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Metadata Record: https://dspace.lboro.ac.uk/2134/10023

Version: Accepted for publication

Publisher: IEEE (© EurAAP)

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Compact Microstrip Band Stop Filter Using SRR and CSSR: Design, Simulation and Results

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Abstract—Size miniaturization of microwave filters is highly desirable in the today’s rapid changing communications world. Split ring resonators (SRRs) have attracted much interest in recent years as key constituent particles for the design of effective media with negative magnetic permeability ($\mu_{eff} < 0$) or left-handed materials (LHM). This paper demonstrates the potential of the sub-wavelength (i.e. electrically very small) split ring resonators and complementary split ring resonators (CSRRs) inclusions to build compact microstrip band stop filters to reject the unwanted spurious bands in microwave regime. It is simple and compatible with MMIC and PCB technology. Moreover, the magnetic coupling between the SRRs and the microstrip line is also investigated. Numerical calculations of the scattering parameters (S-parameters) are performed using the Method of Moments (MoM)-based electromagnetic solver of Ansoft Designer™ software.

I. INTRODUCTION

Rapid development of wireless communications present extraordinary demand for compact bandstop filters [1]. There exist band stop filters with half wavelength and quarter wavelength resonators. The size of those filters is large at the lower end of microwave frequencies [2]. Many microstrip filter designs have been proposed for size miniaturization and performance enhancement in the past few decades but there are still some areas for improvements.

Recently split ring resonators (SRRs) proposed by Pendry et al. [3] attracted much attention as a canonical metamaterial structure that gives rise to an effective magnetic response without the need for magnetic materials. SRRs have been successfully applied to the fabrication of LHM (some times called Double Negative Materials or Negative Refractive Index Materials) [4-6]. SRRs are a pair of concentric annular rings with splits in them at opposite ends. The rings are made of nonmagnetic metal like copper and have a small gap between them as shown in Fig. 1. In an SRR the capacitance between the two rings balances its inductance. A time-varying magnetic field ($H$) applied perpendicular to the rings surface induces currents which, in dependence on the resonant properties of the structure, produce a magnetic field that may either oppose or enhance the incident field. At frequencies below the resonant frequency of the SRR, the real part of the magnetic permeability $Re(\mu_{eff})$ of the SRR becomes large (positive), and at frequencies higher than resonance, $Re(\mu_{eff})$ becomes negative when the axis of the ring is parallel with the magnetic field component. This negative permeability can be used with the negative electric permeability of another structure to produce negative refractive index materials [7-10].

![Fig. 1](image-url) (a) circular and (b) square split ring resonator, (c) circular and (d) square complementary split ring resonator.

On the other hand, the complementary split-ring resonator (CSRR) structure is achieved by etching SRR in the ground plane. Structures complementary to double split rings were designed and produced by applying the Babinet principle to the split rings [11]. In this way structures with apertures in metal surface are obtained, as shown in Fig. 1. These complementary split rings (CSRR) create negative permittivity $Re(\varepsilon_{eff}) < 0$ instead of $Re(\mu_{eff}) < 0$ near the resonance frequency [12, 13].

This paper takes advantage of the small electrical size of SRRs at resonance (typically one tenth of the free space wavelength or less) to design planar compact microstrip band stop filter using two techniques; microstrip line 1) loaded with SRRs and 2) CSRRs etched in the ground plane, beneath the
Final author version. EuCAP 2010, Barcelona, Spain

microstrip line, with their axes parallel to the vector of the electric field.

II. SRR BAND STOP FILTER DESIGN

The resonance frequency obtained from this inclusion (SRR) is typically much smaller than that corresponding to the classical ring or square open loop resonators of similar dimensions. This feature is related to the large distributed capacitance between the two rings. The small electrical size of the SRRs suggests the possibility of applying this peculiar configuration (or some suitable modified version) to the design of compact filters. There are many different parameters that affect the resonance frequency of a SRR, most dominant being the permittivity of the substrate and the length of the resonator. In the microstrip technology, split-ring resonators can only be etched in the upper substrate side, next to the host microstrip transmission line. To enhance the coupling, the distance between the line and the rings should be as small as possible. A microstrip line loaded with split-ring resonators is a single negative medium, and therefore exhibits a stop-band characteristic.

