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SPURIOUS RESPONSE SUPPRESSION IN HAIRPIN FILTER USING CSRR MERGED IN THE FILTER STRUCTURE

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Abstract—In this paper CSRRs[†] are used to suppress the first spurious response in microstrip hairpin filters. The CSRRs are merged in the filter structure, and therefore the filter size is not increased. The design methodology is presented, and a filter with center frequency at 3 GHz is designed, fabricated and tested as an example. The characterization of this new filter shows the efficiency of the proposed approach to improve filter response with spurious rejection up to 20 dB while the size is even slightly reduced.

1. INTRODUCTION

Recent progresses in modern ultra wide-band radar systems and wireless communications demand high-performance and reconfigurable RF subsystems including filters [1]. Parallel coupled line microstrip filters (PCMFs), first proposed in 1958 [2], are among the most commonly used filters in microwave and millimeter-wave systems. Some of the advantages of this kind of filters are their simple design procedure, planar structure and the possibility of designing for a wide range of fractional bandwidth. The PCMFs can be fabricated easily and exhibits reasonably good performance. However, there are some disadvantages with these filters. The first one is their length. Because of several half wavelength ($\lambda/2$) resonators, the filter is too long considering the frequency and the order of the filter. It becomes more crucial in integrated systems. Well known hairpin structures as a modification to parallel coupled line filters provides a possible way to

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† Complementary split-ring resonators

decrease the length efficiently. In microstrip implementation, another important disadvantage is the degradation of rejection level above the pass band due to the existence of a spurious pass band at $2f_0$ (f_0 is the center frequency of the filter). This undesirable band arises because of different phase velocities (consequently, different electrical lengths) for the even and odd modes supported by the inhomogeneous coupled-line sections. Suppressing these undesired pass bands has become interesting for filter designers in recent years [3–6]. Many investigations have been reported. Traditional techniques include using stubs or chip capacitors at the resonator open ends or cascading stop-band filters. However, these techniques are too narrow-band, increasing used area and insertion loss. Several approaches based on modified structures, aimed to obtain equal modal phase velocities, have been proposed recently [3, 4]. Other numerous studies have been devoted to the suppression of harmonics in a wide variety of microwave circuits, including passive [5] and active circuits [6]. These approaches are quite effective, but some of them result in bigger size, complex design or hard fabrication. In this paper, a new technique is presented to suppress the spurious pass bands in microstrip hairpin filters based on complementary split-ring resonators (CSRRs) [7]. CSRRs has been successfully used in microstrip parallel coupled line filters as a cascaded band stop filter [8]. Here, we merge them in hairpin structure with no increase in used area while improving the filter response with harmonic rejection levels up to 20 dB. The design and fabrication are also very easy.

In Section 2, we describe the basic filter structure and its properties. After scrutinizing the characteristics of the proposed structure in Section 3, the design steps are explained in Section 4. A sample filter is designed, and its simulated and measured results are presented in Section 5. Finally, a discussion and the main conclusions of this study will be highlighted in Section 6.

2. MAIN IDEA

The purposed structure is shown in Figure 1. As shown, we used the rejection properties of three CSRRs etched in appropriate locations to reject specific frequencies while having the least effect on the filter pass band response. In comparison with DGS[‡], CSRR structures perform higher Q[§] at the designed frequency and therefore, less insertion loss in lower frequencies than dumbbell shaped DGS [9]. Thus, it is more reasonable to use multiple CSRRs to make a wide reject band without

[‡] Defected Ground Structure
[§] Quality factor

meaningful effect on main response. The design details are discussed in the next section.

We can separate the filter shown in Figure 1 in two parts, the regular hairpin filter and CSRRs. The microstrip hairpin filter shown in Figure 2 is composed of similar parallel coupled lines etched on a dielectric substrate. Because of different phase velocities for even and odd modes of propagation in coupled section, the filter response exhibits a spurious band at $2f_0$. Since the $\lambda/2$ resonators are U-shaped, the coupled sections are shorter than $\lambda/4$, and a non-coupled section, named deadline, remains for each resonator. Recently, CSRRs (see Figure 3(a)) have been proposed as a new constitutive element for the synthesis of negative permittivity based on resonant elements and left handed (LH) transmission line in planar configurations [7–9]. The CSRRs are used in the design of compact planar filters with high performance and controllable characteristics [10]. Also, it has been demonstrated that CSRRs can efficiently suppress the spurious bands in planar circuits [8–11].

