Progress In Electromagnetics Research B, Vol. 5, 107–118, 2008

AN EQUIVALENT CIRCUIT FOR EMI PREDICTION IN PRINTED CIRCUIT BOARDS FEATURING A STRAIGHT-TO-BENT MICROSTRIP LINE COUPLING

P. Bernardi and R. Cicchetti

Department of Electronic Engineering
University of Rome "La Sapienza"
Via Eudossiana, 18-00184 Rome, Italy

G. Pelosi, A. Reatti, S. Selleri, and M. Tatini

Department of Electronics and Telecommunications
University of Florence
Via C. Lombroso, 6/17-50134 Florence, Italy

Abstract—A full-wave analysis of the scattering parameters of a straight-to-bent microstrip line coupling is performed using a FEM technique. The numerical results, showing the influence played by the geometrical parameters of the structure on the electromagnetic coupling, are then employed to derive an equivalent circuit useful to be employed in CAD tools. A third order polynomial approximant useful to compute the equivalent circuit elements is finally provided.

1. INTRODUCTION

Parasitic coupling effects between neighboring microstrip lines are a major source of electromagnetic interference in printed circuit boards since they are composed of several parallel lines presenting many kinds of discontinuities. Coupling between parallel microstrip lines, which results the main cause of crosstalk, is generally predicted using quasi-static approaches [1–9], or full-wave techniques [10–13]. These techniques have been also employed to analyze the frequency behavior of microstrip discontinuities, such as T-junctions [14], gaps [15–19], bends [20], line crossings [21], and to investigate the field radiated from microstrip discontinuities [22] or interconnecting lines [23].

Albeit these approaches are useful for printed circuit boards design, fewer studies have been carried out concerning the electromagnetic coupling between discontinuities. In fact, the coupling occurring between microstrip discontinuities is generally a higher order effect with respect to that exhibited in parallel interconnecting lines. Anyway, since signal frequencies go up and up, as it happens in digital applications, they can result responsible for a reduction of circuit performances and signal integrity.

The aim of the present paper is to analyze and to extract a circuit model for the straight-to-bent microstrip line coupling. The geometry of the problem comprises two microstrip lines, one rectilinear and the other exhibiting a 90° bend. More specifically, the second line runs parallel to the first for a given length and then turns sideways and runs orthogonally to the first line (see Fig. 1).

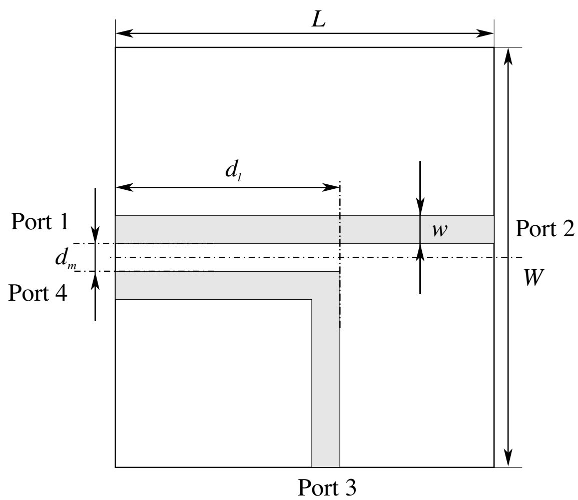


Figure 1. Geometry of the straight-to-bent microstrip line coupling problem.

The structure is analyzed by means of a full-wave finite elements (FEM) technique [24, 25] allowing to obtain a four-port scattering matrix of the whole device, including all the coupling effects [26]. A de-embedding procedure permits to extract the effects due to the coupling caused by the discontinuity itself, leading to an equivalent circuit describing the frequency behavior of the bend. The accuracy obtained employing the proposed equivalent circuit is then proved by comparing the numerical results with those obtained using a commercial software and a full-wave FEM analysis.

