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Multiband EMI filter based on metamaterials

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Abstract: A novel compact multiband microstrip EMI filter based on metamaterials is presented. The filter is implemented by means of split-rings resonators and complementary spiral sub-wavelength resonators, conveniently coupled to the victim transmission line. The suitable combination of these resonators allows us to design several stop-band frequency responses located at 900 MHz (RFID UHF), 1.8 GHz (GSM) and 2.4 GHz (ISM) with a significant rejection level. A 3-stages/5-stages rejection band filter has been designed and fabricated in a PCB. The experimental results show a significant rejection level in agreement with the electromagnetic simulations.

Keywords: EMI filters, split ring resonators (SRRs), complementary spiral resonators (CSRs), microstrip lines, radiofrequency
Classification: Electromagnetic compatibility (EMC)

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1 Introduction

The increasing pollution of the electromagnetic emissions in the last years, due to the explosion of commercial wireless devices, requires the design of electronic systems which are immune to electromagnetic interferences (EMI) and, more specifically, to radiofrequency interference (RFI). Also, since low-cost and highly-integrated circuits and systems are required, new filtering techniques are necessary in order to overcome the limitations of standard EMI filters. Recent developed solutions in order to reduce cost and dimensions of conventional EMI filters consist of strategies based on Electromagnetic Band Gaps [1, 2], a type of metamaterials. Metamaterials are artificial fabricated materials based on periodic (or quasi-periodic) structures with electromagnetic controllable properties generally not found in nature. Among them, the effective single (permeability, μ, or permittivity, ε) or double (also called left-handed) negative media have attracted a great interest in recent years. In fact, a sub-wavelength resonator namely split-ring resonator (SRR) was revealed as an efficient particle in order to implement effective negative-μ media [3]. After this, the first filtering experimental demonstration by means of a periodic array of SRRs was developed [4].

In this paper, a multiband microstrip EMI filter based on metamaterials is proposed. Specifically, the sub-wavelength resonators considered in the design are SRRs and the dual (or complementary) counterparts of the spiral resonators, SRs, [5], which properties at frequencies of interest are described in section 2. The RFI target frequency bands are RFID UHF, GSM, and the 2.4 GHz industrial, scientific and medical (ISM) band.

2 Theoretical analysis: SRRs and CSRs

The properties of the SRRs, and their complementary counterparts, have been discussed from the point of view of their electromagnetic behavior and their equivalent-circuit models [5]. Basically, the SRR are sub-wavelength resonators (i.e., electrically very small) that behave as an LC tank when they are coupled to a host line. These resonant particles consist of a pair of metal rings etched on a dielectric slab with apertures in opposite sides (Fig. 1 (a)). SRRs are mainly excited by means of an external magnetic flux along the ring's axis. As a result of this excitation, they present extreme high positive/negative values of the effective μ below/above their resonance frequency. Therefore, SRRs are able to inhibit signal propagation in the vicinity of the resonance frequency which satisfies the condition $\mu < 0$, according Maxwell equations. Alternatively, this behavior can be explained by the induced current loops in the rings at resonance frequency. The equivalent circuit of the SRR is shown in Fig. 1 (b) and its resonance frequency is given by (1),

$$f_o|_{SRR} = \frac{1}{2\pi\sqrt{L_S C_S}}, \tag{1}$$

where the equivalent capacitance, C_S, corresponds to the edge capacitance of the concentric rings, whereas the equivalent inductance, L_S, can be ap-

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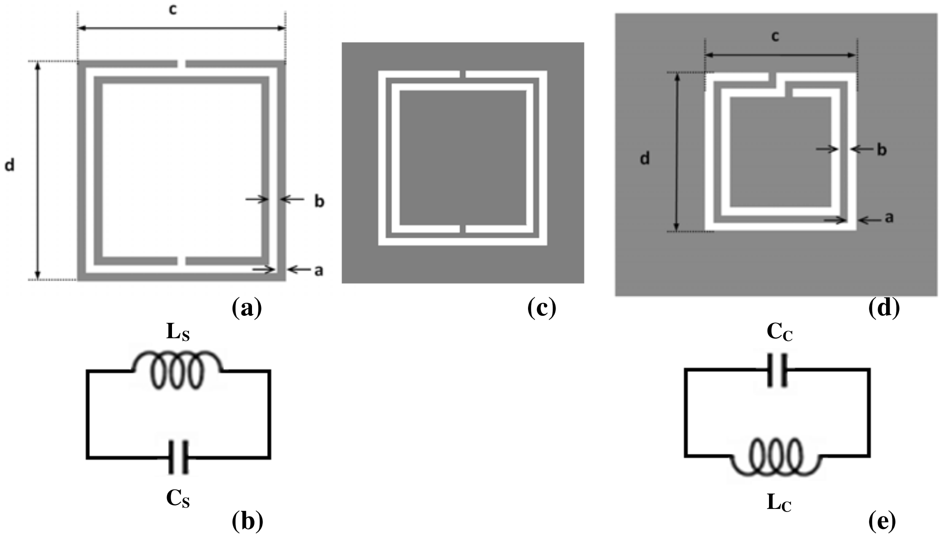

