Hybrid FDTD-MPIE Method for the Simulation of Locally Inhomogeneous Multilayer LTCC Structure

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Abstract

A new hybrid finite-difference time-domain-mixed potential integral equation method (FDTD-MPIE) is proposed for modeling and simulating multilayer planar problems with possible locally inhomogeneous geometries. By using equivalent principle, the original problem can be divided into different regions. The fields in the inhomogeneous regions are modeled by using FDTD method, which is a time domain method providing broad band fields information. The resultant interaction matrix from FDTD can be used as a look-up table for subsequent model coupling procedure. The fields in the layered structure with possible perfect electric conductors are described in terms of the equivalent electric and magnetic surface current densities by a mixed potential electric-field integral representation with less singular kernels. The interactions between the FDTD model and MPIE model are coupled together by enforcing the continuity of the tangential electric and magnetic fields at the equivalent surface using a Galerkin testing procedure. Numerical results of a canonical test problem are presented to validate the hybrid FDTD-MPIE method.

1. Introduction

Emerging applications in the RF, microwave and millimetre wave regimes require the use of new packaging technology possessing the prominent features of high packaging density, cost effectiveness and reliability. One multilayer substrate technology, named Low Temperature Co-fired Ceramic (LTCC), is a good candidate to help achieve such design flexibility and optimised integration in which free vertical space of the multilayer substrate can be fully utilized [1]. The 3D nature of the multilayer LTCC circuit makes it a somewhat complex task for its modelling and simulation, in particular, if there exists some local inhomogeneous objects.

For such a kind of multilayer structures with locally embedded inhomogeneous regions, one single computational electromagnetic method is not readily to handle efficiently such a fairly complex task, irrespective of the surface integral equation techniques, which is solved by MOM (Method of Moments), or the differential equation techniques such as FEM (Finite Element Method) and FDTD (Finite Difference Time Domain Method). The integral equation (IE) techniques are extensively employed to solve the multilayer planar circuits, whereas the differential equation techniques such as FEM or FDTD are especially suitable for dealing with complex inhomogeneous media because its relatively simple formulation. Based on the idea of combining the respective advantages of the two kinds of methods, the hybrid techniques are put forward to model more general geometries in an efficient manner.

Traditionally, the hybrid FEM-IE is one popular hybrid technique widely used in electromagnetic modeling because of the versatility of FEM in geometry and material modeling [2]. Another hybrid technique which couples the powerful yet simple FDTD method with the integral equation method is also attractive, especially when wide band information is needed for some specific complex geometries. In [3], the FDTD method is hybridized with the free-space IE method, where the FDTD method is applied to the locally inhomogeneous regions and coupled with the global IE modeling method. Similar idea can be traced back to the hybrid FEM-IE method [2, 4]. In this paper, a hybrid method, called hybrid FDTD-MPIE (mixed-potential integral equation) method, is proposed to efficiently deal with the locally inhomogeneous multilayer structure, which can be applied to modeling complex LTCC structures. In this hybrid method, the FDTD method is employed to modeling the inhomogeneous regions existing in the global multilayer planar structure, and the multilayer structure is described by multilayer MPIE method.

2. Methodology Statement

To solve the above mentioned complex problem using FDTD-MPIE method, the equivalence principle is applied to introducing an artificial surface (for the perfect electric conductors (PEC) residing in this structure, it is just the surface of the PEC) to enclose the inhomogeneous bodies and exclude it from the planar multilayer structure. The inhomogeneous regions are modeled by the FDTD method in terms of the electric and magnetic field components, whereas the fields in the layered structure including possible PEC structures are described by a mixed-potential integral representation in terms of the equivalent electric and/or magnetic surface current densities. The interactions between the FDTD-modelled region and MPIE-formulated region are coupled together by enforcing the continuity of the tangential electric and magnetic fields at the artificial surface.

The FDTD method [2] is a popular and powerful full-wave numerical method because of its simple formulation exempted from the matrix equation solution. However, to handling multilayer planar structure, the FDTD method...
becomes cumbersome as compared to the widely used mixed potential integral equation (MPIE) method [3]. The MPIE method with less singular integral kernels is chosen to facilitate the numerical modelling of the multilayer structure. The mixed potential integral equation is formulated and solved by using the method of moments (MOM). Since the FDTD method and the MOM method are evolved in the time and frequency domain, respectively, the Discrete Fourier Transform (DFT) is employed to manipulate the domain incompatibility.

3. Methodology Details

3.1 Problem Statement

Consider a three-dimensional geometry consisting of inhomogeneous local region and global layered planar structure with possible PEC structures in Fig. 1. Applying the equivalence principle, our problem can be cast into an internal and an external equivalent problem. For the internal equivalent problem, the EM fields in this inhomogeneous local region $V_1$ enclosed by surface $S_1$ are formulated by the FDTD method. The fields in the planar media $V_2$ are solved by the MPIE method. If there exist some perfect electric conductors with surface denoted by $S_3$, the MPIE method is also employed to model the PEC surfaces. The FDTD and MPIE models describing the corresponding region are coupled together through the boundary conditions on the surfaces $S_4$ and $S_5$,

$$\hat{n} \times \vec{E}_1 = \hat{n} \times \vec{E}_2 \quad \text{on the surface } S_4, \quad (1)$$

$$\hat{n} \times \vec{H}_3 = \hat{n} \times \vec{H}_2 \quad \text{on the surface } S_5, \quad (2)$$

$$\hat{n} \times \vec{E} = 0 \quad \text{on the surface } S_5.$$  

Fig. 1 Multilayer structure with local inhomogeneous object

3.2 MPIE Model

The fields in the planar structure $V_2$ in Fig. 2a can be expressed in terms of the equivalent surface current densities $\vec{J}$ and $\vec{M}$ by using the Formulation-C MPIE method [5,6].

