Miniaturized Coplanar Waveguide Stop Band Filters Based on Multiple Tuned Split Ring Resonators

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***Abstract*—A novel compact stop band filter consisting of a 50 Ω coplanar waveguide (CPW) with split ring resonators (SRRs) etched in the back side of the substrate is presented. By aligning SRRs with the slots, a high inductive coupling between line and rings is achieved, with the result of a sharp and narrow rejection band in the vicinity of the resonant frequency of the rings. In order to widen the stop band of the filter, several ring pairs tuned at equally spaced frequencies within the desired gap are cascaded. The frequency response measured in the fabricated prototype device exhibits pronounced slopes at either side of the stop band and near 0 dBs insertion loss outside that band. Since SRR dimensions are much smaller than signal wavelength, the proposed filters are extremely compact and can be used to reject frequency parasitics in CPW structures by simply patterning properly tuned SRRs in the back side metal. Additional advantages are easy fabrication and compatibility with MMIC or PCB technology.**

***Index Terms*—Coplanar waveguide technology, metamaterials, microwave filters, split ring resonators.**

I. Introduction

THE suppression of frequency parasitics, undesired spurious bands or harmonics in microwave and millimeter wave circuits is a requirement in many applications. Traditional techniques (based on the use of half wavelength short circuit stubs, chip capacitors or cascaded rejection band filters) are either narrow band, increase device area or degrade circuit performance. To overcome these limitations, electromagnetic bandgap (EBG) structures have been recently proposed. EBGs are periodic transmission media able to inhibit signal propagation in certain frequency bands and/or directions [1]. In microstrip technology, wide and deep stop bands have been obtained by etching holes or shaped slots in the ground plane [2], [3]. This technique has been successfully used to improve efficiency in broadband power amplifiers by tuning the EBG to the first harmonic [4]. It has been also demonstrated that the spurious pass bands inherent to the frequency response of parallel coupled line filters can be efficiently rejected by periodically modulating strip width [5]. In coplanar waveguide (CPW) technology, EBGs based on strip width modulation have been recently demonstrated to be very effective for the design of low pass filters with huge stop bands, thanks to the elimination of frequency parasitics [6]. In all cited applications, EBG structures are integrated with the device and no extra area is required. However, EBGs scale with frequency, require several stages to provide significant rejection and, therefore, can be relatively big for certain applications.

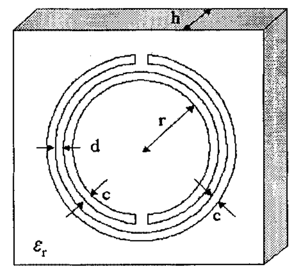

Fig. 1. SRR topology and relevant dimensions.

In this letter, stop band filters based on split ring resonators (SRRs) and compatible with MMIC or PCB fabrication technology are presented for the first time. In contrast to EBG-based devices, SRR filters are sub-wavelength structures, i.e., their dimensions are electrically small. Therefore, high level of compactness is expected by using these structures. Originally proposed by Pendry [7] (see Fig. 1), SRRs are small resonant elements with a high quality factor at microwave frequencies. When they are excited by an external time varying magnetic field applied parallel to the ring axis, an electromotive force around the rings is generated giving rise to current loops in the rings. These current loops are closed through the gap capacitance between concentric rings, which can be significantly high due to the presence of splits in opposite sides. According to this, the SRR behaves as an externally driven LC circuit with a resonant frequency that can be easily tuned by device dimensions (r, c, and d). It has been previously demonstrated that a three dimensional array of rings excited by properly polarized radiation (i.e. magnetic field parallel to ring axis) is able to inhibit signal propagation in the vicinity of the resonant frequency [8]. This has been interpreted as due to the properties of the composite medium, which exhibits a high positive/negative effective magnetic permeability in a narrow frequency range below/above resonance. Following this idea, planar structures consisting of CPWs with SRR elements aligned with the slots and placed in the back side of the substrate are proposed. Since the rings are

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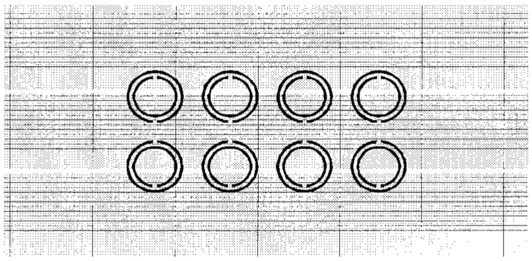

Fig. 2. Layout of the 4-stage singly tuned SRR-CPW stop band filter drawn to scale. Actual device length is 3.5 cm.

parallel and very close to the slots, strong magnetic coupling between line and SRRs is expected in the vicinity of resonance and hence a gap in the frequency response. By virtue of the significant rejection produced by a single SRR pair, the width of the rejected band can be easily tailored by cascading several rings tuned at slightly different frequencies. This is a key advantage in comparison to EBG based filters, where gap width is not an easy controllable parameter. Since rings are etched in the back side metal, the proposed structure can be used to reject frequency parasitics or undesired frequencies in CPW circuits maintaining unaltered their size.

