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COPLANAR WAVEGUIDES INCORPORATING SRRS OR CSRRS

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Abstract—We numerically and experimentally evaluate different designs of coplanar waveguides (CPWs) loaded with split ring resonators (SRRs) and complementary split ring resonators (CSRRs), respectively. In particular, we are interested in their stop-band performance. Starting from structures which consist of two concentric rings, we study devices with only an outer ring, an inner ring or multiple concentric rings. Furthermore, our study shows that introducing slots in the proximity of the SRR or CSRR will modify the stop-band considerably. Single and multiple unit cells for both designs are fabricated and measured. Our results demonstrate the potential of the CSRR/CPW structure for filter applications.

1. INTRODUCTION

There is a necessity in microwave and millimeter-wave circuits to suppress frequency parasitics and harmonics. To overcome the limitations of the conventional techniques, electromagnetic bandgap (EBG) structures have been proposed [1, 2]. However, for some applications EBGs can be relatively large because they rely on the half wavelength rule. Meanwhile, they need a few periods to provide considerable rejection. The emergence of broadband wireless applications has brought new demands for low-cost, miniaturized circuits and modules in the millimeter-wave frequency range. As an alternative to EBGs, a planar transmission line can be coupled to split-ring resonators (SRRs). SRRs were originally proposed by Pendry et al. [3]. Arranged periodically, they can form an effective medium

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with a negative magnetic permeability in the vicinity of the resonant frequency. The electrical dimensions of SRRs are small at the resonant frequency as they are sub-wavelength structures.

The coplanar waveguide (CPW) offers several advantages over the conventional microstrip line. The most important benefit is that the CPW facilitates easy shunt as well as series surface mounting of active and passive devices. Another advantage is that it is easy to have some circuit elements in series or in parallel to the CPW. It has led to several applications in microwave integrated circuits (MICs). These, as well as several other advantages make the CPW ideally suited for microwave integrated circuits and many other applications [4, 5].

In 2003, Martin et al. [6] proposed to integrate SRRs into planar structures fabricated by a standard PCB process. The SRR elements are placed on the backside of the substrate and aligned with the gaps of the CPW [6]. The resulting structure consists of two metal layers. It serves as a bandstop filter (BSF) with a magnetic resonance. In [7], an alternative approach was proposed to construct a BSF. This approach relies on a single metal layer making the device fabrication easier. As the rings need to be excited by a magnetic field, the rings are etched inside the gaps of the CPW after those gaps were widened [7]. A comparison between both structures shows that the one metal layer approach leads to a poor filter performance. The wide gaps hold the SRRs increase the characteristic impedance of the line greatly. This leads to an unacceptable level of return loss. Therefore, the preferred structure was the one proposed earlier with two metal layers.

In 2004, the Babinet principle was applied to the conventional SRR for the first time [8]. The resulting resonator is a complementary SRR (CSRR), which can be etched into the ground plane. The microstrip line on the top of the substrate electrically excites the CSRR [8]. By etching the CSRRs in the center conductor of the CPW, the same stop band behavior in the transmission response can be achieved [9]. However, a large number of unit cells is required to achieve an acceptable rejection level [9]. Moreover, Babinet's principle of duality can be employed in a modified way to be explained in Section 3 to overcome this problem. The structure proposed by us consists of a CSRR incorporated within the CPW [10]. This resonator exhibits dual characteristics of the SRRs loaded microstrip line structure, according to the concept of duality.

Furthermore, it is known that the bandwidth provided by an SRR/CPW structure is rather small and not sufficient for some applications (see, e.g., [11]). To circumvent this drawback it has been proposed to use several SRR cells in series, each of which has a slightly different resonance frequency. Going from one to five SRR cells, for instance, increases the bandwidth by 30% [6]. Naturally, the CSRR/CPW structure has the same limitation because of the duality. Recently, we introduced a concept to widen the bandwidth by introducing slots in close proximity of the CSRRs [10]. These slots can easily be tailored to achieve the desired stop bandwidth. The overall structure (a single CSRR plus slots) is still small since no further cells have to be added.

