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Balanced filter with parallel resonances for very wide band common mode rejection

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A new type of balanced filter with a very wide common mode (CM) free band is presented. In this design, the filter's symmetry line lies parallel to the resonator's current flow. Therefore, when a differential signal is excited, a virtual open circuit is forced all along this symmetry line, which results in the excitation of parallel resonances on the resonators. However, for CM operation, a short circuit is forced all along the resonator, therefore eliminating any parallel CM resonances. The filter was designed with Chebyshev response using four poles at a differential frequency of 1.11 GHz. Its fractional bandwidth is 5%. It was fabricated on a substrate with $\epsilon_r = 10.2$ and a thickness of 1.9 mm. Experimental and simulated results on the test filter show good agreement. The first CM resonance is excited at about 10 times the desired center frequency. This is due to orthogonal resonances of the resonator.

Keywords: index terms – balanced filters; common mode; differential mode

1. Introduction

Balanced filters are key components in high-speed integrated circuits as they provide higher noise immunity compared to single-line filters.[1–3] One of the most important factors in the design of balanced filters is the common mode (CM) free band. In conventional designs, the symmetry line cuts the resonator in half perpendicularly to the current direction. Therefore, CM harmonics can be potentially excited. For half wavelength resonators, the first CM resonance occurs at twice the differential mode (DM) frequency ($f_c = 2f_d$). One way to increase the CM free band is the use of stepped impedance resonators.[4–6] Another method is presented in [7] where the CM resonances of the first and second resonators occur at different frequencies, and the external tap is positioned at an open circuit therefore increasing CM attenuation. In this case, the CM resonance is 3.5 times higher than the DM ($f_c = 3.5f_d$). In [8], a shorted-stub ring resonator is used to extend the CM free band to $f_c = 3.7f_d$.

In our proposed filter, we excite a DM parallel resonance where the symmetry line lies in parallel to the current flow. Since the symmetry line cuts the resonator in half, parallel to the resonant mode, an open circuit is forced all along the resonator. Therefore, a quarter wavelength resonance is excited. However, when it is fed in CM, a short circuit condition is forced all along the resonator; thus any CM parallel mode

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cannot be excited. Our results show that the first CM resonance is excited in an orthogonal mode when the width of the resonator becomes half wavelength. The simulated and measured results show a ratio of about 10:1 between the first CM spurious (f_c) to the DM fundamental (f_d). In this paper, design procedure will be shown along with simulated and experimental results.

2. Resonator design

The proposed structure consists of a quarter wavelength resonator fed as shown in Figure 1 by a 180° phase shifter. The symmetry line lies parallel to the resonant mode (contrary to orthogonal as in conventional designs). When it is fed in DM (Port 1, Port 3), the voltages V_a and V_b are equal, hence, an open circuit is forced along the symmetry line. This causes the DM to have a quarter wavelength parallel resonance at f_d Equation (1).

$$f_d = n \frac{c}{4L_R \sqrt{\epsilon_{\text{eff}}}} \quad (1)$$

where $n = 1, 3, 5, \dots$, L_R is the resonator length, and ϵ_{eff} is the effective permittivity.

For the CM, the voltages V_a and V_b have opposite signs; therefore, a short circuit is forced along the symmetry line, and hence, no CM parallel resonance can be excited. However, this condition is only true when the phase shift remains 180° between the two input signals. If we analyze the behavior of the possible CM resonances for a quarter wavelength resonator, we can see that these may occur at odd multiples of the DM fundamental. For this reason, to eliminate CM resonances we can utilize a simple 180° transmission line at f_d as it would give $n \times 180^\circ$ at odd multiples of f_d .

Another factor that can excite a CM resonance is when the width W becomes half wavelength. In this case, the short circuit at the center of the resonator will excite a quarter wavelength resonance orthogonal to the symmetry line. For this reason, it is important to choose W small enough compared to the resonator length.

To prove the concept, a microstrip resonator at a center frequency of $f_d = 1.1$ GHz was designed on a substrate with permittivity $\epsilon_r = 10.2$, thickness of 1.9 mm, and $\tan\delta = 0.0019$. Copper was used as conductor. At the center frequency a quarter wavelength corresponds to $L_R = 26.5$ mm. The width W is chosen to be 2 mm (Figure 1).

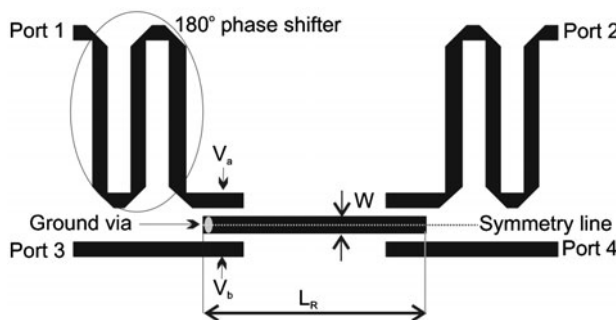


Figure 1. Schematic of proposed resonator.
Note: Symmetry line lies parallel to resonant mode.

