Advanced Electromagnetic Solvers for Interconnect and Package Modeling

by

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- **Why do we need Electromagnetic analysis for Interconnects?**
- Present day circuit boards involve multi-chip environment connected by transmission lines - Cross talk and Pulse degradation is a major problem in this dense environment.
- **Why do we need Electromagnetic analysis for Packaging?**
- To minimize the electromagnetic radiation, interference, and to adhere to electromagnetic compatibility standards.

Methods Of Analysis:

- Analytical Methods — Although provide exact solution, almost non-existent for these type of problems. Mainly, because of complex domains.
- Numerical Methods — Provides approximate solutions. However, they can handle complex materials and structures. Requires intense computations.

Solution Methodology:

- Start with Maxwell's Equations.
- Define various material boundaries.
- Apply the electromagnetic boundary conditions.
- Calculate (Estimate) the electric/Magnetic fields within the problem domain.
- Check whether the fields satisfy the boundary conditions.
- If not, refine the solution.
- The process usually involves converting the operator equation into matrix equation and solving it by standard numerical procedures.

We have two approaches.

1. Differential Equation (DE) Solution Method.
   - The governing equations are sets of differential equations.
   - Solution space is three-dimensional. For open region problems, the space extends to infinity.
   - Generates sparse system matrix.
   - Easy to apply for variety of problems with a general purpose code.
   - Needs more unknowns in the solution for given accuracy.
   - Popular methods are FEM and FDTD.

2. Integral Equation (IE) Solution Method.

- The governing equations are integral equations.

$$\int X(\tau)H(t,\tau)d\tau = Y(t)$$

- Solution space, in most cases, is two-dimensional.
- Generates fully populated system matrix.
- Modifications are required for different types of problems even with a general purpose code.
- Generally needs fewer unknowns for given accuracy.
- Popular method is MoM.

Overview of Method of Moments Solution

$$AX = Y \tag{1}$$

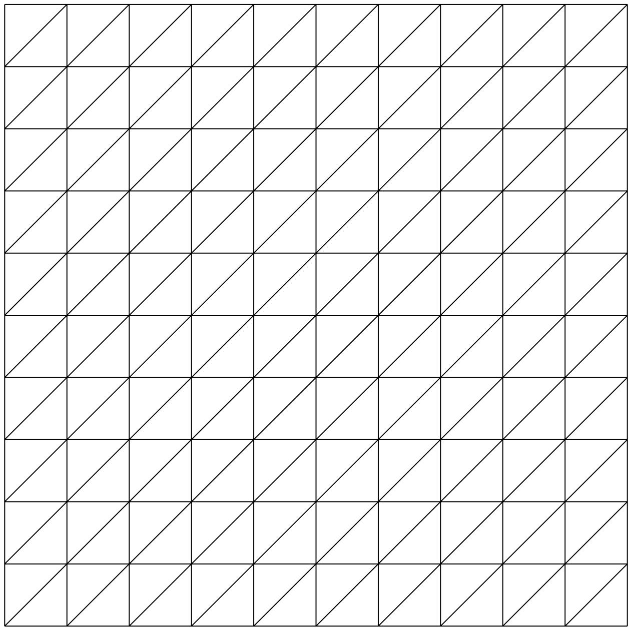
$$X = \sum_{i=1}^{N} \alpha_i p_i \tag{2}$$

