Maxwell meets Kirchhoff: From Circuits towards Fields

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Abstract

With the evolution of technologies towards higher operating frequencies, smaller dimensions and increased system complexity – often in RF and mixed-signal design –, electromagnetic (EM) field effects come into play in what was until not long ago a purely circuit-design world. Not only device, interconnect and substrate parasitics but also, increasingly, 3D components such as embedded passives, bondwires and packages require electromagnetic field simulation for their accurate characterization. 3D electromagnetic simulation is making its way into the design of microelectronic components and both students – the future engineers – and designers need more in-depth knowledge of this domain. This paper discusses the limits of current design approaches, making a 3D electromagnetic simulation necessary. The new course "Technical Electrodynamics" at the TU Darmstadt is shortly presented. Some illustrative examples are also shown.

1 The limits of 2D

The need for electromagnetic field simulation has been recognized for some time now, and the planar (so-called 2D or 2 ½ D) field simulators are an integral part of many design environments. These simulators can efficiently cover many of the current field simulation needs, but they cannot cope with all the 3D effects appearing at high frequencies. Of course, some components, such as IC packages, are by their nature of 3D type and thus impossible to analyze with a planar solver.

Where are the limits of 2D electromagnetic solvers? This question is very difficult to answer in a general manner since there are several factors that need to be taken into account: geometry, dimensions, operating frequency and possible intervening higher harmonics, robustness of the design are the most important ones.

In what concerns the geometry, obviously, components with clear 3D character will probably need a 3D simulation., since in very few cases there are analytical models available for them. It is obvious that complex structures like IC packages, ball grid arrays, multi-chip modules, and Systems in Package (SiP) belong to this category. Even a simple bond wire affects signal performance, especially at high frequencies, and therefore needs to be optimized for reduced parasitic effects. 3D EM simulation allows even a smarter approach by electrically characterizing bond wires and using them as device in circuit design.

During the last years the increasing number of metal layers in IC technology allowed additional devices, like integrated coil inductors and planar multi-layer capacitors. Their three-dimensional geometries and undefined surrounding make analytical modelling difficult and call for 3D simulation to obtain the required design accuracy. This is also valid for vias which are typically insufficiently characterized in IC and PCB design kits. Especially at higher frequencies an accurate characterization of these geometrically simple structures will most probably require a full wave 3D simulation.

Also geometry-related is the distance between the component of interest and other components or layout elements in the surrounding. While for each component taken separately a classical simulation might have sufficient accuracy, the presence of other components very close by introduces supplementary field effects which may require a 3D simulation. The simple resonator example of section 1.1. nicely illustrates this effect.

The structures' dimensions and the frequency range of interest are two closely related issues. Small structures at low frequencies may not always need a 3D simulation, while at higher frequency even a tiny part might exhibit field effects and require a full-wave 3D simulation.

Last but not least, design quality and reliability are also decisive for the choice of one or another simulation tool. To give just an example, a fully impedance-controlled design provides the best premises for avoiding disturbance fields which always occur at discontinuity points. However, this is a very difficult, if not impossible task to achieve in a modern design, in which numerous vias, bumps, bondwires are needed. They all induce impedance variations and most probably require sophisticated simulation for their accurate characterization.

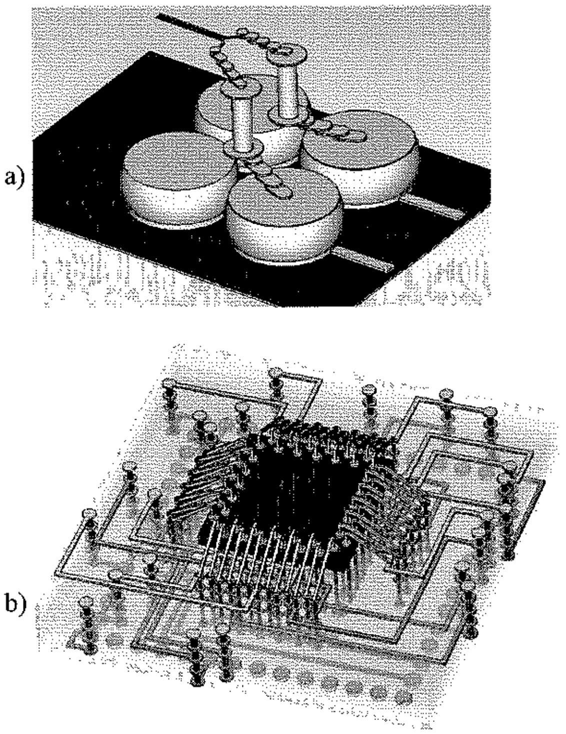

Fig. 1. Typical structures which need 3D EM simulation. a) Vias, bumps and ball grids; b) Full IC packages, bondwires