In order to apply the time varying $\mathbf{H}$-field perpendicularly to the square SRRs surface, a microstrip line which can generate the quasi-TEM wave was used. Microstrip lines are widely used in microwave planar circuit design and microwave integrated circuit (MIC) technology. As it is an open conduit for EM wave transmission, not all of the electric or magnetic fields will be confined in the structure. This fact, along with the existence of a small axial $\mathbf{E}$-field, leads not to a purely TEM wave propagation, but to a quasi-TEM wave of propagation [14]. 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-$\mu$ effect over a narrow band around the resonant frequency of the individual SRRs. Hence, inhibition of signal propagation over this band can be achieved as in Fig.2.

Based on this idea, SRR based band stop microstrip filter has been designed as shown in Fig. 3, where 5 SRRs have been added on each side. The number of SRRs can be varied. The microstrip line with square SRRs (rather than originally proposed circular ones to enhance the SRRs coupling to the central line) printed on a conventional high frequency laminate which is commercially available from Rogers Corporation [15] with 17 $\mu$m thick copper patterns on both sides and dielectric substrate thickness 25 mm. The substrate has a dielectric constant of 3.38 and a dissipation factor of 0.0036 at 10 GHz. In addition, the microstrip line was designed with a 1.46 mm width and a 36 mm length.

Formulas given in [3] which described the SRR structure behaviour were first used to obtain an estimate where the resonances of SRR would occur before the dimensions optimization. These estimates dealt with the radius of the rings, the distance between the rings and the periodicity of the elements. The dimensions of the microstrip line with 50 $\Omega$ impedance were calculated using AWR-TXLINE microstrip line calculator [16]. The geometry of the split ring resonators (SRR) coupled with microstrip line is shown in Fig. 4 with its relevant dimensions.

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Numerical calculations of the scattering parameters are performed using the Method of Moments (MoM)-based
electromagnetic solver of Ansoft Designer™ software. $S_{11}$ and $S_{21}$ values with 7 SRRs are presented in Fig. 5. According to these results, it is very clear that rectangular shaped SRR microstrip lines can be used as effective stop band structures. A peaked notch at 5.41 GHz is visible with a rejection level close to $-50$ dB. A sharp band-stop is obtained in the vicinity of the resonance frequency of the SRRs. The $S_{21}$ exhibits small slopes at both sides of the band-stop and near 0-dB insertion loss outside that band. Fig. 6 shows the frequency response ($S_{11}$ and $S_{21}$) of the proposed filter with various numbers of SRRs on each side.

![Fig. 6](image)

(a) $S_{21}$ and (b) $S_{11}$ of the proposed microstrip filter with various number of SRRs.

Its oblivious that the rejection level depends on the number of SRRs used. To visualize the band stop feature of current suppression, the magnitude of surface current distribution is graphically presented. Fig. 7 shows the surface current distribution inside the band stop frequency region (5.41 GHz) and outside the band stop frequency region of the proposed filter (at a transmission frequency - 4.5 GHz). It can be clearly seen in Fig. 7 (a) that no power is transmitted to Port 2 inside the band stop region. The deference of current level due to the band gap characteristics is obvious. So, determination of the current distribution along proposed structure is a good gauge for prediction of the filter properties.

![Fig. 7](image)

(a) and (b) Surface current distribution at 5.41 GHz and 4.5 GHz.

III. CSSR BAND STOP FILTER DESIGN

In the microstrip technology, CSRRs are achieved by periodically etching capacitive gaps in the ground plane underneath the 50Ω microstrip line. Since CSRRs are excited by the electric field, they produce negative effective permittivity $\text{Re}(\varepsilon_{\text{eff}}) < 0$. Thus, a time varying electric field having a strong component in the axial direction gives rise to an epsilon effective medium. Considering this fact in mind, the working mechanism of a CSRR based band stop 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.

