Split Rings-Based Differential Transmission Lines with Common-Mode Suppression

[1]Jordi Naqui, [2]Armando Fernández-Prieto, [1]Miguel Durán-Sindreu, [1]Jordi Selga, [2]Francisco Medina, [2]Francisco Mesa, and [1]Ferran Martín

[1]GEMMA/CIMITEC, Departament d'Enginyeria Electrònica. Universitat Autònoma de Barcelona. 08193 BELLATERRA (Barcelona), Spain. E-mail: Ferran.Martin@uab.es

[2]Departamento de Electrónica y Electromagnetismo, Universidad de Sevilla. Avenida Reina Mercedes s/n, 41012 Sevilla, Spain. E-mail: Medina@us.es

***Abstract* — A novel microstrip differential transmission line with common-mode noise suppression is proposed and experimentally validated. It is implemented by periodically etching complementary split ring resonators (CSRRs) in the ground plane. For the differential signals, the symmetry of the structure efficiently cancels the electric field components axial to the CSRRs, and these particles have no effect on signal transmission. However, the CSRRs are activated under common mode excitation, with the result of a stop-band behavior. For the designed and fabricated prototype device, over 20 dB suppression of common-mode noise is achieved over a frequency range from 1.18 GHz to 1.74 GHz.**

***Index Terms* — Differential transmission lines, metamaterials, complementary split ring resonators (CSRRs).**

I. INTRODUCTION

High immunity to noise, low crosstalk and low electromagnetic interference are key issues of differential signals that make them very interesting for high-speed digital circuits. However, the presence of common-mode noise in differential lines is unavoidable in practical circuits. This unwanted noise is mainly caused by amplitude unbalance or time skew of the differential signals and must be reduced as much as possible to avoid common-mode radiation or EMI. Therefore, the design of differential lines able to suppress the common-mode noise while keeping the integrity of the differential signals is of great importance.

For GHz differential signals, compact common mode filters based on multilayer LTCC [1] or negative permittivity [2] structures have been reported. These structures are compact and provide efficient common-mode rejection over wide frequency bands, but are technologically complex. There have been also several approaches for the design of common-mode suppressed differential lines based on defected ground structures. In [3], dumbbell shaped periodic patterns etched in the ground plane, underneath the differential lines, were used to suppress the even mode by opening the return current path through the ground plane. This has small effect on the differential signals (odd mode) since relatively small current density returns through the ground plane for such signals. In [4], the authors achieve a wide stop-band for the common-mode by using U-shaped and H-shaped coupled resonators symmetrically etched in the ground plane.

In the present work, another approach for the design of differential lines with common-mode suppression is investigated. It is also based on defect ground structures, but using complementary split ring resonators (CSRRs). As will be later shown, by symmetrically etching the CSRRs in the ground plane, efficient common-mode suppression over a wide band can be achieved. As compared to other approaches, the proposed common-mode suppression strategy is technologically simple (only two metal levels are used), the resulting common-mode filters are electrically small, provide wide and high-rejection stop-bands, and their design is simple.

II. CSRR-BASED DIFFERENTIAL LINES: PRINCIPLE FOR COMMON-MODE SUPPRESSION AND MODELING

The CSRRs were first introduced in [5], where it was demonstrated that these particles are useful for the design of negative permittivity structures in microstrip technology. Etched in the ground plane of a microstrip line, underneath the conductor strip, CSRRs efficiently suppress signal transmission in the vicinity of their resonance frequency. This result can be interpreted as due to the negative effective permittivity of the line, but it can also be explained in terms of circuit theory, as a result of the capacitive coupling between the line and the CSRR. The topology and circuit model of a microstrip line loaded with a CSRRs are depicted in Fig 1(a). As reported in [6], L models the inductance of the line, C accounts for the electric coupling between the line and the resonator, and the CSRR is modeled by the parallel resonant tank, L_c-C_c. The unit cell structure of the proposed differential line is depicted in Fig. 1(b). It consists on a pair of coupled lines with a CSRR etched in the ground plane. The circuit model of this structure is also depicted in Fig. 1(b), where C_m and L_m model the mutual capacitance and inductance between the coupled lines.

The circuit model of Fig. 1(b) explains that the differential signals are insensitive to the presence of the CSRRs, while

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these resonators prevent the transmission of the common-mode at certain frequencies. The equivalent circuit model of the structure of Fig. 1(b) under common mode excitation is depicted in Fig. 2(a), whereas for the odd mode is depicted in Fig. 2(b). For the odd mode, the resonator is short circuited to ground, and the resulting model is that of a conventional transmission line. For the even mode, we obtain the same circuit as that of a CSRR-loaded line (Fig. 1a), but with modified parameters. Thus, we do expect a similar stop band behavior for the common-mode.