This paper gives a comprehensive comparison of the stop-band performance of CPWs loaded with SRRs and CSRRs, respectively. Single and multiple unit cells for both designs are fabricated and measured. We obtain good agreement between simulation and experiment. Furthermore, we investigate structures which consist of two concentric rings and structures with only an outer ring, only an inner ring or multiple concentric rings. In addition, we show that introducing slots in the proximity of the SRRs or CSRRs will modify the stop-band considerably. This effect can be used to custom-tailor the bandwidth to meet the design specification.

2. STRUCTURAL AND EXPERIMENTAL DETAILS

Figure 1 shows the dimensions of the SRRs and CSRRs. Both have an external radius of $r = 3.6\,\mathrm{mm}$, a "width" of $c = 0.27\,\mathrm{mm}$, a "separation" between the rings of $d = 0.43\,\mathrm{mm}$, and a length of the gap or "metallic bridge", respectively, of $g = 0.43\,\mathrm{mm}$. The different structures studied are shown schematically as insets in the subsequent figures. The distance between the centers of any pair of resonators is 8 mm. At the edges of the structure we added the CPW tapers to exclude measurement errors due to soldering connectors to the devices. The taper was verified through simulations and experiments to provide maximum matching between the two sides of the CPW. The total length of all structures with the tapers is 44 mm, while the height is 24 mm. All structures are realized on 0.5 mm thick FR-4 substrate,

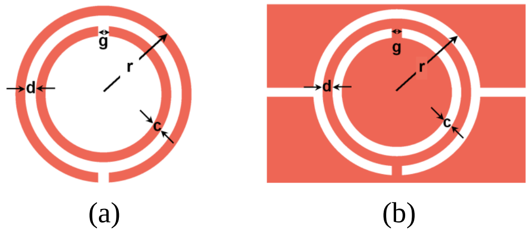


Figure 1. Dimensions of SRR and CSRR.

having a dielectric constant of $\varepsilon_r = 4.2$ and a loss tangent of 0.02.

The performance of the SRR- and CSRR-loaded CPWs were first evaluated using a commercial software package (Ansoft HFSS [12], a 3D full-wave solver based on the finite element method with adaptive iterative meshing). In all cases, the signal propagation is inhibited in the same frequency band. Subsequently, the S-parameters of the fabricated structures are measured between 2 and 6 GHz using an HP E8361A vector network analyzer (VNA) with a microstrip test fixture (Wiltron 3680). A thru-short-line calibration was performed for the CPW. The return loss was better than 28 dB for the band of interest.

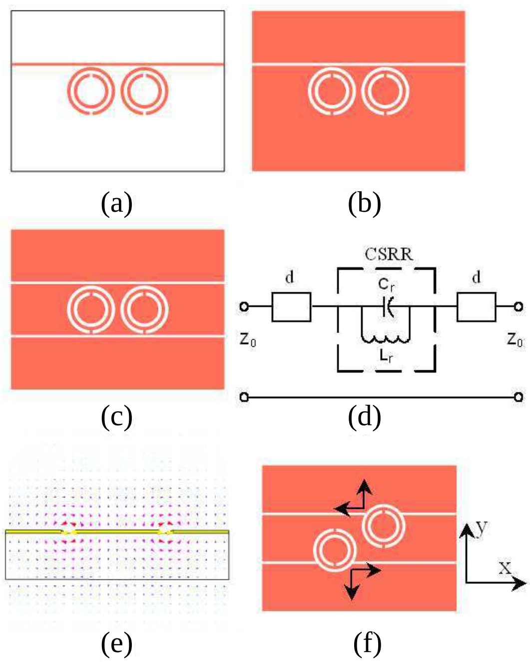


Figure 2. (a) SRRs loading a microstrip line, (b) CSRRs loading a slot line, (c) CSRRs loading the center conductor of a CPW, (d) the equivalent circuit model of a unit cell of the structure in (c), (e) E-field distribution in the CPW and (f) the direction in which we moved the CSRRs.

