Transmission lines loaded with folded stepped impedance resonators (SIRs): modeling and applications

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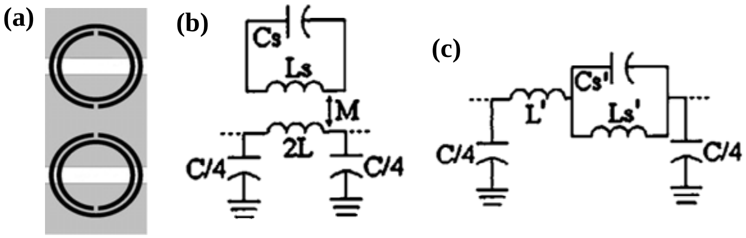
Abstract

Transmission lines loaded with folded stepped impedance resonators (SIRs) are studied. Specifically, the paper is focused on coplanar waveguide (CPW) transmission lines with folded SIRs etched in the back substrate side. The structure is similar to a CPW loaded with split ring resonators (SRRs). However, it is shown that the lumped element equivalent circuit model that describes the unit cell of the structure is radically different, since the interaction between the line and the folded SIRs is dominated by electric coupling, rather than magnetic coupling (as occurs in SRR-loaded CPWs). Advantages and potential applications of these artificial lines are highlighted.

1. Introduction

Transmission lines loaded with split rings have been a subject of interest in recent years [1]. These artificial transmission lines can be engineered in order to inhibit signal propagation in certain frequency bands and to allow backward, forward or composite backward and forward wave propagation in other bands. Specifically, coplanar waveguides loaded with split ring resonators (SRRs) exhibit a stop band behavior that has been interpreted as consequence of the negative effective permeability of the line in the vicinity of SRR resonance [2]. However, the stop band characteristics can also be interpreted from the lumped element equivalent circuit model of the unit cell (Fig. 1), where the SRR is modeled as a resonant tank inductively coupled to the line. At resonance, SRRs are excited, and the injected power is reflected back to the source (a transmission zero at the resonance frequency of the SRRs arises). Thanks to this stop band functionality, SRR-loaded CPWs have been successfully applied to the design of stop band filters [3] (and combined with additional elements to band pass filters [4],[5]).



$$L_s' = \omega_0^2 M^2 C_s \qquad C_s' = \frac{L_s}{\omega_0^2 M^2}$$

$$L' = 2L - L_s' \qquad \omega_0^2 = \frac{1}{L_s C_s} = \frac{1}{L_s' C_s'}$$

Fig. 1: Unit cell of a SRR-loaded CPW (a), equivalent circuit model (b), and transformed equivalent circuit model (c). *L* and *C* are the inductance and capacitance of the line, the SRR is modeled by the tank formed by L_s and C_s, and *M* is the mutual line-to-resonator inductance. The magnetic wall concept has been applied.

SRRs are electrically small particles by virtue of the coupling between the inner and the outer ring. As compared to the first resonance of the individual rings (half-wavelength resonators), the first resonance of the SRR is shifted downwards. Indeed the first resonance frequency can be inferred from a

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quasi-static analysis, from which it follows that the SRR can be modeled by the inductance of a single ring of average radius and a capacitance consisting of the series combination of the edge (distributed) capacitance of the left and right halves of the particle [6]. Besides inter-rings coupling, another possibility to reduce the electrical size of a distributed half-wavelength ring resonator is to widen the strip width at the extremes, as shown in Fig. 2(a). The resulting particle is the folded stepped impedance resonator (SIR) [7]. Electrical size reduction comes from variation in strip width, and also by enhancement of the gap capacitance.

2. Coplanar waveguides loaded with folded SIRs

By loading a CPW with folded SIRs, we expect similar stop band behavior to SRR-loaded CPW. This has been corroborated through the full wave electromagnetic simulation of the structure shown in Fig. 2(a) (see Fig. 3). However, the structure cannot be described by the circuit model of Fig. 1(b) or (c). In spite that the folded SIR can be inductively driven by the magnetic field generated by the line, the wide strip regions of the folded SIR are disposed face-to-face with the upper metallic regions of the CPW structure. Therefore, a significant broadside capacitance between the CPW and the folded SIR arises, and electric coupling is the dominant coupling mechanism. Thus, the equivalent circuit model is that shown in Fig. 2(b).

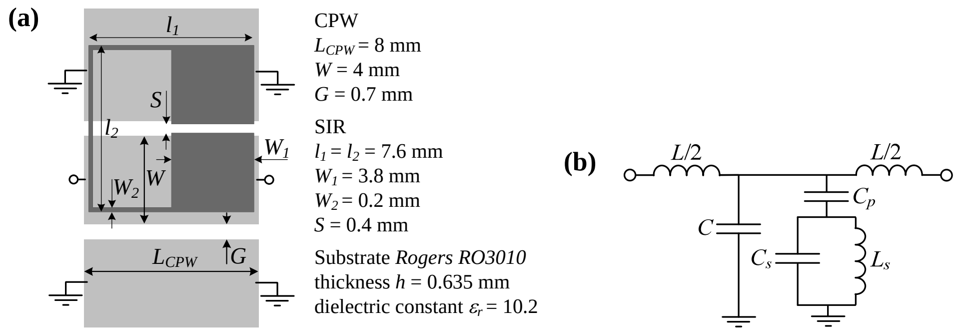

Fig. 2: Unit cell topology (a) and equivalent circuit model (b) of a SIR-loaded CPW. L and C are the inductance and capacitance of the line, C_p is the line-to-SIR capacitance, and L_s and C_s are the inductance and gap capacitance of the SIR. Dimensions and substrate parameters of the structure under study are indicated.