The resonator is fed by 180° phase shifters with mitered bends for matching enhancement. The resonator is weakly coupled to the input lines. This structure is simulated in Sonnet, a commercial full EM simulator [9] and the results are shown in Figure 2.

As it can be seen, the fundamental DM resonance lies at $f_d = 1.1$ GHz. Its simulated unloaded quality factor is $Q_o = 80$. Since it is a quarter wavelength resonator, its harmonics happen at odd resonances of f_d : $n \times f_d$ ($n = 1, 3, 5 \dots$). The first CM resonance is excited at 12 GHz, which corresponds to an orthogonal resonance when $W = \lambda/2$. In the figure, the phase shifter response is also plotted. As it can be observed, the phase shift is close to $n \times \pi$ at the odd resonances (as pointed out in the figure by the perpendicular arrows). This cancels out other possible CM parallel resonances by forcing a short circuit condition.

It is important to note that this filter topology can be applied as long as the symmetry line passes through the middle of the resonator. For this reason, resonator meandering is limited. Nevertheless, for circuit miniaturization, the 180° phase shifters can be meandered or lumped elements can be used.[10]

3. Filter design

A four pole differential Chebyshev filter was designed using the aforementioned substrate. The chosen center frequency is $f_d = 1.1$ GHz with 5% fractional bandwidth. According to the specification of a low pass prototype, the g parameters are [11] $g_0 = g_5 = 1$, $g_1 = g_4 = 0.7$, $g_2 = g_3 = 1.25$.

Which gives the DM coupling coefficients as follows $Q_{e_d} = 14$, $k_{12_d} = 0.053$, $k_{23_d} = 0.04$. [12]

To feed the filter, a tap coupling is used as shown in Figure 3(a), where $W_r = 0.25$ mm. The practical external coupling coefficients are calculated using Sonnet, [9] for different tap positions (L). The results are plotted in Figure 4.

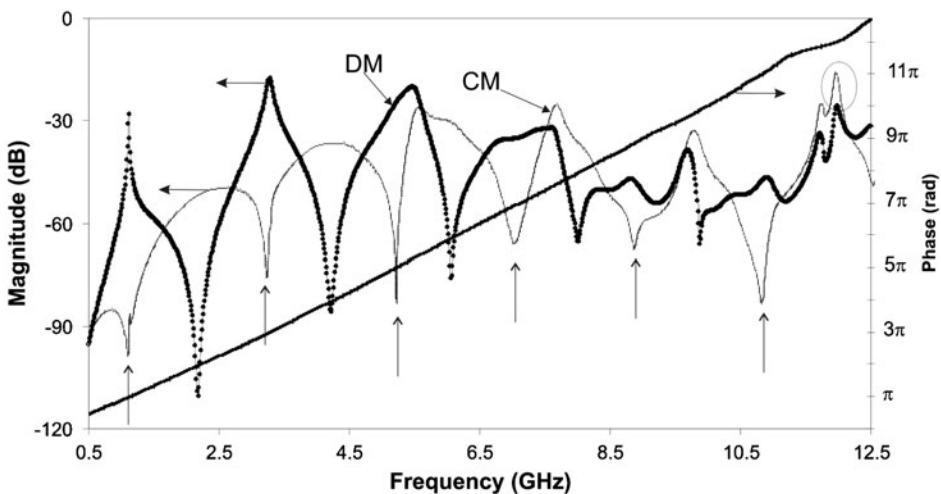


Figure 2. Simulated DM and CM insertion loss of a single resonator and the phase response of phase shifter.

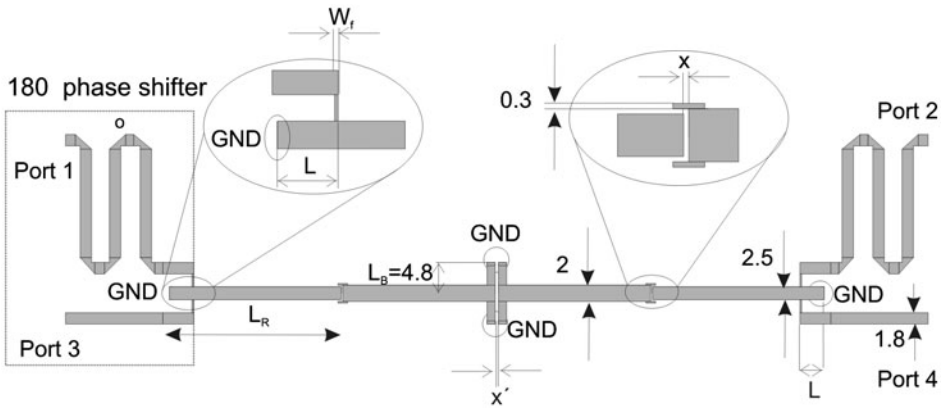


Figure 3a. Filter schematic.
 Note: All dimensions in millimeters.

