Electromagnetic Modeling and Simulation for Packaging Structures with Lossy Conductors

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Abstract— Accurate electromagnetic (EM) analysis for interconnect structures requires to consider the finite conductivity of involved conductors. The conductor loss could be accounted for through an approximate surface impedance when the skin depth of current is small. However, this approximation may not be valid for large skin depth caused by low frequencies or small conductivities. In this work, we treat the lossy conductors as homogeneous dielectric media and use electric field integral equations (EFIEs) to describe the problem. The EFIEs are solved with the method of moments (MoM) in which the Rao-Wilton-Glisson (RWG) and dual basis functions are used to represent the electric and magnetic current densities, respectively. A numerical example is presented to demonstrate the approach.

1. INTRODUCTION

Accurate electromagnetic (EM) analysis based on numerical modeling and simulation is essential for the optimal design of electronic devices or systems [1]. For interconnect and packaging structures, the conductors are usually lossy and we have to account for the skin effect in numerical solutions. In the integral equation approach for solving the problem, one may use the volume-filament method like the partial equivalent electric circuit (PEEC) solver or surface integral equation (SIE) approach with an approximate surface impedance [2–7]. However, they are only efficient to model interconnect conductors which are usually long and thin and cannot handle the conductors with irregular shape such as bends and junctions [8]. The SIE approach is preferred whenever available because it only discretizes the boundaries or interfaces of media, resulting less number of unknowns [1].

To treat arbitrarily-shaped structures with lossy conductors by the SIE approach, the generalized impedance boundary condition (GIBC) approach was proposed by formulating the problem in two regions [8]. The approach treats the lossy conductors as general dielectric media and uses the electric field integral equations (EFIEs) to describe the exterior region of conductors and the magnetic field integral equations (MFIEs) to formulate the interior region of conductors. In this work, we use the EFIEs to describe both the exterior region and interior region of conductors and consider the structural mixture of dielectrics and conductors which were not considered previously. The EFIEs are solved with the method of moments (MoM) in which the the Rao-Wilton-Glisson (RWG) basis function [9] is used to represent the electric current density while the dual basis function is employed to expand the magnetic current density [10]. The two basis functions are also used as testing functions to wisely test the EFIEs so that the conditioning of resulting system matrix can be improved. We present the numerical example for analyzing a typical interconnect structure to illustrate the approach and good results can be observed.

2. SURFACE INTEGRAL EQUATIONS

The interconnect structures include both dielectric substrates and conducting signal lines and ground (conductors). We label the conductors as Region 1, the substrate as Region 2, and the surrounding medium (free space) as Region 0, and the subscripts of parameters indicate the corresponding regions. Consider the EM scattering by a general dielectric object labeled as Region i, the EFIEs can be written as [1]

$$\hat{n} \times [\mathcal{L}_0(\mathbf{J}_i) + \mathcal{K}_0(\mathbf{M}_i)] = -\hat{n} \times \mathbf{E}^{inc}, \quad \mathbf{r} \in S_i \tag{1}$$

$$\hat{n} \times [\mathcal{L}_i(\mathbf{J}_i) + \mathcal{K}_i(\mathbf{M}_i)] = 0, \quad \mathbf{r} \in S_i \tag{2}$$

where $\hat{n}$ is the unit normal vector at the object surface S_i, $\mathbf{J}_i$ and $\mathbf{M}_i$ are the equivalent electric current density and magnetic current density at the object surface, respectively, and $\mathbf{E}^{inc}$ is the incident electric field. Also, $\mathcal{L}$ and $\mathcal{K}$ are the operators which are respectively defined as

$$\mathcal{L}(\mathbf{A}) = i\omega\mu \int_{S_i} \left(\bar{\mathbf{I}} + \frac{\nabla\nabla}{k^2} \right) g(\mathbf{r}, \mathbf{r}') \cdot \mathbf{A}(\mathbf{r}')\, dS' \tag{3}$$

$$\mathcal{K}(\mathbf{A}) = \frac{1}{2}\hat{n} \times \mathbf{A} + \fint_{S_i} \mathbf{A}(\mathbf{r}') \times \nabla g(\mathbf{r}, \mathbf{r}')\, dS' \tag{4}$$

where $\mathbf{A}$ represents a current density, k is the wavenumber, and $g(\mathbf{r}, \mathbf{r}') = e^{ikR}/(4\pi R)$ is the scalar Green's function in which $R = |\mathbf{r} - \mathbf{r}'|$ is the distance between an observation point $\mathbf{r}$ and a source point $\mathbf{r}'$. The above EFIEs can also be applied to a lossy conductor with a finite conductivity when we treat it as a generalized dielectric object. For an interconnect structure, we apply the above EFIEs to both the conductor region and substrate region to yield the following integral equations.