$$\sum_{i=1}^{N} \alpha_i A p_i = Y \tag{3}$$

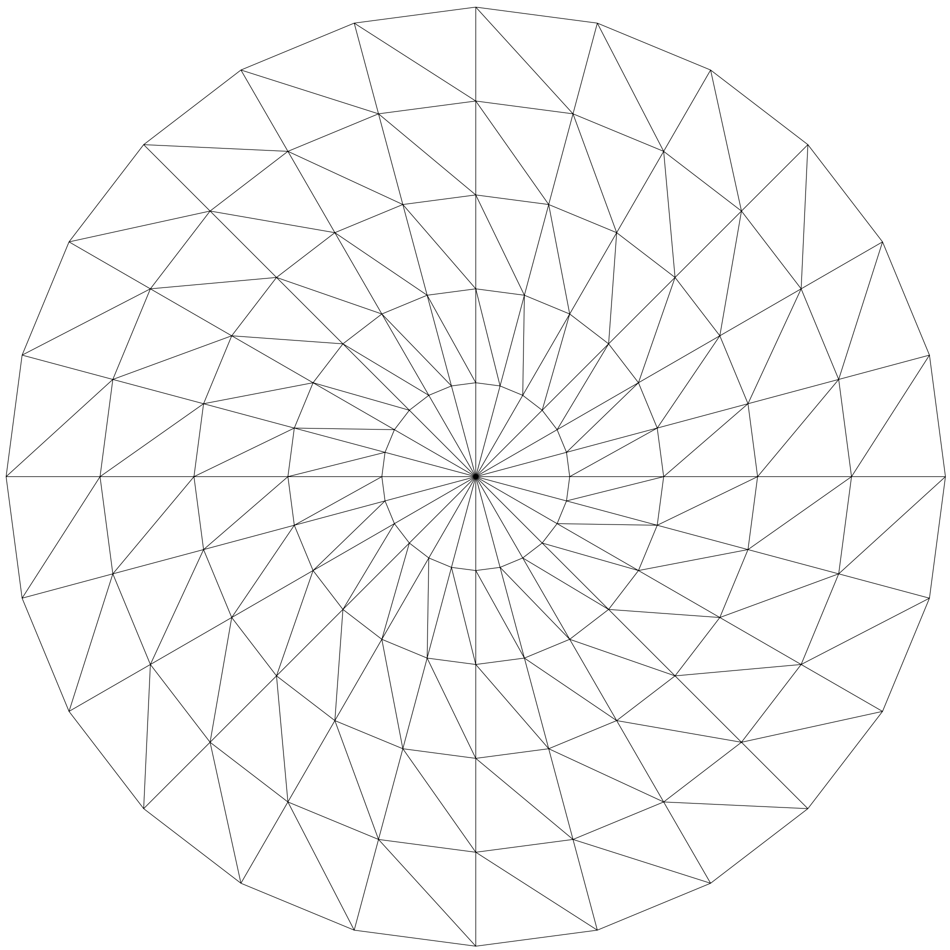
$$\sum_{i=1}^{N} \alpha_i < q_j, Ap_i > \quad = \quad < q_j, Y > \qquad j = 1, 2, \cdots, N \tag{4}$$

