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Finite Element Approach of Unshielded Multiconductor Transmission Lines Embedded in Layered Dielectric Region for VLSI Circuits

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Abstract: This paper presents the quasi-TEM approach for the analysis of unshielded multiconductor transmission lines interconnect in single and two-layered dielectric region using the finite element method (FEM). We mainly focus on designing of four-transmission lines embedded in two-layered dielectric media and five-transmission lines interconnect in single-layered dielectric medium. We compute the capacitance matrices for these configurations. Also, we determine the quasi-TEM spectral for the potential distribution of the integrated circuits.
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Keywords: Capacitance per unit length; fnite element method; VLSI; multiconductor; transmssion lines.

I. Introduction

In The optimization of the electrical performance of microelectronic integrated circuits becomes an important factor when the signal speeds and components densities increase. Therefore, the accurate and efficient computational of self and mutual (coupled) capacitances of multicondcutor interconnect in very high speed integrated circuits is essential for scientists and researchers. The characteristics of microwave integrated circuits' analysis and design must be accomplished accurately in a short time. The significant advantages of printed circuits are somewhat offset by the electromagnetic complexity of the structure, because its inherent inhomogeneous nature makes accurate calculations difficult.

Several methods used for analyzing multiconductor transmission lines include the method of moments (MoM) [1-3], the measured equation of invariance (MEI) [4-6], the Fourier projection method (FPM) [7], the matrix pencil method (MPM) [8], the Fourier transform and mode-matching techniques (FTMM) [9], the partial element equivalent circuit methods (PEEC) [10], the method of line (MoL) [11], the spectral domain analysis (SDA) [12], and the finite difference method [13].

The quasi-TEM approach is successfully used to analyze coupled-microstrip lines of finite length in [14]. Indeed, the problem of computing the capacitance coupling in Very Large Scale Integrated (VLSI) circuits is studied using an approximate extended version of the method of images [15]. Also, the capacitance of a conductor-backed coplanar waveguide with an upper shielding was investigated in [16]. Although, the Eigenmode-based capacitance calculations with applications in passivation layer design was investigated in [17].

We use FEM in designing the four-transmission lines interconnect in two-layered dielectric media and five-transmission lines interconnect in single-layered dielectric medium structures. The FEM is especially suitable and effective for the computation of electromagnetic fields in strongly inhomogeneous media. Also, it has high computation accuracy and fast computation speed. We show that FEM is as suitable and effective as other methods for modeling multiconductor transmission lines of the VLSI circuits.

We compared some of our results of computing the capacitance-per-unit length with the other methods. We specifically compared the modeling of designing of unshielded four-transmission lines interconnect in two-layered dielectric media with the method of moments, measured equation of invariance, and Fourier projection method. Also, results from the matrix pencil method, and Fourier transform and mode-matching techniques were compared for unshielded five-transmission lines interconnect in single-layered dielectric medium and found to be in agreement

II. THEORY FOR THE PROBLEM FORMULATION OF MULTICONDUCTOR INTERCONNECTS IN MULTILAYERED DIELECTRIC MEDIA

In The models are designed in 2D using electrostatic environment in order to compare our results with some of the other available methods. In the boundary condition of the model's design, we use ground boundary which is zero potential ($V=0$) for the shield. We use port condition for the conductors to force the potential or current to one or zero depending on the setting. Also, we use continuity boundary condition between the conductors and between the conductors and left and right grounds.

The quasi-static models are computed in form of electromagnetic simulations using partial differential equations. Recently, with the advent of integrated circuit technology, the coupled microstrip transmission lines consisting of multiple conductors embedded in a multilayer dielectric medium have led to a new class of microwave networks. Multiconductor transmission lines have been utilized as filters in microwave region which make it interesting in various circuit components. For coupled multiconductor microstrip lines, it is convenient to write:

$$Q_i = \sum_{j=1}^{m} C_{sij} V_j \ , (i = 1, 2, ..., m), \qquad (1)$$

where Q_i is the charge per unit length, V_j is the voltage of j th conductor with reference to the ground plane, C_{sij} is the short circuit capacitance between i th conductor and j th conductor. The short circuit capacitances can be obtained either from measurement or from numerical computation. From the short circuit capacitances, we obtain

$$C_{ii} = \sum_{j=1}^{m} C_{sij} \ , \qquad (2)$$

where C_{ii} is the capacitance per unit length between the i th conductor and the ground plane. Also,

$$C_{ij} = -C_{sij}, \qquad j \neq i, \qquad (3)$$

where C_{ij} is the coupling capacitance per unit length between the i th conductor and j th conductor. The coupling capacitances are illustrated in Fig. 1.