Dominant mechanism for CSRR excitation is the electric coupling with a strip on signal layer. The electric field must be applied in the axial direction (z) as shown in Figure 3 [12]. Due to cross polarization effects, they can also be driven by a time varying magnetic field,

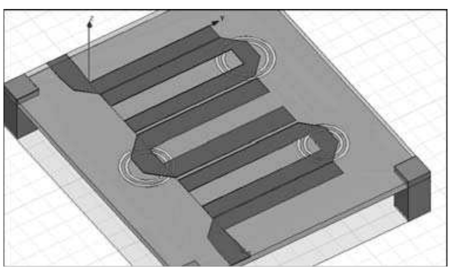


Figure 1. The Purposed filter structure to improve rejection response of the filter.

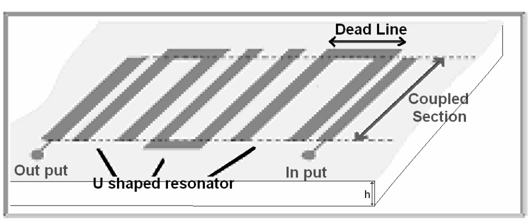


Figure 2. A conventional hairpin filter.

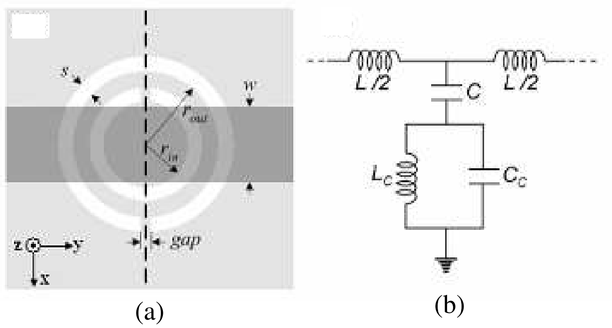


Figure 3. (a) Topology of CSRR and the relevant dimensions for metallic regions depicted in tow gray. (b) Lumped element equivalent circuit for the basic cell of the CSRR loaded microstrip line.

applied to the particle plane (where a magnetic dipole is present, i.e., y direction) [13, 14].

Analytical models are able to provide the equivalent inductance and capacitance of CSRRs (Figure 3(b)). However, these models are valid under some restrictive conditions. As long as the electrical size of the CSRRs is small, it can be described by means of lumped elements.

3. CSRR LOCATION AND ORIENTATION

Hairpin is a suitable structure for adding the CSRRs because of the deadline sections introduced above. Conventional hairpin filters composed of U shaped $\lambda/2$ resonators coupled together shorter than $\lambda/4$ and with some deadlines in the middle. The best location to etch out the CSRRs is under the deadlines because of the E-field (excitation) is maximum in the axial direction at $2f_0$ and minimum at f_0. Therefore, we have maximum coupling at the first spurious band which occurs at almost $2f_0$ while we expect almost no effect on the main response at f_0. The CSRRs designed to resonate around $(2f_0)$ will add a transmission zero at these frequencies while having almost no effect on the main pass band. It is also important to consider enough space for the CSRRs, i.e., the deadline length.

Due to cross polarization effects, CSRRs' orientation becomes important. Although, it has been experimentally verified that magnetic excitation is almost dominated by electric excitation in the axial direction. Meanwhile, the rotation of CSRRs will change the total result. We chose the best directions for them practically.

CSRRs will change the electrical length of the coupled lines due to defect in the ground structure. It means that the electrical length of line increases in comparison to the electrical length of line with the same physical length without defects in the ground. This occurs because of longer ground current path in defected case. However, this can be compensated by decreasing the physical length of the coupled section properly. These characteristics are mainly in higher frequency.

