Microstrip Balanced Bandpass Filter With Compact Size, Extended-Stopband and Common-Mode Noise Suppression

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***Abstract*—In this letter, a novel balanced bandpass filter (BPF) with its simple design procedure are proposed. The filter is based on a novel balanced resonator which is composed by two closed-loop transmission lines of characteristic impedance $Z_{CL} = 50\ \Omega$ and electrical length of 53.13° and one transmission line of characteristic impedance $Z_{HI} = 100\ \Omega$ and electrical length of 53.13°. Also the differential-mode (DM) and common-mode (CM) equivalent circuits of the resonator are given for design purposes. A prototype with measured DM passband at 1.029 GHz and fractional bandwidth (FBW) of 9.833% is presented. The prototype exhibits compact size $(0.149\lambda_g \times 0.228\lambda_g)$, DM stopband with a 40 dB suppression level broadened up to 5.633 f_{0d} and CM suppression level better than -40 dB from 0 to over 3.7 f_{0d} and better than -30 dB from 0 to 5.91 f_{0d}.**

***Index Terms*—Balanced filter, common-mode (CM) suppression, coupled-resonator bandpass filter (BPF), stopband extension.**

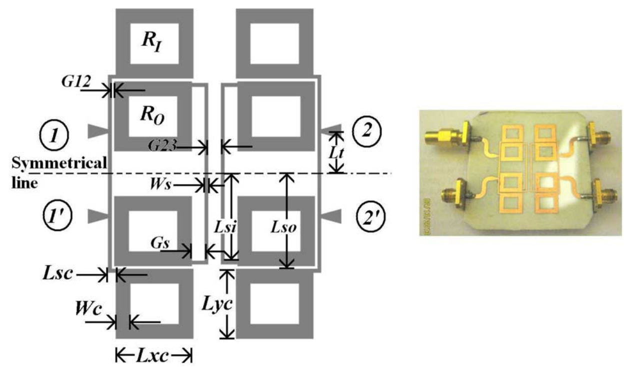

Fig. 1. Proposed balanced filter.

I. Introduction

BALANCED band pass filters should reduce the common-mode signal and provide the desired bandpass frequency response in differential-mode operation. They play an important role in modern wireless communication systems because of their immunity to environmental noise [1].

Many researchers focus on the balanced bandpass filter (BBPF) design [1]–[8]. For instance, in [1], [2] and [7] balanced bandpass filters based on coupled half-wavelength stepped-impedance resonators, coupled-line sections and quarter-wavelength resonators, and center-loaded half-wavelength resonators are reported; however, they are limited in common noise suppression and exhibit bulky size. In [3] two balanced BPFs using the $\lambda/2$ bi-section resonators were proposed; the two exhibit better performance but bigger size than [1], [2], and [7]. In [4] a BBPF based on double-sided parallel-strip line dual-mode resonator is described; however, the double-sided parallel-strip line is not favorable for integrated circuit design. In [8] stopband-extended balanced filters using $\lambda/4$ and/2 stepped-impedance resonators (SIRs) with common-mode suppression and improved passband selectivity are reported; nevertheless, they exhibit larger size than those in [1]–[4], [6] and [7]. In [5] a very compact BBPF using interdigital line resonators (ILRs) with high common-mode noise suppression is presented, but it shows limited differential mode stopband (extended only up to $2.62f_{od}$ with suppression level below -40 dB), and common mode stopband (extended only up to $2.58f_{od}$ with suppression level below -40 dB).

In this letter, a novel balanced BPF is proposed along with its simple design procedure. For design purposes, the DM and CM equivalent circuits are given. A prototype with measured DM passband at $f_{0d} = 1.029$ GHz and FBW of 9.833% is presented.

II. Proposed Resonator

Fig. 1 shows the proposed balanced filter, which is composed by two inner resonators, R_I, and two outer resonators, R_O. Each resonator is composed by two closed-loop transmission lines of characteristic impedance Z_{CL} and electrical length of Θ and one transmission line of characteristic impedance $Z_{HI}(= 2Z_{CL})$ and electrical length of Θ_{HI} as shown in Fig. 2(a).

