Stopband-Extended Balanced Bandpass Filter Using Coupled Stepped-Impedance Resonators

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***Abstract*—A novel fourth-order balanced bandpass filter is proposed based on the half-wavelength ($\lambda/2$) stepped-impedance resonators (SIRs). By properly adjusting the parameters of each SIR, the proposed filter may be made compact and its stopband may also be extended simultaneously. Specifically, a balanced filter with acceptable common-mode rejection is implemented with its differential-mode and common-mode stopbands extended up to 5.5 f_0^d, where f_0^d is the center frequency of differential-mode passband.**

***Index Terms*—Balanced filter (BPF), coupled-resonator BPF, stepped-impedance resonator (SIR), stopband extension.**

I. Introduction

BALANCED circuits play an important role in building a modern communication system particularly under the trend of system-on-chip (SOC). Balanced circuits with differential operation show higher immunity to environmental noise when compared with unbalanced circuits with single-ended signaling. To complete a balanced system, one needs to develop the balanced filters accordingly. A well-designed balanced bandpass filter (BPF) should exhibit the desired differential-mode frequency response and should also be capable of reducing the common-mode signal at the same time. However, pervious works on balanced filters are rather limited [1]–[3].

Recently, a fourth-order balanced coupled-line BPF using parallel-coupled-line structures was proposed in [3], which presents both high selectivity and good common-mode rejection within the differential-mode passband. However, this filter still has several drawbacks, such as requiring via-hole process and exhibiting a spurious common-mode passband around 1.75 f_0^d. In this study, a novel fourth-order balanced BPF based on $\lambda/2$ stepped-impedance resonators (SIRs) is proposed to realize the desired differential-mode characteristics in addition to overcoming the shortcomings in [3]. First, by making good use of structure symmetry to present a perfect electric conductor (PEC) wall along the symmetric-line, the undesired via-hole process may be avoided. Second, by properly adjusting the impedance and length ratios of each SIR, the proposed filter may be made compact and its spurious passbands for both differential-mode and common-mode excitations may be pushed up to a higher frequency so as to extend the bandwidth of stopband [4].

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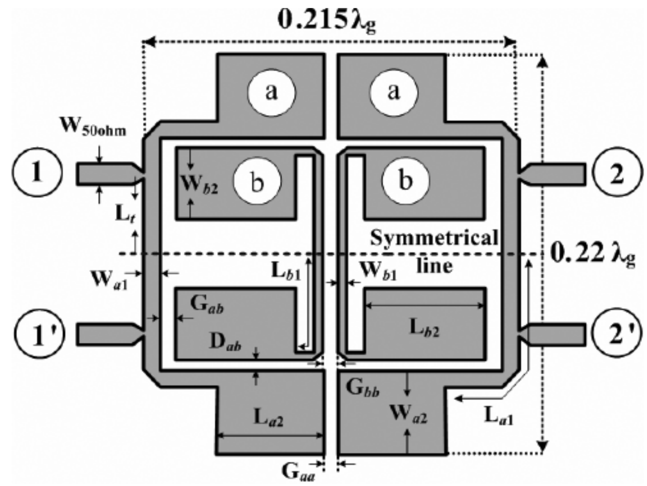

Fig. 1. Physical layout of the proposed fourth-order balanced filter using symmetric $\lambda/2$ SIRs ($W_{50\,\Omega} = 1.9$ mm, $W_{a1} = 1.5$ mm, $W_{a2} = 7.6$ mm, $W_{b1} = 0.8$ mm, $W_{b2} = 6.8$ mm, $L_{a1} = 17.1$ mm, $L_{a2} = 9.5$ mm, $L_{b1} = 11.9$ mm, $L_{b2} = 11.3$ mm, $L_t = 7.2$ mm, $G_{aa} = 1.2$ mm, $G_{bb} = 1.4$ mm, $G_{ab} = 0.8$ mm, $D_{ab} = 0.4$ mm).