4. DESIGN METHOD

CSRRs have been used as band-stop sections cascaded with main filter at input/output lines to improve the stop band performance of band-pass filters [8, 11]. Although, this is very effective and simple but necessitates extra size, which is not desirable in general. Now, if we combine the CSRRs with the filter elements to keep the size unchanged, the main pass band may be affected drastically. The approach is to place the CSRRs in a dead position, which causes no critical effect on

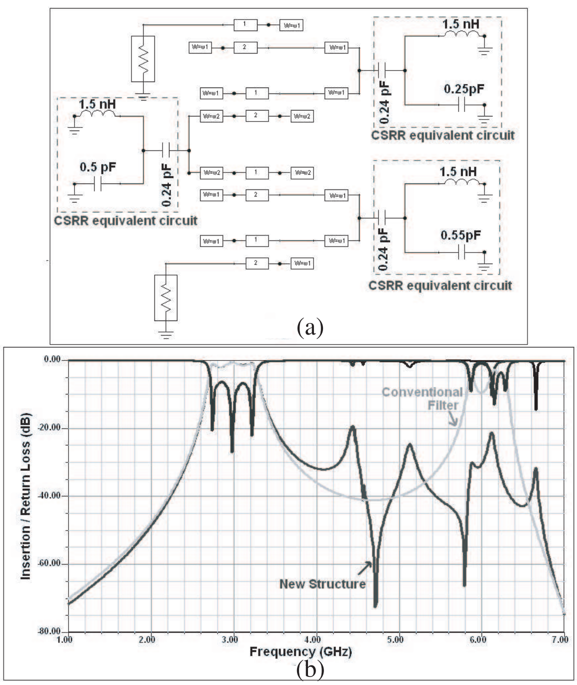


Figure 4. (a) Band pass hairpin filter schematic with three CSRRs coupled to deadlines. (b) Frequency response of filter with CSRRs ((a) schematic) compare whit conventional hairpin filter.

the filter performance. The deadlines, shown in Figure 2, are in such a position that the performance of the filter in its main pass band will not change spectacularly, when we locate our CSRRs under them.

In this section, the design of a third order filter at center frequency of 3 GHz with 500 MHz pass-band on Ultralam2000 substrate ($\varepsilon = 2.6$, $h = 0.7874$ mm), is demonstrated as an example. For spurious band suppression at $2f_0$, three CSRRs are designed and coupled with the three deadlines. As CSRRs will shift second harmonic to lower frequencies without affecting the main pass band as explained above, we chose 4.6, 4.8 and 5.8 GHz as CSRRs resonant frequencies to suppress the down shifted spurious band. At first, we design the hairpin filter and required CSRRs separately using their equivalent circuit. The response is simulated using Ansoft Designer commercial software. The filter schematic coupled with the CSRRs is shown in Figure 4(a), and a comparison between the filter with and without CSRRs is shown in Figure 4(b). As it is seen, the CSRRs work as band-reject elements with almost no effect on filter performance and therefore could be designed independently.

Using Ansoft HFSS full wave simulator, we find that the equivalent electrical length of resonators in presence of DGS is slightly increased. Therefore, the main pass band is shifted to lower frequencies. This is because of small variations in the effective electrical length of the deadlines due to the defects in the ground structure which increases the electrical length of resonator. This can be compensated by decreasing the physical length of the coupled section properly. The EM simulation result and proposed filter are shown in Figure 5.

One of the most important parameters on CSRR response, like

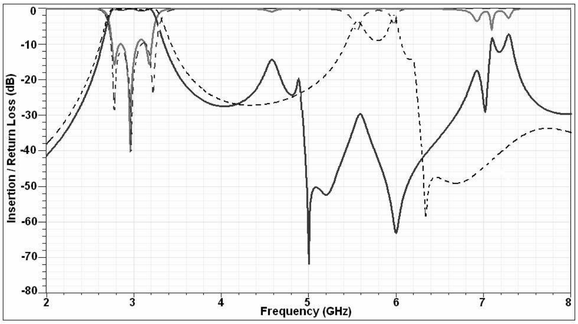


Figure 5. Comparison between simulated responses of Band pass hairpin filter integrated with three CSRR (solid line) and simple band pass hairpin filter (dotted line).

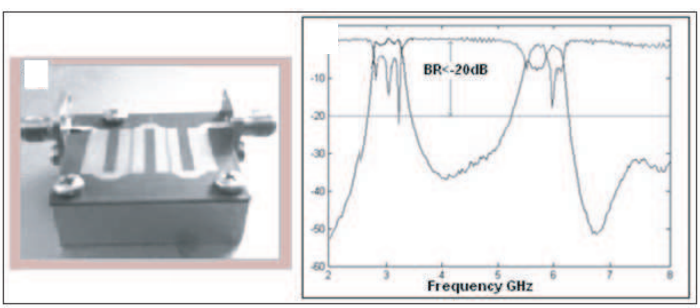
any kind of DGS structure, is the metal box effect, which is ignored in most papers. It is very important from practical point of view that we consider its effect. Here, the separation between the substrate bottom and the box is considered 5 mm.