2. STATEMENT OF THE PROBLEM

The geometry of the problem is sketched in Fig. 1. A rectilinear microstrip and a neighboring bent strip are conceived as a four port device. While some of the geometrical parameters are left to vary to provide a parametrization of the coupling phenomenon, others are kept constant (see Table 1).

Table 1. Microstrip and substrate dimensions and electrical characteristics.

Substrate length (L), width (W), and thickness (h)	$L = 24\,\text{mm}$, $W = 15\,\text{mm}$, $h = 0.762\,\text{mm}$
Substrate electrical characteristics	$\varepsilon_r = 2.2$; $\mu_r = 1$
Strip width (w), and thickness (t)	$w = 0.5\,\text{mm}$, $t = 35\,\mu\text{m}$

The analysis is carried out with a FEM technique, by considering port 1 to 4 as lumped ports [27] and by enclosing the finite structure in an appropriate bounding metallic box simulating packaging and exhibiting openings for letting the microstrip lines through. The box itself is as large as the substrate and its cap is placed 3.8 mm above the substrate. In the numerical simulations the substrate, the microstrip lines, and the metallic box are assumed lossless. So, the structure loses energy only through the box openings excited by the surface and volume waves arising from the straight-to-bent microstrip discontinuity.

Starting from the above mentioned full-wave analysis that provides the scattering parameters of the structure, an equivalent circuit is derived. The frequency range for the numerical analysis is 0–10 GHz, so that the extracted equivalent circuit can be used in a CAD tool to analyze microwave circuits as well as transient phenomena occurring in printed circuit boards excited by digital signals.

3. THE FULL WAVE MODEL

The FEM procedure [24, 25] is applied to solve the vector wave equation

$$\nabla \times \frac{1}{\mu_r} \nabla \times \vec{E} - k_0^2 \varepsilon_r \vec{E} = 0 \tag{1}$$

within the device domain, with suitable boundary conditions. In (1), k_0 is the free-space wavenumber, while ε_r and μ_r are the relative permittivity and permeability, respectively. The unknown electric field $\vec{E}$ inside the device is expressed in terms of vector bases $\vec{w}_i$ as $\vec{E} = \sum_{i=1}^{n} e_i \vec{w}_i$. These bases are the curl conforming vector functions defined in [28]. With this choice, the surface integral arising from the weak formulation of boundary conditions is nonzero only over the device ports p_j, $j = 1, \ldots, 4$. To correctly model the field $\vec{E}^{(j)}$ on these ports the field itself is expanded in terms of an orthonormal basis comprising the first $M^{(j)}$ modes $[\vec{v}_1^{(j)}, \ldots, \vec{v}_{m^{(j)}}^{(j)}]$ of the guiding structure connected to the port:

$$\vec{E}^{(j)} = \sum_{m=1}^{M^{(j)}} \left(a_m^{(j)} + b_m^{(j)} \right) \vec{v}_m^{(j)} \tag{2}$$

where $a_m^{(j)}$ are the known coefficients of the incoming waves, while $b_m^{(j)}$ are the unknown coefficients of the outgoing waves at the j-th port. By explicitly enforcing the tangential electric field continuity at the ports in a weighted residual framework a linear system in the unknowns $[e_i, b_m^{(j)}]$ is obtained.

For what concerns the modes, both analytical and numerical modes can be used [29]. However, in the present case, being the feeding structure a shielded microstrip for which an analytical solution is not available, numerical modes are necessary. These modes have been computed in advance via a two-dimensional FEM technique [25].

Starting from the field amplitude excited at the ports, the scattering parameters of the considered structure are finally derived.

4. THE EQUIVALENT CIRCUIT

In order to extract from the scattering parameters the circuital model of the straight-to-bent microstrip line coupling, the whole device has been subdivided into two main coupled parts, a section of parallel, coupled microstrips (Fig. 1, left), whose behavior is known [30], and the bend area itself (Fig. 1, center). The most relevant part here is of course this latter, where no models are available to establish an equivalent circuit.