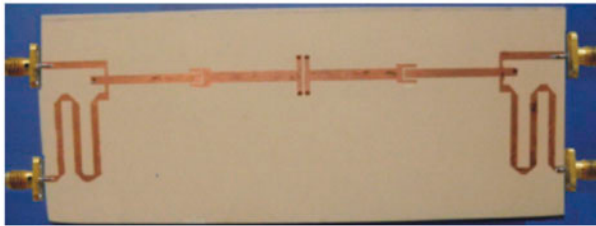


Figure 3b. Filter picture.

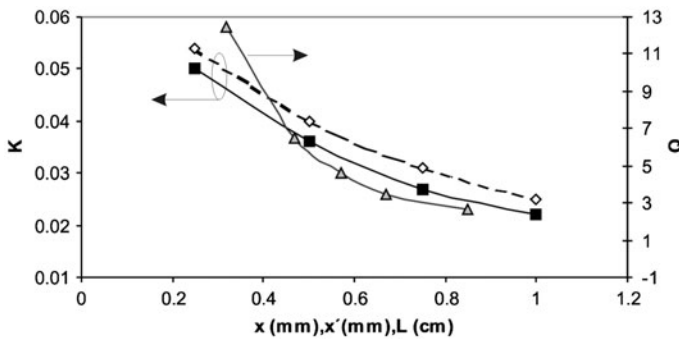


Figure 4. This figure plots coupling coefficient K and quality factor Q against, respectively, x , x' , and L .

To couple the first and second resonators, a small coupling wedge is added to resonator 1 as shown in the exploded sub-figure in Figure 3(a). Resonators 2 and 3 are bent to enhance their mutual coupling since their adjacent coupling ends are both shorted to ground. The mutual coupling coefficients, associated with the gaps x and x' (Figure 3(a)) are obtained through EM simulations and then plotted in Figure 4. For our required

specification, the final filter values are extracted from Figure 4 and shown in Figure 3(a), where $L = 3$ mm, $x = 0.25$ mm, and $x' = 0.5$ mm.

4. Experimental and simulated results

The circuit was fabricated on Rogers 6010 substrate with a thickness of 1.9 mm using a PCB milling machine (Figure 3(b)). Its S-parameters were measured with a two port vector network analyzer (VNA) (Agilent 8510). Since the structure has four ports and the VNA two ports, the port connections between the VNA and the filter were switched until S-parameters between all the ports were measured. 50Ω loads were used to match the unused ports while measuring.

The two port Differential and Common mode parameters were extracted from the two port set of measurements described in reference [13]. Figure 5 shows the experimental and simulated DM responses at the passband. The center frequency is $f_d = 1.11$ GHz. The experimental DM insertion loss (S_{21dExp}) at the passband is lower than 2 dB and the simulation including metal and substrate losses is 1.5 dB. The experimental DM return loss (S_{11dExp}) is greater than about 15 dB throughout the passband and the simulated is better than 20 dB.

Figure 6 shows the DM wide band response. Here, the harmonic resonances occur at odd multiples of the DM fundamental. Figure 7 shows the simulated and experimental CM wide band response. It is evident that the CM response shows a spurious free band of about $10f_d$. In this case, the first CM resonance occurs at around 11.5 GHz, which is in line with the orthogonal resonance shown in Figure 2 for a single resonator. There is a small frequency compared to the simulation of a singly coupled resonator where the first orthogonal CM resonance was 12 GHz. This is thought to be due to the loading of the resonators and the strong external coupling. Moreover, the notch effect caused by the 180° phase shifter is also apparent in Figure 7. It is seen that this eliminates the possible CM resonances similarly as in Figure 2. Figure 8 shows the common mode reject ratio (CMRR) defined as Equation (2).[7]

$$CMRR = 20 \log \frac{|S_{21d}|}{|S_{21c}|} \quad (2)$$

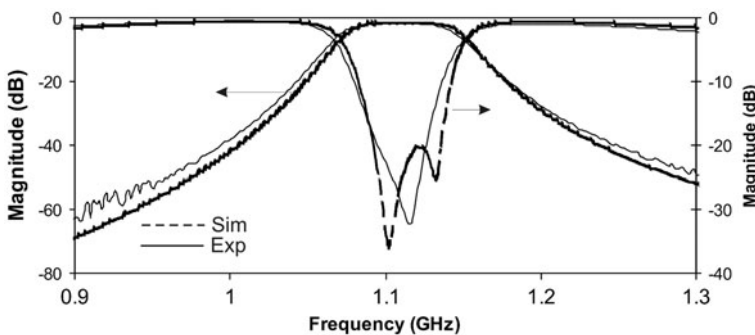


Figure 5. Simulated and experimental insertion loss and return loss of DM at the passband.

