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Fast Calculation of Capacitance Matrix for Strip-Line Crossings and Other Interconnects

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Abstract – In this paper, we consider the problem of capacitance matrix calculation for strip-line and other interconnects crossings. The problem is formulated in the spectral domain using the method of moments. Sinc-functions are employed as basis functions. Conventionally, such a formulation leads to a large, non-sparse system of linear equations in which the calculation of each of the coefficient requires the evaluation of a Fourier-Bessel integral. Such calculations are computationally very intensive. In the method proposed here, we provide simplified expressions for the coefficients in the moment method matrix. Using these simplified expressions, the coefficients can be calculated very efficiently. This leads to a fast evaluation of the capacitance matrix of the structure. Computer simulations are provided illustrating the validity of the method proposed.

Key Words : Capacitance Matrix, Method of Moment, Multilayer Interconnects, Spectral Domain Method

1. Introduction

With the continuous increase in the clock rate of high speed-systems and decrease in the dimensions of the packages and interconnects, the self and coupling capacitances associated with the interconnects are becoming more and more important in determining the system performance. Parasitic capacitive couplings that exist between the interconnects can seriously degrade the signal integrity. The literature on this topic is vast; several methods have been proposed and implemented by numerous researchers. As representative examples, we can cite here the references [1-10]. Broadly, the techniques can be divided into two categories. One is the differential equation method in which the Maxwell's equations are discretized and solved in the differential form. Examples of this approach are the finite-difference method [1] and the finite-element method [2]. These finite methods lead to a large system of equations that, in spite of being sparse, still requires huge computational resources.

The second category of techniques is the integral equation methods. Examples include the boundary-element method [3] and the method of moments [5]. The integral equation techniques usually result in a smaller matrix compared to the differential methods, but these matrices are generally fully populated thereby proving computationally intensive. Therefore, continued effort is required to develop fast algorithms for the evaluation of the capacitance matrix.

Recently, Daniel de Zutter et al. [5] have published a fast method for the calculation of capacitance matrix which is promising. The method is based on the MM formulation in the spectral domain but employs sinc functions as the basis functions as against the customary pulse basis functions. The method was further refined more recently by Jegannathan et al. [12]. In this paper, we perform an in-depth study of the method presented in [12] for various structures such as a strip and a slot crossing, a strip over a perforated ground plane, a bend over a perforated ground plane and multiple stripline crossings. We demonstrate that this method could be used with great effect in all these cases.

2. Analysis

The static potential distribution $\Phi(x,y,z)$ and the charge density distribution $\rho(x,y,z)$ in the structure must obey the Poisson's equation:

$$\nabla^2\phi(x,y,z) = \frac{-\rho(x,y,z)}{\varepsilon} \qquad (1)$$

where ε is the permittivity. In the following analysis, we consider infinitely thin perfectly conducting (PEC) interconnects. We can express the charge density distribution as:

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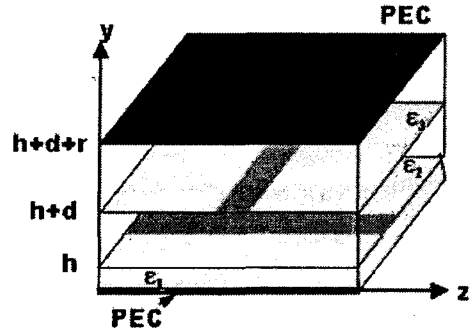

Fig. 1 The structure

$$\rho = \delta(y-h) f_b(x,z) + \delta(y-h-d) f_t(x,z) \qquad (2)$$

Where δ is the Dirac delta function.