At first, a full-wave parametric analysis of the scattering parameters has been performed with respect to the lines distance d_m, and the length d_l in which the lines run parallel, to study the relative behavior and facilitating the de-embedding of the bend contribution. As in [26], the parameter d_m, which has the main influence on the electromagnetic coupling, has been chosen to vary in the 0.2–0.8 mm range, while the parameter d_l has been assumed to vary in the 1.875–11.25 mm range.

Based on this parametric analysis, the layout and the circuital elements forming the equivalent circuit of the structure have been derived (see Fig. 2). The circuit is formed by some capacitors, modeling the fringe effect, and by a capacitor modeling the coupling effect due to the excitation of the electric charge at the microstrip bent edge. Inductors model the perturbation of the surface current and, consequently, of the magnetic field, while resistors model the electromagnetic emission due to the excitation of the higher order modes in the neighborhood of the discontinuity. Low electromagnetic emission is expected from the interconnecting lines since the considered structure is enclosed in a metallic box simulating packaging. So, the structure loses energy only through the openings letting the microstrips through.

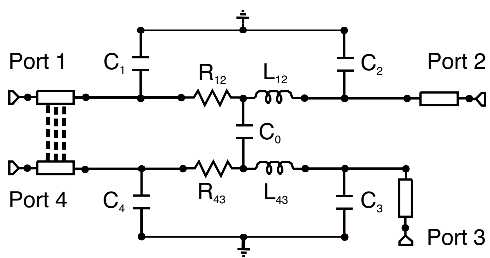


Figure 2. Equivalent circuit of the straight-to-bent microstrip line coupling problem.

The elements forming the equivalent circuit depicted in Fig. 2 cannot be computed in a closed analytical form. Anyway, they can be expressed in terms of the line distance d_m by means of the following third order polynomial approximant

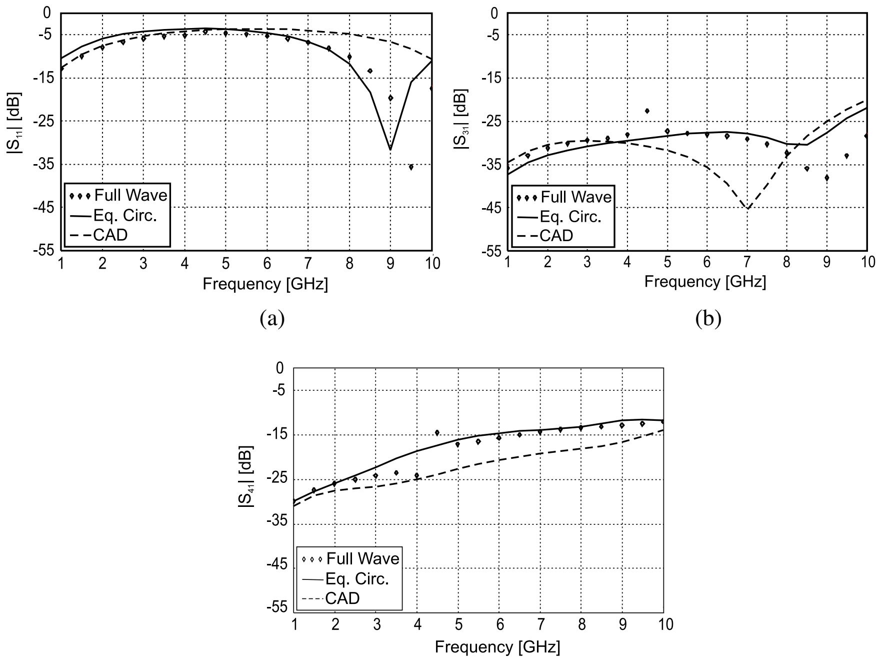
$$p(d_m) = p_0 + p_1 d_m + p_2 d_m^2 + p_3 d_m^3 \tag{3}$$

where $p(d_m) = R_{ij}$, L_{ij}, C_i with $i = 0, \ldots, 4$, and $j = 1, \ldots, 4$.

Other circuit elements modeling coupling, like a mutual inductance, were considered in the preliminary investigation, but their contribution was negligible.