$$\hat{n} \times [\mathcal{L}_0(\mathbf{J}_1) + \mathcal{K}_0(\mathbf{M}_1) + \mathcal{L}_0(\mathbf{J}_2) + \mathcal{K}_0(\mathbf{M}_2)] = -\hat{n} \times \mathbf{E}^{ex}, \quad \mathbf{r} \in S_1 \tag{5}$$

$$\hat{n} \times [\mathcal{L}_1(\mathbf{J}_1) + \mathcal{K}_1(\mathbf{M}_1)] = 0, \quad \mathbf{r} \in S_1 \tag{6}$$

$$\hat{n} \times [\mathcal{L}_0(\mathbf{J}_1) + \mathcal{K}_0(\mathbf{M}_1) + \mathcal{L}_0(\mathbf{J}_2) + \mathcal{K}_0(\mathbf{M}_2)] = 0, \quad \mathbf{r} \in S_2 \tag{7}$$

$$\hat{n} \times [\mathcal{L}_2(\mathbf{J}_2) + \mathcal{K}_2(\mathbf{M}_2)] = 0, \quad \mathbf{r} \in S_2 \tag{8}$$

where S_1 and S_2 are the surface of the substrate and conductors, respectively, and $\mathbf{E}^{ex}$ is a delta-gap source. From the above equations, we can solve the current densities and then find the needed parameters for circuit analysis.

3. THE METHOD OF MOMENTS SOLUTION

The above EFIEs can be solved with the MoM. Since we have both unknown electric current density and unknown magnetic current density on each medium interface, we need to use two basis functions to represent them, respectively. To improve the conditioning of resulting system matrix, we use the RWG basis function to represent the electric current density and the dual basis function to expand the magnetic current density, i.e.,

$$\mathbf{J}_i(\mathbf{r}') = \sum_{n=1}^{N_i} a_n^{(i)} \mathbf{\Lambda}_n(\mathbf{r}') \tag{9}$$

$$\mathbf{M}_i(\mathbf{r}') = \sum_{n=1}^{N_i} b_n^{(i)} \tilde{\mathbf{\Lambda}}_n(\mathbf{r}') \tag{10}$$

where N_i $(i = 1, 2)$ is the number of RWG triangle pairs at the surface of Region i after discretization. The definitions of RWG basis function and dual basis function can be found in [9, 10], respectively. The two basis functions are also used as testing functions to test the above integral equations and we can obtain the following matrix equation

$$\begin{aligned} &\sum_{n=1}^{N_1} \left\{ a_n^{(1)} \langle \mathbf{\Lambda}_m, \mathcal{L}_0(\mathbf{\Lambda}_n) \rangle + b_n^{(1)} \langle \mathbf{\Lambda}_m, \mathcal{K}_0(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} + \sum_{n=1}^{N_2} \left\{ a_n^{(2)} \langle \mathbf{\Lambda}_m, \mathcal{L}_0(\mathbf{\Lambda}_n) \rangle + b_n^{(2)} \langle \mathbf{\Lambda}_m, \mathcal{K}_0(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} \\ &= -\langle \mathbf{\Lambda}_m, \mathbf{E}^{ex} \rangle, \quad m = 1, 2, \ldots, N_1 \end{aligned} \tag{11}$$

$$\sum_{n=1}^{N_1} \left\{ a_n^{(1)} \langle \tilde{\mathbf{\Lambda}}_m, \mathcal{L}_1(\mathbf{\Lambda}_n) \rangle + b_n^{(1)} \langle \tilde{\mathbf{\Lambda}}_m, \mathcal{K}_1(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} = 0, \quad m = 1, 2, \ldots, N_1 \tag{12}$$

$$\begin{aligned} &\sum_{n=1}^{N_1} \left\{ a_n^{(1)} \langle \mathbf{\Lambda}_m, \mathcal{L}_0(\mathbf{\Lambda}_n) \rangle + b_n^{(1)} \langle \mathbf{\Lambda}_m, \mathcal{K}_0(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} + \sum_{n=1}^{N_2} \left\{ a_n^{(2)} \langle \mathbf{\Lambda}_m, \mathcal{L}_0(\mathbf{\Lambda}_n) \rangle + b_n^{(2)} \langle \mathbf{\Lambda}_m, \mathcal{K}_0(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} \\ &= 0, \quad m = 1, 2, \ldots, N_2 \end{aligned} \tag{13}$$

$$\sum_{n=1}^{N_2} \left\{ a_n^{(2)} \langle \tilde{\mathbf{\Lambda}}_m, \mathcal{L}_2(\mathbf{\Lambda}_n) \rangle + b_n^{(2)} \langle \tilde{\mathbf{\Lambda}}_m, \mathcal{K}_2(\tilde{\mathbf{\Lambda}}_n) \rangle \right\} = 0, \quad m = 1, 2, \ldots, N_2. \tag{14}$$

Note that the wavenumber is $k \approx (1 + i)/\delta$ where $\delta \approx \sqrt{2/\omega\mu\sigma}$ is the skin depth for a lossy conductor.