With the Fourier transform defined as:

$$\Phi(y) = \int_{-\infty}^{\infty} \phi e^{-jk_x x} e^{-jk_z z} dx dz \qquad (3)$$

(where, to simplify the notation, the single integral sign stands for both the integration over x and over z)

the Poisson equation becomes :

$$\left(\frac{\partial^2}{\partial y^2} - k_x^2 - k_z^2 \right) \Phi(y) = 0 \qquad (4)$$

($y \neq h$, $y \neq h+d$), which has the solution :

$$\Phi(y) = C_1 e^{\sqrt{k_x^2 + k_z^2}\, y} + C_2 e^{-\sqrt{k_x^2 + k_z^2}\, y} \qquad (5)$$

in the bounded region; the arbitrary constants C_1 and C_2 are decided by the appropriate boundary conditions.

The boundary conditions and the continuity conditions in the Fourier transform domain read

$$\Phi(0) = 0 \qquad (6a)$$

$$\Phi(h+0) = \Phi(h-0) \qquad (6b)$$

$$\varepsilon_2 \frac{\partial}{\partial y} \Phi(h+0) = \varepsilon_1 \frac{\partial}{\partial y} \Phi(h-0) - F_b \qquad (6c)$$

$$\Phi(h+d+0) = \Phi(h+d-0) \qquad (6d)$$

$$\varepsilon_3 \frac{\partial}{\partial y} \Phi(h+d+0) = \varepsilon_2 \frac{\partial}{\partial y} \Phi(h+d-0) - F_t \qquad (6e)$$

$$\Phi(h+d+r) = 0 \qquad (6f)$$

where the argument of Φ is the value of the height y, where ε_1 , ε_2 , ε_3 are the dielectric constants shown in Fig. 1 ; F_t and Fb are the Fourier transforms of the charge density functions $f_t(x,z)$ and $f_b(x,z)$, respectively. Imposing these conditions on the solution of Eqn. (4) and eliminating the arbitrary constants, we find that:

$$\Phi_b = A(k_x,k_z) \sinh(k_r h) \qquad (7)$$

$$\Phi_t = A(k_x,k_z)[\sinh(k_r h)\cosh(k_r d) + \frac{\varepsilon_1}{\varepsilon_2}\cosh(k_r h)\sinh(k_r d)] - \frac{F_b}{\varepsilon_2 k_r}\sinh(k_r d) \qquad (8)$$

Where $\Phi_b = \Phi(h)$, $\Phi_t = \Phi(h+d)$, and $k_r = \sqrt{k_x^2 + k_z^2}$

In the above equations $A(k_x,k_z)$ is given by :

$$A(k_x,k_z) = P_1 F_b + P_2 F_t \qquad (9)$$

where

$$P_1 = \frac{\varepsilon_3}{\varepsilon_2}[\coth(k_r r)\sinh(k_r d) + \frac{\varepsilon_2}{\varepsilon_3}\cosh(k_r d)] P_2 \qquad (10)$$

$$P_2 = \{k_r \varepsilon_3 [\sinh(k_r h)(\coth(k_r r)\cosh(k_r d) + \frac{\varepsilon_2}{\varepsilon_3}\sinh(k_r d)) + \cosh(k_r h)(\frac{\varepsilon_1}{\varepsilon_2}\coth(k_r r)\sinh(k_r d) + \frac{\varepsilon_1}{\varepsilon_3}\cosh(k_r d))]\}^{-1} \qquad (11)$$

Rearranging the above equations, we obtain :

$$\begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} F_t \\ F_b \end{pmatrix} = \begin{pmatrix} \Phi_t \\ \Phi_b \end{pmatrix} \qquad (12)$$

where

$$R_{11} = P_2(\sinh(k_r h)\cosh(k_r d) + \frac{\varepsilon_1}{\varepsilon_2}\cosh(k_r h)\sinh(k_r d)) \qquad (13)$$

$$R_{12} = P_2 \sinh(k_r h) \qquad (14)$$

$$R_{21} = P_2 \sinh(k_r h) \qquad (15)$$

$$R_{22} = P_1 \sinh(k_r h) \qquad (16)$$

We note that

$$\phi_t = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \Phi_t e^{jk_x x} e^{jk_z z} dk_x dk_z \qquad (17a)$$

$$\phi_b = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \Phi_b e^{jk_x x} e^{jk_z z} dk_x dk_z \qquad (17b)$$