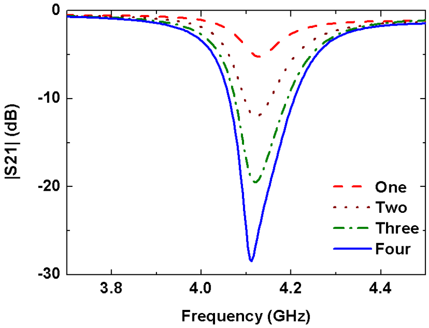


Figure 3. The transmission response of one, two, three, and four unit cells etched into the center conductor of the CPW.

3. THE EVOLUTION BEHIND THE CSRR-CPW STRUCTURE

A simple structure is considered as shown in Fig. 2(a). It consists of a microstrip line loaded with two SRRs on the top of the substrate and a ground plane on the bottom side. Applying Babinet's principle to this structure leads to a slot line loaded with CSRRs as depicted in Fig. 2(b). The CPW requires another slot line as in Fig. 2(c). The unit cell of this structure can be modeled (Fig. 2(d)) as a CPW loaded with CSRRs [13]. As mentioned earlier, many cells are required to achieve acceptable performance [9]. Fig. 3 shows the transmission response of four structures with one, two, three, and four unit cells, respectively. It is noticed that many cells are required to achieve a good rejection level. This is in agreement with the results presented in Ref. [9]. Studying the field distribution in the CPW (Fig. 2(e)), shows that the electric field is enhanced close to the gaps of the CPW. This inspired us to move the two CSRRs in the opposite y-directions (as indicated by the vertical arrows in Fig. 2(f)) until their centers coincide with the gaps of the CPW. In addition, we move the CSRRs towards each other in x-directions (as indicated by the horizontal arrows in Fig. 2(f)) until they hold the same x-position. This leads to a structure which is central for our manuscript. The structure is shown in the inset of Fig. 7(a). For this geometry, the excitation of the CSRRs is enhanced. Moreover, the total size required to achieve a specific performance will be much smaller. The equivalent circuit model is still valid for the unit cell if the magnetic wall concept is considered. As the excitation is enhanced, this should be reflected in the parameters of the model.

4. NUMERICAL AND EXPERIMENTAL RESULTS

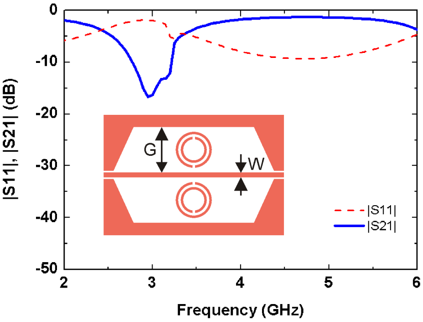


Figure 4. Simulated insertion loss (solid line) and return loss (dashed line) for the single metal CPW structure with SRRs on the top. The SSRs have been placed at the middle propagation path. The CPW signal strip width "W" is 1 mm, and its gap "G" is 9 mm.

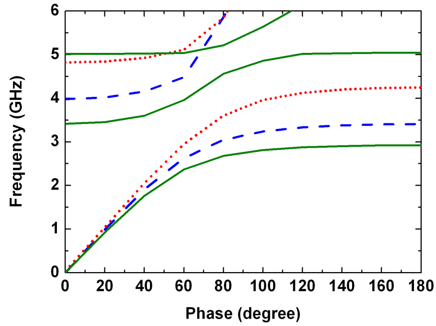
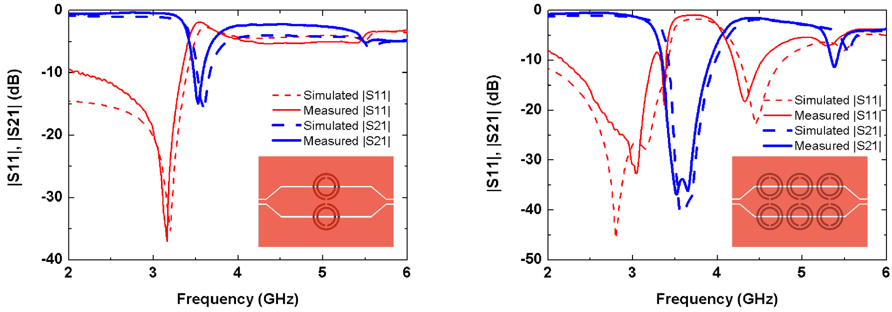


Figure 5. Dispersion analysis of the structure with only inner outer rings (dashed lines), inner rings (dotted lines), and both (solid lines).

