Advanced Surface Based MoM Techniques for Packaging and Interconnect Analysis

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Introduction

Fast integral equation methods are now being applied for packaging and other such “low frequency” problems, which makes surfaced based MoM an increasingly attractive alternative to finite based techniques (FEM, FDTD, ...) .

Surface techniques produce significantly fewer unknowns than volume based techniques due to there ability to solve EM problems with 2D meshes over the 3D surfaces, as opposed to full volumetric meshing, as well as relaxing the restrictions on aspect ratios within the mesh.

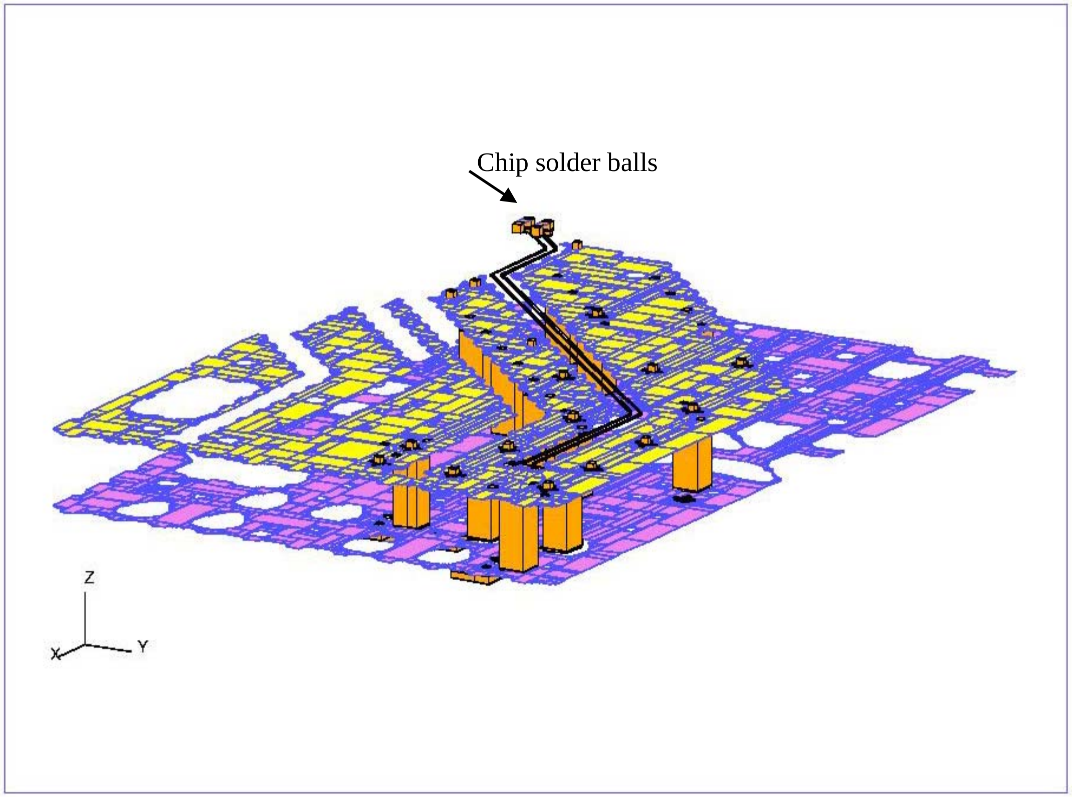
Here we explore some of the advantages and applications of MoM on real, product level packaging and interconnect structures. To be discussed:

- High aspect ratios (Reduced problem size)
- Low frequency (<50GHz, improved accuracy)
- Surfaced based dielectric solution (Reduced problem size)
- MoM fast solution techniques (Faster solve times)
- Massive parallelization (Faster solve times)

The subsequent examples used to illustrate these points were done with IBM’s internally developed full-wave 3D MoM solver, EMSurf. *www.alphaworks.ibm.com/tech/**eip***