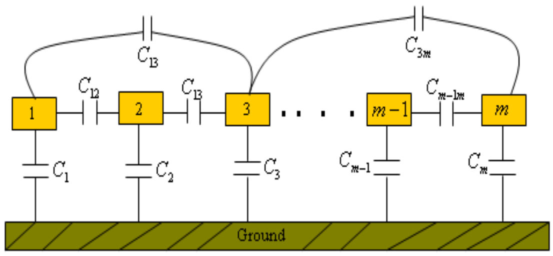

Figure 1. The per-unit length capacitances of a general m-conductor transmission line.

For m -strip line, the per-unit-length capacitance matrix [C] is given by [18]:

$$[C] = \begin{bmatrix} C_{11} & -C_{12} & \cdots & -C_{1m} \\ -C_{21} & C_{22} & \cdots & -C_{2m} \\ \vdots & \vdots & & \vdots \\ -C_{m1} & -C_{m2} & \cdots & C_{mm} \end{bmatrix}. \qquad (4)$$

III. RESULTS AND DISCUSSION

The models are designed with finite elements are unbounded (unshielded or open), meaning that the electromagnetic fields should extend towards infinity. This is not possible because it would require a very large mesh. The easiest approach is just to extend the simulation domain "far enough" that the influence of the terminating boundary conditions at the far end becomes negligible. In any electromagnetic field analysis, the placement of far-field boundary is an important concern, especially when dealing with the finite element analysis of structures which are open. It is necessary to take into account the natural boundary of a line at infinity and the presence of remote objects and their potential influence on the field shape [19]. In all our simulations, the open multiconductor structure is surrounded by a W X H shield, where W is the width and H is the thickness.

The models are designed in two-dimensional (2D) using electrostatic environment in order to compare our results with the other available methods. In the boundary condition of the model's design, we use ground boundary which is zero potential ($V=0$) for the shield. We use port condition for the conductors to force the potential or current to one or zero depending on the setting. Also, we use continuity boundary condition between the conductors and between the conductors and left and right grounds. The quasi-static models are computed in form of electromagnetic simulations using partial differential equations.

In this paper, we consider two different models. Case A investigates the designing of unshielded four-transmission lines interconnect in two-layered dielectric media. For case B, we illustrate the modeling of unshielded five-transmission lines interconnect in single-layered dielectric medium. The results from both models are compared with some other results in the other methods and found to be close.

A. Unshielded Four-Conductor Transmission Lines

Figure 2 shows the cross section for unshielded four-conductor transmission lines with the following parameters:

ε_{r1} = dielectric constant of the dielectric material = 5.0.

ε_{r2} = dielectric constant of the free space = 1.0.

W = width of the dielectric material = 10mm.

w = width of a single conductor line = 1mm.

H_1 = distance of conductors 1 and 2 from the ground plane = 3mm.

H_2 = distance of conductor 4 from the ground plane = 1mm.

H_3 = distance of conductor 3 from the ground plane = 2mm.

s = distance between the two coupled conductors = 1mm.

t = thickness of the strips = 0.01mm.

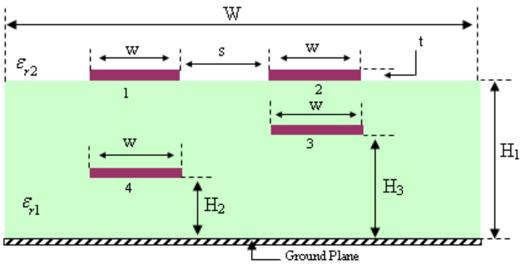

Figure 2. Cross section of unshielded four-conductor transmission lines.

