# Differential Bandpass Filters with Common-Mode Suppression based on Stepped Impedance Resonators (SIRs)

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**Abstract — A novel strategy for the design of common-mode suppressed differential (or balanced) filters, based on stepped impedance resonators (SIRs), is presented. The differential mode band pass response is achieved by coupling parallel LC resonators, implemented by a patch capacitance and a grounded inductance, through admittance inverters. Such inverters are implemented by means of 90° transmission lines, whereas the grounded inductances are implemented by means of mirrored stepped impedance resonators (SIR). For the differential mode, the symmetry plane is a virtual ground, the wide strip section of the SIR is effectively grounded, and the SIR behaves as a shunt inductance. However, for the common mode, where the symmetry plane is an open (magnetic wall), the SIR is a shunt connected series resonator, providing a transmission zero, which can be used for the rejection of the common mode in the differential filter pass band. The equivalent circuit model of the proposed structure is validated through electromagnetic simulation and experimental data of order-3 and -5 Chebyshev differential bandpass filters. Moreover, guidelines for the design of balanced filters with wide bandwidths, including ultra-wideband (UWB) bandpass filters, are provided.**

**Index Terms —Differential filters, stepped impedance resonator (SIR), microstrip, common-mode suppression.**

## I. INTRODUCTION

The design of differential filters with common-mode noise suppression is of high interest in balanced circuits, where high immunity to environmental noise, interference and crosstalk between different elements are key advantages over their single-ended counterparts. Several strategies for the implementation of balanced bandpass filters with common-mode rejection have been proposed [1]-[10]. Essentially, such filters are designed by using symmetry properties. Namely, they are symmetric structures, where the electric wall of the symmetry plane for the differential mode makes the structure to exhibit band pass functionality. However, through a proper design, it is possible to achieve common-mode rejection in the differential filter pass band thanks to the effects of the magnetic wall for the common mode.

Based on these ideas, moderate or narrow band [6],[7], dual-band [2]-[5], and ultra-wideband (UWB) [9],[10] balanced filters have been recently reported. Most of these common-mode suppressed balanced filters are based on distributed elements, and filter optimization requires parametric analysis. This is the case, for instance, of the UWB balanced filters implemented by means of branch line sections with open-circuited stubs attached along the symmetry plane [9], or by means of open-ended parallel coupled lines [10].

In this paper, a very simple circuit model (that combines transmission line sections and lumped elements) for the implementation of narrow and moderate bandwidth balanced bandpass filters with common mode suppression is proposed. Then, it is demonstrated that such circuit model can be synthesized to a very good approximation in microstrip technology by implementing the lumped elements through patch capacitances and stepped impedance resonators (SIRs). The advantages of this approach are: (i) easy design, and the possibility to implement standard response filters, such as balanced Chebyshev band pass filters, (ii) compact size, (iii) high and wideband common-mode rejection, and (iv) simple fabrication and good isolation (since vias are not required and the ground plane is not etched). It will also be pointed out that by alleviating the requirement of keeping the ground plane unaltered, it is potentially possible to achieve very wide differential filter bandwidths and small size, yet preserving the design methodology, based on the equivalent circuit model.

## II. PROPOSED DIFFERENTIAL FILTER WITH COMMON MODE SUPPRESSION AND CIRCUIT MODEL

The proposed circuit for the implementation of balanced bandpass filters with common mode suppression is depicted in Fig. 1(a), where the transmission line sections present between the lumped elements are 90° lines at the central filter frequency, $f_o$. For the differential mode, the symmetry plane is an electric wall, and the capacitances $C_z$ are grounded. The resulting structure is thus the canonical circuit of a bandpass filter, consisting on a cascade of parallel LC resonators coupled through admittance inverters (Fig. 1b) [11]. For the common mode, the symmetry plane is a magnetic wall, and the equivalent circuit (Fig. 1c) exhibits a stop band behavior. Indeed, except for the presence of the capacitances $C_p$, such circuit is the canonical circuit of a stopband filter. As long as the admittance inverters exhibit their functionality in a narrow (or moderate) band, the synthesis of balanced filters with

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standard responses (Chebyshev or Butterworth) following this approach is bandwidth limited. Nevertheless, we will discuss later how to implement wide band balanced bandpass filters by replacing the admittance inverters with series LC resonators.

