ON THE USE OF SPLIT-RING RESONATORS AND COMPLEMENTARY SPLIT-RING RESONATORS FOR NOVEL PRINTED MICROWAVE ELEMENTS: SIMULATIONS, EXPERIMENTS AND DISCUSSIONS

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ABSTRACT

Several novel printed microwave elements are designed making use of either split-ring resonators (SRRs) or complementary split-ring resonators (CSRRs). As an example in this paper, simple 50-Ω microstrip lines are loaded with SRR and CSRR, and very compact band-reject filters have been obtained. Some important stop-band characteristics of these filters have been studied and compared in a detailed manner. Simulations have been accompanied by measurements and good agreement has been obtained between numerical and experimental results.

I. INTRODUCTION

Recently, there has been a growing interest in using the split-ring resonator (SRR) [1] and the complementary split-ring resonator (CSRR) [2] as constituent particles for the design of novel planar microwave components, in particular, band-pass and band-reject filters [2],[3],[4]-[6],[7]-[9]. The advantage of using this kind of resonators for filter design is that they are significantly smaller in size than conventional resonator structures (generally less than one-tenth of a wavelength) enabling the design of very compact filters.

It has been demonstrated that when loaded with SRRs, microstrip lines behave as high-Q, band-reject filters with deep stop-bands in the vicinity of their resonant frequencies due to the generation of an effective medium with negative permeability [4]-[5]. Similarly, a CSRR-loaded microstrip line, which can be considered as the dual of the SRR-loaded line, inhibits signal propagation over a narrow band around the resonant frequency of the CSRRs [2]-[3]. However, as a result of the dual relationship between the SRR and CSRR, this sort of signal inhibition is due to the presence of an effective medium with negative permittivity over the stop-band. In either case, previously propagating waves (in the absence of SRRs or CSRRs) become evanescent waves as a result of the impenetrable nature of the single-negative (SNG) medium.

In this study, our main goal is to design novel printed microwave elements that use SRR and/or CSRR as the main component. For the time being we focus on novel filter designs, in particular band-reject filters and we perform a comparative investigation of SRR- and CSRR-based band-reject filters by examining their stopband characteristics in a detailed manner. Two very simple band-reject filter topologies, one for the SRR and the other for the CSRR, with exactly the same SRR and CSRR dimensions are chosen so that a fair comparison of their stopband characteristics can be performed. Both topologies offer very compact band-reject filters. However, some important stop-band characteristics of SRR-based band-reject filters significantly differ from their CSRR-based counterparts. Some other designs that use SRRs and CSRRs will be presented during the presentation of this paper.

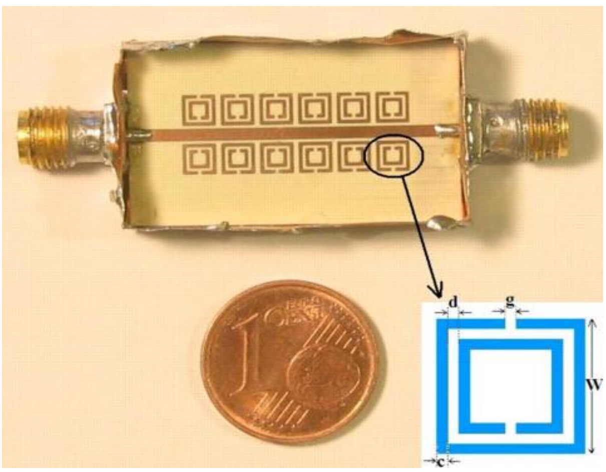

Figure 1: Fabricated SRR-based microstrip band-reject filter; Relevant dimensions: $W = 3$ mm, $c = d = g = 0.3$ mm

II. SRR- AND CSRR-BASED BAND-REJECT FILTERS

a) SRR-Based Band-Reject filter

A microstrip transmission line generates magnetic field lines that close upon themselves around the line. If two arrays of SRRs are placed closely at both sides of the central line, a significant portion of the magnetic field lines induced by the line is expected to cross the SRRs with the desired polarization giving rise to a negative-μ effect over a narrow band around the resonant frequency of the individual SRRs. Hence, inhibition of signal propagation over this band can be achieved.