$$\Rightarrow \boldsymbol{Z}\boldsymbol{X} = \boldsymbol{Y} \tag{5}$$

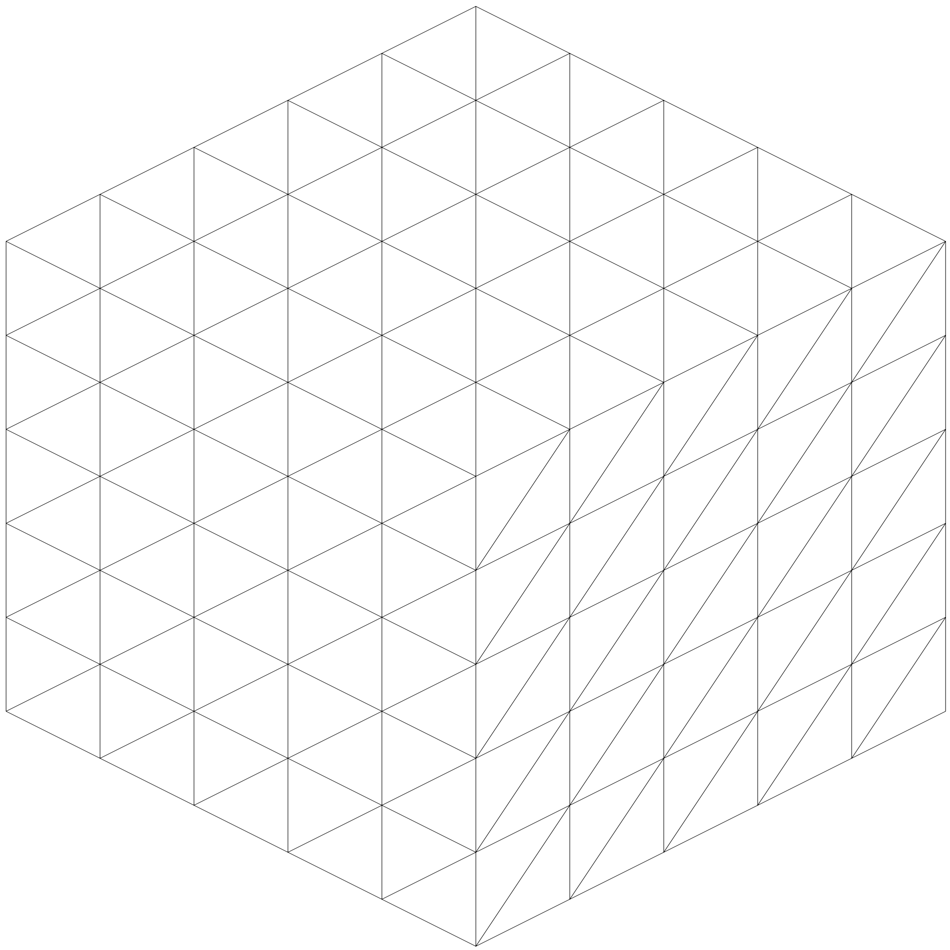
Geometrical Modeling: Here, we use triangular patch modeling. Approximates any body, both simple and complex, in a most efficient way.



Triangulated body of a plate



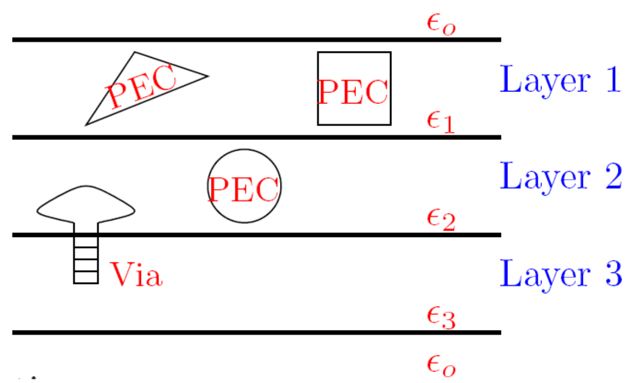
Triangulated body of a disk



Triangulated body of a cube

Electrostatic Solution

Multi-Conductor Transmission Line



- Generate $[R]$, $[G]$, $[L]$ and $[C]$ matrices.
- Calculate signal velocities.
- Calculate pulse distortion or cross talk

Full Wave Solution

The method involves the following steps:

For PEC portion of the structure,

- Develop the integral equation using boundary conditions on the electric field.

For non-conducting (dielectric) portion of the structure,

- Develop the integral equation using boundary conditions on both the electric and magnetic fields.
- The unknowns in the equations are the induced currents.

The scattered Electric field $\boldsymbol{E}^s$ is given by,

$$\boldsymbol{E}^s(\boldsymbol{r}) = -j\omega\,\boldsymbol{A}(\boldsymbol{r}) - \nabla\Phi(\boldsymbol{r}) \tag{6}$$

where

$$\boldsymbol{A}(\boldsymbol{r}) = \mu \int_S \frac{\boldsymbol{J}(\boldsymbol{r}')\,e^{-jkR}}{4\pi R}\,dS' \,, \tag{7}$$

$$\Phi(\boldsymbol{r}) = \frac{-1}{j\omega\epsilon} \int_S \frac{\nabla\cdot\boldsymbol{J}(\boldsymbol{r}')\,e^{-jkR}}{4\pi R}\,dS' \,, \tag{8}$$