5. NUMERICAL RESULTS

In this section numerical results concerning the straight-to-bent coupling computed using the full-wave model, a commercial — non-full-wave — CAD tool for microwave planar circuits, and the proposed equivalent circuit are presented. In Figs. 3–4, some results concerning



(a) (b) (c)

Figure 3. Magnitude of the scattering parameters versus frequency for $d_m = 0.4\,\text{mm}$, $d_l = 3.75\,\text{mm}$. Full wave analysis (*circles*); CAD simulator (*dashed line*); CAD simulator enhanced with the proposed equivalent circuit (*continuous line*): (a) S_{11}, (b) S_{31}, and (c) S_{41}.

the scattering parameters comparison among: the proposed test case analyzed with the full-wave FEM technique (dotted line); the structure analyzed by means of a commercial CAD exploiting the built-in microstrip analysis tools (dashed line); and, finally, the same structure analyzed by means of the mentioned CAD simulator but including the proposed equivalent circuit (continuous line), are shown. From these figures it appears that a good numerical accuracy, not obtainable using commercial software, is achievable by means of the proposed equivalent circuit.

Table 2 summarizes the results in terms of an average error defined as the difference between the magnitude of the scattering parameters obtained using the CAD simulator and the full-wave analysis, taken as reference. In particular, Δ_{CAD} is the numerical error introduced by the commercial CAD alone, while Δ_{EC} is that introduced by the same CAD simulator but exploiting also the proposed equivalent circuit.

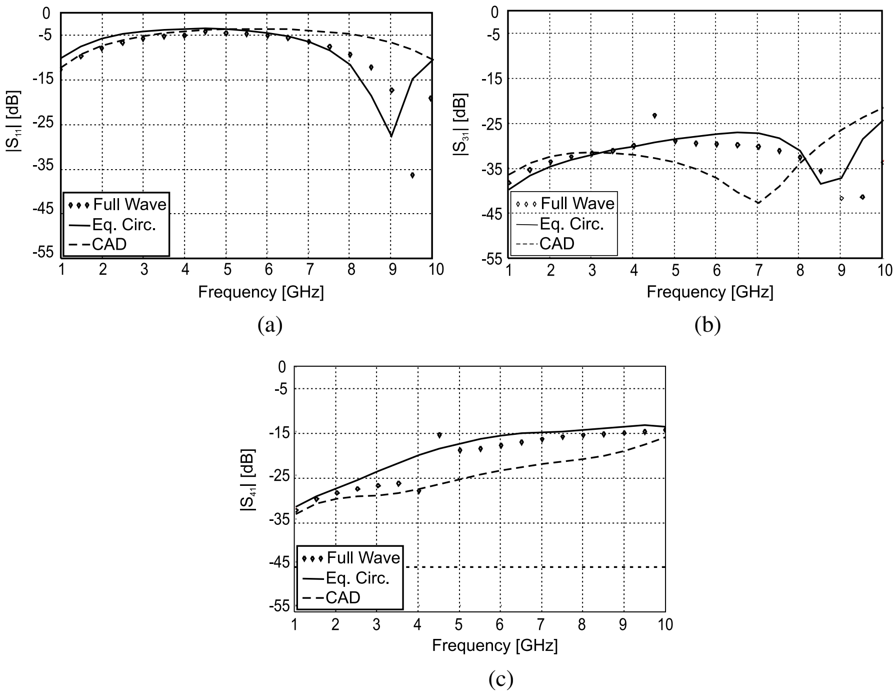


Figure 4. Magnitude of the scattering parameters versus frequency for $d_m = 0.6\,\mathrm{mm}$, $d_l = 3.75\,\mathrm{mm}$. Full wave analysis (*circles*); CAD simulator (*dashed line*); CAD simulator enhanced with the proposed equivalent circuit (*continuous line*): (a) S_{11}, (b) S_{31}, and (c) S_{41}.

An extensive numerical analysis, not reported for the sake of brevity, has been carried out to confirm the good accuracy attainable with the proposed model.