The Potential functions must satisfy :

$$\lim_{x,z \to topstrip} \phi_t(x,z) = c_t \qquad (18a)$$

$$\lim_{x,z \to bottomstrip} \phi_b(x,z) = c_b \qquad (18b)$$

where c_t and c_b are the constant potentials at which the top and bottom structures are held. The Moment Method requires that the structures be divided into small cells. Then the unknown charge density function is expanded using a sinc function basis. For instance, on the top structure we have the charge density given by:

$$f_t(x,z) = \sum_{i=1}^{M} f_{ti} \sin c[\frac{\pi}{\Delta x}(x - x_{ci})] \times \sin c[\frac{\pi}{\Delta z}(z - z_{ci})] \qquad (19)$$

where (x_{ci}, z_{ci}) are the coordinates of the center of the ith cell on the top structure and Δx and Δz are the sampling intervals in the x and z directions. A similar expansion is valid for the bottom strip. Following the details provided in [5], we have the system of simultaneous equations:

$$[\alpha]\ f_t + [\beta]\ f_b = \Phi_t$$
$$[\gamma]\ f_t + [\delta]\ f_b = \Phi_b \qquad (20)$$

where $[\alpha]$, $[\beta]$, $[\gamma]$, $[\delta]$ are all square matrices, Φ_t , Φ_b are constant column vectors having c_t and c_b as the elements, respectively. The elements of the matrices have been derived in [5]. For instance, the elements of the $[\alpha]$, $[\beta]$, $[\gamma]$, $[\delta]$ matrices are given by:

$$\alpha_{ij} = \frac{A_{cell}}{2\pi}\int_0^{\frac{\pi}{\Delta}} \mathbf{R_{11}}(k_r)J_0(k_r\rho_{ij})k_r dk_r \qquad (21a)$$

$$\beta_{ij} = \frac{A_{cell}}{2\pi}\int_0^{\frac{\pi}{\Delta}} \mathbf{R_{12}}(k_r)J_0(k_r\rho_{ij})k_r dk_r \qquad (21b)$$

$$\gamma_{ij} = \frac{A_{cell}}{2\pi}\int_0^{\frac{\pi}{\Delta}} \mathbf{R_{21}}(k_r)J_0(k_r\rho_{ij})k_r dk_r \qquad (21c)$$

$$\delta_{ij} = \frac{A_{cell}}{2\pi}\int_0^{\frac{\pi}{\Delta}} \mathbf{R_{22}}(k_r)J_0(k_r\rho_{ij})k_r dk_r \qquad (21d)$$

where $A_{cell} = \Delta x \cdot \Delta z$, ρ_{ij} is the distance between the centers of the i^{th} and j^{th} cell, J_0 is the zeroth order Bessel function. $\mathbf{R}_{11}$, $\mathbf{R}_{12}$, $\mathbf{R}_{21}$, $\mathbf{R}_{22}$ are the kernel functions. The details of the kernel function are given by Eqs. (13) to (16).

3. New Method

In this paper, we provide a simplified formula for the integrals in (21). This substantially speeds up the calculation of the coefficients. Specifically, we can split the range of integration 0 to π/Δ into three intervals: 0 to k_1, k_1 to k_2, and k_2 to π/Δ where k_1 is such that k_1h, k_1d, k_1r are all very small, say less than 0.1; k_2 is such that k_2h, k_2d, k_2r are all greater than, say 3.0. Employing small argument / asymptotic approximations appropriately for the hyperbolic functions in the kernels, we may, after some algebraic manipulations, arrive at the formulae provided below in Table 1 and Table 2.