General Advantages of MoM

Motivation for High Aspect Ratios



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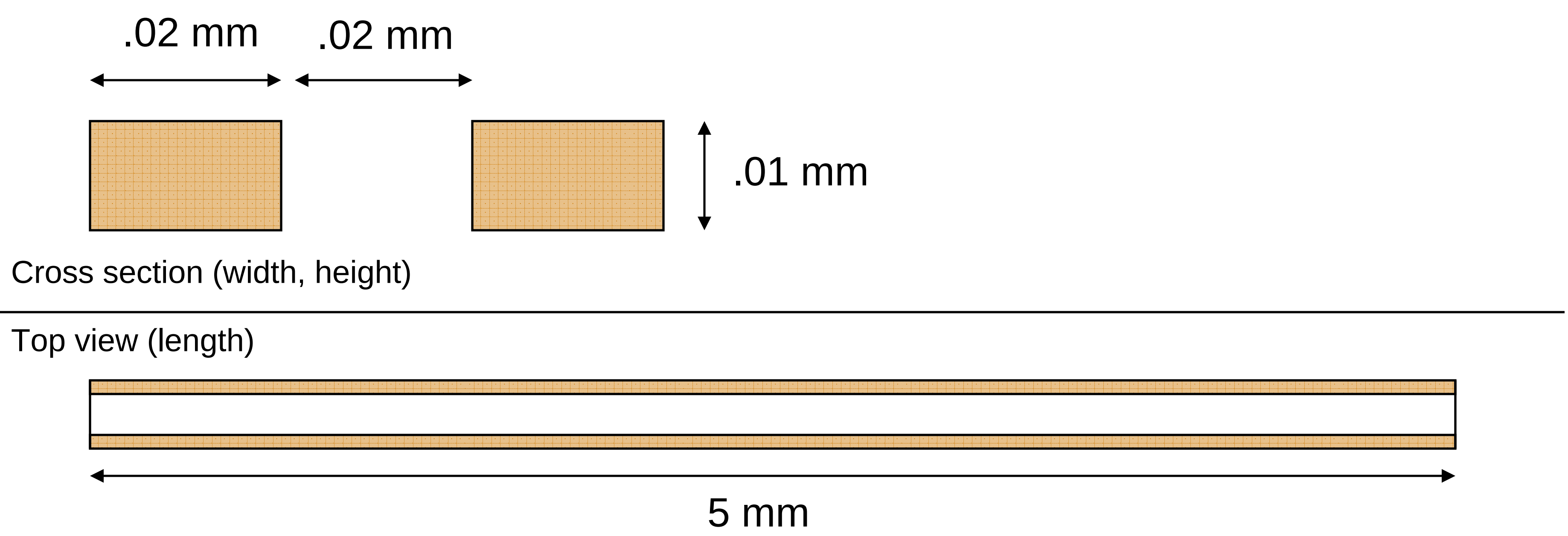
- Picture shows real package fan-out from chip to pads.
- 600:1 aspect ratio in cross-section to length of signal lines. Even higher to capture edge effects.
- Additionally, ground planes (6mm x 11mm) will contain features, holes, etc. with discretization on the order of 0.01mm (1000:1 aspect ratio)
- Trying to produce close to equilateral triangles or uniform quadrilaterals, will “over-grid” the structure and will significantly increase problem size.
- The ability to handle high aspect ratio mesh elements with drastic changes in adjacent element sizes is key.

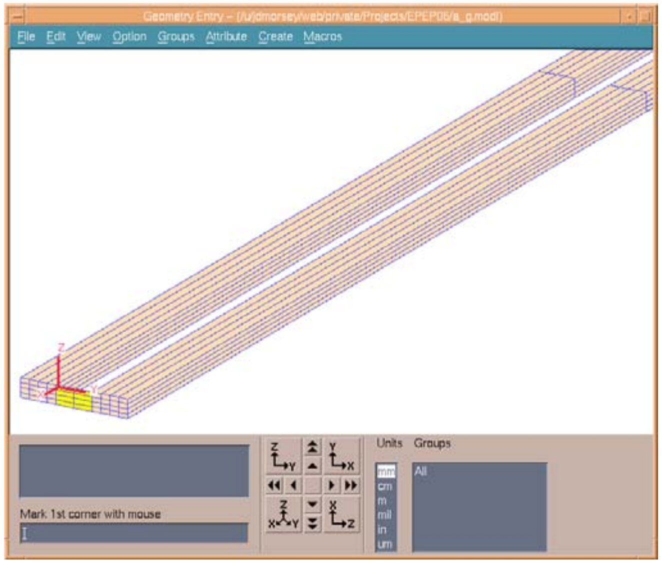
Impact of High Aspect Ratios

- Example used to illustrate this need, involves the differential pairs of signal lines whose cross-section and top view are shown above.
Line length is 5mm, line thickness is 10 microns.

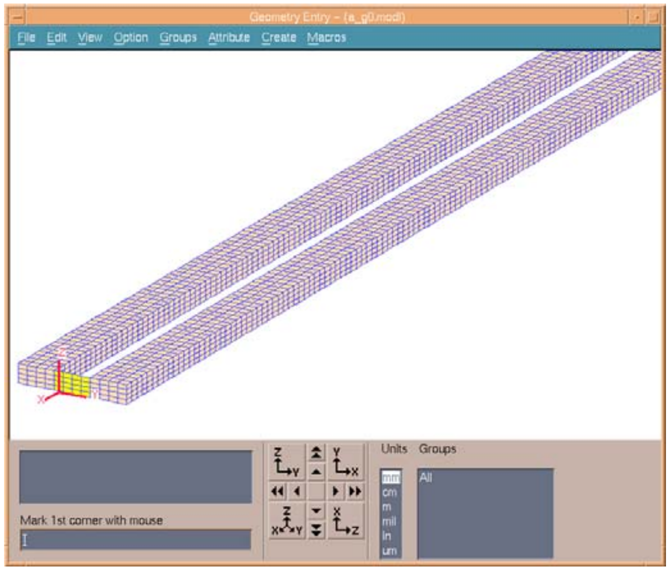
- Nearly uniform gridding results in the over-gridding of the model and huge increase in unknowns. Result is that direct LU decomposition of high aspect ratio mesh is faster then any technique of over-gridded mesh.