Specifically, under DM operation, a virtual-short would appear along the symmetric-line, therefore each resonator may be considered as a closed loop transmission line loaded with a short-circuited stub as shown in Fig. 2(b). The input impedance of the DM equivalent-half-circuit is given by (1) [9]

$$Z_{in}^{d} = \frac{(1 + Z_{SC}Y_{22})}{Z_{SC}(Y_{11}Y_{22} - Y_{21}Y_{12}) + Y_{22}} \tag{1}$$

where the input impedance of the short circuited-stub Z_{SC} and the Y-parameters Y_{ij} are

$$\begin{cases} Z_{SC} = jZ_{HI}\mathrm{Tan}(\Theta_{HI}/2) \\ Y_{11} = Y_{22} = \frac{-2j}{Z_{CL}}\mathrm{Cot}\Theta_{CL} \\ Y_{12} = Y_{21} = \frac{2j}{Z_{CL}}\mathrm{Csc}\Theta_{CL}. \end{cases} \tag{2}$$

From (1) and (2), one can see that the electrical length where resonance occurs is when the denominator in (1) is zero. Since

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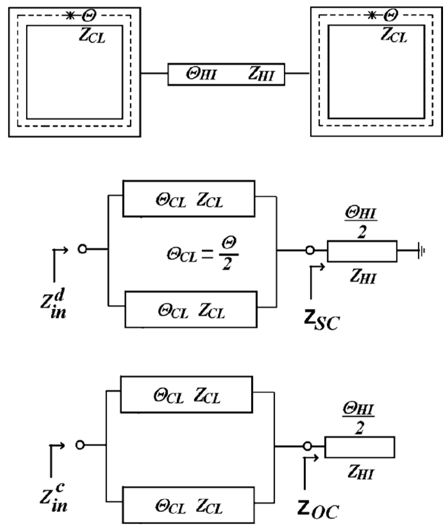

Fig. 2. (a) Basic resonating structure, (b) differential-mode equivalent-half-circuit, and (c) common-mode equivalent-half-circuit.

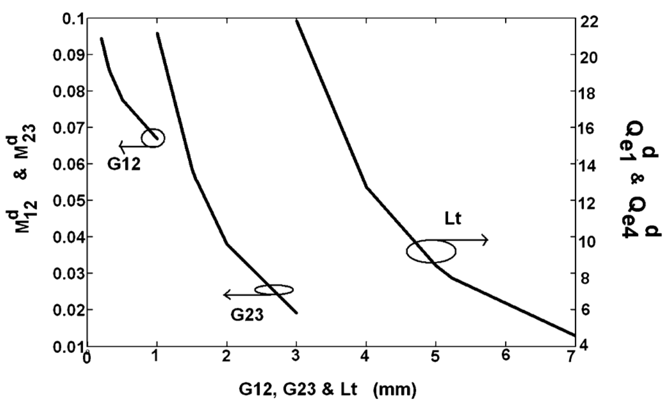

Fig. 3. Differential-mode design curves.

compact size structures are desired in this work, we consider $\mathrm{Z_{HI}} = 2\mathrm{Z_{CL}}$ and $\Theta_{\mathrm{CL}} = \Theta_{\mathrm{HI}}/2 = \Theta/2$ therefore the electrical lengths where resonance occurs are $\Theta_{\mathrm{CL}} = 26.565^{\circ}$ and $\Theta_{\mathrm{HI}} = 53.13^{\circ}$. Also it can be shown that the center frequency under DM operation f_{od} is given by (3) where c is the speed of the light in free space, $\varepsilon_{\mathrm{eff}}$ is the static effective relative dielectric constant and L is the length of the ring resonator of the closed loop transmission line. It is worth mentioning that the Θ_{CL} would increase if $\mathrm{Z_{HI}} < 2\mathrm{Z_{CL}}$ and Θ_{CL} would decrease if $\mathrm{Z_{HI}} > 2\mathrm{Z_{CL}}$. However, Θ_{CL} cannot be too short and the value of $\mathrm{Z_{HI}}$ cannot be too high because it can lead to unsuitable structures

$$\mathrm{f_{od}} = \frac{\Theta_{\mathrm{CL}}2\mathrm{c}}{\pi\mathrm{L}\sqrt{\varepsilon_{\mathrm{eff}}}} = \frac{2 * c * 26.565}{180\mathrm{L}\sqrt{\varepsilon_{\mathrm{eff}}}}. \quad (3)$$

Alternatively, under CM operation, a virtual-open is present along the symmetric line. Thus each resonator may be treated as a closed loop resonator loaded with an open-circuited stub, as shown in Fig. 2(c). From an analogous synthesis it can be found that the fundamental resonance frequency under CM operation is $f_{\mathrm{oc}} = 3.38 f_{\mathrm{od}}$.