Rewriting the integral (21a) using k_1 and k_2, we obtain the following equation.

$$\alpha^{ij} = \frac{A_{cell}}{2\pi}\left(\int_0^{k_1}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r + \int_{k_1}^{k_2}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r + \int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r\right)$$

$$= \frac{A_{cell}}{2}\left(\mathbf{I}_1 + \int_{k_1}^{k_2}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r + \mathbf{I}_2\right)$$

where $\mathrm{I}_1 = \int_0^{k_1}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r$, $\mathrm{I}_2 = \int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{11}(k_r)J_0(k_r\rho^{ij})k_r dk_r$).

We can approximate I_1 and I_2 as follows.

1) Integration from 0 to k_1

$$\mathbb{I}_1 = \int_0^{k_1}\mathbb{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r \qquad (22)$$

The integrand $\mathbf{R}_{11}(k_r)$can be expressed as follows:

$$\mathbf{R}_{11}(k_r) = \frac{\left[\sinh(k_rh)\cosh(k_rd) + \frac{\varepsilon_1}{\varepsilon_2}\cosh(k_rh)\sinh(k_rd)\right]}{\left\{k_r\varepsilon_3\left[\sinh(k_rh)\left(\coth(k_rr)\cosh(k_rd) + \frac{\varepsilon_2}{\varepsilon_3}\sinh(k_rd)\right) + \cosh(k_rh)\left(\frac{\varepsilon_1}{\varepsilon_2}\coth(k_rr)\sinh(k_rd) + \frac{\varepsilon_1}{\varepsilon_3}\cosh(k_rd)\right)\right]\right\}}$$

Using small argument approximation; we have :

$$\sinh x = x, \quad \cosh x = 1, \quad \coth x = \frac{1}{x}$$

and $\mathbf{R}_{11}(k_r)$ can be simplified as follows :

$$\mathbb{R}_{11}(k_r) = \frac{\left((k_rh) + \frac{\varepsilon_1}{\varepsilon_2}(k_rd)\right)}{k_r\varepsilon_3\left[\frac{h}{r} + \frac{\varepsilon_2}{\varepsilon_3}k_r^{\,2}hd + \frac{\varepsilon_1}{\varepsilon_2}\frac{d}{r} + \frac{\varepsilon_1}{\varepsilon_3}\right]}$$

$$= \frac{rh\varepsilon_2 + rd\varepsilon_1}{\left[\varepsilon_2\varepsilon_3h + \varepsilon_1\varepsilon_3d + r\varepsilon_1\varepsilon_2\right]}$$

The second equality above is obtained using $\frac{\varepsilon_2}{\varepsilon_3}k_r^{\,2}hd \approx 0$

Let $a_1 = \frac{rh\varepsilon_2}{\left[r\varepsilon_1\varepsilon_2 + h\varepsilon_2\varepsilon_3 + d\varepsilon_3\varepsilon_1\right]}$ and $a_2 = \frac{rd\varepsilon_1}{\left[r\varepsilon_1\varepsilon_2 + h\varepsilon_2\varepsilon_3 + d\varepsilon_3\varepsilon_1\right]}$,

then $\mathbf{R}_{11}(k_r) = (a_1 + a_2)$ and (22) becomes as follows:

$$\mathbf{I}_1 = \int_0^{k_1}\mathbf{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r = \int_0^{k_1}(a_1 + a_2)J_0(k_r\rho_{ij})k_r dk_r = (a_1 + a_2)\int_0^{k_1}J_0(k_r\rho_{ij})k_r dk_r \qquad (23)$$

From reference [11], we have :

$$\int x^{p+1}J_p(\alpha x)dx = \frac{1}{\alpha}x^{p+1}J_{p+1}(\alpha x) + c$$

when this is applied to (23) with p=0, $\alpha = \rho_{ij}$, $x = k_r$, we obtain

$$\mathbf{I}_1 = (a_1 + a_2)\frac{k_r}{\rho_{ij}}J_1(k_r\rho_{ij})\Big|_0^{k_1} = \frac{k_1J_1(k_1\rho_{ij})(a_1 + a_2)}{\rho_{ij}} \qquad \text{where } \rho_{ij} \neq 0$$

When $\rho_{ij} = 0$,

we need to consider the limit $\lim_{\rho^{ij}\to 0}\frac{J_1(k_1\rho^{ij})}{\rho^{ij}}$. (24)

From reference [11], we have:

$J_p(x) = \frac{1}{p!}\left(\frac{x}{2}\right)^p$ where p>0 and x approaches to 0.