Impact of High Aspect Ratios



200:1 aspect ratio mesh



2:1 aspect ratio mesh (Gated by signal line height)

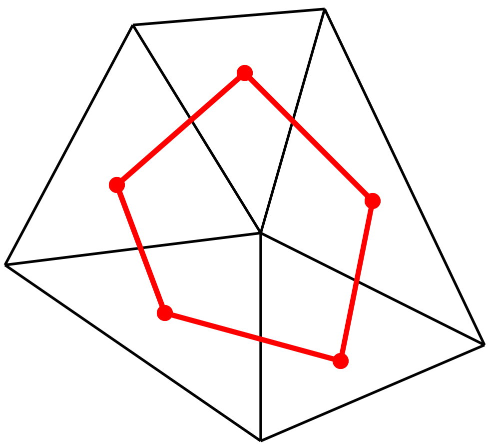
		solution type	# Unknowns	Time (seconds)	# of iterations
1 Diff. Pair	Nearly uniform grid	PFFT	64K	415	6
	High aspect ratio grid	LUD	0.8K	3	N/A

				Time (hours)	
16 Diff. Pair	Nearly uniform grid	PFFT	1M	2.5	9
	High aspect ratio grid	LUD	13K	0.5	N/A

Low Frequency Accuracy

*Note: Low frequency means that the mesh elements are very small compared to wavelength (<50GHz)

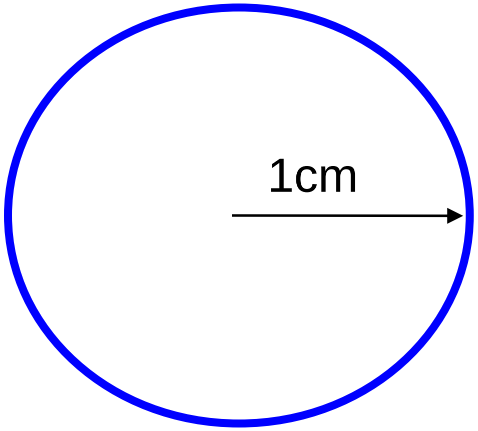
- With proper care, MoM can provide superior accuracy at low frequencies compared to other methods
- Traditionally, special application of Loop/Tree basis functions has been used to avoid low frequency problems
- However, if the integration scheme is done properly, then the capacitive contributions around a loop of line testing (razor blade testing) functions will cancel **EXACTLY** regardless of integration accuracy. This avoids low frequency breakdown in accuracy.
- Since there is no special treatment for small "low-frequency" meshes this…
  - Allows for direct application of MoM (including fast solution techniques) to any problem with no special treatment
  - Allows for a single solution method over all frequency ranges
  - Allows for capturing fine features in large objects.
  - Allows for wide variations in gridding size within the same mesh.



Composite of 5 line testing functions (red) over 5 triangles in mesh

Verification of Low Frequency Accuracy

A 1cm radius loop of a 10micron wire produces accuracy in both radiation resistance and loop inductance from full-wave solver to a few percent, until two values differ by more the machine precision! Uses only local basis/testing functions, no loop/tree or other special treatement!



- A 1cm radius wire loop antenna was modeled to verify low frequency accuracy
- Loop was 16-sided "ribbon" of width 10microns
- Compared to low frequency, analytic results for Rrad of a wire loop antenna, and inductance of thin circular wire loop.
- Chart goes from 75 to 750,000 sections per wavelength

	Analytic*		IBM Solver**	
Freq	Rrad	Reactance	Rrad	Reactance
100KHz	3.70E-17	6.92E-02	3.29E-17	6.72E-02
1MHz	3.70E-13	6.92E-01	3.61E-13	6.72E-01
10MHz	3.70E-09	6.92E+00	3.61E-09	6.72E+00
100MHz	3.70E-05	6.92E+01	3.63E-05	6.73E+01
1GHz	NOT VALID		5.97E-01	7.99E+02

15 orders of magnitude between Real and Imag.