The geometry is enclosed by a 10 X 10mm shield. From the model, we generate the finite elements mesh as in Fig. 3. Table 1 shows the statistical properties of the mesh. While, Fig. 4 shows the contour plot of the potential distribution with port 1 as input. The potential distribution along the line that goes from (x,y) = (0,0) to (x,y) = (10mm, 10mm) is portrayed in Fig. 5.

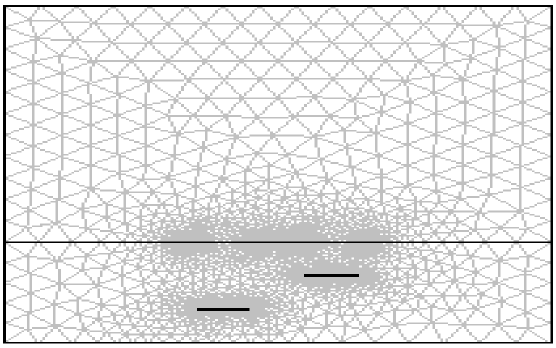

Figure 3. Mesh plot of unshielded four-conductor transmission lines.

TABLE I. MESH STATISTICS OF THE UNSHIELDED FOUR-CONDUCTOR TRANSMSSION LINES

Items	Value
Number of degrees of freedom	103940
Total Number of mesh points	4731
Total Number of elements	9315
Triangular elements	9315
Quadrilateral	0
Boundary elements	548
Vertex elements	22

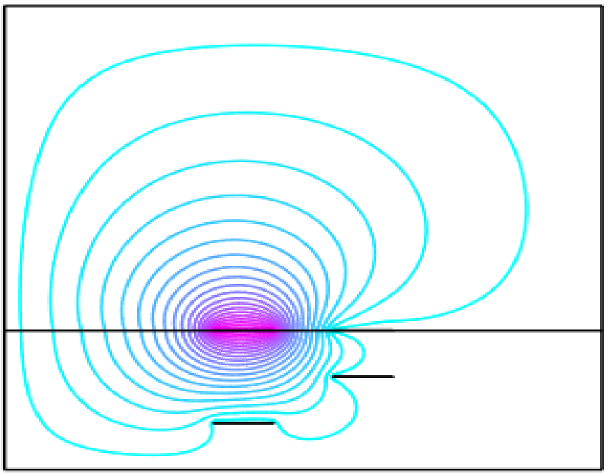

Figure 4. Contour plot of the potential distribution of unshileded four-conductor transmission lines.

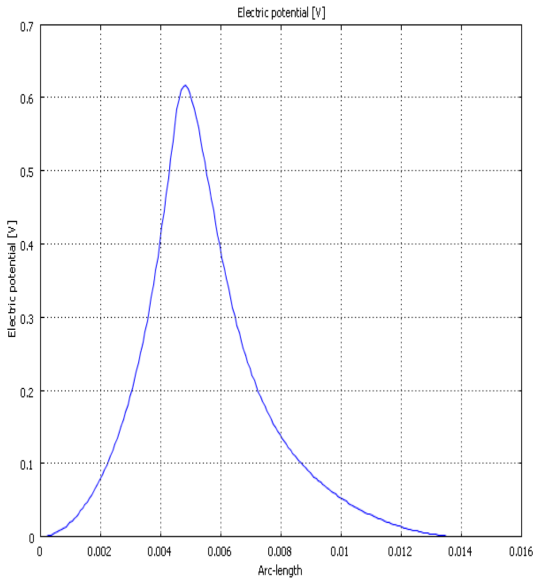

Figure 5. Potential distribution of unshielded four- conductor transmission lines using port 1 as input along a line from (x,y) = (0,0) to (x,y) =(10, 10) mm.

Table 2 shows the finite element results for the capacitance-per-unit length of unshielded four-transmission lines embedded in two-layered dielectric media. It compares the results based on our work with those from other methods.