Fig. 1. (a) Topology of the SRR with its relevant dimensions, and its equivalent-circuit model (b). (c) Topology of the CSRR. (d) Topology of the CSR with its relevant dimensions, and its equivalent-circuit model (e). Metallization zones are depicted in grey.

proximated by a single ring with the averaged perimeter of the actual SRR. The complementary split-ring resonators (CSRRs) are the dual counterparts of the SRRs and basically consist of pair of rings etched on a metallic surface (negative image of SRRs, Fig. 1 (c)). From duality arguments, it has been demonstrated that negative permittivity media ($\varepsilon < 0$) can be generated by means of CSRRs [5]. Thus, this resonant particle is also suitable in order to develop reject band filtering implementations. The CSRR can be excited by an axial electric field and it presents a resonance frequency roughly equal than SRR as well as an equivalent LC tank model.

There are other planar topologies derived from the CSRR with their corresponding resonance frequency such as the complementary spiral resonator (CSR), which is depicted in Fig. 1 (d). Due to its topology, it presents an equivalent model (Fig. 1 (e)) consisting of an LC tank with an equivalent capacitance similar than the corresponding to the CSRR but with a four times higher inductance. Therefore, if CSR and CSRR (or SRR) are compared with similar dimensions, the resonance frequency of the former resonator is reduced in a factor of 2. This implies that it is possible to achieve similar rejection band frequencies than in the CSRRs case but with a miniaturization factor about 2. Thus, the CSR resonance frequency corresponds to (2),

$$f_o|_{CSR} = \frac{1}{2\pi\sqrt{L_C C_C}} = \frac{f_o|_{CSRR}}{2}, \tag{2}$$

where C_C and L_C correspond to the equivalent capacitance and inductance of the CSR, respectively.

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3 EMI filter design

The starting point consists of a conventional microstrip line which can be potentially affected by RFI in the range of RFID UHF (f_{o1}~900 MHz), GSM frequency uplink and downlink bands (f_{o2}~1.8 GHz) and ISM (f_{o3}~2.45 GHz). The EMI filter design methodology involves three main stages. First of all, the suitable sub-wavelength resonator particle is selected for each band by taking into account not only the stop-band resonance frequency for each band, but also minimization area criteria. Secondly, the electromagnetic simulation of the resonators distributed conveniently in the top and bottom area of the PCB is done. Finally, a feedback tuning of the dimensions of the particles during the simulation process is required in order to achieve the desired specifications.

The sub-wavelength particles considered in this work correspond to the original SRR and the dual counterpart of the SR, the CSR. Fig. 2 shows the implemented layout of the EMI filter. The design strategy is based in the implementation of the SRRs in order to develop the stop-band filter at the higher frequency band (ISM). These particles have been etched in the top side of the PCB, close to the host microstrip line and they are exited magnetically at their resonance frequency. Specifically, a 5-stage SRR has been implemented (Fig. 2 (a)). The dimensions of the SRRs are slightly modified in several stages, since the modification of the size of each ring implies that each one operates at a slightly different resonance frequency. As result, a wider stop-band response is achieved. Concerning the lower frequency bands (i.e. the corresponding with the higher dimensions required resonators), two arrays of 3-stage CSRs have been used in order to develop the stop-band responses at RFID UHF and GSM, due to their intrinsic small size, as explained above. Also, they can be etched in the metal ground plane of the PCB and, therefore, no extra area is required (Fig. 2 (b)).

The EMI filter has been designed by using a *Rogers RO3010* substrate (dielectric permittivity, ε_r=10.2 and thickness, h=1.27 mm). A 50 Ω microstrip line has been designed (dimensions: width, w=1.18 mm, and length, l=47 mm). A square topology has been chosen for all the resonators in order to enhance the coupling to the host line. Since the distance of the SRRs to the host line is a key point, they have been placed as close as possible to the microstrip line (200 μm). Concerning CSRs, they have been etched underneath the microstrip line in order to maximize the electrical coupling to it. Since the number of resonators stages determines the level of rejection of each stop-band filter response, a higher rejection level is expected in case of SRRs. The reduction in the number of stages of CSRs is due to the requirement to include two rejection bands and, thus, in order to obtain a compact design. Finally, the distance between adjacent SRRs and CSRs has a direct impact in the rejection bandwidth. Therefore it has been also considered as a significant parameter for the final implementation (200 μm).

