Overview of High-Performance Wide-Band Balanced Bandpass Filters Using Ring Resonators

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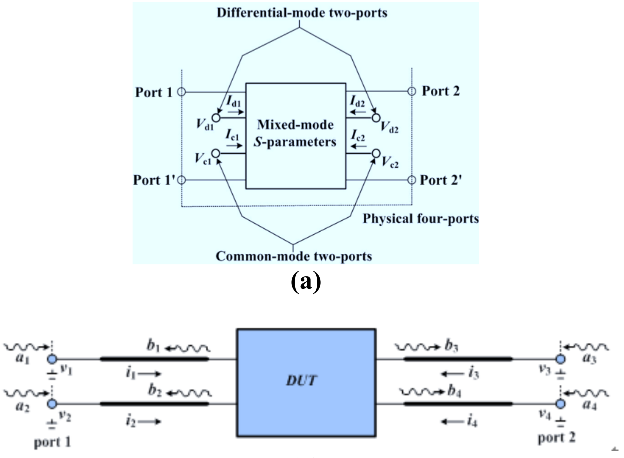
Abstract

Ring-resonator-based balanced wide-band bandpass filters with sharp-rejection differential-mode passband and broad-band common-mode suppression are reported in this paper. Both half- and full-wavelength ring resonators are used in these filtering devices to realize wide- and ultra-wideband bandwidths for the differential-mode transmission band. Furthermore, they exhibit a common-mode-suppression bandwidth that can cover up to three octaves and a quasi-elliptic-type differential-mode passband by means of transmission-zero generation. Two different topologies of wide-band balanced bandpass filters are discussed and verified through experimental 3-GHz microstrip prototypes.

1. Introduction

With the rapid development of high-data-rate 4/5-Generation (4/5G) microwave communication systems, more and more attention has been recently detected in the design of wide-band RF circuits for their front ends [1]. In this trend, differential-mode or balanced broad-band bandpass filters may be very required due to their potential for environmental-noise suppression, as well as higher dynamic range and increased robustness to electromagnetic interference [2, 3]. It is the author's opinion that main desired features for these devices are as follows: (i) simple balanced-circuit structures, (ii) high selectivity and wide-band harmonic suppression for the differential-mode transfer function, and (iii) broad-band common-mode mitigation (going from DC up to even several octaves) [4].

In this article, an overview of some author's recently-developed ring-resonator-based wide-band balanced bandpass filter architectures are described. In these circuits, different techniques to realize common-mode mitigation throughout ultra-broad spectral ranges are exploited [5-7]. These balanced bandpass filters exhibit several desired features, including simple circuit design, compact size, enhanced out-of-band differential-mode attenuation and sharp-rejection capabilities, wide-band common-mode suppression, and ease of integration with other circuits and/or antennas. Proof-of-concept microstrip prototypes of these wide-band differential-mode bandpass filters are also shown and compared with the state-of-the-art.



(a)

(b)

Figure 1. **(a)** Circuit used to obtain the mixed–mode *S*-parameters in balanced devices. **(b)** RF differential two-port or single-ended four-port circuit.

2. Wide-band Balanced Bandpass Filters with Broad-band Common-Mode Suppression

2.1. Mixed-Mode S-Parameters

In microwave circuits, mixed-mode *S*-parameters include differential-, common-, and cross-mode signals. Cross-mode signals occur when there are imbalances in microwave circuits and are mostly due to manufacturing imperfections. As a result, the signal energy is converted from differential to common mode or from common to differential mode [3]. To illustrate this concept, a 4×4 matrix of sixteen standard *S*-parameters representing a four-port balanced circuit is transformed to a set of four 2×2 mixed-mode *S*-parameter submatrices as in (1). Here, the four 2×2 submatrixes represent four possible mode circuit responses as follows: differential-mode input to differential-mode output, differential-mode input to common-mode output, common-mode input to differential-mode output, and common-mode input to common-mode output.

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14}\\ S_{21} & S_{22} & S_{23} & S_{24}\\ S_{31} & S_{32} & S_{33} & S_{34}\\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \Leftrightarrow \begin{matrix} \begin{bmatrix} S_{dd11} & S_{dd12}\\ S_{dd21} & S_{dd22} \end{bmatrix} & \begin{bmatrix} S_{dc11} & S_{dc12}\\ S_{dc21} & S_{dc22} \end{bmatrix}\\ \begin{bmatrix} S_{cd11} & S_{cd12}\\ S_{cd21} & S_{cd22} \end{bmatrix} & \begin{bmatrix} S_{cc11} & S_{cc12}\\ S_{cc21} & S_{cc22} \end{bmatrix} \end{matrix} \quad (1)$$