TABLE II. VALUES OF CAPACITANCE MATRIX (IN PF/M) FOR UNSHIELDED FOUR-CONDUCTOR TRANSMSSION LINES

Capacitance per unit length	MoM[1-3]	MEI[4]	FPM[7]	This work
C_{11}	70.158	89.514	70.158	73.052
C_{12}	-12.842	-12.832	-12.839	-12.948
C_{13}	-12.960	-13.110	-12.967	-13.239
C_{14}	-22.240	-23.014	-22.230	-22.549
C_{22}	87.327	87.028	87.227	90.823
C_{23}	-54.195	-55.462	-54.234	-56.029
C_{24}	-4.052	-3.988	-4.049	-3.924
C_{33}	133.935	128.861	128.500	139.354
C_{34}	-15.606	-14.935	-14.210	-16.520
C_{44}	141.170	141.312	135.940	145.967

B. Unshielded Five-Conductor Transmission Lines

Figure 6 shows the cross section for the unshielded five-conductor transmission lines with the following parameters:

ε_{r1} = dielectric constant of the dielectric material = 2.0.

ε_{r2} = dielectric constant of the free space = 1.0.

W = width of the dielectric material = 31mm.

w = width of a single conductor line = 3mm.

h = distance of conductors from the ground plane = 1mm.

s = distance between the two coupled conductors = 2mm.

t = thickness of the strips = 0.01mm.

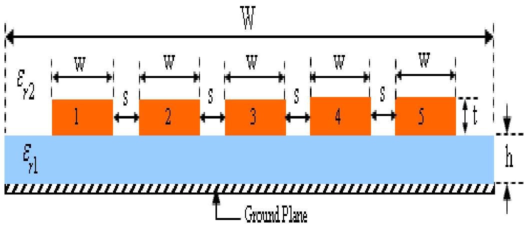

Figure 6. Cross section of unshielded five-conductor transmission lines.

The geometry is enclosed by a 31 X 5mm shield. Figure 7 shows the 2D surface distribution of the model. From the model, we generate the finite elements mesh plot as in Fig. 8. Table 3 shows the statistical properties of the mesh. While, Fig. 9 shows the contour plot of the potential distribution with port 1 as input. In addition, Fig. 10 shows the comparison analysis of the potential distribution of the model with and without dielectric substrate along the line that goes from (x,y) = (0,1mm) to (x,y) = (43mm, 1 mm). It observed that the peak valu of electric potential stayed same as the dielectric is placed in the substrate when we use the first conductor as input.

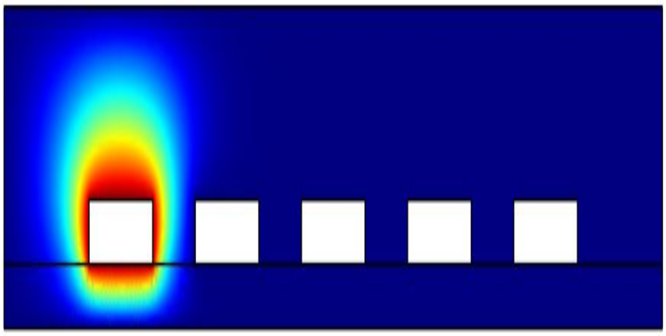

Figure 7. 2D surface potential distribution of the unshielded five-conductor transmission lines.

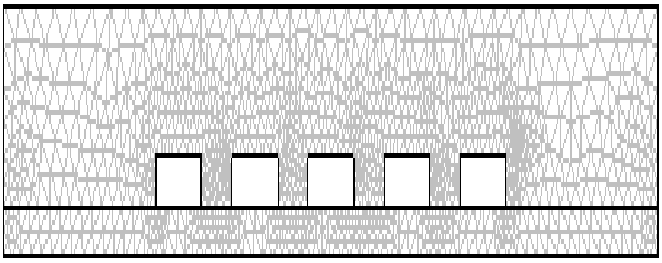

Figure 8. Mesh plot of the unshielded five-conductor transmission lines.

