Selective Mode Suppression in Coplanar Waveguides Using Metamaterial Resonators

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Abstract

In this paper, it is shown that split ring resonators (SRRs) and complementary split ring resonators (CSRRs) can be used to selectively suppress the odd (slot) mode or the even (fundamental) mode, respectively, in coplanar waveguides (CPWs). To this end, it is necessary to symmetrically etch the SRRs and the CSRRs in the line. An interpretation of this behavior is reported. The paper is also supported by experimental results, and some applications are highlighted.

1. Introduction

Coplanar waveguides loaded with pairs of split ring resonators (SRRs) (see Fig. 1a) have been proposed as a mean to achieve one-dimensional planar negative permeability structures [1]. As consequence of the negative effective permeability, these structures inhibit the fundamental (even) mode of the CPW in the vicinity of the resonance frequency of the SRRs. Alternatively, the stop band behavior of these structures can be interpreted as due to the inductive coupling between the CPW and the pairs of SRRs at resonance. The circuit model (unit cell) of CPW transmission lines loaded with pairs of SRRs was first introduced in [1], and later revised in [2]. In [1], the magnetic wall concept was used, taking benefit of the symmetry of the structure and the even nature of the fundamental mode of the CPW. In [2], the unit cell was modeled by considering both SRRs (i.e., the magnetic wall concept was not used). Indeed, the main relevant improvement of the model reported in [2], as compared to the model reported in [1], is the position of the inductance modeling the shunt strips of CPWs loaded with the pairs of SRRs and shunt connected strips (i.e., left handed lines). However, this aspect is not fundamental for this paper since we are not considering left handed lines, that is, the CPW lines are only loaded with SRRs.

The lines considered in this paper are CPWs loaded with single SRRs symmetrically etched in the back substrate side. As will be shown, these lines are transparent to signal propagation for the fundamental (even) CPW mode, whereas they inhibit the odd (slot) mode in the vicinity of SRR resonance. For completeness, we will also analyze CPWs loaded with complementary split ring resonators (CSRRs) [3] symmetrically etched in the central strip. As will be shown, these CSRR-loaded CPW lines are transparent for the slot mode and opaque for the fundamental mode in the vicinity of CSRR resonance. The circuit model of a CPW loaded with symmetrically etched SRRs/CSRRs is provided in this paper, and used to analyze the behavior of the line. The paper is supported by experimental results, and, finally, some potential applications are highlighted.

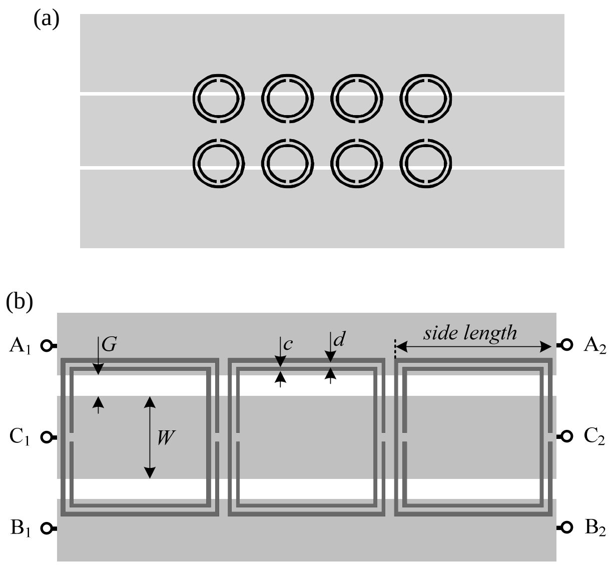

Figure 1: CPW loaded with symmetrically etched SRRs; CPW loaded with pairs of SRRs (a) [1], and CPW loaded with single SRRs (b). The ground plane is depicted in light grey. The SRRs are etched in the back side metallization. The relevant dimensions are indicated.