Based on this idea, an SRR-based band-reject microstrip filter has been designed and fabricated as shown in Figure 1, where 6 SRR pairs (i.e., totally 12 SRRs) have been employed. The width of the central strip is set to 1.15 mm to make the line's characteristics impedance approximately 50 Ω so that relatively low return loss levels are suffered at both port sides. To enhance the coupling of the SRR structures to the central line, square-shaped SRRs rather than originally proposed circular ones have been used. The filter has been implemented on a RO4003C high-frequency laminate (ε_r = 3.38, 0.508 mm (20 mil) substrate height and 1oz. (35 μm metal thickness) copper cladding), which is commercially available from Rogers Corporation. The distance between the rings and the line is set to 0.3 mm. After soldering 3.5-mm SMA female connectors at both ports, scattering parameters are measured using an Agilent N5230A vector network analyzer. Numerical calculations of the scattering parameters are performed using the Method of Moments (MoM)-based electromagnetic solver of Ansoft Designer commercial software. Measured and simulated insertion and return losses are presented in Figure 2, which exhibits a good agreement. The center frequency of the filter is 9.25 GHz. Some minor discrepancies between the measured and simulated return loss values can be attributed to some impedance mismatches as a result of coax-to-microstrip transitions at both connector sides and also imperfections in fabrication process.

b) CSRR-Based Band-Reject Filter

The CSRR is considered as the dual counterpart of the conventional SRR. Thus, a time-varying electric field having a strong component in the axial direction gives rise to an effective-ε medium. Considering this fact in mind, working mechanism of a CSRR-based band-reject filter can be explained as follows: a microstrip transmission line induces electric field lines that originate from the central strip and terminate perpendicularly on the ground plane. Due to the presence of dielectric substrate, field lines are tightly concentrated just beneath the central conductor and the electric flux density reaches its strongest value in the vicinity of this region. Therefore, if an array of CSRRs is etched on the ground plane aligned with the strip, a strong electric coupling with the desired polarization is expected.

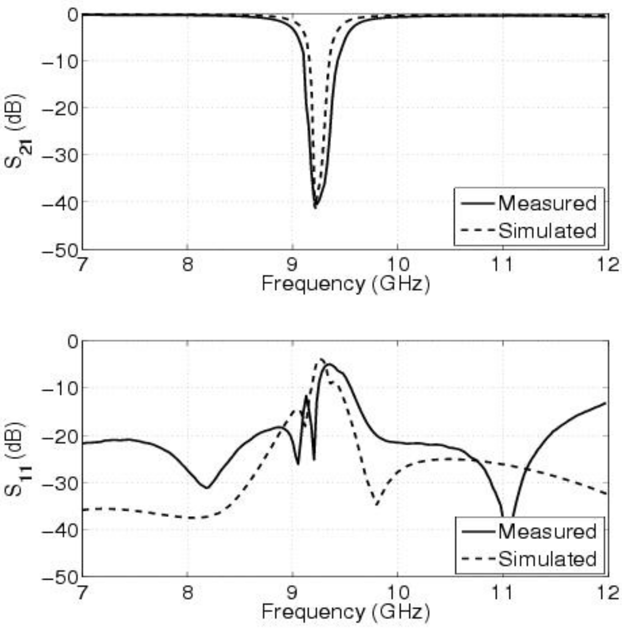

Figure 2: Measured and simulated scattering parameters of the SRR-based band-reject filter

Based on this aforementioned discussion a CSRR-based band-reject filter has been designed and fabricated as shown in Figure 3. All dimensions of the CSRRs have been selected identical to their SRR counterparts so that the operating frequency of the filter is also around 9.25 GHz. Again 6 CSRR stages (CSRRs do not appear in pairs) have been employed. During the fabrication process, the filter has been implemented on the same high frequency laminate. Unfortunately, because the distance between the line and the CSRRs is determined by the thickness of the laminate, this configuration does not allow us to adjust the distance between the CSRRs and the line easily unless a laminate with different substrate height is used. Shape of the CSRRs is not expected to have a drastic effect on the amount of coupling but we have preferred to make use of square CSRRs to be consistent with the topology in the SRR-based case. Therefore, the comparative analysis of the two cases is expected to depend only on whether the microstrip line is loaded with SRRs or CSRRs and should be independent of all dimensions and material properties. The structure has been simulated using the Finite Element Method (FEM)-based High-Frequency Structure Simulator (HFSS) commercial software of Ansoft Corporation. Scattering parameters of the fabricated prototype have been measured using the same Agilent N5230A vector network analyzer. Also, the analyzer has been operated using the same calibration settings for both cases in order to be consistent in the accuracy of measurements. Plots of the insertion and return losses for both numerical and experimental cases are presented in Figure 4. Very good agreement has been obtained between simulated and measured results. If a minimum rejection level of -20 dB in the stop-band is assumed for this filter, the stop-band