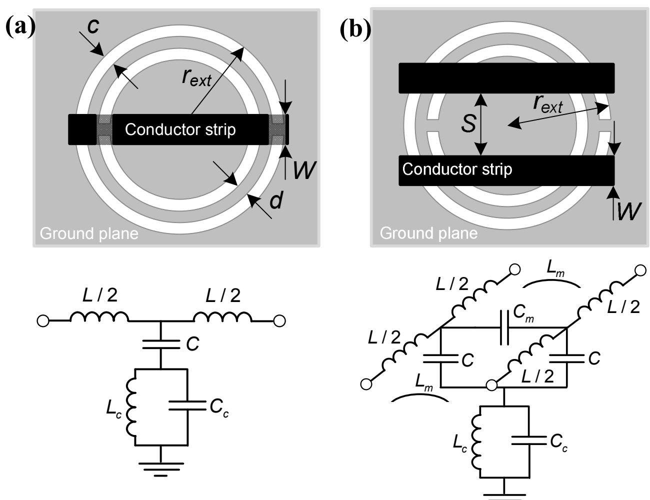

Fig. 1. Topology and circuit model (elemental cell) of a microstrip line (a) and differential line (b) loaded with a CSRR.

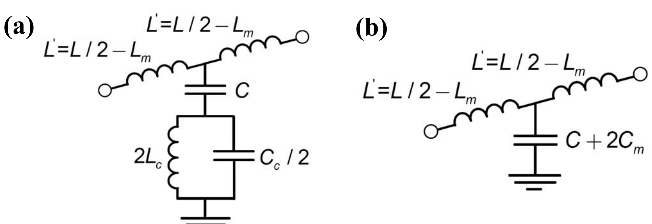

Fig. 2. Circuit models for the even mode (a) and odd mode (b).

In terms of field distributions, it is well known that the CSRR (first resonance) can be excited by means of a time varying axial electric field [5]. For the common mode, there is a strong density of electric field lines in the same direction below both lines. This causes CSRR excitation and hence a stop band. For the odd mode, the electric field distribution depends on the level of coupling between both lines. In tightly coupled lines, the electric field lines are mainly concentrated in the (necessarily narrow) gap region between the lines. In weakly coupled lines, the electric field intensity is higher below the lines (similar to the even mode). However, the direction of the electric field lines is opposite in both strips of the differential line. If the structure is symmetric, (i.e., the gaps of the CSRRs are aligned with the symmetry plane of the differential lines), the opposite electric field vectors in both lines exactly cancel and the CSRR is not activated.

To verify the integrity of the differential signals in these CSRR-loaded lines, we have designed a differential line with weakly coupled lines (the layout is depicted in Fig. 3). The width and distance between the lines necessary to obtain a 50Ω odd mode impedance has been determined by means of the transmission line calculator incorporated in the *Agilent ADS* commercial software (a *Rogers RO3010* microwave substrate with dielectric constant ε_r = 10.2 and thickness h=1.27mm has been considered). To analyze the effects of the asymmetry in the circuit, we have also simulated the structure that results by rotating the CSRR 90°. The simulated differential and common-mode insertion losses for both structures are depicted in Fig. 3 (these simulations have been obtained by means of the *Agilent Momentum* commercial software). For the even mode the results are comparable (in the region of interest) and a notch appears at the frequency where the shunt impedance (Fig. 2a) vanishes:

$$f_z = \frac{1}{2\pi\sqrt{2L_c(C_c/2+C)}} \qquad (1)$$

However, for the odd mode, whereas the insertion loss is less than 0.1dB (in the considered frequency range) for the symmetric structure, a notch appears in the structure with the rotated CSRR. Thus, these results validate the common-mode suppression principle and point out the need to symmetrically etch the CSRRs in the differential line in order to preserve the differential signal integrity over a wide band.

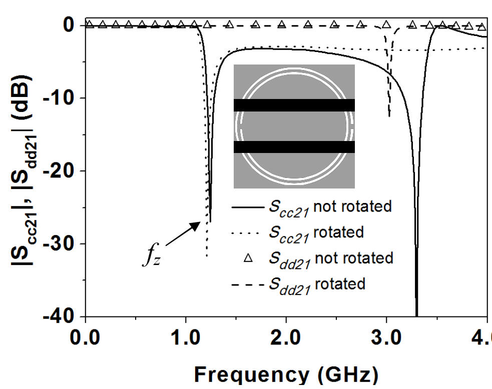

Fig. 3. Simulated common-mode $|S_{cc21}|$ and differential $|S_{dd21}|$ insertion loss for the structure of the inset, with and without 90° rotated CSRR. Dimensions are c=0.2mm, d=0.2mm, r_{ext}=5mm, W=1mm, S=2.5mm.