2. Selective mode suppression in SRR- and CSRR-loaded CPW transmission lines

The first CPW transmission lines under study are loaded with single and symmetrically etched SRRs, as depicted in Fig. 1(b). For the fundamental CPW mode, there is a magnetic wall at the symmetry plane of the structure, and the SRRs cannot be excited at their first resonance since they exhibit an electric wall at their symmetry plane at this resonance [4]. The magnetic field lines generated by the currents flowing on the CPW structure are contra directional in the slot regions. Since the SRRs are symmetrically etched in the back substrate side, the axial components of the magnetic field lines within the SRR region exactly cancel, there is not a net axial magnetic field in that region, and the SRRs cannot be magnetically driven (the symmetry also precludes that the particles can be excited by means of the electric field present between the central strip and the ground planes). Thus, the structure is transparent for the fundamental CPW mode. However, there is a net axial magnetic field within the SRR region for the slot (odd) mode, the particle is excited at its first resonance and, as a result, the injected power is expected to return back to the source at that frequency.

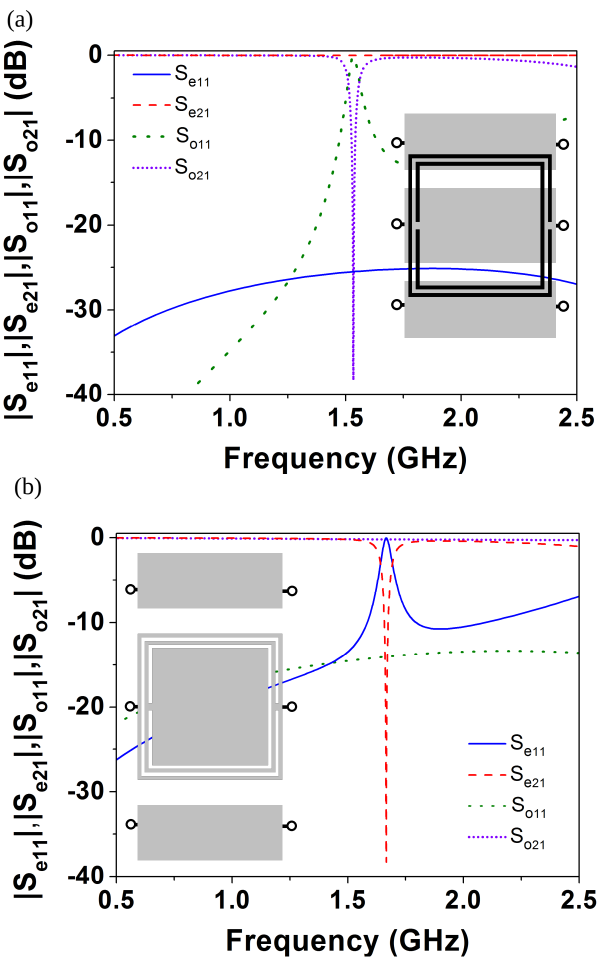

Figure 2: Frequency response for CPW (*e*) and slot (*o*) mode of the indicated CPW loaded with (a) SRR and (b) CSRR. The substrate is the *Rogers RO3010* with thickness h=1.27 mm and dielectric constant ε_r=10.2. The dimensions are: for the SRR and CSRR, c=d=0.2 mm, and *side length*=7.6 mm; for the CPW lines, W=4 mm (a), W=8 mm (b), G=1 mm (a), and G=1.4 mm (b). The characteristic impedance of the CPW mode (even mode) is 50 Ω. The even and odd modes are fed by, respectively, a 50 Ω coplanar port and a 100 Ω differential port.

Let us now consider that the CPW is loaded with a square-shaped CSRR symmetrically etched in the central strip, as the inset of Fig. 2(b) illustrates. In this case, the magnetic wall of the CPW structure (fundamental mode) is perfectly aligned with the magnetic wall of the particle at its resonance frequency [5], and signal is inhibited in the vicinity of CSRR resonance. Conversely, for the slot mode, there is not a net axial electric field in the inner metallic region of the CSRR, the resonator cannot be excited, and the line is transparent for this mode (symmetry also cancels the particle activation through the magnetic field induced in the line).