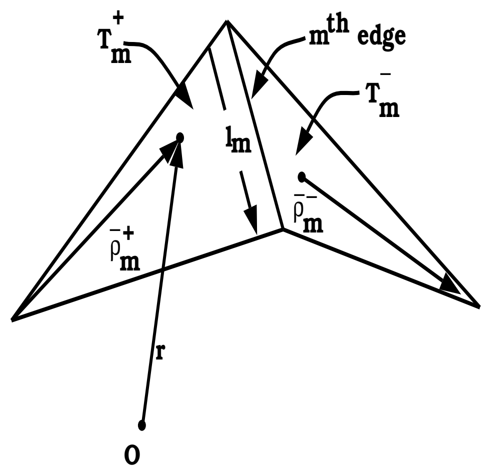
$$R = |\boldsymbol{r} - \boldsymbol{r}'| \tag{9}$$

Applying the Boundary Condition, $\boldsymbol{E}_{tan} = 0$ on the PEC surface, we have

$$[j\omega \boldsymbol{A}(\boldsymbol{r}) \; + \; \nabla \Phi(\boldsymbol{r})]_{tan} = \boldsymbol{E}^{i}_{tan}(\boldsymbol{r}) \tag{10}$$

- Using suitable basis functions to approximate $\boldsymbol{J}$, that is,

$$\boldsymbol{J} = \sum I_n \boldsymbol{f}_n$$



RWG Basis functions

$$\boldsymbol{f}_m(\boldsymbol{r}) = \begin{cases} \frac{l_m}{2A_m^+}\boldsymbol{\rho}_m^+ & \text{for } \boldsymbol{r} \in T_m^+ \\ \frac{l_m}{2A_m^-}\boldsymbol{\rho}_m^- & \text{for } \boldsymbol{r} \in T_m^- \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

- f_n's also used as weighting functions.
- Convert the integral equation into matrix equation.

$$[Z][I] = [V] \quad \text{and} \quad [I] = [I_n]$$

- Solve the matrix equation to obtain $I_n \Longrightarrow$ Current induced on the structure is known.
- Calculate required parameters such as near field, far-field, RCS and so on.

General Purpose Codes Based on RWG Method

- PATCH Developed by Sandia National Lab.
- FERM Developed by MIT Lincoln Lab.
- IE3D Commercial Software.
- FEKO Commercial Software.
- There are host of other codes developed by many companies which all use RWG functions.
- It is quite easy to develop a new and more efficient code incorporating latest developments in computer technology and numerical solution procedures.

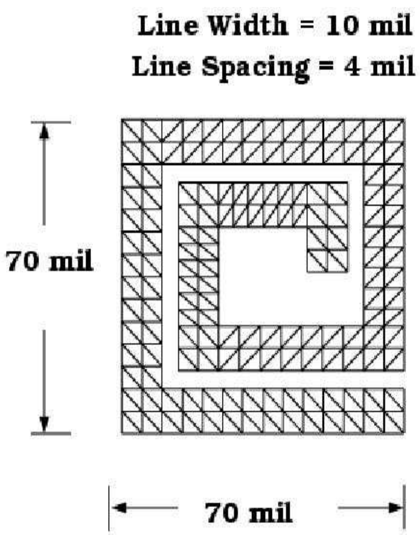
Design Tool for SIP (System in a Package) or SOP (System on a Package)

- EMSIP - Design Tool developed by AU based on RWG functions. An Accurate and Sophisticated Tool for EM Analysis - Provides reliable design than commercially available software tools viz. SONNET and ANSOFT.
- SONNET Uses Periodic Greens Function. ANSOFT Uses Finite Element Scheme. Both methods are NOT ideal SIP Modeling Tools.
- EMSIP Tool - Based on Method of Moments - Most suitable for SIP design. Both time and frequency marching is possible.

Example - Parallel Plate Capacitor

- Top Plate - 74 mils $\times$ 46 mils.
- Bottom Plate - 84 mils $\times$ 58 mils.
- Plate Separation - 1 mil.
- Theoretical Bounds: 0.75 - 1.08 pf
- SONNET : 1.2 pf
- EMSIP : 0.81 pf

Example - Spiral Inductor



- SONNET : 7.0 nH
- EMSIP : 7.3 nH

Recent Developments

In the past few years, MoM was improved in two ways:

1. Improving the matrix-vector products in iterative solution - Fast Multipole Moment (FMM) method. - Very successful - 10 million unknown problem has been solved.
2. Developing new basis functions, along the lines of wavelets, to generate a sparse matrix - reduces the memory requirements.