If p=1, then we obtain $J_1(x) \underset{x\to 0}{=} \left(\frac{x}{2}\right)$.

Applying the above result to (24), we obtain

$$\lim_{\rho_{ij}\to 0}\frac{J_1(k_1\rho_{ij})}{\rho_{ij}} = \lim_{k_1\rho_{ij}\to 0}\frac{J_1(k_1\rho_{ij})\cdot k_1}{k_1\rho_{ij}} = \left(\frac{k_1\rho_{ij}}{2}\right)\cdot\frac{k_1}{(k_1\rho_{ij})} = \frac{k_1}{2}$$

Thus for $\rho_{ij}=0$, the integral equals $\mathbf{I}_1 = \frac{k_1^2}{2}(a_1+a_2)$

We can obtain Table 1 by using similar procedure to (21b)~(21d).

Table 1. The approximations for the integrals in the range from 0 to k1

Integral	Result when $\rho_{ij}=0$	Result when $\rho_{ij}\neq 0$
$\int_0^{k_1}\mathbf{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$\frac{(a_1+a_2)k_1^2}{2}$	$\frac{(a_1+a_2)k_1 J_1(k_1\rho_{ij})}{\rho_{ij}}$
$\int_0^{k_1}\mathbf{R}_{12}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$\frac{a_1k_1^2}{2}$	$\frac{a_1k_1 J_1(k_1\rho_{ij})}{\rho_{ij}}$
$\int_0^{k_1}\mathbf{R}_{21}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$\frac{a_1k_1^2}{2}$	$\frac{a_1k_1 J_1(k_1\rho_{ij})}{\rho_{ij}}$
$\int_0^{k_1}\mathbf{R}_{22}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$\frac{(a_1+a_3)k_1^2}{2}$	$\frac{(a_1+a_3)k_1 J_1(k_1\rho_{ij})}{\rho_{ij}}$
values of the constants		
$a_1=\frac{rh\varepsilon_2}{[\varepsilon_1\varepsilon_2r+\varepsilon_2\varepsilon_3h+\varepsilon_1\varepsilon_3d]}$, $a_2=\frac{rd\varepsilon_1}{[\varepsilon_1\varepsilon_2r+\varepsilon_2\varepsilon_3h+\varepsilon_1\varepsilon_3d]}$, $a_3=\frac{dh\varepsilon_3}{[\varepsilon_1\varepsilon_2r+\varepsilon_2\varepsilon_3h+\varepsilon_1\varepsilon_3d]}$		

2) Integration from k_2 to π/Δ

$$\mathbf{I}_2 = \int_{k_2}^{\pi/\Delta}\mathbf{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r \tag{25}$$

For large x , we have the following approximations:

$$\sinh x \approx \frac{e^x}{2},\quad \cosh x \approx \frac{e^x}{2},\quad \coth x \approx 1$$

and $\mathbf{R}_{11}(k_r)$ can be simplified as follows :

$$\mathbf{R}_{11}(k_r) = \frac{(k_rh)(k_rd)\left[1+\left(\frac{\varepsilon_1}{\varepsilon_2}\right)\right]}{(k_r\varepsilon_3)(k_rh)\left[\left(k_rd+\frac{\varepsilon_2}{\varepsilon_3}k_rd\right)+\left(\frac{\varepsilon_1}{\varepsilon_2}\right)k_rd+\left(\frac{\varepsilon_1}{\varepsilon_3}\right)k_rd\right]}$$

$$= \frac{\left[1+\frac{\varepsilon_1}{\varepsilon_2}\right]}{(k_r\varepsilon_3)\left[1+\frac{\varepsilon_2}{\varepsilon_3}+\frac{\varepsilon_1}{\varepsilon_2}+\frac{\varepsilon_1}{\varepsilon_3}\right]}$$