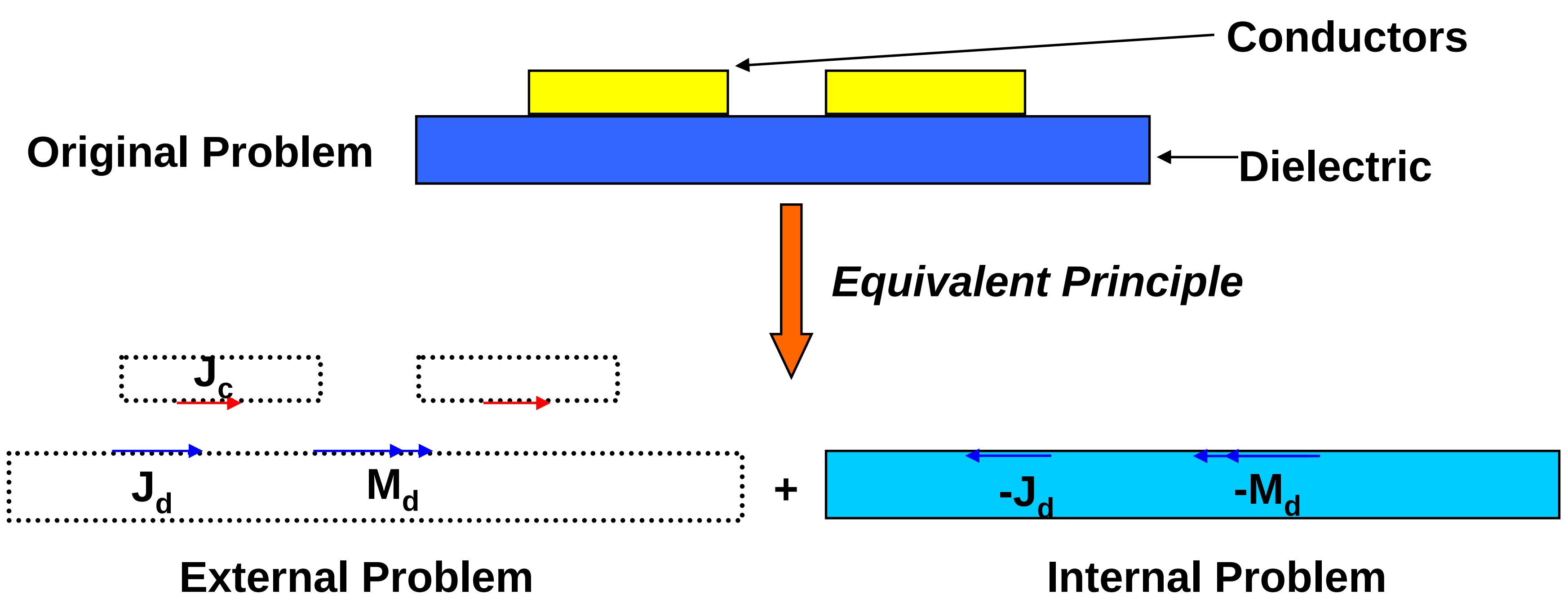
750,000 sections-per-wavelength

* Analytic radiation resistance for zero diameter wire, and inductance for thin wire loop antenna

** MoM solution for "ribbon" loop (16-sided polygon)

Surface Based Dielectric Solutions

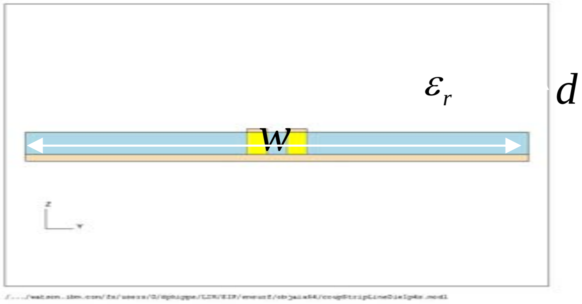
- To keep the "surface based" meshing advantage of the MoM solver, the preferred dielectric implementation is to mesh only the surfaces of the dielectric bodies
- Avoids costly volume gridding of the dielectric materials, a key advantage of MoM

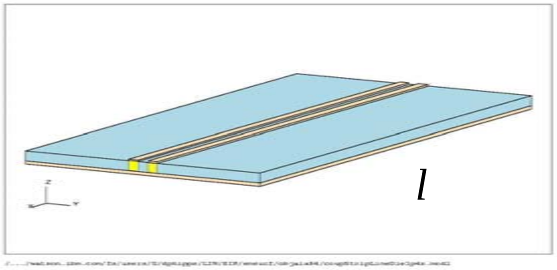


$$J_c = \hat{n} \times H \qquad J_d = \hat{n} \times H \qquad M_d = -\hat{n} \times E$$

Surface Based Dielectric Solutions

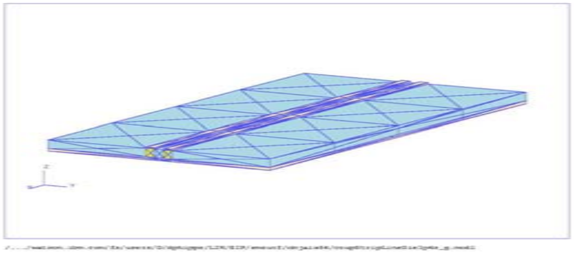
- Simple coupled microstrip example showing 4X reduction in unknowns when using MoM with surface meshing of dielectric compared to MoM using volume meshing of dielectric.
- The background is NOT meshed in either example, since both are MoM implementation. Even larger reductions compared to volume methods.