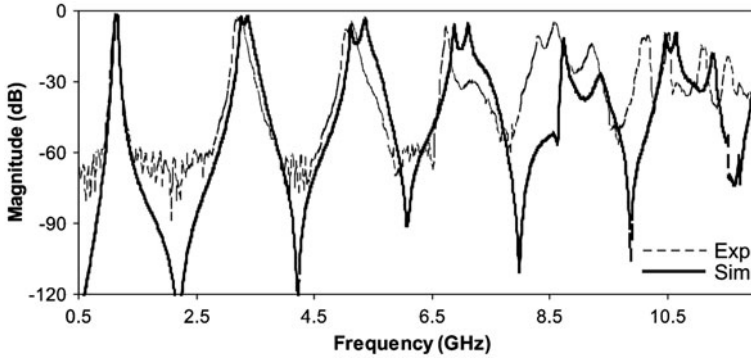


Figure 6. Experimental and simulated wide band DM response of filter.

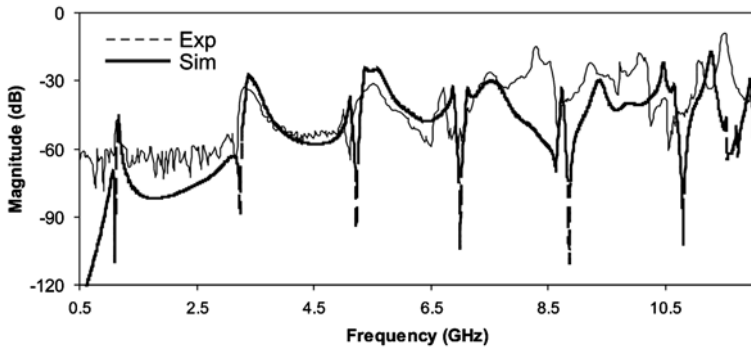


Figure 7. Experimental and simulated wide band common mode response of filter.

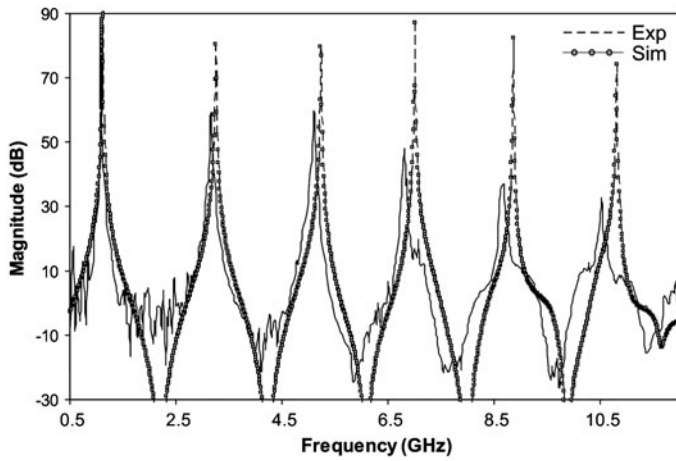


Figure 8. CMMR of simulated and experimental results.

Table 1. Performance comparison with previous works.

	f_d (GHz)	S_{21} @ f_d (dB)	CM resonance (f_c)
[6]	1.02	3.51	$3.43 f_d$
[7]	1.02	3.88	$3.5 f_d$
[2]	2.45	2.6	$2.7 f_d$
[4]	1.51	2.4	$2.4 f_d$
[8]	1.02	1.7	$3.7 f_d$
This work	1.1	2	$10 f_d$

At the passband, it reaches 65 dB for the experimental results and it peaks to 90 dB in the simulated results. Throughout the passband, it is greater than 45 dB in the experimental results. Due to the notch effect, a peak is observed at 3.2, 5.2, 7, and 8.85 and 10.8 GHz as the CM signal is highly attenuated.

Table 1 shows a comparison of this work with the previous literature. As can be seen, none of the previous works achieve such a high $f_c:f_d$ ratio 10:1.

5. Conclusions

A novel type of balanced filter at 1.11 GHz with 5% fractional bandwidth has been presented where a very wide CM free band has been achieved. The filter is based on parallel mode $\lambda/4$ resonators where the symmetry line lies parallel to the current flow. This effect eliminates CM parallel resonances as there is a short circuit condition. The first CM resonance occurs at about 10 times the DM center frequency (f_d), which corresponds to an orthogonal resonance when the resonator width becomes half wavelength. Good matching between experimental and simulated results has been achieved.

Disclosure statement

No potential conflict of interest was reported by the authors.

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