III. Design of CSRR-based Differential Lines

To efficiently suppress the common-mode noise it is necessary to achieve wide stop bands for the even mode. To this end, the strategy is to widen the stop band of the individual resonators, to couple them as much as possible, to etch CSRRs with slightly modified dimensions in order to obtain different transmission zero frequencies within the

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desired stop band, or a combination of all these effects. To widen the rejection bandwidth of an individual CSRR (which is relevant to achieve wide stop bands), it is necessary to increase the coupling capacitance, C, and to reduce the inductance, L_c, and capacitance, C_c, of the CSRR as much as possible. According to it, weakly coupled lines will be considered, since the width of the lines necessary to achieve an odd mode impedance of 50Ω is wider, and this enhances the coupling capacitance of the even mode. To reduce the inductance and capacitance of the CSRR, preserving the coupling level, it is necessary to increase the rings width, c, and separation, d. Obviously, this results in a larger CSRR size (for a given transmission zero frequency), but the achievable bandwidth is also larger.

In the present paper, the bandwidth is enhanced by tightly coupling identical CSRRs. We have considered two different structures: in one of them, the rings of the CSRRs are wide and appreciably separated; in the other one, the rings are narrow and tiny spaced. In both cases, in order to enhance the inter-CSRR's coupling, we have considered square-shaped rings.

In the first design, the purpose has been to reduce the size of the structure as much as possible. For this reason, we have considered a CSRR unit cell with narrow and tiny spaced rings (c=0.2mm and d=0.2mm). These values are close to the limit of the available technology. With these values, the model of the CSRR reported in [6], and the per-unit length capacitance of the coupled lines (common mode), we have estimated the side of the CSRR in order to obtain a transmission zero frequency at f_z=1.4GHz (obviously, optimization has been required since the model reported in [6] is valid under conditions not exactly fulfilled in the structure). The simulation of the common mode insertion loss is depicted in Fig. 4. The circuit simulation of the structure with the parameters extracted according to the procedure reported in [7] is also depicted in Fig. 4. There is good agreement between the circuit and electromagnetic simulation. In order to enhance the rejection bandwidth, we have implemented an order-3 structure with tightly coupled CSRRs. The bandwidth is closely related to the level of inter-resonator's coupling. Therefore, we have separated the CSRR 0.15mm in order to enhance the bandwidth as much as possible. The simulation of the resulting structure is shown in Fig. 5, where for comparison purposes we have also included the circuit simulation. The simulated circuit is that resulting by cascading the elemental cells, but with the addition of coupling capacitances between adjacent resonators. The coupling capacitance has been considered to be an adjustable parameter, and we have found that the capacitance that provides a better fit is C_{Coup}=0.11pF. The dimensions of the structure are 23mm×7.6mm, that is $0.28\lambda\times0.09\lambda$ (where λ is the guided wavelength at the central frequency). The device is thus very small, although bandwidth has not been optimized in this structure. It is clear that the differential signal is not altered by the presence of the CSRRs (see also Fig. 5).

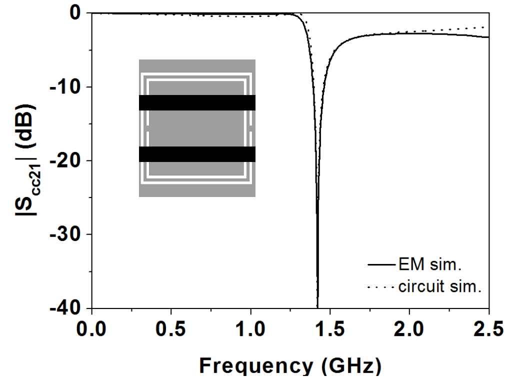

Fig. 4. Simulated common-mode insertion loss $|S_{cc21}|$ for the structure shown in the inset. CSRR dimensions are: c=0.2mm, d=0.2mm, W=1mm, S=2.5mm, and side length 7.6mm. Extracted parameters are L'=4.93nH, C=1.06pF, C_c=2.68pF and L_c=3.36nH.