To demonstrate the previous statements, we have simulated (by means of the commercial software *Agilent Momentum*) the transmission and reflection coefficients of a CPW loaded with a single square-shaped SRR for the even and odd mode (see Fig. 2a). As can be seen, the structure is transparent to the fundamental (even) mode, but a notch is clearly visible at SRR resonance for the slot mode. For the CPW loaded with a CSRR (Fig. 2b), the fundamental mode is inhibited in the vicinity of CSRR resonance, whereas the slot mode is transmitted between the input and output ports.

The main conclusions of this section are: (i) a CPW loaded with a symmetric SRR exhibits for the odd mode an identical behavior to that of a CPW loaded with pairs of SRRs for the fundamental mode, that is, a notch in the transmission coefficient; however, the line is transparent to the fundamental mode; (ii) a CPW loaded with a CSRR in the central strip inhibits the fundamental mode in the vicinity of particle resonance (similar to microstrip lines with CSRRs etched in the ground plane), but it is transparent to the odd mode.

3. Circuit model of a CPW loaded with symmetric SRRs

The lumped element equivalent circuit model of the structure of Fig. 1(b) (unit cell) is depicted in Fig. 3(a). The coupling between adjacent resonators is considered to be negligible. The metallic terminals at ports 1 and 2 (shown in Fig. 1b) are also indicated for a better comprehension. C models the slot capacitance of the CPW line, L_e is the inductance of the line for the fundamental mode, L_o is the inductance of the line for the odd mode, the SRR is modeled as a resonant tank (L_s-C_s), M is the mutual inductance between the SRR and each half of the CPW transmission line, and, finally, C_a accounts for the electric coupling between the line and the SRRs. The electric coupling between the CPW transmission line and the SRR has been neglected so far. However, contrary to previous reported structures (for instance, that shown in Fig. 1a), in the structure of Fig. 1(b), the slits of the SRR are aligned with the line axis. It is well known that SRRs exhibit cross polarization, that is, they can be excited by means of an axial magnetic field, but they can also be driven by means of an electric field with a non negligible component in the plane of the particle and orthogonal to the plane containing the slits. Since for the odd mode of a CPW, there is a net electric field across the slots of the CPW transmission line, the electric coupling cannot be a priori neglected.

For the fundamental (even) mode, the terminals A_1, A_2, B_1 and B_2 are grounded, a magnetic wall arises in the symmetry plane, the SRR is opened, and the equivalent circuit model is simply that of a conventional transmission line (Fig. 3b). For the odd mode, the feeding signal is applied between the terminals A_1 and B_1 (i.e., port 1 and 2 are differential ports). Thus, the symmetry plane exhibits a virtual ground, and the equivalent circuit model that results after applying the electric wall concept is identical to that of a CPW loaded with a pair of SRRs [1], namely a transmission line inductively coupled to a SRR, but including electric coupling as well (Fig. 3c).

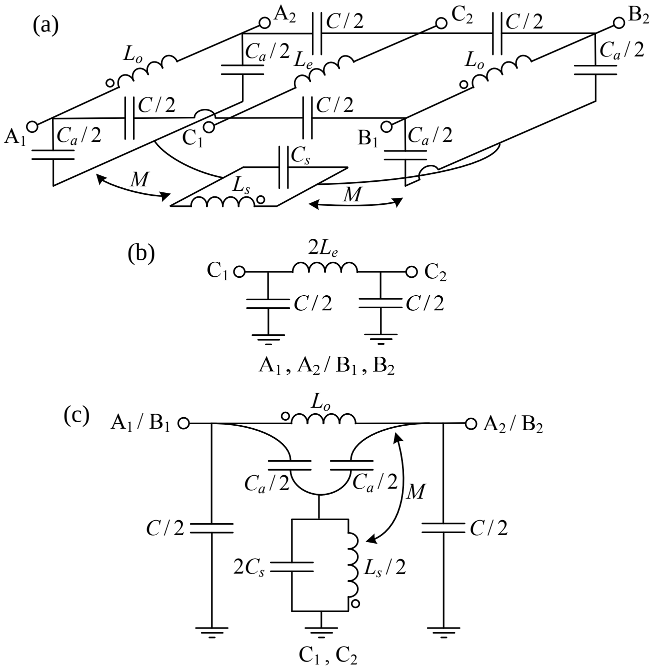

Figure 3: Equivalent circuit model (unit cell) of a CPW loaded with symmetrically etched SRRs (a); equivalent circuit model for the even mode (b); equivalent circuit model for the odd mode (c).