II. Balanced Filter Structure

The proposed fourth-order balanced filter illustrated in Fig. 1 is composed of four symmetric $\lambda/2$ SIRs which are similar to the ones adopted in [5]. Different from [5] which used the unbalanced feed structure with single-ended signaling, the proposed balanced filter has used the balanced feed structure for giving extremely different boundary conditions with differential operation. Specifically, under differential-mode and common-mode excitations, one may present the perfect electric wall (PEC) and the perfect magnetic wall (PMC), respectively, along the symmetric-line of the balanced filter structure. Thus, it is possible to reduce the level of common-mode noise in addition to possessing the desired bandpass frequency response in differential-mode operation.

Each $\lambda/2$ SIR in Fig. 1, as illustrated in Fig. 2(a), is symmetric and has different characteristic impedances Z_{i1} and Z_{i2} and lengths L_{i1} and L_{i2}, where the subscript i denotes the resonators a and b, respectively. The associated parameters such as the impedance ratio R_i and the length ratio α_i are defined by

$$R_i = \frac{Z_{i2}}{Z_{i1}}, \quad \alpha_i = \frac{L_{i2}}{(L_{i1} + L_{i2})}. \; i = a, b.$$

Under differential-mode operation, a virtual-short (PEC) would appear along the symmetric-line, therefore each resonator, resonating at f_0^d, may be treated as a shorted $\lambda/4$ SIR as shown in Fig. 2(b). Alternatively, under common-mode

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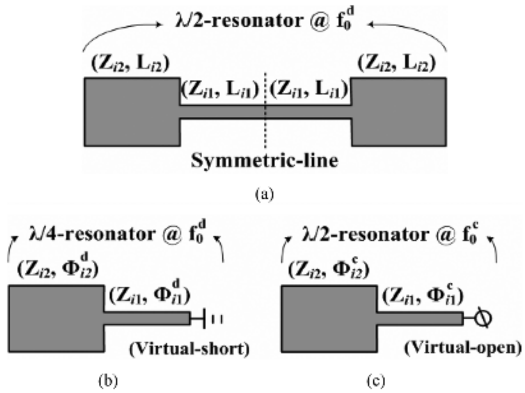

Fig. 2. (a)Basic SIR structure, (b) differential-mode equivalent-half-circuit, and (c) common-mode equivalent-half-circuit.

operation, a virtual-open (PMC) would present along the symmetric-line, thus each resonator, resonating at f_0^c ($f_0^c > f_0^d$), may be treated as a $\lambda/2$ resonator with both ends opened as shown in Fig. 2(c).

The balanced BPF shown in Fig. 1 is fabricated in the microstrip structure on the FR4 substrate (ε_r =4.4, $h = 1$ mm, $\tan\delta = 0.02$). It is designed with a differential-mode center frequency f_0^d at 1 GHz and 3-dB fractional bandwidth (FBW) of 10%. For characterization, the balanced structure, as a four-port device, is first measured by the Agilent E5071B network analyzer to give the standard four-port S-parameters $S^{\rm std}$. Then the two-port differential-mode and common-mode S-parameters, $S^{\rm dd}$ and $S^{\rm cc}$, may be extracted from the four-port S-parameters $S^{\rm std}$ as given in [3] and [6].

III. Design of the Stopband-Extended Balanced Filter

To design a stopband-extended balanced filter with desired differential-mode frequency response, the physical dimensions of each resonator must be determined first. According to [7], the differential-mode stopband response is mainly determined by the intercoupled resonators (resonators b). To push the first differential-mode spurious harmonic to a higher frequency such as $5.5f_0^d$, the parameters $R_b = 0.25$ and $\alpha_b = 0.5$ should be chosen for the resonators b. For the SIR to possess the fundamental resonance frequency at $f_0^d (= 1$ GHz), the physical dimensions (W_{b1}, W_{b2}, L_{b1}, and L_{b2}) of resonators b should properly be selected. The dimensions (W_{a1}, W_{a2}, L_{a1}, and L_{a2}) of input/output (I/O) resonators (resonators a) are then arranged so that the filter may be made compact and an additional cross-coupled path between I/O resonators may be established.