Using this $\mathbf{R}_{11}(k_r)$ in (25), we obtain

$$\mathbf{I}_2 = \int_{k_2}^{\pi/\Delta}\mathbf{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r = \frac{\left[1+\frac{\varepsilon_1}{\varepsilon_2}\right]}{\varepsilon_3\left[1+\frac{\varepsilon_2}{\varepsilon_3}+\frac{\varepsilon_1}{\varepsilon_2}+\frac{\varepsilon_1}{\varepsilon_3}\right]}\int_{k_2}^{\pi/\Delta}J_0(k_r\rho_{ij})dk_r$$

$$= a_4\int_{k_2}^{\pi/\Delta}J_0(k_r\rho_{ij})dk$$

where, $a_4 = \frac{\left[1+\frac{\varepsilon_1}{\varepsilon_2}\right]}{\varepsilon_3\left[1+\frac{\varepsilon_2}{\varepsilon_3}+\frac{\varepsilon_1}{\varepsilon_2}+\frac{\varepsilon_1}{\varepsilon_3}\right]}$

We can obtain Table 2 by using similar procedure to (21b)~(21d) in $[k_2, \pi/\Delta]$.

Table 2. The approximations for the integrals in the range from k2 to π/Δ

Integral	Result	Values of the Constants
$\int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{11}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$a_4\int_{k_2}^{\frac{\pi}{\Delta}}J_0(k_r\rho_{ij})dk_r$	$a_4=\frac{\left[1+\frac{\varepsilon_1}{\varepsilon_2}\right]}{\varepsilon_3\left[1+\frac{\varepsilon_2}{\varepsilon_3}+\frac{\varepsilon_1}{\varepsilon_2}+\frac{\varepsilon_1}{\varepsilon_3}\right]}$
$\int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{12}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	0	
$\int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{21}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	0	$a_5=\frac{\left[1+\frac{\varepsilon_3}{\varepsilon_2}\right]}{\varepsilon_3\left[1+\frac{\varepsilon_2}{\varepsilon_3}+\frac{\varepsilon_1}{\varepsilon_2}+\frac{\varepsilon_1}{\varepsilon_3}\right]}$
$\int_{k_2}^{\frac{\pi}{\Delta}}\mathbf{R}_{22}(k_r)J_0(k_r\rho_{ij})k_r dk_r$	$a_5\int_{k_2}^{\frac{\pi}{\Delta}}J_0(k_r\rho_{ij})dk_r$	

In all these cases, the integral in the range k_1 to k_2 can be evaluated using a numerical technique such as the Gaussian Quadrature. Making use of the formulae provided in these tables to calculate the coefficients in the matrices considerably speed up the calculations.

4. Numerical Results

The above method was implemented with a PC of a 2.6 GHz processor. In structures of Fig. 2~3, the dielectric constants were selected as $\varepsilon_1=2.0\cdot\varepsilon_0$, $\varepsilon_2=9.0\cdot\varepsilon_0$, and $\varepsilon_3=4.0\cdot\varepsilon_0$. The length of the strips was taken as 1050μm and the width as 210*μm*. The parameters *h=d=r= 300μm* were used. Capacitance matrices were evaluated and the results are given in Table 3 and Table 4. As can be seen in the tables, the method provided here works several times faster than a direct evaluation of the coefficients. Although we have shown here only limited results, simulations were carried out for a large number of cases. In all these cases, we find the method described here works very fast.