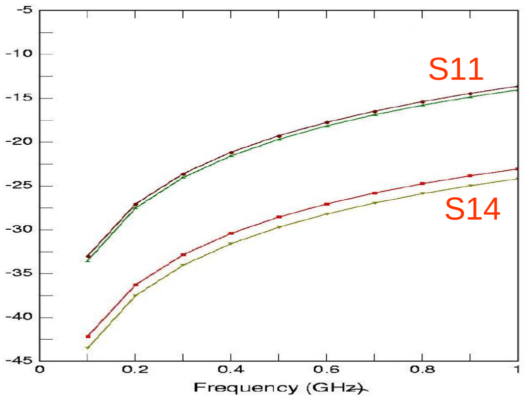




$l = 10mm$ $w = 5mm$

$d = 0.3mm$ $\varepsilon_r = 2.6$





- **Number of unknowns**

Volume: 3353, Surface: 810

4x reduction in unknowns

Efficient MoM Based Methods

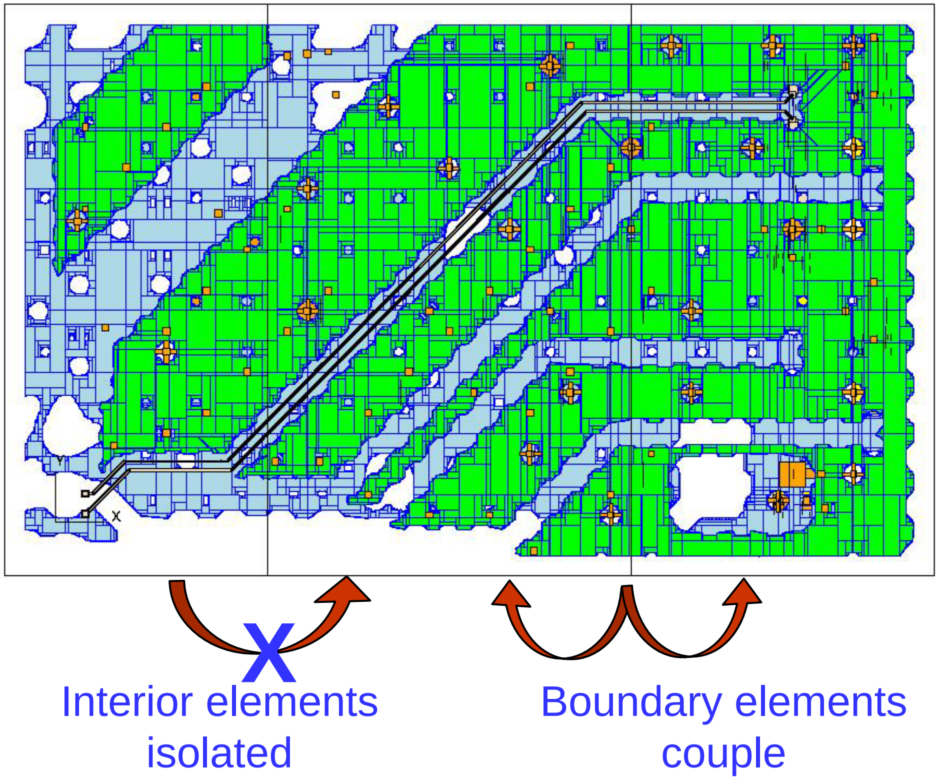
Reduced Coupling

- Classic method for handling problems that are too large for typical modeling tools is to decompose the problem into adjacent domains/partitions. As an example, an SCM is shown below with 3 partitions.

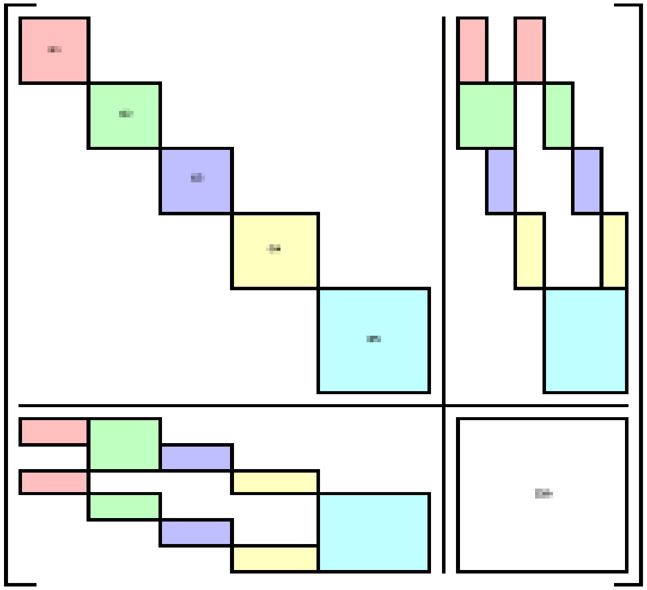
- Brute Force Domain Decomposition
  - Produces separate/independent problems
  - No displacement current (coupling) between domains
  - No conduction current between domains, except at finite number of ports.
  - Independent solutions result in port discontinuities/parasitics at boundary of each domain.

- Reduced Coupling
  - Partitions problem, but combines partitions into a single matrix solution.
  - EM coupling between elements internal to a partition and boundary crossing elements.
  - No coupling exists between elements in different domains, except through the common boundary elements.
  - Result is essentially equivalent to placing a port with zero parasitics at each unknown which crosses a partition boundary.

SCM (only 2 layers, 2 nets are shown)
75k MoM unknowns ~ 3.75M FEM



Reduced Coupling Matrix Topology



Sparse Matrix topology for Reduced Coupling.