From the electromagnetic simulation of the structure of Fig. 2(a) corresponding to the odd mode, we can extract the parameters of the model of Fig. 3(c), according to the procedure described in [6]. Actually, the procedure described in [6] does not account for electric coupling. The circuit simulation obtained from the extracted parameters does not accurately fit to the full wave simulations of Fig. 2(a) for the odd mode. This means that electric coupling must be considered for an accurate description of the structure. Therefore, we have inferred the new circuit values (including C_a) by curve fitting. The comparison between the circuit and electromagnetic simulations is shown in Fig. 4, where the element values are indicated (see figure caption). As can be appreciated, good agreement is obtained by including electric coupling in the circuit simulation.

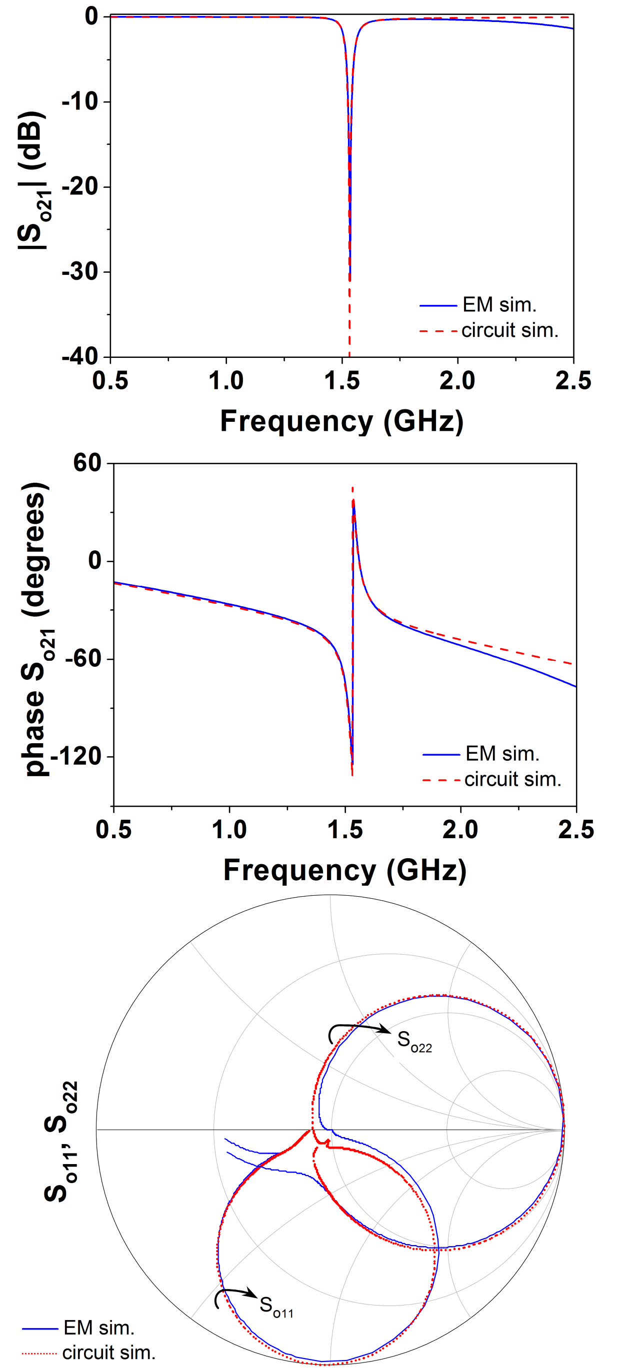

Figure 4: Comparison of the electromagnetic and circuit simulation of the structure of Fig. 2(a) for the odd mode. The element values (referred to the circuit of Fig. 3c) are: C= 1.38 pF, L_o=2.96 nH, L_s=3.66 nH, C_s= 2.73 pF, M=0.66 nH, and C_a= 0.4 pF.