The circuit used to obtain the mixed-mode S-parameters of balanced devices is shown in Fig. 1(a) and (b). The details of the transformation proof can be found in [2-4]. The transformation from standard S-parameters to mixed-mode S-parameters is given in (2). Using the relationships in (2), the transformation of mixed-mode S-parameters (S_{mm}) from standard S-parameters (S_{std}) can be derived. The resulting mixed-mode submatrices are given in (3)-(6). For a measurement system with no noise, no data inaccuracies, and no calibration inaccuracies, the linear descriptions of the circuit behavior must be equivalent through these mathematical transformations [2]. This is a basic mathematical requirement for linear matrix transformations. Next, examples of planar ring-resonator-based wide-band balanced bandpass filters are presented.

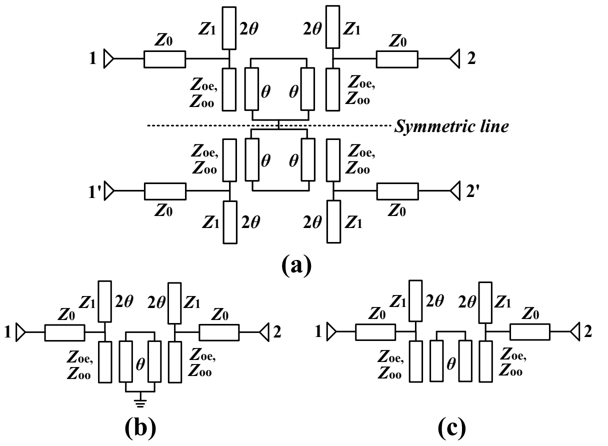


Figure 2. Balanced filter using half-wavelength ring resonators. **(a)** Circuit schematic. **(b)** Differential-mode equivalent. **(c)** Common-mode equivalent.

$$S_{mm} = M S_{std} M^{-1}, \qquad M = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -1 & 0 & 0\\ 0 & 0 & 1 & -1\\ 1 & 1 & 0 & 0\\ 0 & 0 & 1 & 1 \end{bmatrix} \quad (2)$$

$$S_{dd} = \frac{1}{2}\begin{bmatrix} S_{dd11} = (S_{11} - S_{12} - S_{21} + S_{22}) & S_{dd12} = (S_{13} - S_{14} - S_{23} + S_{24})\\ S_{dd21} = (S_{31} - S_{32} - S_{41} + S_{42}) & S_{dd22} = (S_{33} - S_{34} - S_{43} + S_{44}) \end{bmatrix} \quad (3)$$

$$S_{dc} = \frac{1}{2}\begin{bmatrix} S_{dc11} = (S_{11} + S_{12} - S_{21} - S_{22}) & S_{dc12} = (S_{13} + S_{14} - S_{23} - S_{24})\\ S_{dc21} = (S_{31} + S_{32} - S_{41} - S_{42}) & S_{dc22} = (S_{33} + S_{34} - S_{43} - S_{44}) \end{bmatrix} \quad (4)$$

$$S_{cd} = \frac{1}{2}\begin{bmatrix} S_{cd11} = (S_{11} - S_{12} + S_{21} - S_{22}) & S_{cd12} = (S_{13} - S_{14} + S_{23} - S_{24})\\ S_{cd21} = (S_{31} - S_{32} + S_{41} - S_{42}) & S_{cd22} = (S_{33} - S_{34} + S_{43} - S_{44}) \end{bmatrix} \quad (5)$$

$$S_{cc} = \frac{1}{2}\begin{bmatrix} S_{cc11} = (S_{11} + S_{12} + S_{21} + S_{22}) & S_{cc12} = (S_{13} + S_{14} + S_{23} + S_{24})\\ S_{cc21} = (S_{31} + S_{32} + S_{41} + S_{42}) & S_{cc22} = (S_{33} + S_{34} + S_{43} + S_{44}) \end{bmatrix} \quad (6)$$

2.2. Microstrip Wide-Band Balanced Filter Using Half-Wavelength Ring Resonators

Fig. 2(a) shows the wide-band balanced filter using half-wavelength ring resonators with four open-ended stubs [5]. When the differential-mode signals are excited from ports 1 and 1' in Fig. 2(a), a virtual short-circuit appears along the half-wavelength ring resonator (see Fig. 2(b)). Thus, a bandpass-type response is realized through the resulting open/short-ended coupled lines [5]. Two transmission zeros at $f_{tz1} = 0.5f_0$ and $f_{tz2} = 1.5f_0$ (f_0 is the center frequency) are also created by the open-ended stubs to improve the selectivity and harmonic rejection in the differential mode.