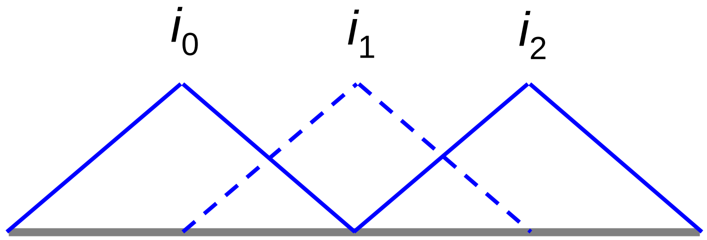
- The Reduced Coupling fast algorithm, takes a geometry and partitions it into adjacent domains to convert the normally dense matrix into a sparse matrix shown on the left.
- Full EM coupling is observed between other elements internal to the same domain and elements crossing the boundary between domains.
- No coupling exists between elements in different domains, except through the common boundary elements.

Matrix is factored with nearly zero fill-in

- If we color code the domains (figure assumes 5 domains), this results in the matrix topology shown
  - A block diagonal matrix in the upper left representing internal element interactions
  - A sparse matrix in the lower right representing interactions between boundary elements
  - The remaining matrix is sparse with boundary element interactions with internal elements from multiple partitions/domains.

FFT Based Fast Algorithms

- Temporarily consider the small MoM problem of the one dimensional line current shown on the right with the 3 basis functions i_0, i_1, and i_2.
- If the 3 elements of the mesh are of equal length, then the linear system of equations will resemble …

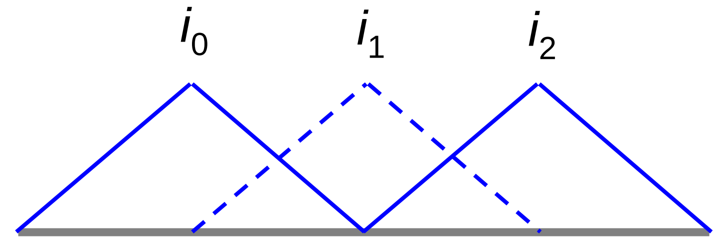


$$\mathbf{Z} \cdot \mathbf{I} = \mathbf{V} \rightarrow \begin{bmatrix} z_0 & z_{-1} & z_{-2} \\ z_1 & z_0 & z_{-1} \\ z_2 & z_1 & z_0 \end{bmatrix} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix}$$

- Here z_0 is the value of the self terms, which are all three the same since the basis/testing functions will be identical, z_{-1} is the interaction between a basis and the testing functions immediately to its left, etc.

FFT Based Fast Algorithms

$$\begin{bmatrix} z_0 & z_{-1} & z_{-2} \\ z_1 & z_0 & z_{-1} \\ z_2 & z_1 & z_0 \end{bmatrix} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix}$$



- The Z matrix above is Toeplitz, meaning that the 2nd row is a copy of the 1st row, shifted to right by 1 element. A new element is added to column 1. The 2nd row is then a copy of the 3rd, etc.
- Note that the linear, discrete convolution given below provides the same three expressions for **V** in addition to some extra and unused "equations".

$$[z_{-2} \quad z_{-1} \quad z_0 \quad z_1 \quad z_2] * [0 \quad 0 \quad i_0 \quad i_1 \quad i_2] = [v_0 \quad v_1 \quad v_2 \quad 0 \quad 0]$$

- The Z*I matrix-vector multiplication needed by the iterative solver is taken using the convolution above, which is taken with FFTs. This is NlogN instead of N^2 complexity, and is the source of the increase in efficiency of the solution.
- In addition only the unique matrix elements need to be computed.

Precorrect-FFT (PFFT) Fast Algorithms

- One such FFT based algorithm (PFFT) works on this principle.

- PFFT projects all the basis and testing functions in the mesh onto a uniform grid of point sources. Then the uniformity of the projected mesh can be exploited using convolutions taken with FFTs.
- Interactions between distant mesh elements is approximated by interactions between their projections onto the point source grid.

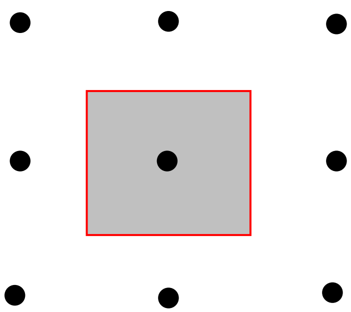


Illustration of cell overlapped with projection grid

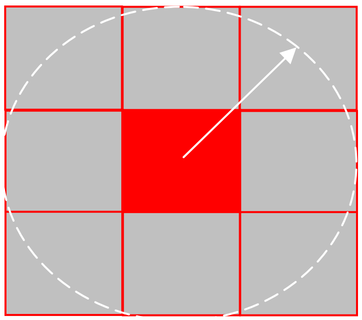


Illustration of near field corrections

- Near by interactions (at minimum adjacent elements) are not approximated correctly with the grid projections, and need to be computed directly and corrected for
- This method requires more runtime and memory than Reduced Coupling, but if done properly produces the “true” solution as opposed to approximating the solution by Reduced Coupling.
- The Reduced Coupling matrix can be used to effectively precondition the iterative solver for the FFT based methods.