4. Circuit model of a CPW loaded with symmetric CSRRs

The lumped element equivalent circuit model of the CPW loaded with CSRRs in the central strip (Fig. 2b) is shown in Fig. 5 (inter-resonator coupling has not been considered). C

models the slot capacitance of the CPW line, L_e is the inductance of the line for the fundamental mode, L_o is the inductance of the line for the odd mode, the CSRR is modeled as a resonant tank (L_c-C_c), and, finally, M accounts for the magnetic coupling between the line and the CSRR. The magnetic coupling between the CPW transmission line and the CSRR has been neglected so far. However, contrary to previous reported structures, in the structure of Fig. 2(b), the slits of the CSRR are aligned with the line axis. Under these conditions, cross polarization effects are present and, hence, inductive coupling must be also included for accurate modeling.

Following a procedure similar to that explained in the previous section, we have extracted the parameters for the even mode corresponding to the electromagnetic simulation of the structure shown in Fig. 2(b) [7]. The comparison between the electromagnetic and circuit simulation is depicted in Fig. 6 (the element values are indicated in the caption), where it can be appreciated that the circuit and electromagnetic simulations are in good accordance.

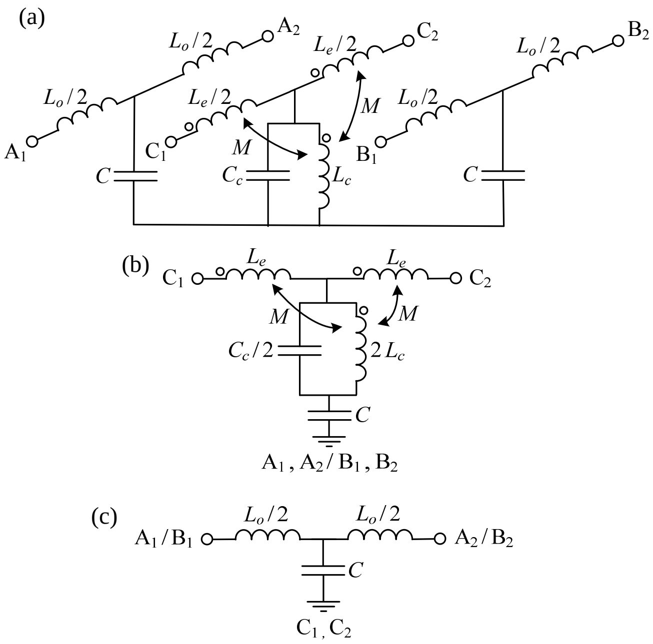

Figure 5: Equivalent circuit model (unit cell) of a CPW loaded with symmetrically etched CSRRs (a); equivalent circuit model for the even mode (b); equivalent circuit model for the odd mode (c).

5. Experimental validation

In order to experimentally validate the selective mode suppression in CPWs, we have designed some structures. One of them consists of a CPW loaded with a SRR in its back substrate side and with a CSRR in the central strip (Fig. 7a), while another structure is the same structure without the SRR. We have fed the CPWs by means of a slot line to generate the odd mode, and it is clear from Fig. 7b that the presence of the SRR inhibits this mode at SRR resonance (while this mode is not affected by the CSRR). On the other hand, we have designed the same structures without the CPW to slot line transition (Fig. 8a), and we have obtained the transmission coefficient (Fig. 8b) which corresponds to the fundamental mode (the structure has not been fabricated; hence it has been obtained through full wave electromagnetic simulation). In this case, the situation is reversed, that is, the notch is caused by the CSRR, and the line is transparent at the resonance frequency of the SRR.