Here, we aim for a complete and fair comparison for all structures which have been proposed. We shall start with the one proposed in Ref. [7] for which we only show simulations. It consists of one metal layer only. Note that a device with only a single metal layer is easier to be fabricated than a structure based on two metalized layers. The gaps of the CPW are broadened to provide an enough space to hold the SRRs. The SRRs are excited magnetically because the magnetic field is concentrated in the gaps. Fig. 4 shows the transmission parameters obtained numerically. The transmission depicts a bandstop behavior due to the magnetic resonance frequency. Observing the return loss, it is noticed that the performance is incredibly poor. The unacceptable return loss arises from the fact that the structure is highly mismatched.

Next, we shall present the simulated and measured results for the structures with a single and three SRRs cells placed on the bottom layer of the substrate. The dispersion analysis (Fig. 5) shows that there is an unexpected narrowband mode around 5 GHz which does not appear in the cases of outer or inner rings only. This is a result of having two resonators with close modes. The same effect has been observed for metamaterial bandpass filters [14].

Figure 6(a) shows simulated (dashed line) and measured (solid line) magnitudes for the insertion and return losses for a single SRR



(a) (b)

Figure 6. (a) Simulated (dashed line) and measured (solid line) insertion and return losses for a CPW loaded with a single pair of SRRs positioned on the bottom layer of the substrate and (b) simulated (dashed line) and measured (solid line) insertion and return losses for a CPW loaded with three SRR pairs placed on the bottom layer of the substrate.

unit cell. A notch in the transmission response is observed in the vicinity of the magnetic resonance frequency. The suppression level is about 15 dB. The stop band is rather narrow because the negative permeability occurs in a narrow bandwidth. The return loss (S_{11}) level at lower frequencies is 14 dB in the simulation and only 9 dB in the measurements. However, the measured data obtained experimentally are in good agreement with the simulation. A second mode is observed around 5.5 GHz. It results from the coupling of the outer and inner rings. The small discrepancies between simulation and measurements are attributed mainly to the inhomogeneities in the SRRs.

Some papers discussed already the resonances and polarizabilities of SRRs [15], the inherent saturation of the resonant frequency when increasing the number of the rings [16], the miniaturization of the CSRRs loaded microstrip lines [17], and the group velocity in split ring resonators coupled to microstrip lines [18]. We carried out an extensive study for this kind of filter design. We simulated structures which have only an outer ring, only an inner ring, or both rings. We found magnetic resonance frequencies of 3.92, 4.9, and 3.6 GHz, respectively. The rejection level at the resonance frequency was almost the same. This means that one could use only a single ring instead of a concentric double SRR. Moreover, miniaturization is supported by using two concentric rings. Our studies show that the two rings couple to each other. This leads to a new resonance frequency which is lower than that of both of the two individual rings. This lower frequency could also be obtained by using one single ring, but this would have to have a larger radius. This finding inspired us to investigate structures with a higher number of concentric rings. We find that the resonance frequency deceases another 2% when going from two to four concentric rings (two additional rings were added in the center of the two ring structure to keep the outer SRR dimensions the same). We conclude that only a very small spectral shift would be observed if further rings are added. This can be understood intuitively as adding concentric rings inside the first two rings increases the metallic area in the middle of the structure. There is a saturation in the total resonator parameters, so the shift in the resonance frequency saturates [16]. Moreover, adding more rings with the dimensions given above ($r = 3.6$ mm, $c = 0.27$ mm, and $d = 0.43$ mm) will deteriorate the field exciting the rings [18]. The inner rings will be excited only with a little amount of the magnetic field. Therefore, it is logical that the shift in the resonance frequency saturates. However, reducing the distance between the rings will be an avenue to increase the coupling and, hence, to decrease the resonance frequency. SRRs are considered as lumped or quasilumped elements in [15]. Their electrical size is $\lambda_g/8$ according to the outer radius of the SRRs and their resonance frequency, where λ_g is the guide wavelength. In the case of CSRRs the electrical size is $\lambda_g/6$. However, for a fair comparison one should take into account two structures with the same performance and compare them. Moreover, the structure with CSRRs is only one metal layer that might be desirable in many applications.