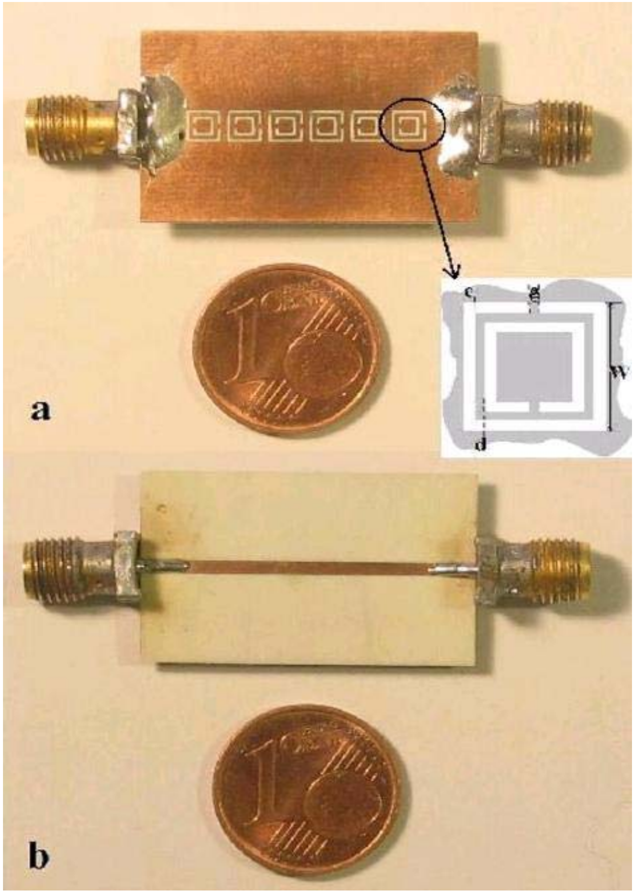

Figure 3: Fabricated CSRR-based microstrip band-reject filter; a) Ground plane, b) 50-Ω line; Relevant dimensions: $W = 3$ mm, $c = d = g = 0.3$ mm

extends from 7.9 GHz to 10.7 GHz yielding a center frequency of approximately 9.3 GHz, which is very close to the center frequency of the SRR-based filter. Small discrepancies can be attributed to tolerances in fabrication process and impedance mismatches created by the coax-to-microstrip transitions just like the SRR-based case. Impedance mismatch problem is evident from the return loss level which is quite high even outside of the stopband.

III. DISCUSSIONS AND CONCLUSIONS

Based on the measurement and simulation results certain similarities and certain discrepancies are observed in the stop-band characteristics of SRR- and CSRR-based band-reject filters. Figure 2 and Figure 4 reveal that the center frequencies of rejection bands of the SRR-based (9.25 GHz) and CSRR-based (9.3 GHz) filters are very close to each other. One of the major differences between the designed filters is the bandwidth of their stop-bands. The CSRR-based filter provides a much wider stopband in its frequency response as seen in Figure 4, whereas the SRR-based filter looks more like a very high-Q notch filter with a very narrow band as shown in Figure 2. Although the CSRR-based filter has a wide stop-band, its sharp transitions between the passband and stopband regions (especially the lower transition edge) reveal its high-Q nature. Another major difference between the two designs is the signal rejection ability of the filters. It is observed that the SRR-based filter gives a maximum rejection level of approximately 40 dB whereas CSRR-based one gives near 60 dB rejection levels.

Because the resonators in both designs have dimensions in the order of one-eleventh of a wavelength at their resonant frequencies and both topologies are completely planar, design of very compact promising devices for printed-circuit board (PCB) and in even more compact dimensions for monolithic microwave integrated circuit (MMIC) technologies might be accomplished. The differences between the SRR- and CSRR-based filters in terms of their bandwidths and rejection capabilities can make them preferable depending on applications. Some other designs that use SRRs and CSRRs will be presented during the presentation.

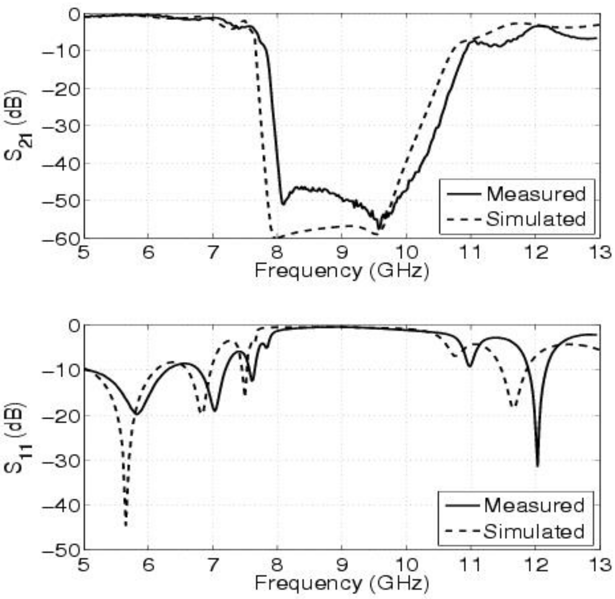

Figure 4: Measured and simulated scattering parameters of the CSRR-based band-reject filter

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