II. Desing of the SRR-CPW Stop Band Filter

A typical layout for a four stage simple tuned stop band filter is depicted in Fig. 2. SRRs are symmetrically disposed in pairs just below the slots to obtain high inductive coupling at resonance. To enhance this coupling, it is convenient to design the host CPW with narrow slot widths in comparison to the radius of the inner ring, r. Another important requirement is the characteristic impedance of the CPW, that must be set to 50 Ω to avoid mismatching in the pass band of the structure. Alternatively, SRRs can be patterned in the upper substrate side between the central strip and ground planes. This has the advantage of easy fabrication (a single metal level suffices), but has two drawbacks: lower magnetic coupling and very wide slots. Since a 50 Ω line cannot be obtained with the slot widths required to accommodate the rings, matching networks at the input/output ports are needed. This complicates device design and increases its length. Therefore, we have only considered matched CPWs with SRRs etched in the back side metal. To obtain a 50 Ω line, the widths of central strip and slots have been set to W $= 5.4$ mm and G $= 0.3$ mm, respectively, (the parameters of the *Arlon 250-LX-0193-43-11* substrate have been considered—$\varepsilon_r = 2.43$, thickness $h = 0.49$ mm). Ring dimensions have been determined following [9] to give a resonant frequency of $f_o = 7.7$ GHz, i.e., $c = d = 0.2$ mm, $r = 1.3$ mm. Finally, the distance between adjacent ring pairs has been set to $l = 5$ mm, a substantially small value compared to the EBG period for this substrate at the resonant frequency of the rings (17 mm). Overall device dimensions could be further reduced by etching a lower number of ring pairs. It has been found that a single SRR pair is able to produce significant rejection, but at the expense of lower frequency selectivity.

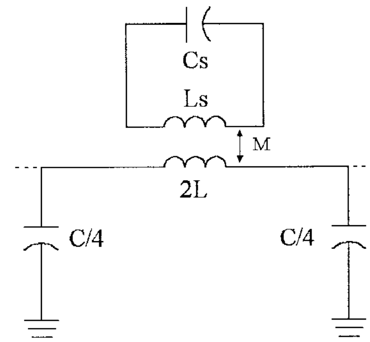

Fig. 3. Lumped element equivalent circuit of the elemental cell for the SRR-CPW filter. Due to symmetry, the magnetic wall concept has been used and the circuit corresponds to one half the basic cell.

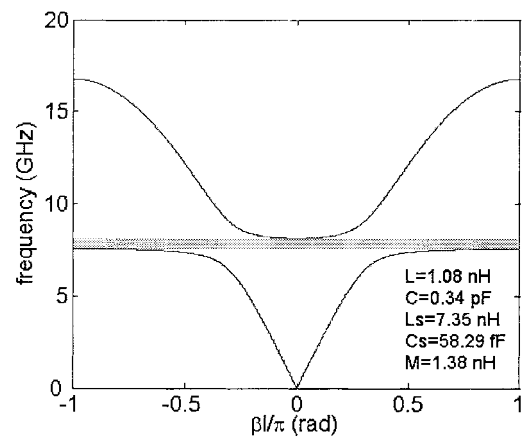

Fig. 4. Dispersion diagram for the lumped element equivalent circuit model of the SRR-CPW stop band filter.

III. Results

To gain more insight on the reflection properties of these structures we have obtained the dispersion relation. This has been inferred from the lumped element equivalent circuit of the unit cell (depicted in Fig. 3), which is valid in the long wavelength regime ($\beta l \ll 1$, where β is the propagation constant for guided waves). L and C are the per-section inductance and capacitance of the line, while SRRs are modeled as parallel resonant circuits (with inductance L_s and capacitance C_s) magnetically coupled to the line through a mutual inductance, M. After some calculation, the dispersion relation has been found to be

$$\cos(\beta l) = 1 - \frac{LC\omega^2}{2} + \frac{\frac{C}{C'_s}}{4\left(1 - \frac{\omega_o^2}{\omega^2}\right)} \qquad (1)$$