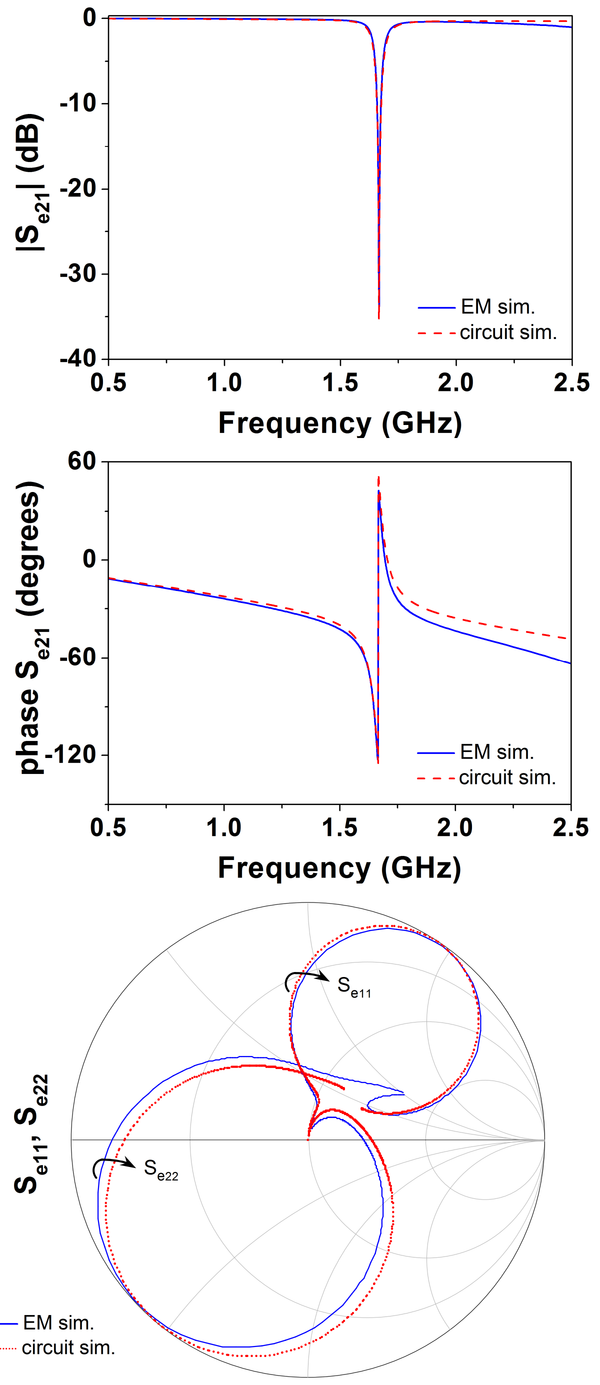

Figure 6: Comparison of the electromagnetic and circuit simulation of the structure of Fig. 2(b) for the even mode. The element values (referred to the circuit of Fig. 5b) are: C= 0.75 pF, L_e=2.13 nH, L_c=0.49 nH, C_c= 17.3 pF, and M=0.2 nH.