![Fig. 8](image)

Fig. 8 CSRRs etched into the ground plane of the microstrip band stop filter.

Based on this aforementioned discussion a CSRR based band stop filter has been designed, Fig. 8 shows the geometry of the CSRR loaded microstrip. All dimensions of the CSRRs have been selected identical to their SRR counterparts so that the operating frequency of the filter is also around 5.4 GHz. Again seven CSRRs have been employed. 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. The 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 band stop filter 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. Scattering parameters ($S_{11}$ and $S_{21}$) plots are presented in Fig. 9. If a minimum rejection level of -20 dB in the stop-band is assumed for this filter, the stop-band extends from 4 GHz to 5.8 GHz.

It is important to note that the response of CSRR is not rigorously the same as the conventional SRR shown in Fig. 1. This is due to the presence of the dielectric slab which introduces an additional boundary condition at a distance of the CSRR plane. However, they will be approximately similar and the behaviour of the complementary structure excited by an axial electric field will be similar to that of the original SRR excited by an axial magnetic field, providing in both cases a rejected frequency band around the resonance frequency of the particle.

To demonstrate the performance of the proposed stop band filter based on CSRRs, the filter with 1, 3, 5 and 7 CSRRs has been designed and simulated. The plots of $S_{11}$ and $S_{21}$ (which shows the band stop bandwidth and rejection level of the microstrip filter) are presented in Fig. 10. In all cases, a deep rejection band is obtained around the design frequency, with sharp cut-offs, maximum rejection of 50 dB and low return losses. Below the rejection frequency band a flat and perfectly matched pass band is present with very low insertion losses and nearly linear phase variation. Its important to mention here this behaviour is due to the presence of negative effective permittivity and positive permeability near resonant frequency which prevent the wave propagation.

The magnitude of surface current distribution of the CSRR loaded microstrip band stop filter is graphically presented in Fig. 11 which shows the magnitudes at a transmission frequency such as 2 GHz and band stop frequency such as 5 GHz for comparison, it can be clearly seen that no power is transmitted from Port 1 to Port 2 inside the band stop region.

IV. MUTUAL COUPLING INVESTIGATION

Finally, in order to understand the time varying $H$-field coupling effect between the microstrip line and the square SRRs array in Section II, a microstrip line loaded with 1, 3, 5
and 7 SRRs on each side is designed and the surface current distribution is presented in Fig. 12. From Fig. 6 and Fig. 12 its obvious that the rejection level depends on the number of SRRs used and the magnetic coupling (to achieve high levels of suppression with few device stages, high magnetic coupling is required). The surface current intensity (in A/m) represents a grade of ten colours in a range; light blue is the minimum and red is the maximum. It can be seen that, generally, the currents decreases as the number of the SRRs used increased and deeper rejection level is achieved.

![Simulated surface current distribution](image)

(a) one; (b) three; (c) five and (d) seven square SRRs on each side at 5 GHz.

V. CONCLUSIONS

In this paper, a compact stop band microstrip filter based on SRRs and CSRRs has been proposed, successfully designed and simulated. The resulting device is very compact (compared to filters designed from conventional resonators), produces very high rejection with sharp cut-offs in the forbidden band, and exhibits a flat and lossless pass band. This behaviour has been interpreted as corresponding to a frequency band with negative valued permittivity and permeability provided by the SRRs and CSRRs. The size of the structure could be further reduced by tailoring SRR and CSRR dimensions, using a properly modified version of the CSRR or using dielectric substrate with high permeativity. It was also shown that the microstrip line magnetically coupled with split ring resonators (SRRs) and has stop band characteristics which is very promising in filter design. CSRRs are usually etched in the ground plane of the substrate. So compared with the SRR, the CSRR does not occupy extra space and for this reason it is highly suitable for designing of size miniaturized microwave devices. Furthermore, comparing to the SRR stop band width, CSRR filter has a wider band stop extends from 4 GHz to 5.8 GHz.

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