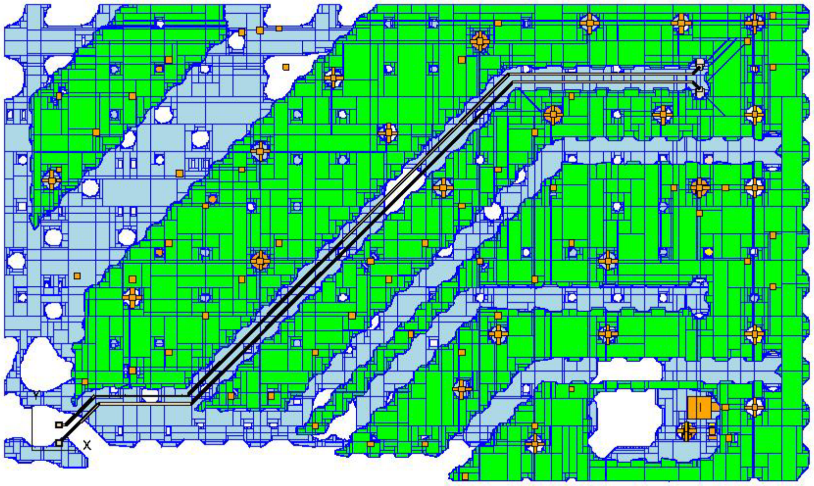
Reduced Coupling (Validation)

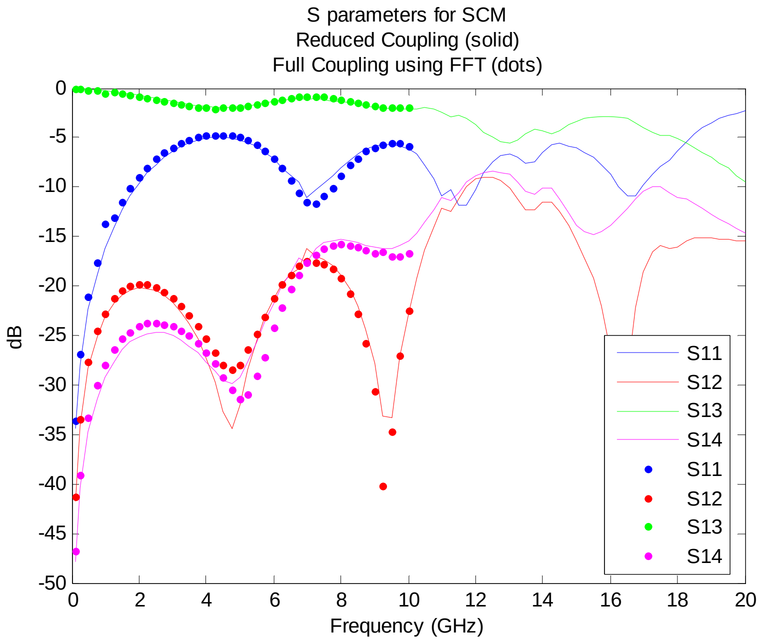
- Allegro extracted SCM produces 75K surface MoM unknowns (equivalent 3.75M FEM)

- 32 partitions were used to decompose the problem for the Reduced Coupling solution.
  - This would never give accurate results using the Brute Force approach.

- Results using Reduced Coupling (solid lines) and true "Full Coupling" solution (dotted lines)
  - Results using RC are almost identical to full coupling solution, but produce results in a fraction of the solve time and memory.

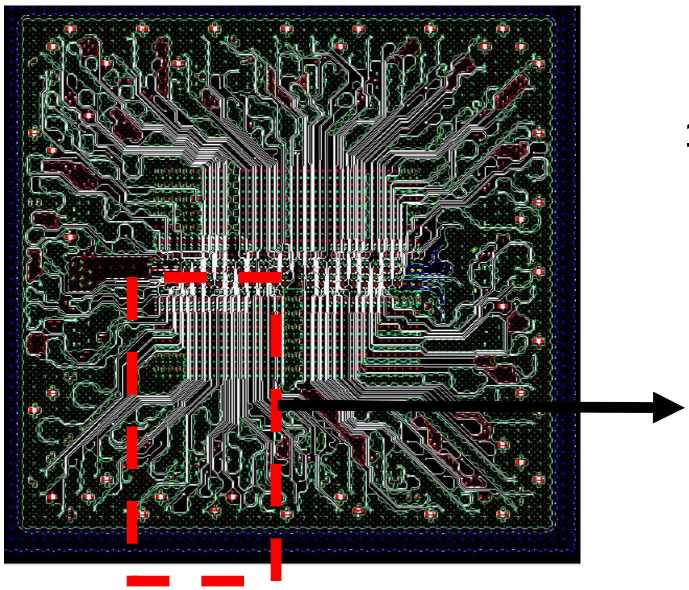
SCM (only 2 layers, 2 nets are shown)
75k MoM unknowns ~ 3.75M FEM unknowns