1.1 An illustrative example

Let us consider a simple structure, an integrated LC resonator, realized in LTCC technology, shown if Fig. 2 [3]. It is representative for passive structures embedded in the RF SiP substrate.

For accurately characterizing the L and C parts of the structure, each of them was simulated separately in the 3D electromagnetic simulator CST STUDIO SUITE [2]. As a result of the simulation, S-parameter models for the two components are obtained, which can then be connected together in a circuit simulation (Fig. 3a). This approach is equivalent to neglecting the field coupling of the two elements.

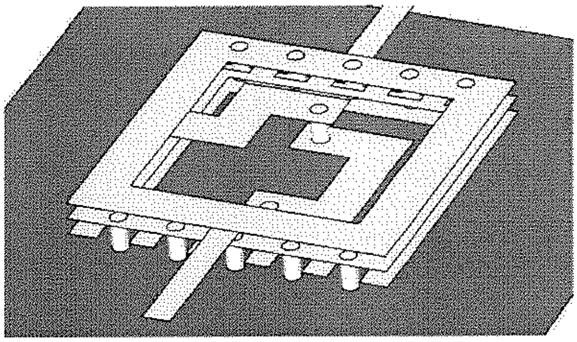

Fig. 2. LC resonator in LTCC technology

To check if these separate models can be used as such with enough accuracy, a second simulation was performed, in which both the L and the C parts were included together in a single 3D model.

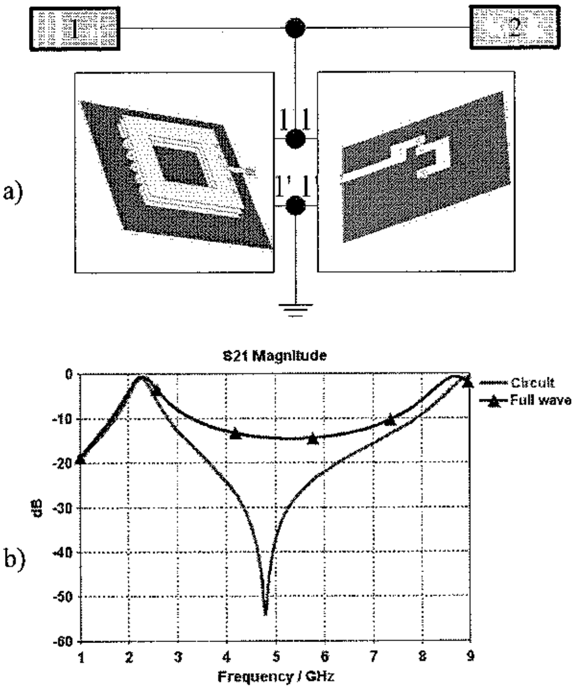

Fig. 3. a) Network model for the LC resonator with the two blocks separately characterized by 3D simulation; b) S-parameters for case a) (denoted "Circuit") and for the LC resonator simulated as a single 3D structure (denoted "Full wave")

The corresponding S-parameters are shown in Fig. 3b. Obviously, the capacitor and inductor components of the resonator are placed so close to each other in this configuration that a complete 3D simulation of the whole structure is necessary. However, if the operating frequency is low enough, below 1 GHz, the S-parameters (not shown here) agree quite well in the two setups.

2 Challenges

3D electromagnetic field simulators are still relatively little used in microelectronics. There are several challenges the EM-newcomer is facing.

2.1 Vocabulary

Circuit design specialists know this very well: even analog and RF designers have difficulties in understanding each other. The ones talk about harmonics, saturation and volts, the others about intermodulation, compression and dBm.