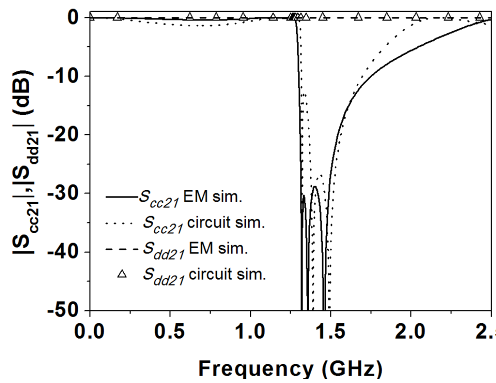

Fig. 5. Simulated common-mode and differential-mode insertion loss $|S_{cc21}|$ and $|S_{dd21}|$ for the order-3 structure that results by cascading 3 unit cells like the one shown in Fig. 4.

To enhance the bandwidth, we have considered CSRRs with wider rings and inter-ring's space. The target is to achieve at least 20dB common-mode rejection in the frequency range between 1.2GHz and 1.8GHz. The model of the CSRR is not so simple in this case because the particle cannot be considered to be electrically small; therefore we have directly made the optimization at the layout level. It has been found that three square shaped CSRRs separated 0.2mm, with a side length of 10.8mm and c=1.2mm and d=0.8mm, suffice to achieve the target specifications. The structure has been fabricated by means of a *LPKF H100* drilling machine. Access lines have been added in order to solder the connectors. The photograph of the whole structure is depicted in Fig. 6. Fig. 7 shows the simulated differential and common-mode insertion loss of the structure, as well as the measured even and odd mode frequency response. The dimensions of the active region of the structure are 32.8mm×10.8mm, that is $0.43\lambda\times0.14\lambda$. It is remarkable that the measured insertion loss for the differential signal is smaller than 0.5 dB in the considered range, being the loss tangent of the substrate 0.0023.

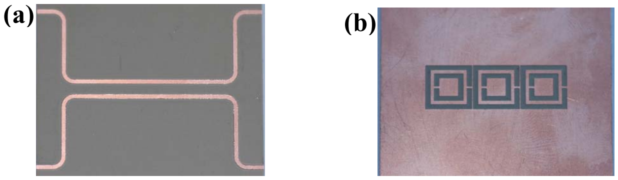

Fig. 6. Photograph of the (a) top view and (b) bottom view of the differential line with wide band common-mode rejection.

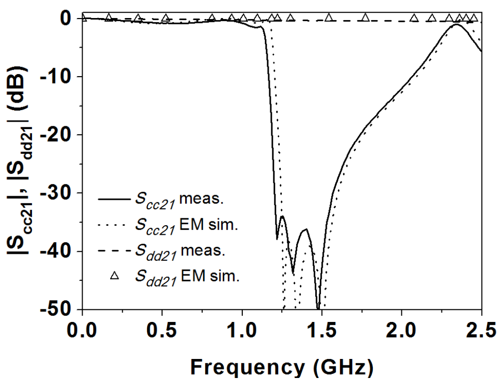

Fig. 7. Common-mode and differential-mode insertion loss $|S_{cc21}|$ and $|S_{dd21}|$ for the structure of Fig. 6.

Our fabricated wide band structure (Fig. 6) is compared with other structures reported in the references (see table I). The combination of size, bandwidth and stop-band rejection is competitive. The structure in [2] exhibits small dimensions and relatively wide bandwidth, but it needs three metal levels. In summary, we have presented an alternative and promising approach for the design of differential lines with common-mode suppression.

TABLE I: COMPARISON OF SEVERAL DIFFERENTIAL LINES

Ref	*length* [λ]	*Width* [λ]	*Surface* [λ^2]	*FBW* [%]	
				–10 dB	–30 dB
[2]	0.26	0.16	0.04	60	24
[3]	0.76	0.47	0.36	53	40
[4]	0.44	0.44	0.19	87	----
This	**0.43**	**0.14**	**0.06**	**54**	**24**

IV. CONCLUSIONS

We have demonstrated that CSRRs are useful particles for the suppression of the even mode in microstrip differential lines. The circuit models of the structure for both the differential and common modes have been reported and validated. The fabricated prototype device exhibits a rejection bandwidth for the common mode that extends from 1.18 GHz up to 1.74 GHz with more than 20 dB rejection. The measured insertion loss for the differential mode is better than 0.5 dB from DC up to at least 2.5 GHz. Therefore, the presence of the CSRRs has little influence on the differential signals. Since the CSRRs are compact resonators, the required space of the differential line to achieve efficient common-mode suppression is small. Therefore, the proposed approach is of interest for application in structures based on differential lines. The immediate future work by the authors will be the combination of CSRRs and other electrically small resonators for the design of differential line band pass filters with common-mode suppression.

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