Overview of FMM method

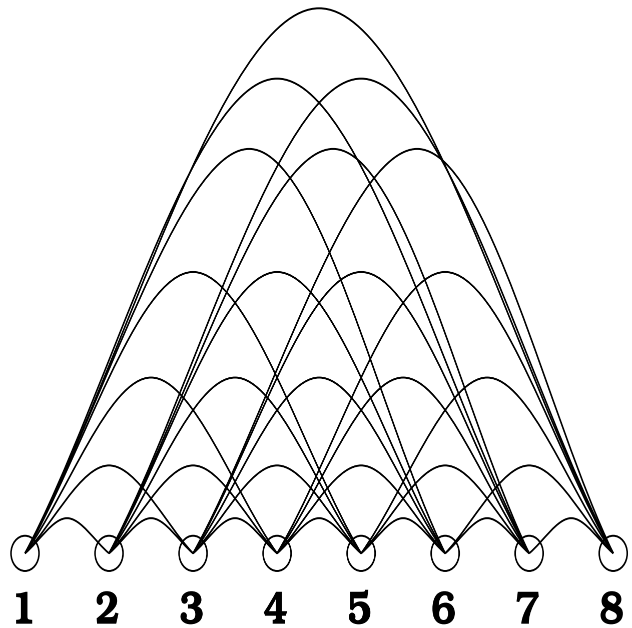
Fast Multipole Moment method is based on the following concepts:

- The computation time depends on the number of matrix elements and the matrix inversion.
- In simple terms, each matrix element may be viewed as calculating the electric field at a given point by a source located at other point $\Rightarrow Z_{mn}$ is the field at the location m due to the basis function at location n.
- Information is transferred from location m to location n.

FMM method Continued ....

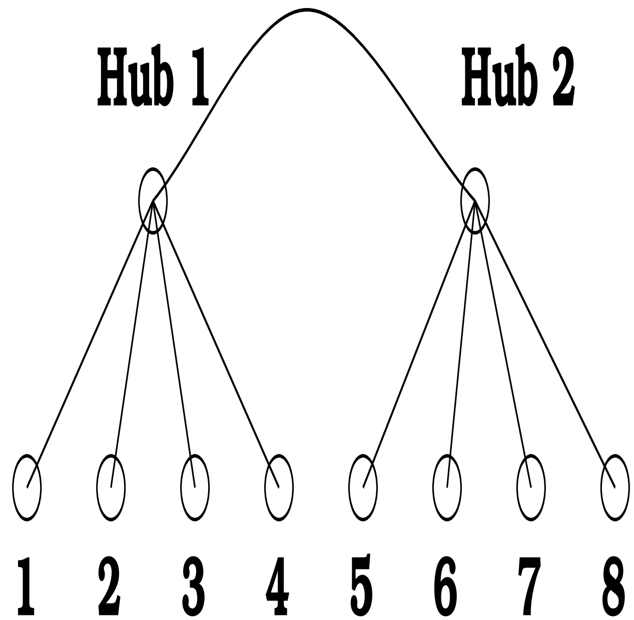
- Using the analogy of telephone company, the scenario implies that there is direct connection from every customer to every other customer $\Rightarrow$ one needs N^2 connections. If the matrix is symmetric, one can reduce the number of connections $\Rightarrow 1 + \sum_{i=1}^{N} N - i$

FMM method Continued ....



FMM method Continued ....

- It is more efficient to establish local hubs from where the calls are routed.