It is not much different with field simulation: many things in the circuit and field worlds are similar but just bear different names. What circuit simulation specialists call "edge-to-independent meshes incidence matrix" is named "curl matrix" by field simulation experts. A 3D "discretization mesh" is very similar to a (non-planar) "circuit graph". In some 3D methods, such as the Finite Integration Technique [5] and PEEC [7], a quantity is associated to each edge of this graph which has the dimension of capacitance, resistance or inductivity – all well-known also to circuit designers. Only, field simulation experts call these quantities "elements of the material matrix".

2.2 Simulation complexity

Circuit or analytic models provide an abstraction of the physical behaviour by using device models and therefore allow a quick simulation. They are already well integrated in the design environment and large model libraries are available.

3D field simulations on the other hand require the so-called discretization of the full 3D component (division of space in small elements, such as bricks or tetrahedra, whose number can reach, for just one component, tens to hundreds of thousands). This inevitably makes the simulation of a device with several such components much slower than the simulation based on a circuit model.

Figure 4 shows an example of such high complexity: a full system for biomedical signal acquisition designed in RF SiP technology by the Technical University Hamburg Harburg of Germany [1], that was integrally imported into the 3D simulator.

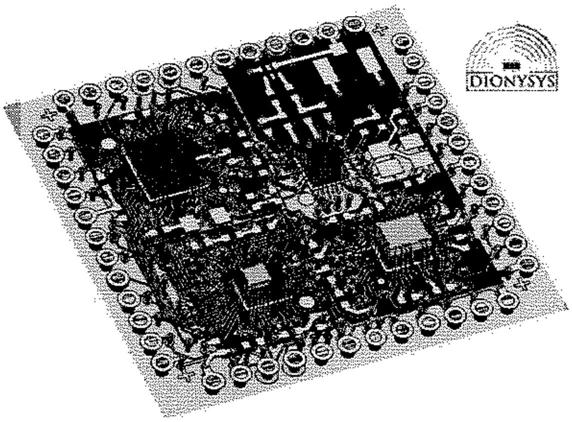

Fig. 4. 3D electromagnetic model of RF SiP for biomedical signal acquisition.

2.3 Expert knowledge in a new domain

Last but not least, in the attempt of mixing circuit and field simulations, two worlds – circuit design and electromagnetic design – come together. We know the circuit world better – many of us had at least one electronic design project in secondary school. Electromagnetic field is taught years later in university and therefore people are not so familiar with it.

Obviously, it is often difficult for someone used to Maxwell's equations to think in circuit terms, or vice-versa. Moreover, the requirements, simulation constraints, and limitations of a circuit simulator are quite different from those characterizing an electromagnetic field simulation. This gives many designers the feeling that they would almost need to „learn“ a completely new profession, in order to be able to efficiently include the other kind of simulation in their daily work. Efforts from the side of both the design environment providers and the 3D electromagnetic field simulation companies are under way with the goal to make this (soon absolutely necessary) step as smooth as possible.

So where to start?

The modern designer doesn't in fact need to be an "all-round talent", with a deep knowledge in both circuit design and electromagnetic field simulation.

Mastering the EM-specific **nomenclature** is of course a must – but also a very easy first step. Additionally, some specific knowledge of EM is needed: a basic understanding of **Maxwell's**

equations and of **electric and magnetic fields** can be very useful.

A third ingredient for the future EM-simulation specialist regards the **requirements and possibilities of the simulation** itself. The next section 3 explains these in more detail.

The only part that takes longer is probably to learn how to reach, through clever choices of simulation techniques and parameters, a **trade-off between simulation time and accuracy**. This includes decisions on when a 3D simulation is necessary and when a simpler model obtained with other techniques is sufficient.

3 EM Simulation in a Nutshell

3.1 What an EM simulation is made of

Often, a first clear picture of a scientific domain can be gained by an even short answer to a few simple questions. For EM simulation, the main questions are: What are the input data? What are the important program settings? What types of output data can I expect?

Input data: 3D geometry, material parameters, excitations

The 3D geometry can be either directly constructed by using specialized software or, as most often the case in microelectronics, exported directly from the circuit design tool (the user selects the relevant parts and a transfer of the geometric, material parameter and excitation ports information is performed towards the 3D simulator). This transfer can be automated to a large extent such that a minimum of user interaction is necessary, as shown e.g. in [1]. This step should therefore not represent a problem even for users with little experience in 3D EM simulation. The result of these steps is a three dimensional model of the structure that needs to be characterized and might look like the chip package shown in Fig. 1b.