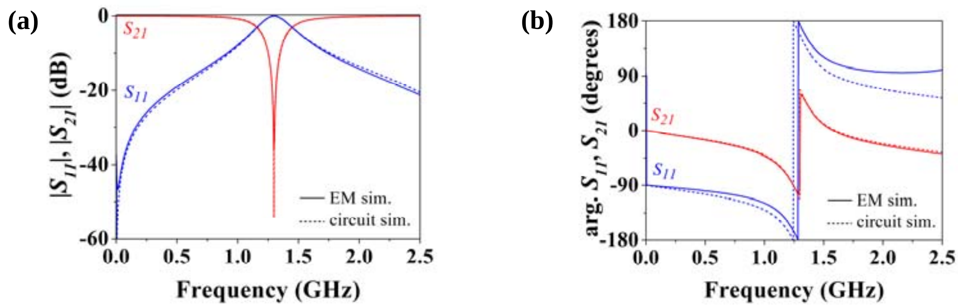

Fig. 3: Frequency response of the SIR-loaded CPW of Fig. 2. Transmission (S_{21}) and reflection (S_{11}) coefficients (a), and phase response (b). The full wave electromagnetic simulation and the circuit simulation have been obtained by means of the *Agilent ADS* commercial software. For the circuit simulation, the parameters of the model of Fig. 2(b) are: L = 2.4 nH, C = 0.96 pF, C_p = 1.1 pF, L_s = 12.88 nH, and C_s = 0.06 pF.

By using analytical formulas and curve fitting, the electrical parameters of the circuit of Fig. 2(b) can be extracted. We have simulated the frequency response of the circuit model with extracted parameters. The results are compared to those inferred from electromagnetic simulation in Fig. 3. Good agreement is obtained, which is indicative of the validity of the proposed model. It is noticeable that the transmission zero is mainly given by the resonator formed by the inductance L_s and the capacitance C_p, rather than being given by the intrinsic resonance of the folded SIR. Since the capacitance C_p is a broadside capacitance, the transmission zero (usually a design parameter or specification) can be achieved by means of a very small folded SIR. This is an advantage over SRR-loaded CPWs. However, notice that a periodic structure consisting of a CPW loaded with folded SIRs cannot be considered a negative effective permeability one-dimensional metamaterial. The reason is that the series reactance is always inductive. However, above the transmission zero, the shunt reactance is positive and this means that a CPW periodically loaded with SIRs can behave as a one-dimensional negative effective permittivity medium in a certain band.

3. Potential applications

CPWs loaded with folded SIRs can be applied to the design of compact stop band filters, sensors and microwave identification (ID) codes. In this latter case, the CPW must be loaded with folded SIRs designed to exhibit certain predetermined transmission zero frequencies. The absence or presence of these frequencies (detected as notches in the transmission coefficient frequency response) in the spectrum determines the unique ID code. Figure 4(a) and (b) depicts, respectively, the layout of two 3-bit ID codes corresponding to the IDs ‘101’ and ‘010’, and the frequency response. Metallic vias and backside strips connecting the ground planes have been used to avoid the (undesired) slot mode.

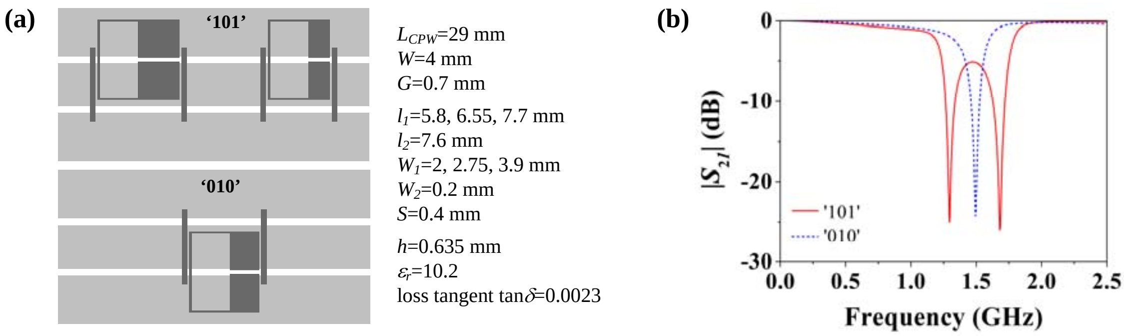

Fig. 4: Layout (a) of the 3-bit ‘101’ and ‘010’ codes of the proposed ID card and transmission coefficient (b).

4. Conclusion

In conclusion, CPW transmission lines loaded with folded SIRs have been studied. These structures exhibit a stop band behavior that has been interpreted from the proposed lumped element equivalent circuit model. Contrary to SRR-loaded CPWs, the reported SIR-loaded CPWs exhibit a line-to-resonator coupling dominated by the electric field. The circuit model has been validated by comparison to full wave electromagnetic simulation. Finally, several applications have been highlighted.

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