Figure 6(b) shows the simulated and measured insertion and return losses for three SRR cells. A significant improvement in the suppression level compared to the case of only one SRR cell. For the three cells it is almost 40 dB. Furthermore, the increase in the pair number leads to a sharper rejection band. The measurements are in very good agreement with the simulations. For frequencies above 4 GHz the return loss is higher than that of the structure with the single pair.

A previous dispersion analysis for the CPW containing CSRRs showed that the structure has a bandgap between 4.2 and 5.6 GHz [10], i.e., the expected stop-band resonance frequency is close to 5 GHz. Fig. 7(a) depicts the simulated and measured insertion and return losses for a structure with a single CSRR cell. If -10 dB is taken as a reference level, the stop-band ranges from 4.6 to 5.5 GHz in good agreement with the dispersion analysis. The simulated results and the calculations of the dispersion characteristics are confirmed by the measured S-parameters of the fabricated structure. However, outside the frequency gap, the structures exhibit excellent matching with insignificant insertion loss. It is remarkable that the measured rejection

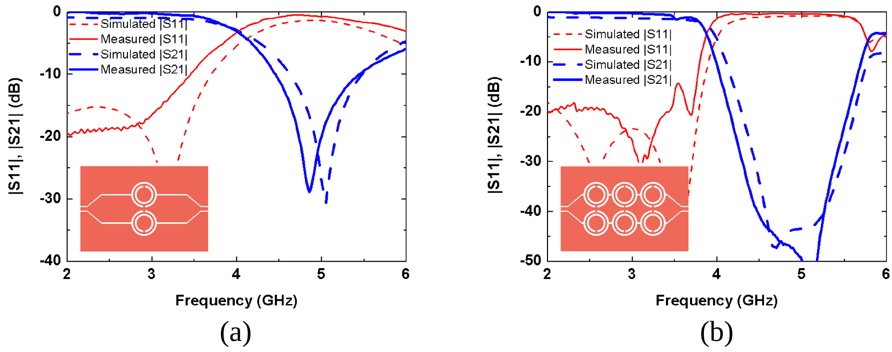


Figure 7. (a) Simulated (dashed line) and measured (solid line) insertion and return losses for a CPW incorporating a single pair of CSRRs and (b) simulated (dashed line) and measured (solid line) insertion and return losses for a CPW incorporating three CSRR pairs.

level in the forbidden band, which is close to 30 dB for the CSRR structure, is at least twice that of the structure with an SRR. Multiple pairs of SRRs are necessary to obtain this suppression level. This means that this structure with only one cell and one metal layer can achieve the same behavior as a double layer structure with many SRR cells. The discrepancy between the resonance frequencies of SRR and CSRR arises mainly from the effect of the dielectric substrate affecting the resonance frequencies in a different way. This is in agreement with the results in Ref. [19].

Hence, it is clear that CSRR provides an effective way to eliminate frequency parasitics in CPW structures. Moreover, the return loss level at lower frequencies is about 20 dB, which is also better than that of the structure containing SRRs. In addition, only one metal layer simplifies the fabrication process considerably.

The simulated and measured insertion and return losses for a structure with three CSRR cells are shown in Fig. 7(b). The rejection level is higher and the bandwidth is increased as compared to the case of only one CSRR cell. The 10 dB bandwidth ranges from 4 GHz to 5.65 GHz and is in better agreement with the dispersion analysis (not shown) than that observed for one CSRR cell. This is indeed logical and understandable, since the dispersion analysis is carried out for a structure which has an infinite number of cells. A remarkable improvement in the suppression level is observed. It is almost 50 dB in this case. The measurements are again in very good agreement with the simulations.