III. Design of a Balanced Bandpass Filter at 1 GHz

The filter shown in Fig. 1 was designed as follows.

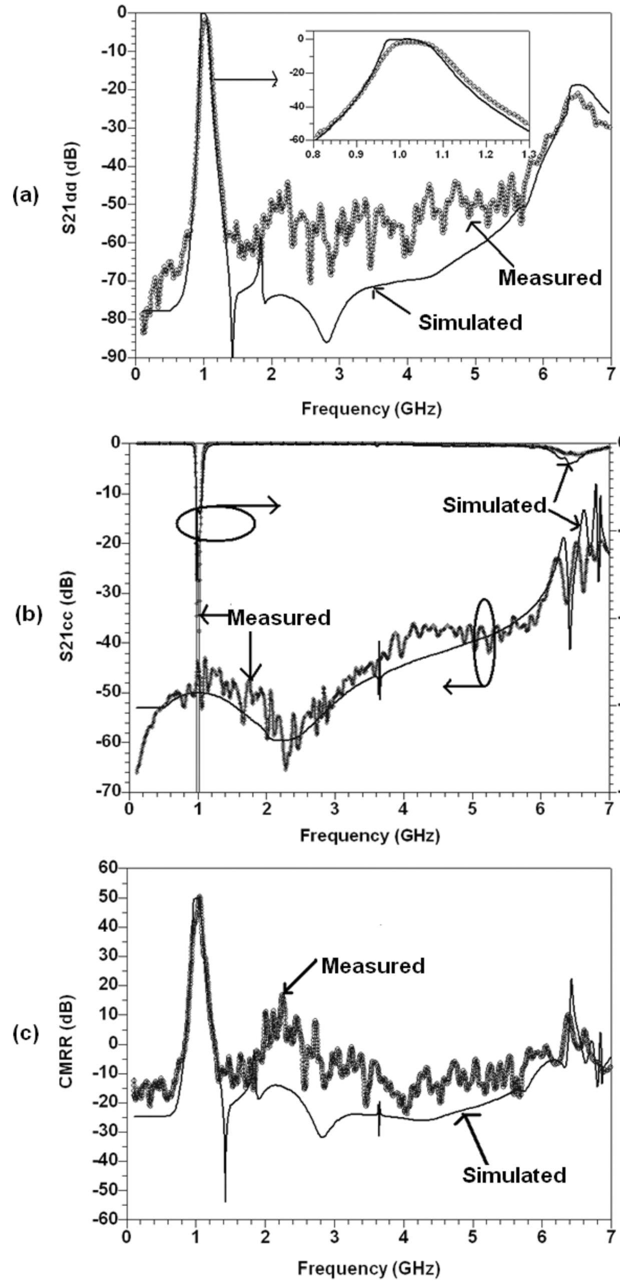

Fig. 4. Measured and simulated responses. (a) $\mathrm{S_{21dd}}$, (b) $\mathrm{S_{11dd}}$ and $\mathrm{S_{21cc}}$, and (c) CMRR.

Step 1: Resonator design. The filter uses two resonators $\mathrm{R_I}$ and $\mathrm{R_O}$ as shown in Fig. 1. Each resonator is composed by two closed-loop transmission lines of characteristic impedance $\mathrm{Z_{CL}} = 50\ \Omega$ and electrical length of 53.13° at $f_{\mathrm{od}} = 1$ GHz. Moreover, the transmission line has a characteristic impedance $\mathrm{Z_{HI}} = 100\ \Omega$ and electrical length of 53.13° at f_{od} as shown in Fig. 2. The physical dimensions on the given substrate with $\varepsilon_r = 3.5$ and $\mathrm{h} = 0.8$ mm are: $\mathrm{Ws} = 0.45$ mm, $\mathrm{Lsi} = 10.71$ mm, $\mathrm{Lso} = 11.71$ mm, $\mathrm{Lyc} = 8.6$ mm, $\mathrm{Gs} = 1.58$ mm, $\mathrm{Lsc} = 0.95$ mm, $\mathrm{Wc} = 1.8$ mm, and $\mathrm{Lxc} = 9.6$ mm.