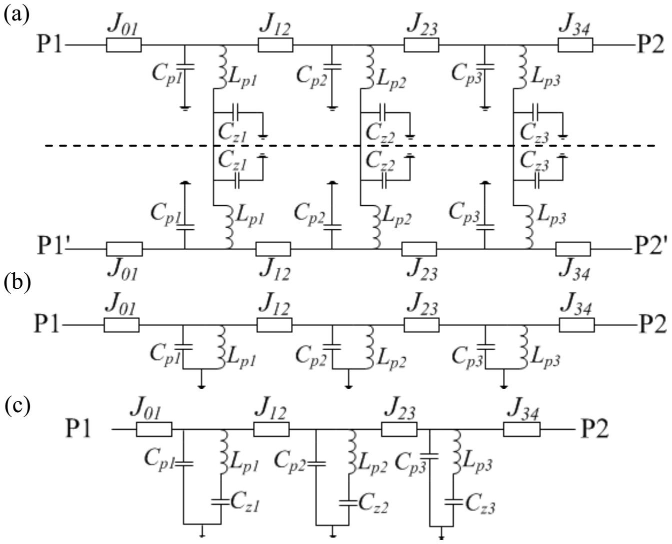

Fig. 1. Circuit model of the proposed balanced bandpass filters with common-mode suppression (a), and equivalent circuits for the differential (b) and common (c) modes.

Let us consider the implementation of an order-3 balanced common-mode suppressed Chebyshev bandpass filter with central frequency $f_o$ = 2.4GHz, 0.15 dB ripple, and fractional bandwidth *FBW* = 40%. In this first example, we have considered identical LC parallel resonators (those of the differential mode circuit, $L_p$ and $C_p$), and admittance inverters with variable admittance. By applying the well know transformations from the low pass filter prototype [11], the element values are found to be $L_p$ = 1.465 nH and $C_p$ = 3 pF, and the admittances of the inverters are $J_{01,34}$ = 0.0178 S, and $J_{12,23}$ = 0.0157 S. For the suppression of the common mode, we have forced the transmission zeros given by the resonances of the series resonators $L_p$-$C_z$ to be identical and equal to the central frequency of the differential mode response, $f_o$. Since the inductances $L_p$ are determined by the differential mode filter specifications, it follows that $C_z$ = 2.925 pF. The differential and common mode filter responses (inferred from the *Agilent ADS* circuit simulator) are depicted in Fig. 2, where the ideal Chebyshev response is included for comparison purposes (the spurious present in the differential mode response is due to the limited bandwidth of the inverters). The common mode is efficiently suppressed over the differential filter pass band, as it is required in these balanced filters.

To implement this filter in microstrip technology, we have first obtained the widths of the transmission line sections corresponding to the calculated admittances of the inverters by means of a transmission line calculator (the considered substrate is the *Rogers RO3010*, with thickness $h$ = 0.635 mm and dielectric constant $\varepsilon_r$ = 10.2). The capacitances $C_p$ have been implemented by means of quasi-square patches (external patches), where patch dimensions have been calculated from the well known formula giving the capacitance of an electrically short low-impedance transmission line section. Finally, the pair of grounded resonators $L_p$-$C_z$ are implemented through mirrored stepped impedance resonators (SIRs). The dimensions of these SIRs have been calculated in order to accurately synthesize the required elements values up to at least $2f_o$, according to the procedure reported in [12]. This device has been fabricated using a standard photo/mask etching technique. The layout (including filter dimensions) and the photograph of the fabricated device are shown in Fig. 3 (total filter size is 26.49 mm × 32.78 mm, i.e., $0.51\lambda_g \times 0.63\lambda_g$, $\lambda_g$ being the guided wavelength at $f_o$). Notice that the transmission lines have been meandered in order to reduce the filter length.