Figures 5–7 give the values of the equivalent circuit elements at

Table 2. Error magnitude of the scattering parameters.

Scattering Parameters	Δ_{EC}	Δ_{CAD}
S_{11}	0.099	0.136
S_{21}	0.049	0.056
S_{31}	0.018	0.025
S_{41}	0.029	0.058

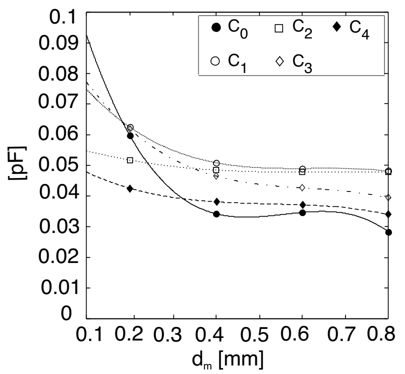


Figure 5. Values of the capacitors of the proposed equivalent circuit (*symbols*) and their interpolant polynomial functions (*lines*) versus d_m.

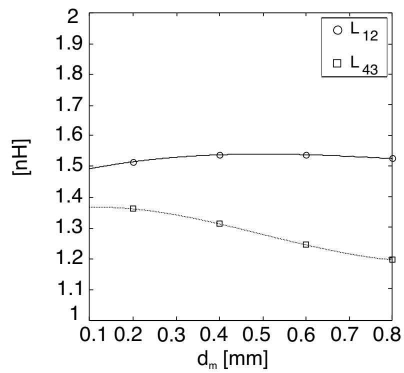


Figure 6. Values of the inductors of the proposed equivalent circuit (*symbols*) and their interpolant polynomial functions (*lines*) versus d_m.

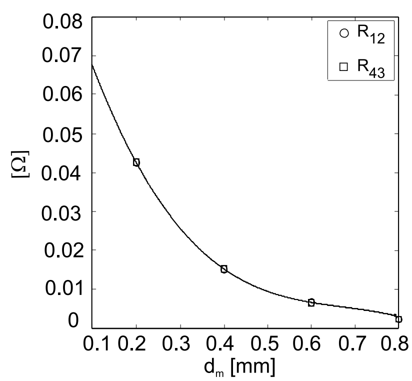


Figure 7. Values of the resistors of the proposed equivalent circuit (*symbols*) and their interpolant polynomial functions (*lines*) versus d_m. The resistors R_{12} and R_{43} presents similar values for the structure analyzed.

discrete values of d_m, together with the curves obtained by means of the interpolant polynomial (3), whose coefficients are reported in Table 3. From these figures it appears that the resistors modeling the emission phenomena have small values since the considered microstrip structure is enclosed in a metallic box, with small openings, simulating packaging. Consequently, larger vales of these elements are expected for unshielded structures.

Table 3. Interpolating polynomial coefficients.

Quantity to be interpolated	Coefficients			
	p_0	p_1	p_2	p_3
C_0	0.144	−0.623	1.144	−0.683
C_1	0.093	−0.212	0.341	−0.182
C_2	0.059	−0.050	0.072	−0.034
C_3	0.099	−0.261	0.412	−0.224
C_4	0.056	−0.098	0.180	−0.113
R_{12}	0.103	−0.404	0.578	−0.286
R_{43}	0.102	−0.403	0.577	−0.286
L_{12}	1.460	0.373	−0.529	0.208
L_{43}	1.352	0.262	−1.231	0.826

6. CONCLUSIONS

A full-wave parametric analysis of a straight-to-bent microstrip structure has been performed and an equivalent circuit of the structure has been proposed. The circuit is composed of lumped elements modeling the reactive phenomena and the spurious emission caused by the excitation of the higher order modes at the microstrip discontinuity. The numerical results show that the coupling phenomena are strongly dependent on the frequency and on the geometrical parameters of the structure. Finally, low electromagnetic emission has been observed since the structure has been enclosed in a metallic box having small apertures.

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