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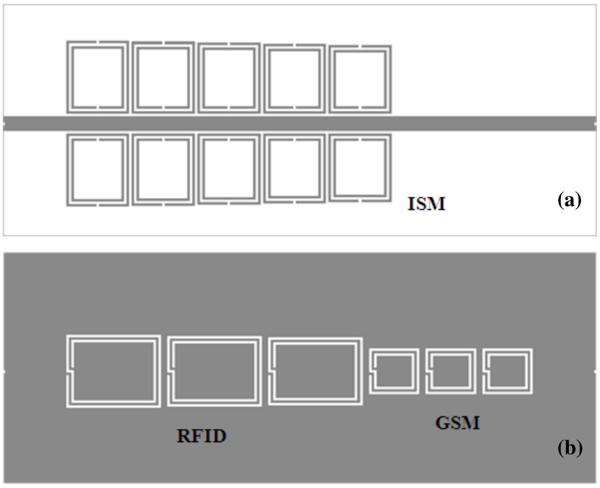

Fig. 2. Topology of the designed multiband microstrip EMI filter. (a) Top layer with microstrip line and the SRRs designed at 2.45 GHz. (b) Bottom layer with CSRs etched in the ground metal tuned at 900 MHz and 1.8 GHz, respectively. Metallization zones are depicted in grey. Dimensions are: $a=b=0.2$ mm for all particles. ISM: $c=5$ mm, $d=5.5-5.8$ mm. GSM: $c=3.7$ mm, $d=4$ mm. RFID: $c=5.5-5.9$ mm, $d=7.5$ mm.

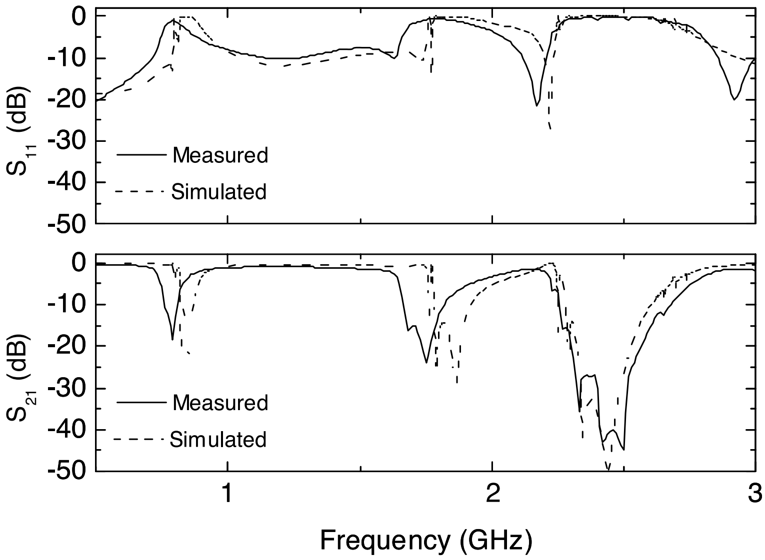

Fig. 3. Electromagnetic simulated and measured frequency responses of the insertion losses (S21) and return losses (S11) of the proposed EMI filter.

4 Simulated and experimental results

Fig. 3 shows a good agreement between the obtained electromagnetic simulations (developed by means of *Agilent Momentum*) and experimental results of insertion

(S21) and return losses (S11). In fact, a reasonable matching (a slight

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shift is typically produced by the simulator) with the frequency of the rejected bands is achieved. Concerning the rejection level, the measured values correspond to 18 dB for the RFID UHF band, 24 dB for the GSM band and 40 dB for the ISM band. As expected, similar levels of attenuation are obtained by using the two arrays of 3-stages of CSRs, whereas a higher rejection is achieved by means of the SRRs, due the larger number of stages implemented. This fact also implies a wider bandwidth in the stop-band frequency response. The losses of the allowed bands present an average value of 1.5 dB and are basically due to the presence of connectors and ohmic losses. Measured return losses show a good matching (lower than 10 dB at the allowed frequency bands).

5 Conclusion

In summary, a new multiband filter for the rejection of undesired RFI has been proposed. The topology consist of the combination of several stages of SRRs and CSRs conveniently designed in order to inhibit the propagation of potential common coupling signal interferers at RFID UHF, GSM and ISM bands. The main advantages of this kind of metamaterial filter topologies is the low cost (just conventional metallization or etching process is needed with no extra electrical components) and low area impact. A good agreement has been achieved between simulations and experimental testing. The measured results show rejection levels (>20 dB/40 dB) which can satisfy with a significant efficiency the conventional electromagnetic compatibility normative.

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