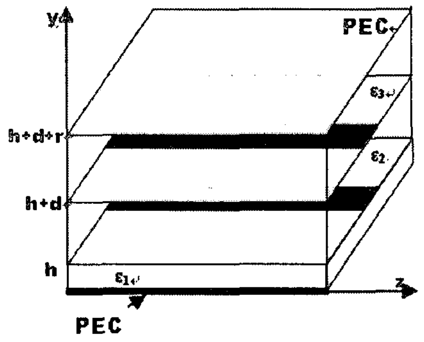

Fig. 2. Parallel stripline crossing structure

Table 3. The results for a parallel stripline crossing in Fig. 2

Method	Cell size (㎛)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	196.32	-68.772	-68.775	166.12	5m 16s
Direct approach as in[5]	30	197.02	-69.743	-69.745	166.71	40m 55s

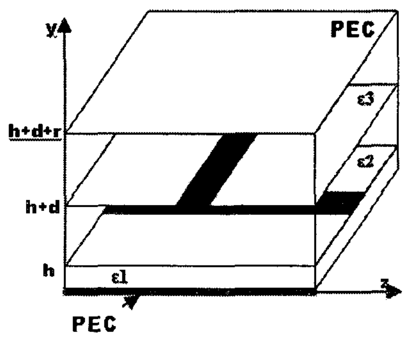

Fig. 3. Perpendicular stripline crossing structure

Table 4. The results for a perpendicular stripline crossing in Fig. 3

Method	Cell size (㎛)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	187.38	-52.941	-52.941	158.56	5m 50s
Direct approach as in[5]	30	187.39	-53.02	-53.019	158.56	44m 8s

In the structure of Fig. 4, the dielectric constants were selected as $\varepsilon_1 = 2.0 \cdot \varepsilon_0$, $\varepsilon_2 = 9.0 \cdot \varepsilon_0$, and $\varepsilon_3 = 4.0 \cdot \varepsilon_0$. The parameters $h=d=r=300\mu m$ were used. The width and length of patch are 1350㎛ and 810㎛ and the width and length of slot in the patch are 630㎛ and 210㎛ on the top plane. The width and length of the strip are 210㎛ and 810㎛ on the bottom plane. The structures on each plane are bilaterally symmetric. Capacitance matrices were evaluated and the results are given in Table 5. The whole matrix size was 1257 by 1257.

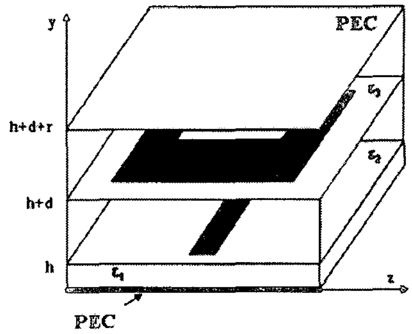

Fig. 4. A plane with slot over strip

Table 5. The results for a plane with slot over strip in Fig. 4

Method	Cell size (㎛)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	468.66	-92.584	-91.162	140.12	13m 9s
Direct approach as in[5]	30	469.35	-92.147	-92.167	140.32	1h 26m 25s

In the structure of Fig. 5, the dielectric constants were selected as $\varepsilon_1 = 2.0 \cdot \varepsilon_0$, $\varepsilon_2 = 9.0 \cdot \varepsilon_0$, and $\varepsilon_3 = 4.0 \cdot \varepsilon_0$. The parameters $h=d=r=300\mu m$ were used. The width and length of strip are 210㎛ and 1140㎛ on the top plane. The width and length of patch are 2160㎛ and 1140㎛ on the bottom plane. the width and length of the perforation in the patch are 300㎛ and 150㎛. The space between perforations is 420㎛ in length and width. And the strip on the top plane is positioned in the first space between perforation columns from the left side. The structure on the bottom plane is bilaterally symmetric. Capacitance matrices were evaluated and the results are given in Table 6. The whole matrix size was 2702 by 2702.