Step 2: Establish the design parameters (external and mutual coupling coefficients). According to the spec-

TABLE I
COMPARISON WITH PREVIOUS STUDIES

	f_{od} (GHz)	FBW (%)	S_{21dd} @ f_{od} (dB)	DM Stopband (below 40dB) up to	S_{21cc} (below 40dB) up to	Size (λ_g^2)
[1]	1.02	12	3.51	$4f_{od}$	Limited <30dB	0.215x0.22
[3]	1.025	11.5	3.88	$3.5f_{od}$	$3.5f_{od}$	0.233x0.34
[5]	2.45	8.5	2.62	$2.62f_{od}$	$2.7f_{od}$	0.16x 0.157
[7]	1.508	6.02	2.48	$5.3f_{od}$	$2.7f_{od}$	0.33x0.389
This	1.02	9.83	1.76	$5.633f_{od}$	$3.7f_{od}$	0.149x0.228

ification of a four-pole Butterworth low pass prototype with FBW=10% the design parameters are $Q_{e1}^d = Q_{e4}^d = 7.654, M_{12}^d = M_{34}^d = 0.084$ and $M_{23}^d = 0.0541$ where Q_{e1}^d and Q_{e4}^d are the required external couplings coefficients for the first and last resonators and M_{ij}^d are the differential-mode mutual coupling coefficients between resonators.

Step 3: The practical external coupling coefficients are calculated, from full wave simulations [3], [11], for different tap position Lt and then plotted as shown in Fig. 3.

Step 4: The mutual coupling coefficients, associated with the gaps $G12$ and $G23$, are calculated from full wave simulations [3], [11] for different values and then plotted as shown in Fig. 3.

Step 5: In the last step the associated values with Lt, $G12$, and $G23$ are chosen directly from Fig. 3. We determined that the corresponding value to $Q_{e1}^d = Q_{e4}^d = 7.654, M_{12}^d = M_{34}^d = 0.084$ and $M_{23}^d = 0.0541$ are $\mathrm{L_t} = 5.23$ mm, $\mathrm{G12} = 0.32$ mm, and $\mathrm{G23} = 1.580$ mm, respectively.

IV. EXPERIMENTAL AND SIMULATED RESULTS

The circuit was fabricated and measured with a vector network analyzer to give the standard four-port S-parameters. The two-port differential-mode and common-mode-parameters were extracted from the four-port-parameters as given in [10]. The wideband measured and simulated differential-mode and common-mode responses of the filter are illustrated in Fig. 4. The filter has a compact size, excluding feed lines, of $0.149\lambda_g \times 0.228\lambda_g$, where λ_g is the guided wavelength of 50 Ω line on the substrate at the center frequency.

A. Differential-Mode Response

Fig. 4(a) and (b) show the measured and simulated differential-mode frequency responses ranging from over 0.1 to 7 GHz. The measured differential-mode center frequency is at 1.029 GHz, the measured 3 dB bandwidth is 9.833%, the minimum insertion loss including SMA connectors is 1.767 dB, and input return losses are better than 10 dB within the bandwidth. Note that the proposed balanced filter exhibits simulated and measured DM stopband with a -40 dB suppression level broadened up 5.633 f_{0d}.

B. Common-Mode Response

The wideband measured and simulated common-mode responses of the proposed balanced filter are illustrated in Fig. 4(b). Good agreement between measured and simulated results is also obtained. CM suppression levels better than -40 dB from 0 to 3.7 f_{0d} and better than -30 dB from 0 to 5.91 f_{0d} are obtained in simulations and measurements.

Additionally, it can be seen in Fig. 4(c) that the common-mode rejection ratio (CMRR), calculated as suggested in [2], remains above 42.4 dB within the bandwidth and the maximum measured CMRR is 50.8 dB.

The results are summarized and compared with previous works in Table I. Note that proposed circuit exhibits compact size, improved DM stop-band and CM rejection band.

V. CONCLUSION

A novel balanced BPF was proposed. The filter has measured f_{0d} at 1.029 GHz and measured FBW of 9.833%. The proposed filter exhibits compact size, extended stopband under DM operation, and extended CM suppression.

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