5. DESIGN EXAMPLE

In this section, we utilize the above steps to design a sample filter at center frequency of 3 GHz with a bandwidth of 17%. First we design a conventional 3rd order hairpin filter on ultralam2000 substrate ($\varepsilon_r = 2.6$ and $h = 0.7874$ mm) using the Ansoft filter designer. The fabricated filter and measured results are shown in Figure 6. The first spurious response at $2f_0$ has arisen, and the rejection performance of the filter has been degraded to less than -20 dB at 5.3 GHz.

Then, we have added three CSRRs with radii of $r = 2.4, 2.7, 2.9$ mm to resonate at 4.5, 5 and 5.6 GHz respectively to the filter. We have also reduced the coupled section lengths about 7% to compensate the effect of ground defects on the electrical lengths as explained in Section 3. The resulted filter has been also simulated and fabricated. The images of fabricated hairpin filter with CSRRs and measured results are shown in Figure 7. There is a good agreement between simulated and measured results. (Figures 5 and 7(b)).

Finally, the proposed and conventional filter responses are compared in Figure 8. A minimum improvement of -20 dB is achieved in rejection band up to 6.8 GHz. By comparing Figure 5 with Figure 7(b), it is observed that the measured passband is slightly narrower, which could be considered due to fabrication errors. Also



(a) (b)

Figure 6. (a) Fabricated hairpin filter. (b) Measurement result of fabricated band pass hairpin filter ($N = 3$, $f_0 = 3$ GHz, $BW = 560$ MHz, $\varepsilon_r = 2.6$, $h = 0.7874$ mm).

a little shift in CSRR resonant frequencies occurs because of etching tolerance. A spurious band is still observed around 7 GHz which is not the second response shifted to upper frequencies. As it is explained in [15], the slow wave factor is a nonlinear function of the effective permittivity and frequency such that the upper frequencies are more affected and move to lower frequencies. Therefore, the response seen around 7 GHz is the third one which is shifted to lower frequencies. Let us emphasize that the second response is also shifted lower (5 GHz), and we have compensated it by CSRR resonances at around 5 GHz.

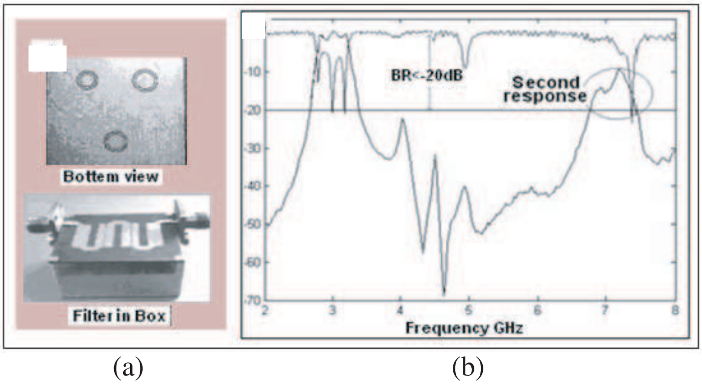


Figure 7. (a) Fabricated filter integrated with three CSRR DGS. (b) Measurement results.

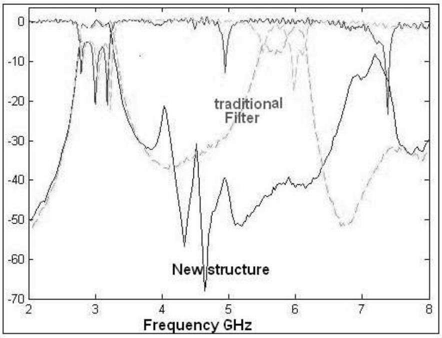


Figure 8. Comparison between simple filter and purposed structure frequency response (filter with CSRR).

6. CONCLUSION

A new simple and effective application of the well known CSRRs has been proposed to suppress the first spurious response of the conventional hairpin filters. The proposed method keeps the size unchanged or even decreases it slightly. The design method is very easy. The CSRRs have been located properly such that they have almost no effect on the center frequency response. Therefore, the main filter and CSRRs could be designed independently. A sample filter at center frequency of 3 GHz has been designed, fabricated and tested to confirm the efficiency of the method. There was a good agreement between the simulated and measured results, and an improvement of around 20 dB has been achieved in the rejection band of the filter.

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