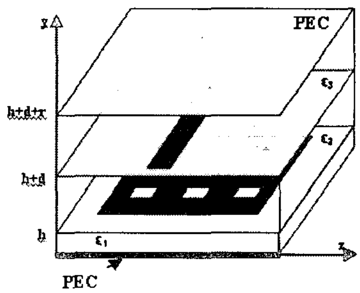

Fig. 5. A stripline over a perforated plane

Table 6. The results for a stripline over a perforated plane in Fig. 5

Method	Cell size (㎛)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	225.36	-135.78	-135.85	713.63	1h 13m 35s
Direct approach as in[5]	30	225.54	-136.18	-136.13	714.01	6h 42m 22s

In the structure of Fig. 6, the dielectric constants were selected as $\varepsilon_1 = 2.0 \cdot \varepsilon_0$, $\varepsilon_2 = 9.0 \cdot \varepsilon_0$, and $\varepsilon_3 = 4.0 \cdot \varepsilon_0$. The parameters $h=d=r=300\mu m$ were used. The width and length of the long strip are 2160μm and 210μm on the top plane and the short strip 210μm and 450μm. The width and length of patch are 2160μm and 1140μm on the bottom plane. the width and length of the perforation in the patch are 300μm and 150μm. The space between perforations is 420μm in length and width. The structure on the bottom plane is bilaterally symmetric. Capacitance matrices were evaluated and the results are given in Table 7. The whole matrix size was 3045 by 3045.

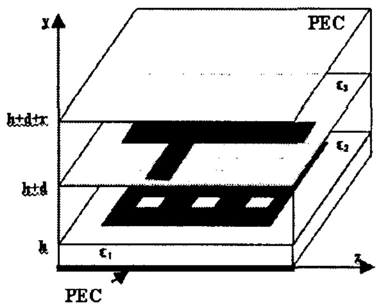

Fig 6. A bended stripline over a perforated plane

Table 7. The results for a bended stripline over a perforated plane in Fig. 6

Method	Cell size (μm)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	467.69	285.38	285.18	806.74	1h 57m 50s
Direct approach as in[5]	30	468.25	286.47	286.24	807.96	10h 3m 12s

In the structure of Fig. 7, the dielectric constants were selected as $\varepsilon_1 = 2.0 \cdot \varepsilon_0$,$\varepsilon_2 = 9.0 \cdot \varepsilon_0$, and $\varepsilon_3 = 4.0 \cdot \varepsilon_0$. The parameters h=d=r=300μm were used. The width and length of the strip are 210μm and 1050μm on the top plane. The space between strips is 210μm in width. The width and length of the strip are 1470μm and 210μm on the bottom plane. The structures on each plane are bilaterally symmetric. Capacitance matrices were evaluated and the results are given in Table 8. The whole matrix size was 1078 by 1078.

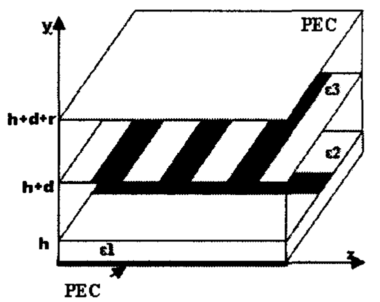

Fig. 7. A perpendicular multiple stripline crossing

Table 8. The results for a perpendicular multiple stripline crossing in Fig. 7

Method	Cell size (μm)	C_{tt}(fF)	C_{tb}(fF)	C_{bt}(fF)	C_{bb}(fF)	Calculation time
Method presented here	30	193.11	31.812	2.482	43.445	15m 8s
		31.82	200.08	31.806	42.386	
		2.44	31.812	193.1	43.445	
		43.433	42.379	43.442	228.37	
Direct approach as in[5]	30	193.04	31.755	2.498	43.352	1h 56m 23s
		31.769	200.08	31.738	42.598	
		2.478	31.755	193.04	43.352	
		43.381	42.58	43.357	228.37	

5. Conclusions

Calculation of capacitance matrix is critical in high speed package design. Although there are a large number of methods for this purpose, all of them are computationally intensive. So there is a continual need for improving the speed of these methods. Here we have presented one such method. Simulations have indicated that this method is very efficient.

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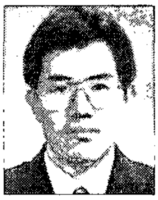

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