Then, according to the specification of the quasi-elliptic response with $f_0^d = 1$ GHz and 3 db-FBW = 10%, the differential-mode coupling coefficients and I/O external quality factors calculated from [8] may be expressed as

$$Q_e^{\rm dd} = \frac{g_0 g_1}{FBW} = 9.55, \quad M_{ab}^{\rm dd} = \frac{FBW}{\sqrt{g_1 g_2}} = 0.087$$
$$M_{bb}^{\rm dd} = \frac{FBW \cdot J_2}{g_2} = 0.0767$$
$$M_{aa}^{\rm dd} = \frac{FBW \cdot J_1}{g_1} = -0.017$$

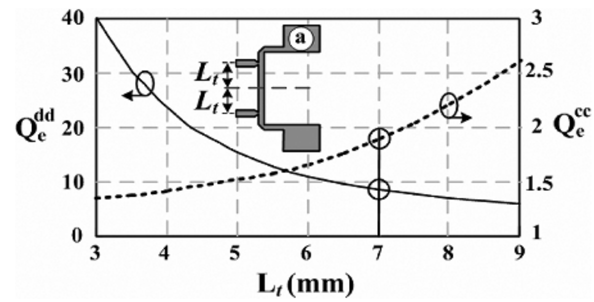

Fig. 3. Simulated differential-mode and common-mode external quality factors against the tap position of I/O resonators.

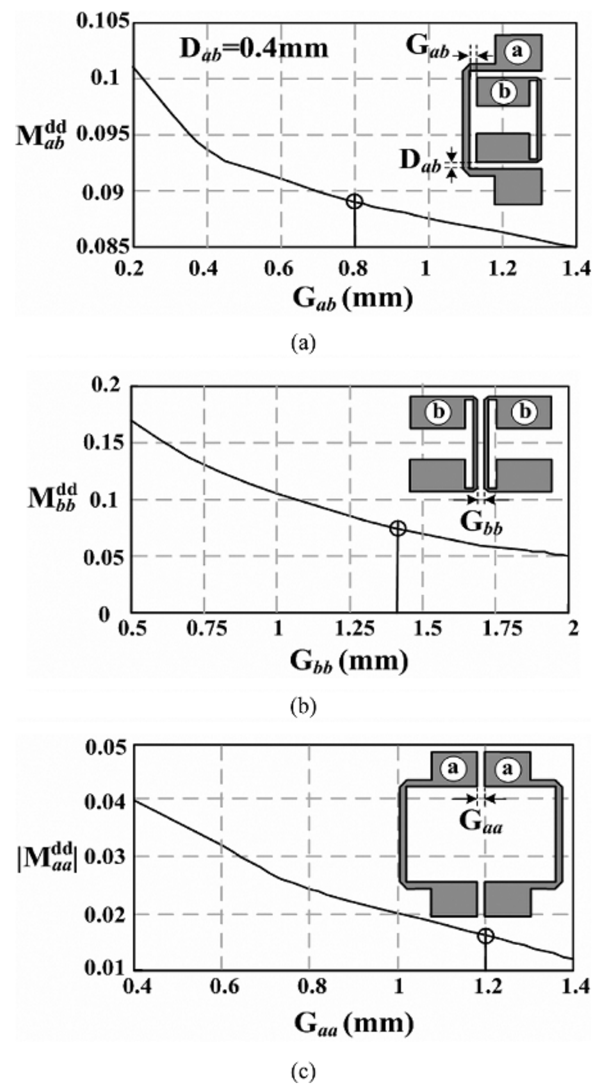

Fig. 4. Simulated differential-mode coupling coefficients versus the gaps between adjacent resonators: (a) mixed coupling, (b) magnetic coupling, and (c) electric coupling.

where g_1, g_2, J_1, and J_2 are the element values of the lowpass prototype filter. Instead of using the four-port to two-port conversion technique [6] used in measurement, the required differential-mode and common-mode parameters M_{ij} and Q_e are extracted from the corresponding differential-mode and common-mode excitation circuits, which have the termination impedances $(2Z_o)$ and $(Z_o/2)$, respectively. In this study, the