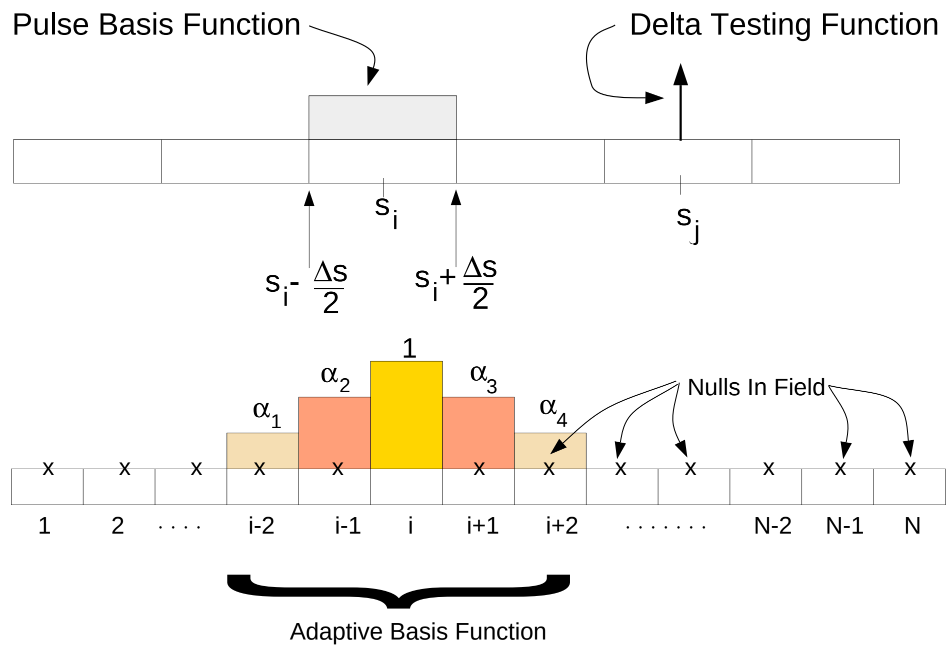
Adaptive Basis Functions

- In this work, we develop basis functions, which generate a strong diagonal matrix. In some cases, the off-diagonal elements may be simply discarded.
- None of the major advantages of the MoM are sacrificed.
- Helps in generating for parallel processing.

Construction of Adaptive Basis Functions

Consider the i^{th} column of a MoM matrix:

$$Z^i = [Z_{1,i}, Z_{2,i}, Z_{3,i}, , ...Z_{N,i},]$$



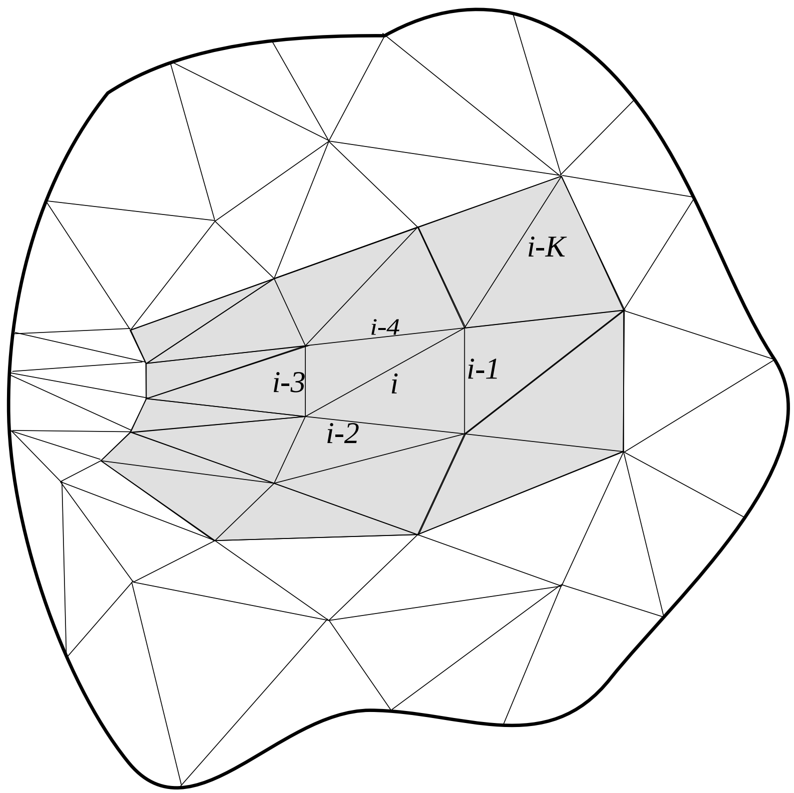
$$
\begin{aligned}
\alpha_1 Z_{1,i-2} + \alpha_2 Z_{1,i-1} + Z_{1,i} + \alpha_3 Z_{1,i+1} + \alpha_4 Z_{1,i+2} &= 0 \\
\alpha_1 Z_{2,i-2} + \alpha_2 Z_{2,i-1} + Z_{2,i} + \alpha_3 Z_{2,i+1} + \alpha_4 Z_{2,i+2} &= 0 \\
&\vdots \\
\alpha_1 Z_{N-2,i-2} + \alpha_2 Z_{N-2,i-1} + Z_{N-2,i} + \alpha_3 Z_{N-2,i+1} + \alpha_4 Z_{N-2,i+2} &= 0 \\
\alpha_1 Z_{N-1,i-2} + \alpha_2 Z_{N-1,i-1} + Z_{N-1,i} + \alpha_3 Z_{N-1,i+1} + \alpha_4 Z_{N-1,i+2} &= 0 \\
\alpha_1 Z_{N,i-2} + \alpha_2 Z_{N,i-1} + Z_{N,i} + \alpha_3 Z_{N,i+1} + \alpha_4 Z_{N,i+2} &= 0.
\end{aligned} \tag{12}
$$