Main program settings

In 3D simulations, the infinite 3D space needs to be truncated in order to simulate it. The size of the computational domain is one of the settings that influences the solution accuracy. On the boundary of this computational domain, boundary conditions need to be imposed to ensure uniqueness of the solution. One choice would be a boundary condition that simulates the open space. Last but not least, there is the choice of the mesh type, simulation method and whether the simulation should be performed in time or in frequency domain. A short overview of numerical simulations methods is presented in section 3.2.

Output data

There is a variety of results that can be obtained through a 3D simulation. Among them are S- Z- and Y-parameters, an equivalent circuit model that characterizes the port-behaviour of the device, electric currents on traces, grounds and in general on all metallic parts, electric and magnetic fields in any point of the domain, farfield patterns ...

In summary:

- **input data**: geometry, material parameters, excitations
- **important program settings**: size of the computational domain, boundary conditions, choice of the solver
- **output data**: S- Z- and Y-parameters, equivalent circuit model, currents on metallic parts, electric and magnetic fields in any point of the domain ...

3.2 Methods for full-wave 3D EM simulation

For achieving the EM simulation (so-called full-wave, i.e. without assuming any low-frequency approximations), specialized software packages are used, which implement specific numerical methods.

Among the numerical methods for 3D field analysis, the best-known are the finite element (FEM) method [4], the finite integration technique (FIT) [5], the finite-difference time-domain (FDTD) [6], as well as the PEEC [7]. The FEM and PEEC are typically applied in frequency domain, the FDTD in time domain. The FIT is the only method which can be easily applied in both frequency and time domain.

Each of these methods first discretizes the 3D geometry by using specific discretization meshes. Three representative 3D discretization meshes are shown in Fig. 5.

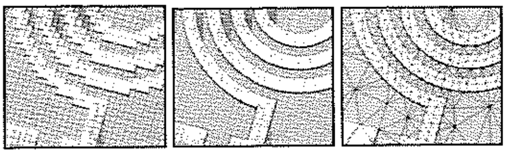

Fig. 5 Detail of a planar coil mesh. From left to right: staircase, confomal hexahedral, tetrahedral.

The electromagnetic field equations – Maxwell's equations – are automatically discretized by the simulation software on the discretization mesh and, depending on the method, solved either in frequency or in time domain. **Transient** (time-domain) simulations are typically performed using an explicit time-marching scheme and have lower memory and computing time requirements than frequency domain simulations. They are ideally suited for broadband simulations of large or very complex structures. Broadband frequency-domain results are obtained from the time-domain signals by means of a Fourier transformation. Frequency domain simulations on the other side require the solution of a system of equations at every frequency point of interest. This requires both a relatively large memory, and a relatively long computing time. For not so large models, they can however be quicker than transient simulations, especially if clever interpolation techniques are used for evaluating the results between the (few) calculated frequency points.

If one starts with EM simulation, he should probably start with FIT, due to the ease of understanding. That is why it is presented in more detail in the next section.

3.2 The Finite Integration Technique

As in any other domain, a user of an electromagnetic field simulation program with a minimum of inside knowledge is likely to achieve optimal results. That is why, in this section, we will try to shortly describe the way in which the electromagnetic field equations are discretized with the Finite Integration Technique (FIT).

Let us demonstrate the derivation of the FIT-discretized form of Faraday's law:

$$\int_{\partial S} \vec{E}\cdot d\vec{r} = -\frac{d}{dt}\int_{S} \vec{B}\cdot d\vec{S}$$

on the face $S \equiv j$ of a mesh cell, depicted in Fig. 6. The integral on the left hand side (representing the electric voltage along the closed contour of edges which form the face boundary) can be written as an algebraic sum of the edge voltages. The integral on the right hand side is directly one of the FIT unknowns, the magnetic flux through the face j. The discretized equation thus becomes:

$$-e_1 + e_2 - e_3 + e_4 = -\frac{d}{dt}b_j\,. \qquad (1)$$

Note that we have only used the additive property of the integral, and did not perform any approximation. By writing such relations for all the faces in the mesh, then grouping all the signs plus and minus into a matrix $\mathbf{C}$, Faraday's law has the form given by (2).