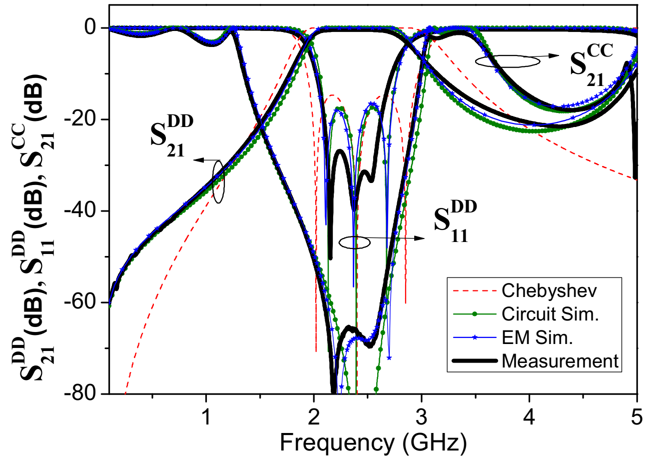

Fig. 2. Differential-mode insertion and return loss, and common-mode insertion loss of the designed order-3 balanced bandpass filter.

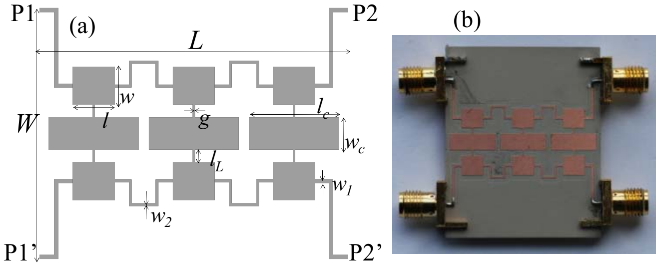

Fig. 3. Layout (a) and photograph (b) of the fabricated order-3 balanced bandpass filter. Dimensions are: $W$= 26.49 mm, $L$= 32.78 mm, $w$= 4 mm, $l$= 4.475 mm, $g$= 0.2 mm, $l_L$=1.32 mm, $l_C$= 9.6 mm, $w_C$= 3.4 mm, $w_1$= 0.434 mm and $w_2$= 0.297 mm.

The simulated (using the *Agilent Momentum* commercial software) and measured (inferred from a 4-port PNA N5221A vector network analyzer) frequency responses of the filter for the differential and common mode are also depicted in Fig. 2. The agreement between circuit simulation, electromagnetic simulation and measurement is very good, and validates the circuit model and the proposed methodology for common mode suppressed balanced filter design. The measured differential insertion loss is better than 0.5dB, the maximum differential return losses are 28 dB in the pass band, and the differential stop band exhibit a rejection better than 12dB up to $2f_0$. The measured common mode rejection within the differential filter pass band is better than 45 dB.

To demonstrate the potential of the proposed approach, an additional order-5 balanced filter has been designed with the following specifications: $f_o$ = 2.4GHz, 0.15 dB ripple, and $FBW$ = 40%. In this case however, the transmission zeros are located at different positions (2GHz – 2.4GHz - 2.8GHz) in order to efficiently suppress the common mode over a wider band. The element values are $L_p$ = 1.264 nH and $C_p$ = 3.5 pF, and the admittances of the inverters are $J_{01,56}$ = 0.0183 S, $J_{12,45}$ = 0.0161 S and $J_{23,34}$ = 0.0125 S. The layout of the fabricated device is depicted in Fig. 4, and the simulated and measured frequency responses are shown in Fig. 5. The measured differential insertion and return losses are better than 0.9 dB and 12 dB respectively. The differential stop band exhibit a good rejection (30 dB) up to $2f_0$. Filter size is $0.48\lambda_g \times 1.26\lambda_g$, and the common mode rejection is better than 60 dB in a band extending from 1.67 GHz up to 2.95 GHz.