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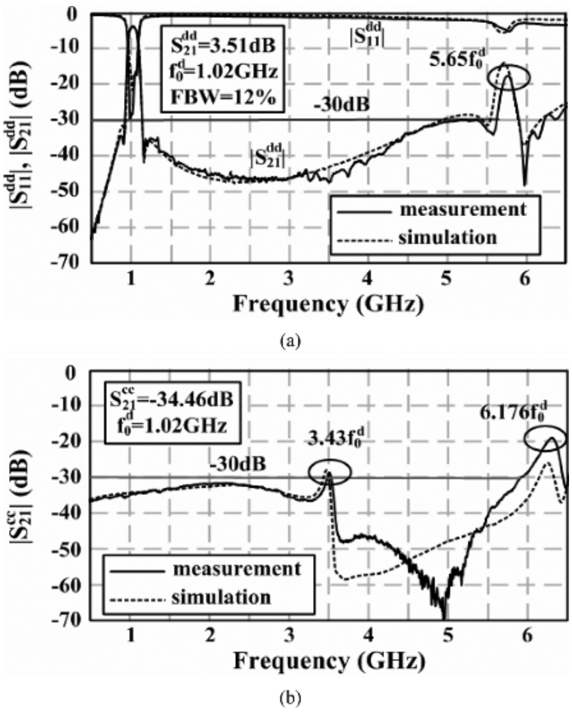

Fig. 5. Wideband measured and simulated frequency responses of the proposed fourth-order balanced filter shown in Fig. 1: (a) differential-mode response and (b) common-mode response.

extraction process is accomplished by the fullwave simulator ADS Momentum. Once the physical dimensions of each resonator are determined, the dimensions associated with the tap position L_t of I/O resonators (resonators a) and the gaps (G_{aa}, G_{bb}, G_{ab}, and D_{ab}) between adjacent resonators may be obtained by using the design curves as shown in Figs. 3 and 4.

IV. Filter Responses

A. Differential-Mode Response

The wideband measured and simulated differential-mode responses of the proposed balanced filter (Fig. 1) are illustrated in Fig. 5(a). Good agreement between measured and simulated results is obtained. For the differential-mode response, the center frequency is at 1.02 GHz, with a minimum insertion-loss of 3.51 dB and a bandwidth of 12%. Moreover, with the proper arrangement of impedance ratio R_b and length ratio α_b of resonators b, the differential-mode spurious passband has been pushed up to $5.65 f_0^d$. The implemented filter is compact and has a size of 33.4 mm × 36.2 mm $(0.215\lambda_g \times 0.22\lambda_g)$, where λ_g is the guided wavelength of the microstrip at the passband center frequency.

B. Common-Mode Response

Under common-mode excitation, the signal along the main path (from input resonator a through inter-coupled resonators b and then to output resonator a) is relatively weak like the one illustrated in [3]. Alternatively, the signal along the cross-coupled path (from input resonator a directly to output resonator a) is relatively strong, therefore, the common-mode response is mainly determined by the coupling directly between I/O resonators. Moreover, the corresponding common-mode external quality factor (Q_e^{cc}) is quite small, which presents an unmatched termination around f_0^d. Therefore, only an acceptable common-mode suppression may be obtained around f_0^d

The wideband measured and simulated common-mode responses are shown in Fig. 5(b). The common-mode signal is suppressed with a level of -34.46 dB around f_0^d, and almost below -30 dB from 0.5 to 6 GHz. The common-mode signal has a suppressed spurious response around $3.43 f_0^d$ which is associated with the first spurious harmonic of the resonator b. This spurious response has been suppressed due to the relatively weak signal along the main path and the poor Q_e^{cc} value associated with I/O resonators. Note that the open stub associated with tap position L_t has created an additional transmission zero at 5 GHz so that the common-mode rejection is improved around this stopband.

V. Conclusion

In this letter, a novel fourth-order balanced BPF using symmetric $\lambda/2$ SIRs is proposed. Design procedures and the corresponding frequency responses are also carefully examined. With the adoption of symmetric coupled-resonator structures, it is possible to obtain the desired differential-mode frequency response and also to avoid the undesired via-hole process. Meanwhile, by the proper arrangement of impedance and length ratios of each resonator, a compact balanced filter is implemented with its differential-mode and common-mode stopbands extended up to $5.5 f_0^d$.

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