dBm
This work	16 dBm	26 dBm

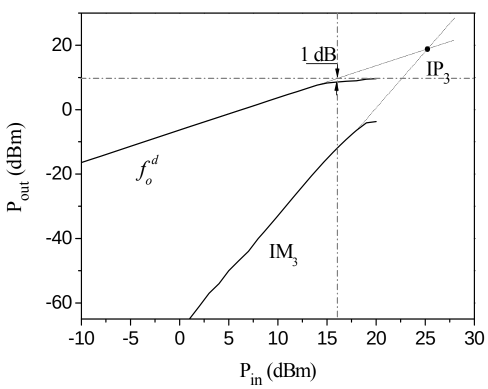

Fig. 7. Measured $P_{in\text{-}1dB}$ and two-tone IIP_3 with 1 MHz frequency spacing.

VI. CONCLUSION

A low-profile balanced tunable BPF using $\lambda_g/2$ resonator has been presented in this letter. The frequency tuning mechanism of this resonator has been studied and it has been used to design a balanced tunable BPF. Interestingly, it has been found that the common-mode suppression of the BPF can be kept at a high level by adding a varactor to the center of the resonator. The simulated and measured results are given and they show that the differential-mode passband can be tuned from 0.725 GHz to 0.811 GHz and the common-mode suppression is always higher than 25 dB in this frequency range.

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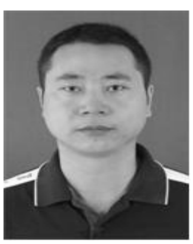

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