In a similar way, the discrete equivalent of all Maxwell's equations, the so-called Maxwell's Grid Equations, can be obtained:

$$\mathbf{C}\hat{\mathbf{e}} = -\frac{d}{dt}\hat{\hat{\mathbf{b}}} \qquad \tilde{\mathbf{C}}\hat{\mathbf{h}} = \frac{d}{dt}\hat{\hat{\mathbf{d}}} + \hat{\hat{\mathbf{j}}} \qquad (2)\,(3)$$

$$\mathbf{S}\hat{\hat{\mathbf{b}}} = \mathbf{0} \qquad \tilde{\mathbf{S}}\hat{\hat{\mathbf{d}}} = \mathbf{q} \qquad (4)\,(5)$$

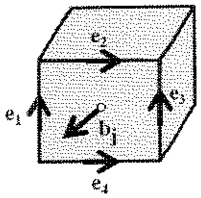

Fig. 6 Allocation of the electric voltage (e) and magnetic flux (b) components in the mesh.

In these equations $\hat{\mathbf{e}}$ and $\hat{\mathbf{h}}$ denote the electric and magnetic voltages along primary and dual edges, respectively.

The symbols $\hat{\hat{\mathbf{d}}}$, $\hat{\hat{\mathbf{b}}}$ and $\hat{\hat{\mathbf{j}}}$ are the electric, magnetic, and current-density fluxes across primary and dual grid faces. The topological matrices $\mathbf{C}$, $\tilde{\mathbf{C}}$, $\mathbf{S}$ and $\tilde{\mathbf{S}}$ represent the discrete equivalents of the curl- and the div-operators, with the tilde indicating the dual grid.

The discrete analogues of material property relations express the coupling between voltages and fluxes, through the material matrices $\mathbf{M}_{\varepsilon}$, $\mathbf{M}_{\mu^{-1}}$ and $\mathbf{M}_{\sigma}$:

$$\hat{\hat{\mathbf{d}}} = \mathbf{M}_{\varepsilon}\hat{\mathbf{e}}; \quad \hat{\mathbf{h}} = \mathbf{M}_{\mu^{-1}}\hat{\hat{\mathbf{b}}}; \quad \hat{\hat{\mathbf{j}}} = \mathbf{M}_{\sigma}\hat{\mathbf{e}} + \hat{\hat{\mathbf{j}}}_{A} \quad (6)$$

These matrices have diagonal form on Cartesian meshes and contain the unavoidable approximations of any numerical procedure.

3.3 Field equations are not that different from circuit equations

That circuit (Kirchhoff's) equations are obtained from the field (Maxwell's) equations is a well-known fact. However, this direct connection is not easily visible in many numerical methods. In the Finite Integration however, the intervening matrices are well-known to the circuit designer:

- The matrix $\mathbf{C}$ has the same meaning as the edges-to-independent-meshes incidence matrix which is used in the loop-current (mesh) analysis; note also that $\widetilde{\mathbf{C}} = \mathbf{C}^T$. In field analysis however, the dependent meshes (loops) are not eliminated, for efficiency reasons.
- The matrix $\tilde{\mathrm{S}}$ has the same meaning as the edges-to-nodes incidence matrix, used in nodal analysis.
- The matrices $\mathbf{M}_\varepsilon$, $\mathbf{M}_\mu$ and $\mathbf{M}_\sigma$ have the dimensions of capacitance, inductance and conductance, respectively and can be assimilated with the diagonal matrices containing the edge circuit elements.

For static states, the appropriately combined FIT equations (2-6) lead to exactly the same well-known equations of the Modified Nodal Analysis or Loop-Current Analysis methods.

4 Technical Electrodynamics Course at the TU Darmstadt

At the TU Darmstadt, in recognition of the technological trend, a novel course "Technical Electrodynamics" was included in the Master's Program "Information and Communication Engineering" starting with the winter semester 2010-2011.

The course covers not only fundamental issues of electrodynamics, but also basics of 3D EM simulation and the coupling between the "field" and the "circuit" worlds (cosimulation).

The associated exercise and practical applications class is meant to familiarize the students with the use of a 3D simulator through the simulation "from A to Z" (from geometry definition to result postprocessing) of several typical high-frequency devices. Numerical issues such as convergence for both the linear system of equations and the field solution, accuracy as well as practical knowledge regarding possible sources of error in 3D simulations are also acquired.

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