$$\vec{E} = \left( \vec{G}_M^{EM} ; \vec{J} \right) + \left( \vec{G}_M^{EM} ; \vec{M} \right)$$

$$= -j \omega \mu_0 \left( \vec{G}_M^{EM} ; \vec{J} \right) - \frac{1}{j \omega \epsilon_0} \left( \vec{G}_M^{EM} ; \vec{M} \right)$$

$$\vec{H} = \left( \vec{G}_M^{EM} ; \vec{M} \right) + \left( \vec{G}_M^{EM} ; \vec{J} \right)$$

$$= -j \omega \mu_0 \left( \vec{G}_M^{EM} ; \vec{M} \right) - \frac{1}{j \omega \mu_0} \left( \vec{G}_M^{EM} ; \vec{J} \right)$$

(3)

where the dyadic Green's function $\vec{G}_M^{EM}(\vec{r}; \vec{r}')$ denotes the P-type fields at $\vec{r}$ due to the Q-type currents at $\vec{r}'$. $\vec{G}_M^{EM}$ and $\vec{G}_M^{EM}$ are the respective dyadic Green's functions for the magnetic and electric vector potentials, $G$ and $G'$ are the corresponding scalar potential kernels. The electric and magnetic equivalent surface currents are defined as $\vec{J}_e = \hat{n} \times \vec{H}$ and $\vec{M}_e = \vec{E} \times \hat{n}$.

The MPIE is solved by using the method of moments technique, in which the equivalent surface is discretized into small patches, here the rectangular element is chosen as the cell element. Accordingly, the fields on the equivalent surface is expanded using rooftop basis functions,

$$\vec{E} = \sum_{i=1}^{N} \vec{E}_i, \quad \vec{H} = \sum_{i=1}^{N} \vec{H}_i, \quad \text{on the surface } S_4 \text{ and } S_5.$$  

(5)

(a) MPIE model of the multilayer structure

(b) FDTD model of the local region

Fig. 2 Equivalent problems
3.3 FDTD Model

As mentioned before, the inhomogeneous volume \( V_1 \) in Fig. 2b will be treated by using the FDTD method. However, unlike the situation in the frequency domain hybrid FEM-IE method, we can not formulate the coupling between the FDTD and MPIE model in a direct way using an overall matrix. Therefore, the local interaction matrix approach proposed in [3] is applied to handling our multilayer problem. Instead of directly manipulating the unknowns on the equivalent surface, we opt to establish an interaction matrix using the FDTD method. Similar to (3) and (4), the interaction matrix will describe the relationship between the fields and the equivalent currents on surface \( S_e \). Since the fields on surface \( S_e \) with the MPIE model is discretized into roofop basis functions, we will impose each basis function as an individual electric or magnetic current source on the FDTD model. Corresponding to each of those sources, one FDTD simulation can generate one set of electric and magnetic fields on surface \( S_e \), which fills up one column of the interaction matrix. Finally, the complete interaction matrix can be constructed by performing \( N \) (the number of the basis functions) FDTD simulations.

This interaction matrix contains a wide frequency range of electromagnetic fields information on surface \( S_e \), which is obtained from the time domain results of FDTD by using Fourier transform. All those entries in the interaction matrix will be pre-computed and used as a look-up table for the subsequent coupling equation construction.

3.4 Coupling Equation

The hybridization of the FDTD and MPIE method for this problem is fulfilled by enforcing boundary conditions, i.e., the continuity of the tangential fields on the equivalent surfaces in (1) and (2). In analogy to the approach in hybrid FEM-IE method [2], those boundary conditions are finally enforced explicitly by using a Galerkin weighting procedure,

\[
\begin{align*}
\iint_{S_e} \hat{n} \times (E - \overline{E}) \, dS &= 0 \\
\iint_{S_e} \hat{n} \times (\overline{H} - \overline{H}) \, dS &= 0 \\
\iint_{S_e} \hat{n} \times \overline{E} \, dS &= 0.
\end{align*}
\]

Eqs. (6) and (7) will result in a complete matrix equation for the overall problem, whose solution will yield the results for the original locally inhomogeneous multilayer problem.

4. Numerical results

A canonical problem, which is similar to the one used in [4], is modeled by using our hybrid FDTD-MPIE method. In this problem, a four-layer planar structure with two dielectric slabs is normally incident by a plane wave with an amplitude of 100V/m propagating in z-direction. The dimension and configuration of this problem are shown in Fig. 3. A cubical volume \( V_1 \) with the same permittivity and permeability as its surrounding layers, is designated as the inhomogeneous object to be simulated by FDTD model. Since this canonical problem has analytical solution, the comparison will be eased. The results obtained by our hybrid FDTD-MPIE method are compared with the analytical solution shown in Fig. 4, where good agreement can be observed.

![Fig. 3 Two dielectric layers can be observed.](image)

![Fig. 4 Amplitude of E along the z axis in V1 at two different frequencies: (a) 0.8GHz, (b) 6GHz](image)
5. Conclusions

The hybrid FDTD-MPIE method is an alternative to the hybrid FEM-IE method in the sense that as long as the inhomogeneous local area and the expansion basis is the same, the wide band results of the FDTD simulation can be re-used to save computational costs. Possible measures, such as DCIM [7], ADI-FDTD [8] and parallel computing, can be introduced to enhance the hybrid FDTD-MPIE method, by which further computational burden relief can be foreseen.

References