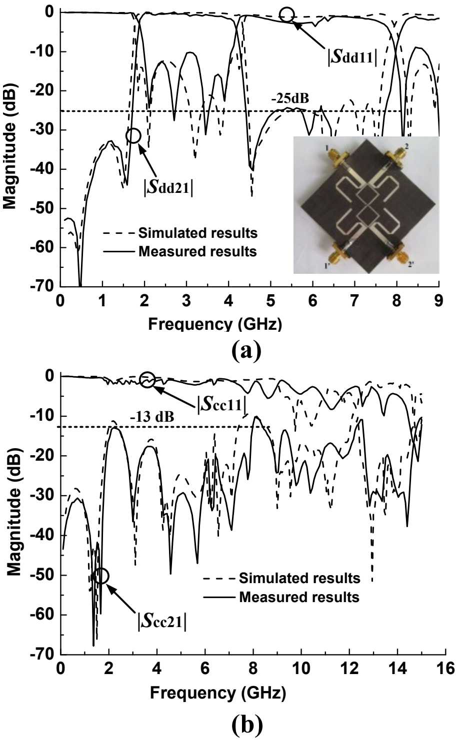
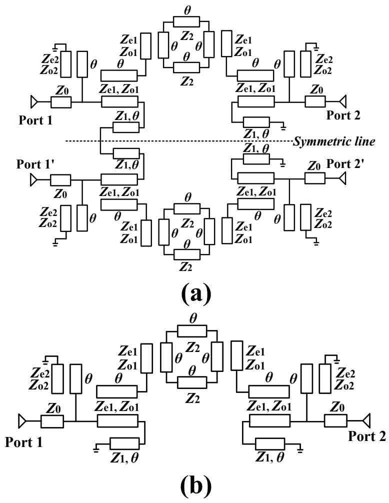
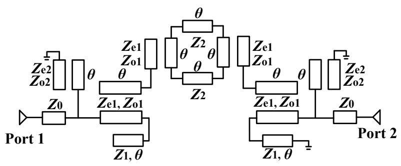


Figure 3. Simulated and measured mixed-mode S-parameters of the balanced filter using half-wavelength ring resonators. **(a)** Differential mode. **(b)** Common mode.





(c)

Figure 4. Balanced filter using full-wavelength ring resonators. **(a)** Circuit schematic. **(b)** Differential-mode equivalent. **(c)** Common-mode equivalent.

Moreover, the in-band balance can also be adjusted by means of the characteristic impedance Z_1. On the other hand, when the common-mode signals are excited from ports 1 and 1', a virtual open appears along the center of the half-wavelength ring resonator (see Fig. 2(c)). Thus, a resonant-type all-stop performance is realized [4].

Fig. 3(a)-(b) show the measured and simulated mixed-mode S-parameters of a 3-GHz prototype of the wideband balanced bandpass filter with half-wavelength ring resonators. For the differential mode, the main measured characteristics are as follows: five transmission zeros at DC, 0.5 GHz, 1.6 GHz, 4.57 GHz, and 5.9 GHz, 3-dB fractional bandwidth of 79% (1.85-4.23-GHz range), minimum in-band insertion loss of 1.35 dB, in-band return loss higher than 10 dB from 2 GHz to 4.05 GHz, and 25-dB upper stopband from 4.4 GHz to 7.8 GHz (i.e., 2.6f_0). For the common mode, the minimum rejection level of the stopband is 13 dB from DC to 8 GHz (i.e., 2.67f_0) and of 10 dB from DC to 15 GHz (i.e., 5f_0).

2.2. Microstrip Wideband Balanced Filter Using Full-Wavelength Ring Resonators

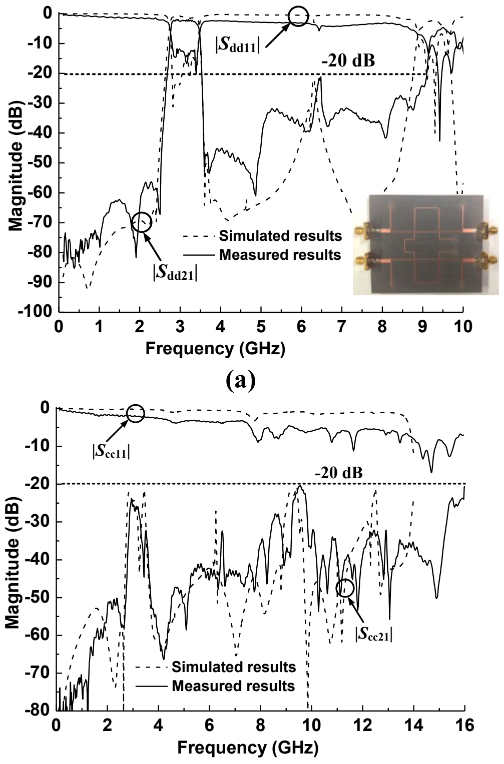
The ideal circuit schematic of the balanced filter using full-wavelength ring resonators is shown in Fig. 4(a), and its equivalent half circuits for differential/common-mode operation are shown in Fig. 4(b) and (c). Through the study of this circuit [2], its close-to-differential-passband transmission-zero positions can be derived in terms of electrical length θ to be as follows:

$$\theta_{tz1} = \arccos\sqrt{\frac{Z_{e1}+Z_{o1}-2Z_2}{Z_{e1}+Z_{o1}+2Z_2}},\ \theta_{tz2} = \pi - \theta_{tz1} \qquad (7)$$

$$\theta_{tz3} = \arccos\frac{Z_{e2}-Z_{o2}}{Z_{e2}+Z_{o2}},\ \theta_{tz4} = \pi - \theta_{tz3} \qquad (8)$$

These transmission zeros allow to increase the selectivity of the differential-mode transfer function. Moreover, the differential-mode-passband width and the common-mode suppression increases as the sum of Z_{e1} and Z_{o1} is higher. Note that these are particular characteristics for this type of filter with regard to other prior-art ones as those in [8-14].

The measured and simulated mixed-mode S-parameters of a 3-GHz microstrip demonstrator of the broad-band balanced bandpass filter with full-wavelength ring resonators are compared in Fig 5. A fairly-close agreement between the simulation and the experiment is observed that serves to validate this balanced filter concept. For the differential mode, the main measured characteristics are as follows: five transmission zeros at 1.91 GHz, 2.5 GHz, 3.58 GHz, 3.71 GHz, and 4.37 GHz, 3-dB fractional bandwidth of 21.9% ((2.76-3.44-GHz range), minimum in-band insertion loss of 2.2 dB, minimum in-band return loss of 12.5 dB, and 20-dB upper stopband from 3.54 GHz to 9.1 GHz (i.e., 2.94f_0). For the common-mode operation, the minimum rejection level of the stopband is 20 dB from DC to 16 GHz (i.e., 5.16f_0).



(a)

(b)

Figure 5. Simulated and measured mixed-mode S-parameters of the balanced filter using full-wavelength ring resonators. **(a)** Differential mode. **(b)** Common mode.

3. Conclusions

This article has presented an overview of recently-proposed wide-band balanced bandpass filters based on half/full-wavelength ring resonators. As demonstrated in Table I where a comparison with some prior-art broad-band balanced bandpass filters is provided, these half/full-wavelength-ring-resonator-based balanced filters exhibit higher order and number of transmission zeros for the differential mode. Furthermore, extended upper stopband for the differential mode and very-broad common-mode suppression up to three and five octaves are attained. Based on these principles, more multi-functional balanced circuits, such as balanced couplers, balanced crossovers, and balanced filtering baluns for fully-balanced microwave circuits and systems (see [15-18] for some past examples) are expected to be developed as future research work.

4. Acknowledgement

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Table I Comparisons of measured results of some balanced filters.

Filter Structures	3-dB bandwidth (%)	Transmission zeros & order	Upper stopband $\lvert S_{dd21} \rvert$ (dB)	$\lvert S_{cc21} \rvert$ (dB)
Ref. 7	12.9%	2 & fifth	< -30, 2.9f_0	< -25, 3.1f_0
Ref. 8-I	10.5%	3 & third	< -30, 2.91f_0	< -30, 3.0f_0
Ref. 9	62.5%	0 & third	<- 20, 2.32f_0	<- 20, 1.7f_0
Ref. 10-I	11.0%	2 & second	< -20, 2.52f_0	<- 20, 2.1f_0
Ref. 11	123%	2 & fourth	< -15, 2.62f_0	< -15, 2.6f_0
Ref. 12	10.0%	0 & second	< -20, 2.2f_0	< -18, 1.5f_0
Ref. 13	115%	0 & third	<- 20, 2.21f_0	< -15, 2.6f_0
Ref. 14-II	**70.7%**	**2 & fourth**	**< -20, 2.80f_0**	**< -14, 2.8f_0**
Ref. 5	**79.0%**	**3 & fourth**	**< -25, 2.60f_0**	**< -13, 1.6f_0**
Ref. 6-II	**21.9%**	**5 & sixth**	**< -20, 2.94f_0**	**< -20, 5.2f_0**

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