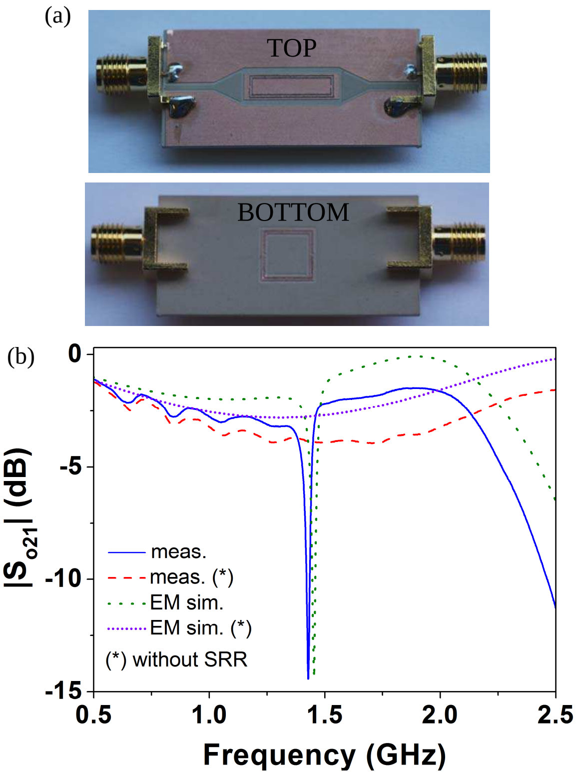

Figure 7: CPW loaded with a SRR and a CSRR and fed through a slot line to generate the slot mode (a) and frequency response (b). The substrate is the *Rogers RO3010* with h=1.27 mm, ε_r=10.2, and loss tangent tanδ=0.0023. The dimensions are: for the SRR, c=d=0.2 mm, and *side length*=7.6 mm; for the CSRR dimensions, c=d=0.2 mm, *longitudinal side length*=12.6 mm, and *transverse side length*=3.6 mm; for the CPW, W=4 mm, and G=1 mm; for the slot line, the slot width is 1.5 mm.

Notice that in Fig. 7(b) the response exhibits certain insertion losses due to the impedance mismatch on the coaxial (50 Ω impedance) to slot line (it has been found that it exhibits about 100 Ω impedance) transition. Nevertheless, this is irrelevant for the purpose of this work, since the main aim is to demonstrate the selective mode suppression of both CPW even and odd modes by using either SRRs or CSRRs.

6. Potential applications

CPW structures loaded with single SRRs or CSRRs may find applications in several fields. For example, CPW transmission lines with symmetrically loaded SRRs inhibit the slot mode, keeping the fundamental mode unaltered. Thus, a set of SRR properly designed can be useful in certain CPW applications where the slot mode typically appears and must be suppressed. Another potential application of SRR-loaded lines concerns the implementation of novel sensors and detectors based on the loss of symmetry of the reported structures [8]. The lack of symmetry can be caused by many different reasons, such as a displacement or rotation, the presence of particles,

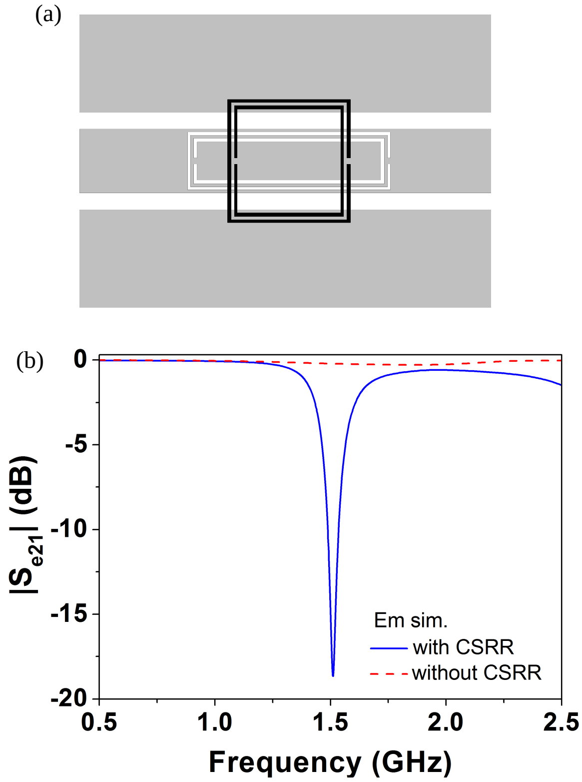

Figure 8: CPW loaded with a SRR and a CSRR and excited through the fundamental (even) mode (a) and frequency response (b). The substrate and dimensions are those indicated in the caption of Fig. 7.

inhomogeneities in the surrounding medium, etc., and sensing/detection can be simply carried out by measuring the transmission coefficient (many other sensors based on the variation of the resonance frequency of split rings have been reported [9-16]).

For which concern CSRR-loaded CPWs, the presence of these particles causes notches in the transmission coefficient for the fundamental mode, and this can be useful for the rejection of interfering signals in communication systems. As long as the CSRRs are etched in the central strip, this undesired signal suppression can be achieved without the penalty of increasing device area and cost.