4. NUMERICAL EXAMPLES

To demonstrate the approach, we consider the EM analysis for a typical interconnect structure, i.e., two conducting signal lines on a one-layer dielectric substrate with a ground as sketched in Fig. 1. The dielectric substrate is lossless but the conducting signal lines and ground are lossy. The geometry are characterized with $l = 10.0$, $w = 5.0$, $h = 0.3$, $d = 0.1$, $s = s_1 = s_2 = 0.2$, and $t_1 = t_2 = 0.05$, all in millimeter (mm). Here l is the length that the ground, substrate, and signal lines commonly have, w is the width that the ground and substrate commonly have, h is the height of the substrate, d is the thickness of the ground, s is the spacing between the two signal lines whose widths are s_1 and s_2, and thicknesses are t_1 and t_2, respectively. The relative permittivity of the dielectric substrate is $\epsilon_r = 4.0$ and the conductivity of conductors is $\sigma = 5.8 \times 10^7$ S/m (the relative permeability $\mu_r = 1.0$ for both substrate and conductors). Fig. 2 shows the solutions of S parameters (magnitude) for the structure with a comparison to the result from a finite element method (FEM) solver.

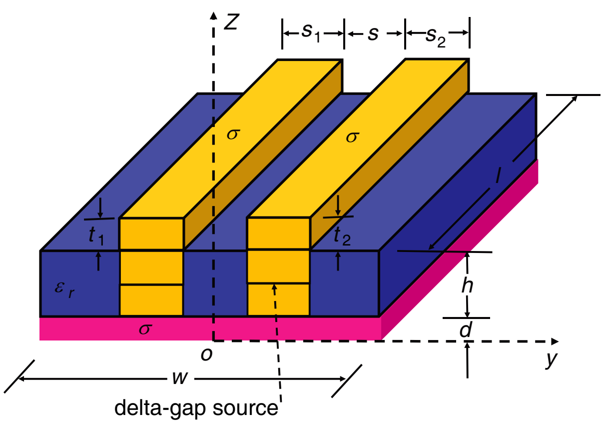

Figure 1: Geometry of a typical interconnect and packaging structure. A conducting signal line is at the top of a one-layer dielectric substrate with a ground.

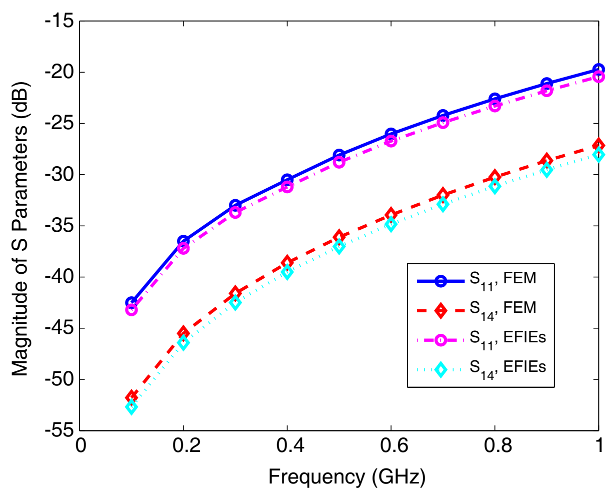

Figure 2: S parameter for the interconnect and packaging structure including a signal line and a one-layer dielectric substrate. The geometry is defined with $l = 10.0$, $w = 5.0$, $d = 0.1$, $s = 0.2$, $t = 0.05$, and $h = 0.3$, all in millimeters, and the substrate has a relative permittivity $\varepsilon_r = 4.0$.

5. CONCLUSION

In this work, we consider the lossy conductors in the EM analysis for interconnect structures. The conductors are treated as general homogeneous dielectric media and we use the two-region EFIEs to formulate both conductor region and dielectric substrate region together. The EFIEs are solved by the MoM in which the electric and magnetic current densities at region boundaries are represented with the RWG and dual basis functions, respectively. The basis functions are also used as testing functions to alternatively test the EFIEs so that the conditioning of system matrix can be improved. We present a typical numerical example to illustrate the approach and good results have been observed.

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