TABLE III. MESH STATISTICS OF THE UNSHIELDED FIVE-CONDUCTOR TRANSMSSION LINES

Items	Value
Number of degrees of freedom	21044
Total Number of mesh points	1004
Total Number of elements	1792
Triangular elements	1792
Quadrilateral	0
Boundary elements	272
Vertex elements	26

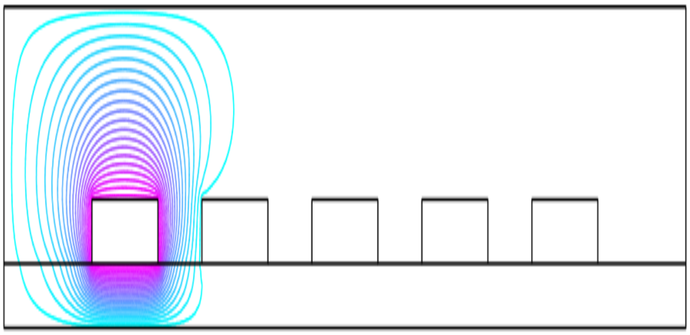

Figure 9. Contour plot of the potential distribution of the unshielded five-conductor transmission lines.

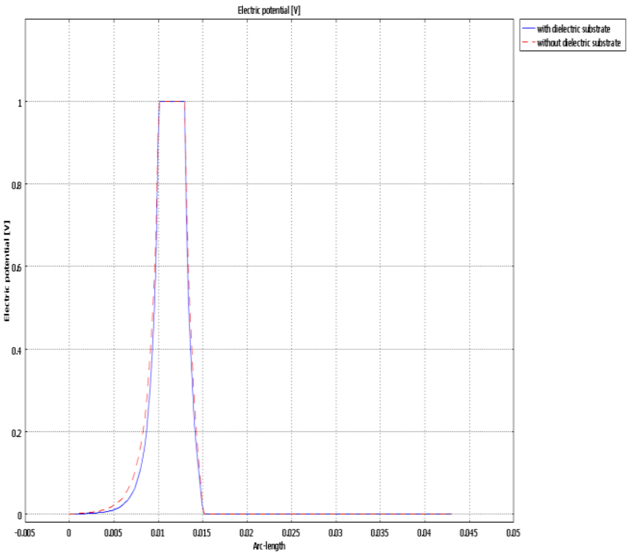

Figure 10. Comparison Analysis of Potential distribution of the model with and without dielectric substrate

Table 4 shows the finite element results for the capacitance-per-unit length of the unshielded five- transmission lines interconnect in single-layered dielectric medium. It compares the results from our work with those from other methods.

TABLE IV. VALUES OF THE FELF AND MUTUAL CAPACITANCES COEFFICIENT (IN PF/M) FOR UNSHIELDED FIVE-CONDUCTOR TRANSMSSION LINES

Capacitance per unit length	(MPM) [8]	(FTMM) [9]	This work
C_{11}	93.668	89.660	100.073
C_{12}	-8.453	-8.110	-5.983
C_{13}	-0.809	-0.795	-0.016
C_{21}	-0.345	-0.319	-5.983
C_{22}	95.329	92.173	100.899
C_{23}	-8.318	-7.962	-5.975
C_{24}	-0.758	-0.730	-0.016
C_{33}	95.341	92.145	100.816

Tables 2 and 4 provide the results of FEM in two-dimensional compared with other methods for the characteristics of unshielded two-layered multiconductor transmission lines and unshielded a single-layered multiconductor transmission lines with a thin strip thickness, respectively. The results of capacitance matrices for self and mutual capacitances, which are useful for the analysis of crosstalk between high-speed signal traces on the printed circuit board, are compared with other methods' data for the validity of the proposed method.

IV. Conclusion

In this article, we have presented the modeling in 2D of unshielded four-transmission lines embedded in two-layered dielectric media and five-transmission lines interconnect in single-layered dielectric medium. We have shown that FEM is suitable and effective as other methods for modeling multiconductor transmission lines in VLSI circuits. Some of the results obtained using FEM for the capacitance-per-unit length agree well with those found in other methods. Also, we determine the quasi-TEM spectral for the potential distribution of the models. The results obtained in this research are encouraging and motivating for further study.

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