with $C'_s = L_s/(M^2\omega_o^2)$, $L'_s = C_s M^2 \omega_o^2$ and $\omega_o^2 = 1/(L_s C_s) = 1/(L'_s C'_s)$. Fig. 4 shows the previous expression in a $\omega - \beta$ representation. A narrow gap above and below the resonant frequency is visible. The frequency response of the structure of Fig. 2 confirms the presence of a narrow rejected band centered at that frequency (Fig. 5). To widen this gap, the distance between adjacent ring pairs, l, can be reduced. However, further gap width control is obtained by means of a multiple tuned structure (Fig. 6). This consists of 5 ring pairs, each with a different resonant frequency. Tuning has been implemented by increasing r in 0.05 mm step increments

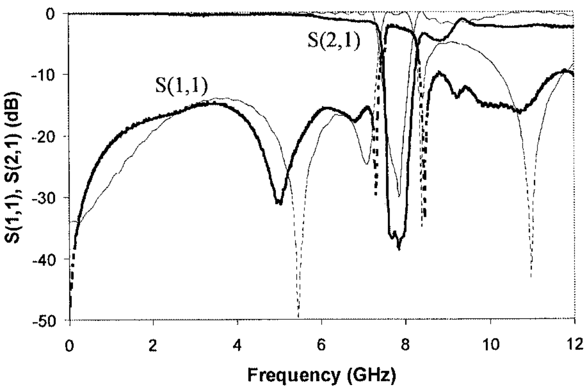

Fig. 5. Simulated (thin line) and measured (bold line) insertion and return losses for the singly tuned SRR-CPW structure. Simulations and measurements have been carried out by means of the *CST Microwave Studio* commercial software and the *Agilent 8722ES* vector network analyzer, respectively.

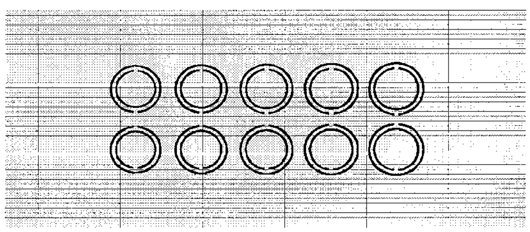

Fig. 6. Layout of the multiple tuned SRR-CPW stop band filter drawn to scale. Actual device length is 4 cm.

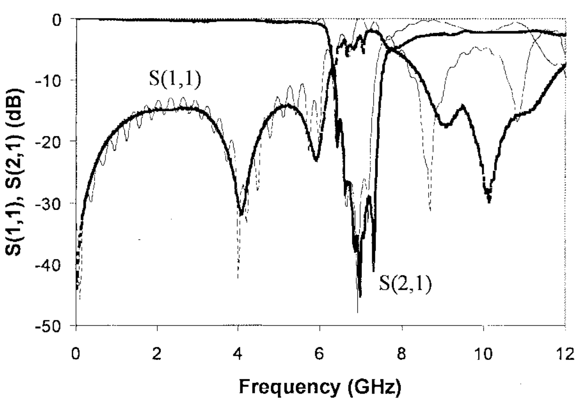

Fig. 7. Simulated (thin line) and measured (bold line) insertion and return losses for the multiple tuned SRR-CPW structure.

and leaving unaltered c and d. The simulated and measured frequency responses, depicted in Fig. 7, show that the rejected band broadens toward lower frequencies. This is expected since an increment of r has the effect of decreasing the resonant frequency of SRRs. It is remarkable the pronounced cutoff at either side of the gap and the absence of significant insertion losses in the pass band. This is very important to use SRRs for the elimination of undesired frequencies in CPW circuits operating in the pass band of the ring backed structure. Since the dimensions of the rings are very small, the stop band can be further widened by adding more ring pairs. Therefore, the proposed multituned stop band filter is compact, broadband and compatible with MMIC and PCB technology.

IV. Conclusion

A new type of CPW stop band filter based on magnetically coupled split ring resonators (SRRs) has been proposed. The structure, a 50 Ω CPW with ring pairs symmetrically placed in the back side of the substrate and aligned with the slots, is very compact provided ring dimensions are small compared to signal wavelength at resonance. It has been experimentally demonstrated that by using an array of rings each tuned at a different frequency, the stop band can be widened and tailored. Due to the high inductive coupling between the line and SRRs at resonance, significant insertion losses ($>$30 dBs) in the rejected band and very good frequency selectivity have been measured. From a technological point of view, the structure is compatible with MMIC and PCB processes. These ideas can be also applied to microstrip technology by placing the rings in the upper side of the substrate, near the strip. Work is in progress in this direction.

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