Solving Eq. 12, the new basis function g_i can be written as

$$
g_i = \alpha_1 p_{i-2} + \alpha_2 p_{i-1} + p_i + \alpha_3 p_{i+1} + \alpha_4 p_{i+2} \tag{13}
$$

$$
\begin{aligned}
[I] &= [Z_d]^{-1}\left([V] - [Z_{off}][I]\right) \\
&= [I_d] - [Z_d]^{-1}[Z_{off}][I]
\end{aligned} \tag{14}
$$

For 3D problems, the cluster is chosen as follows:



Thin Dielectric Solution

- In the conventional MoM, the dielectric material is treated as a slab and triangles are placed over the surface of the slab.
- For the present day chip design and microstrip problems, the dielectrics are extremely thin.
- Cannot be solved using commercial Three Dimensional Codes.
- Requires New analysis methods. A more efficient numerical solution is possible for such cases.

Consider the following problem:

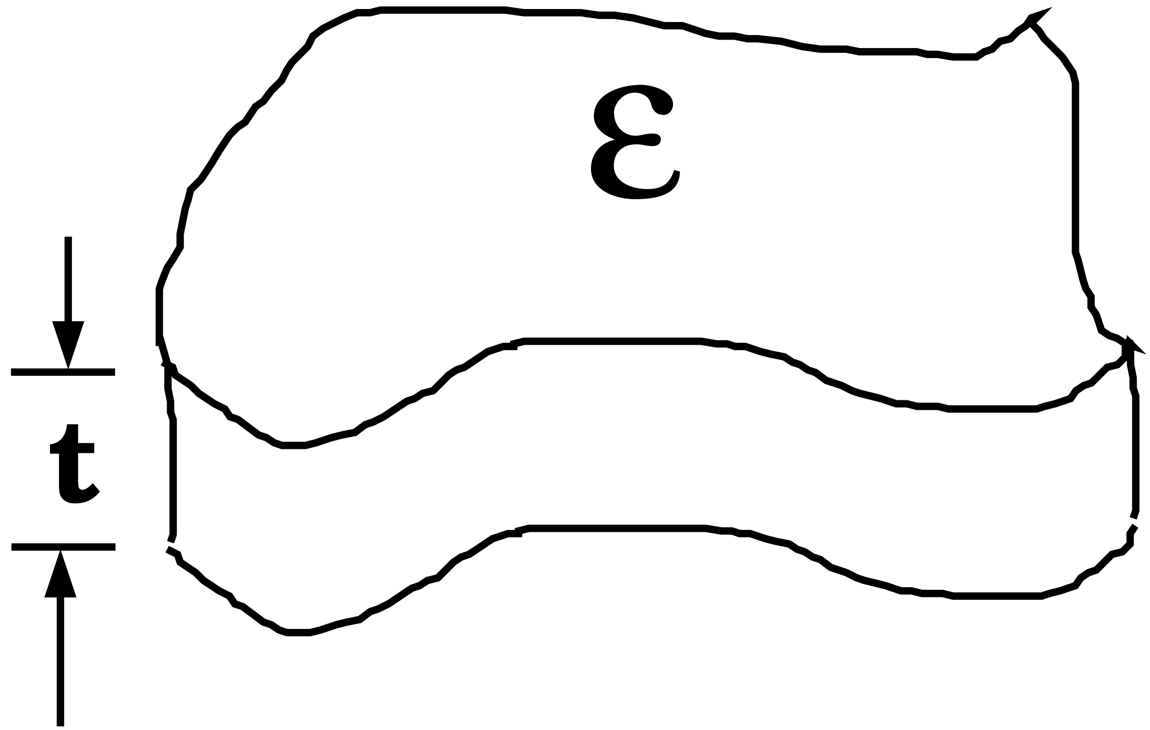


Figure 1: Superthin Dielectric Layer

Basic Analysis of Super Thin Dielectric Layer

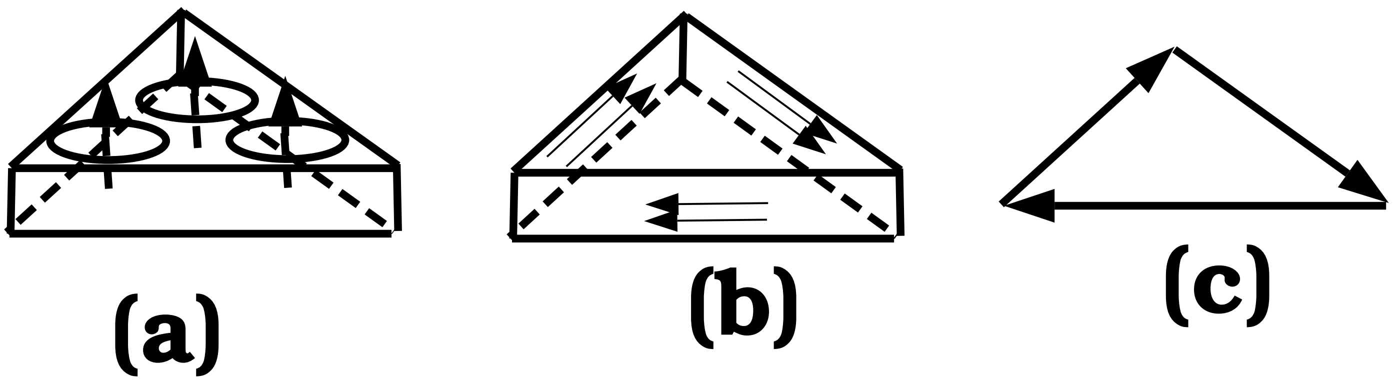
Using the equivalence principle, the potential theory and free-space Green's function, a pair of integral equations involving the unknown polarization current components $\boldsymbol{J}_t$ and $\boldsymbol{J}_n$ to excitation field are derived and solved.

Numerical Solution

Method of Moments Procedure

1. Geometrical Modeling - The slab is divided into prism elements with triangular base
2. The tangential current component $\boldsymbol{J}_t$ is modeled by standard RWG basis functions
3. The normal component J_n is modeled by two methods: a) using equivalent magnetic loop currents, and b) constant electric currents

Equivalent Magnetic Loop Currents



$$J_n = -j\omega\epsilon_0 \left(M_1^n + M_2^n + M_3^n\right) \quad (15)$$

Constant Normal Electric Current

- For this case, J_n is assumed to be constant along the thickness.
- To support such currents, we must have two charge layers at top and bottom of the dielectric slab.
- These charge layers must have equal and opposite values.

Conclusions

In this work,

- Full wave electromagnetic solution methods available to estimate field coupled to various components is presented.
- Only integral equation solution method, MoM, is considered.
- The solution method is versatile and accurate.
- New developments to make the method efficient are also presented.