In the following, we show that slots added to the structure in the

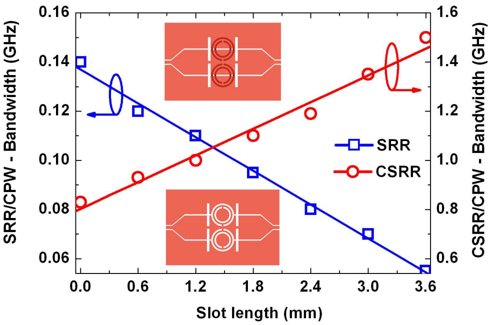


Figure 8. Bandwidth of structures containing slots close to the concentric rings as a function of the slot length. Left scale and open rectangles: SRR/CPW with slots. Right scale and open circles: CSRR/CPW with slots.

proximity of the SRRs or CSRRs significantly modify the bandwidth. Here, we study the influence of the slot length for structures containing one pair of SRRs or CSRRs, respectively. The symbols in Fig. 8 depict the simulated bandwidth for the two types of structures versus the slot length. The solid lines represent linear fits to the data. The slots are etched into the ground plane and the center conductor as shown in the insets of Fig. 8. The slot width is 0.8 mm. The slot length does not exceed a tenth of the resonance wavelength in order to preserve the size requirements of metamaterials. Surprisingly, a variation of the slot length affects the bandwidth differently for SRR and CSRR structures. The bandwidth decreases for the SRR structure as the slot length increases. In contrast, it increases in the case of CSRR structure. This can be seen as another proof for Babinet principle of duality which inspired us to incorporate CSRRs into CPW. Note, that the y-axis scale on the right side (CSRR) of Fig. 8 is ten times that of the left side (SRR). Yet, it is worth to mention that the percentage by which the bandwidth increases or decreases is similar for both structures. Hence, the slots influence both structures by almost the same weight.

Both slots (in a ground plane and in the center conductor) can be modeled as a series inductance with lumped resistance. The SRR behaves inductively in the lower band (less than the resonance frequency). For frequencies above the resonance region, the SRR exhibits a dominant capacitive behavior, which results from the effective capacitance between the internal and the external rings. The CSRR structure shows an inductive behavior in the resonance region. This explains why the slots have affected the later structure more strongly. As an example, Fig. 9 shows the simulation (a) and measurement (b) for the insertion and the return losses of a single CSRR cell with and without the slots. The slots length is equal to the outer radius, which is 3.6 mm. This example is a proof of the concept and in good agreement between the measured results and the numeric calculations.

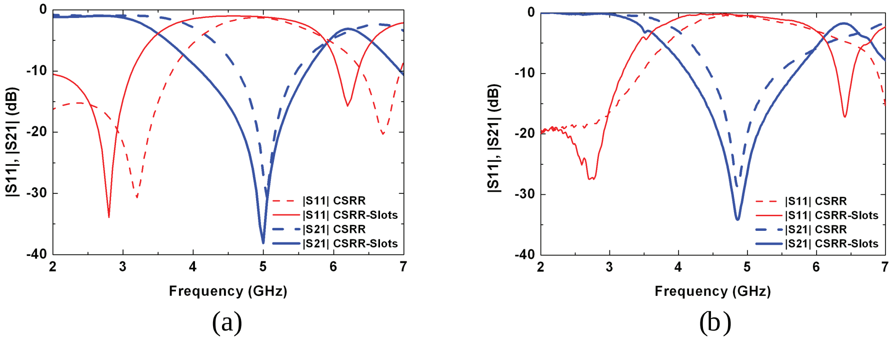


Figure 9. (a) Simulated insertion and return losses for a CPW incorporating a single pair of CSRRs (dashed line) and a single pair of CSRRs with slots (solid line) and (b) measured insertion and return losses for a CPW incorporating a single pair of CSRRs (dashed line) and a single pair of CSRRs with slots (solid line).

5. CONCLUSION

By experimental and numerical study, we have systematically evaluated and compared the performance of bandstop filters based on metamaterials with SRRs or CSRRs resonators coupled to a CPW. Our study demonstrates the superior performance of the CSRR/CPW structure. In addition, we have shown that introducing slots in the proximity of the SRRs or CSRRs can modify the bandwidth considerably. This effect can be used to fit the bandwidth for the design specifications.

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