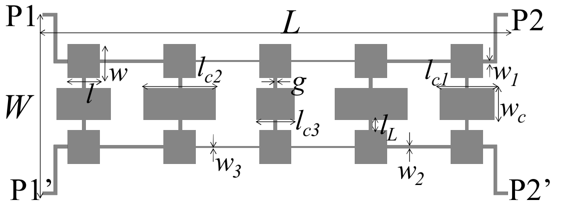

Fig. 4. Layout of the fabricated order-5 balanced bandpass filter. Dimensions are: $W$= 25 mm, $L$= 65.27 mm, $w$= 4.67 mm, $l$= 4.475 mm, $g$= 0.5 mm, $l_L$=1.446 mm, $l_{C1}$= 7.6 mm, $w_C$= 4.4 mm, $l_{C2}$= 10.2 mm, $l_{C3}$= 5.4 mm, $w_1$= 0.51 mm, $w_2$= 0.36 mm and $w_3$= 0.18 mm.

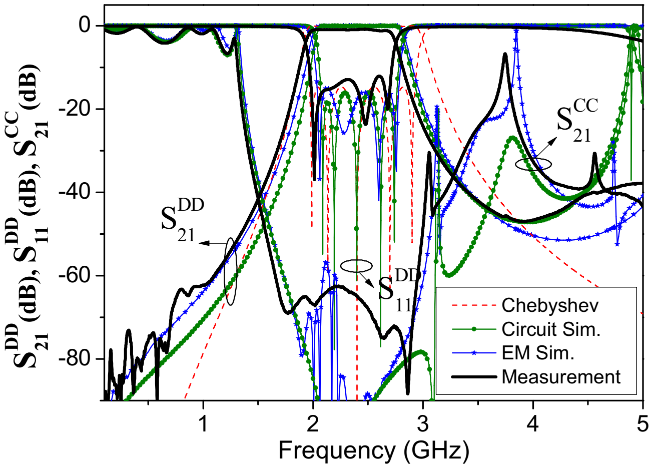

Fig. 5. Differential-mode insertion and return losses, and common-mode insertion loss of the designed order-5 balanced bandpass filter.

## III. DISCUSSION

The main advantages of the proposed filters are their simple design procedure (supported by an accurate equivalent circuit model), easy fabrication (i.e., standard microstrip technology without vias), back side isolation (the ground plane is kept unaltered), and their capability to efficiently suppress the common mode over a wide band. The fractional bandwidth can be expanded by allowing ground plane etching. By this means, it is possible to replace the admittance inverters with LC series resonators thus synthesizing the canonical circuit of a bandpass filter (differential mode). To implement wide band filters, it is necessary to achieve high capacitances and low inductances for the series resonators, and low capacitances and high inductances for the parallel resonators. Therefore, by meandering the inductive strip of the parallel resonators, and by implementing the series capacitors through broadside patch capacitances (this requires opening a window in the ground plane), we do expect that wide band balanced filters can be implemented. Work is in progress towards the design and fabrication of ultra wideband (UWB) balanced bandpass filters with common-mode suppression.

## IV. CONCLUSION

We have proposed a new strategy for the design of common-mode suppressed balanced filters using stepped impedance resonators (SIRs), based on an accurate equivalent circuit model. Filter size, easy design and fabrication, and efficient common-mode suppression are relevant advantages of the approach. To circumvent the limited fractional bandwidths achievable with the reported approach, it is possible to replace the admittance inverters with semi-lumped series resonators. This approach will be explored as a continuation of the present work for the implementation of common-mode suppressed UWB balanced filters.

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