In this paper, the potentiality of the reported structures is illustrated by means of a proof-of-concept demonstrator of a radiofrequency bar code [17]. The idea is to each SRRs with different dimensions (i.e., providing different resonance frequencies) in the back substrate side of a CPW transmission line. If the SRRs are aligned with the symmetry plane of the CPW structures, the line is transparent. However, we can codify the line by laterally displacing the SRRs, since this produces a transmission zero in the transmission coefficient at the corresponding frequency, and this can be easily monitored. This frequency domain codification is similar to that reported in [18], but in our case it is not necessary to remove the SRR to set a logic '0'; it suffices by aligning it with the line; hence, our approach opens the possibility to implement reconfigurable radiofrequency bar codes. A 3-bit bar code with the sequence ‘101’, that is, with two SRRs laterally shifted and with one SRR centered is depicted in Fig. 9(a), whereas Fig. 9(b) shows the simulated frequency response. For comparison, the simulated frequency response corresponding to the code ‘010’, is also depicted. With the purpose to prevent the presence of the odd mode, the ground planes are connected through backside strips and vias. With these results, the radiofrequency bar code proof-of-concept based on CPW structures loaded with SRRs is validated.

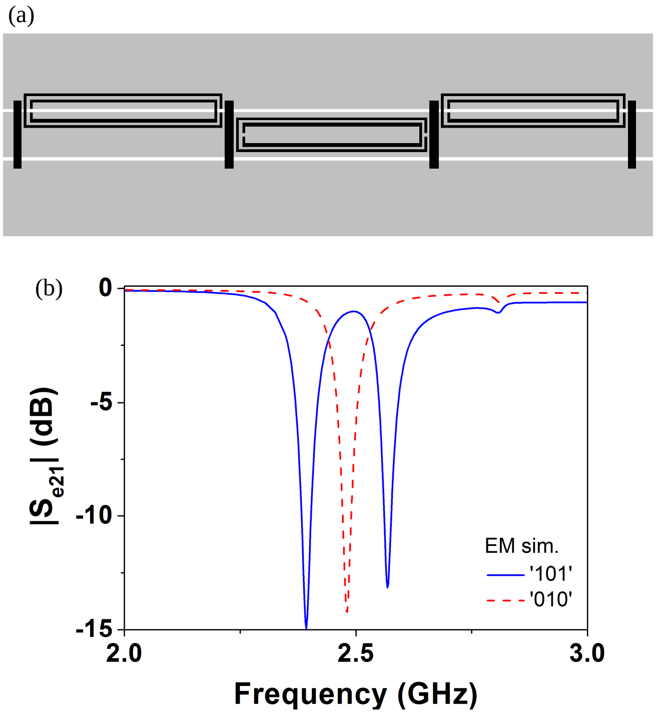

Figure 9: CPW loaded with three SRRs resonating at 2.39 GHz, 2.48 GHz and 2.57 GHz and codified with the code ‘101’ (a), and frequency response (b). The frequency response corresponding to the code ‘010’ is also depicted. The substrate is the *Rogers RO4003C* with h=0.8128 mm, ε_r=3.55, and tanδ=0.0021. The dimensions are: for the SRRs, c=d=0.2 mm, *transverse side length*=2.47 mm, and *longitudinal side length*=14.3 mm, 13.75 mm, and 13.25 mm; for the CPW, W=3.3 mm and G=0.2 mm.

7. Conclusions

In conclusion, the selective suppression of either the fundamental (even) or the slot (odd) mode in CPW structures by using complementary split ring resonators (CSRRs) and split ring resonators (SRRs), respectively, has been demonstrated. In order to preserve the integrity of the mode for which the line is transparent, it is necessary to etch the particles symmetrically in the line. We have provided the circuit models of SRR and CSRR symmetrically loaded CPW transmission lines, including those for even and odd mode excitations, and it has been demonstrated through parameter extraction that these models describe the structures to a good approximation. The selective mode suppression has been experimentally validated and potential applications of these structures have been highlighted, with special emphasis to radiofrequency bar codes. A proof-of-concept demonstrator of a CPW transmission line with a 3-bit spectral signature has been provided. Work is in progress to implement practical bar codes with a higher number of bits, and to the development of new sensors based on the symmetry properties of CPW transmission lines.

Acknowledgements

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