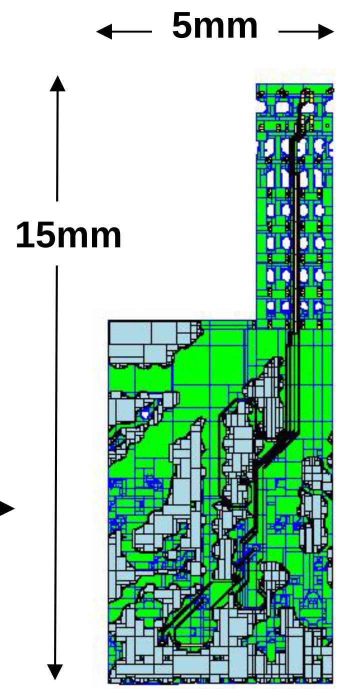


Reduced Coupling (Validation)

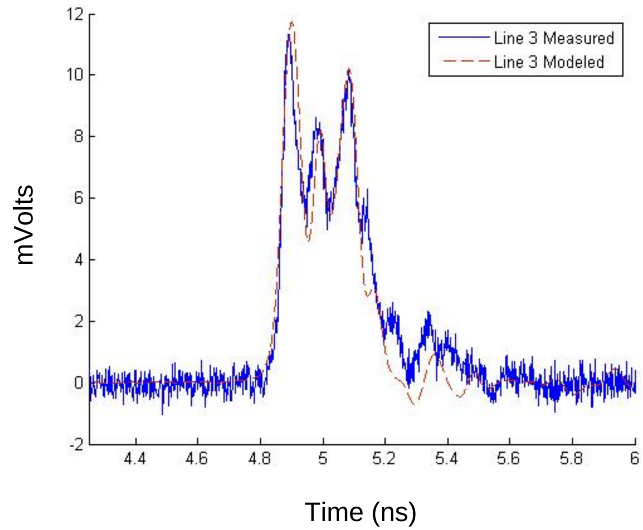
- Plasma SCM (given as “challenge” problem at EPEP conference 2006)



View of fan-out layer from Allegro



Top view of 4 net SCM model



Far end cross talk between two adjacent lines

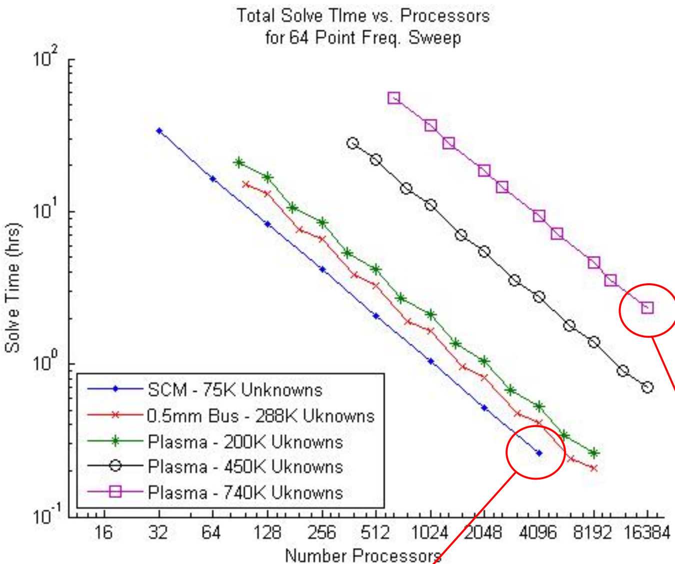
- Example of 5mm x 15mm section of Plasma SCM.
- 4 nets, 7 power/ground planes, Allegro extracted with full detail, 200K surface unknowns
- 1.5hrs per frequency point for solution on single processor using 64 partitions.
- Comparison of far end coupled noise to measurement.

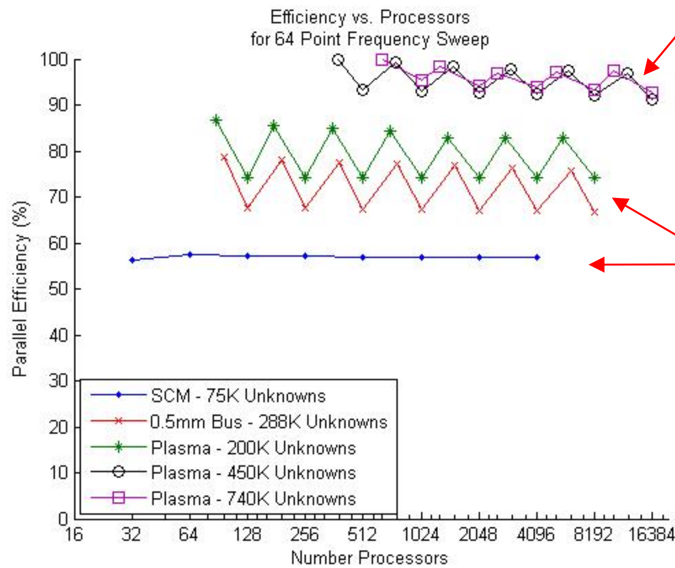
Reduced Coupling Parallelization

First SCM example in Blue

Second SCM (Plasma) example in Green

True efficiency unknown
Normalized to 100% peak





True efficiency

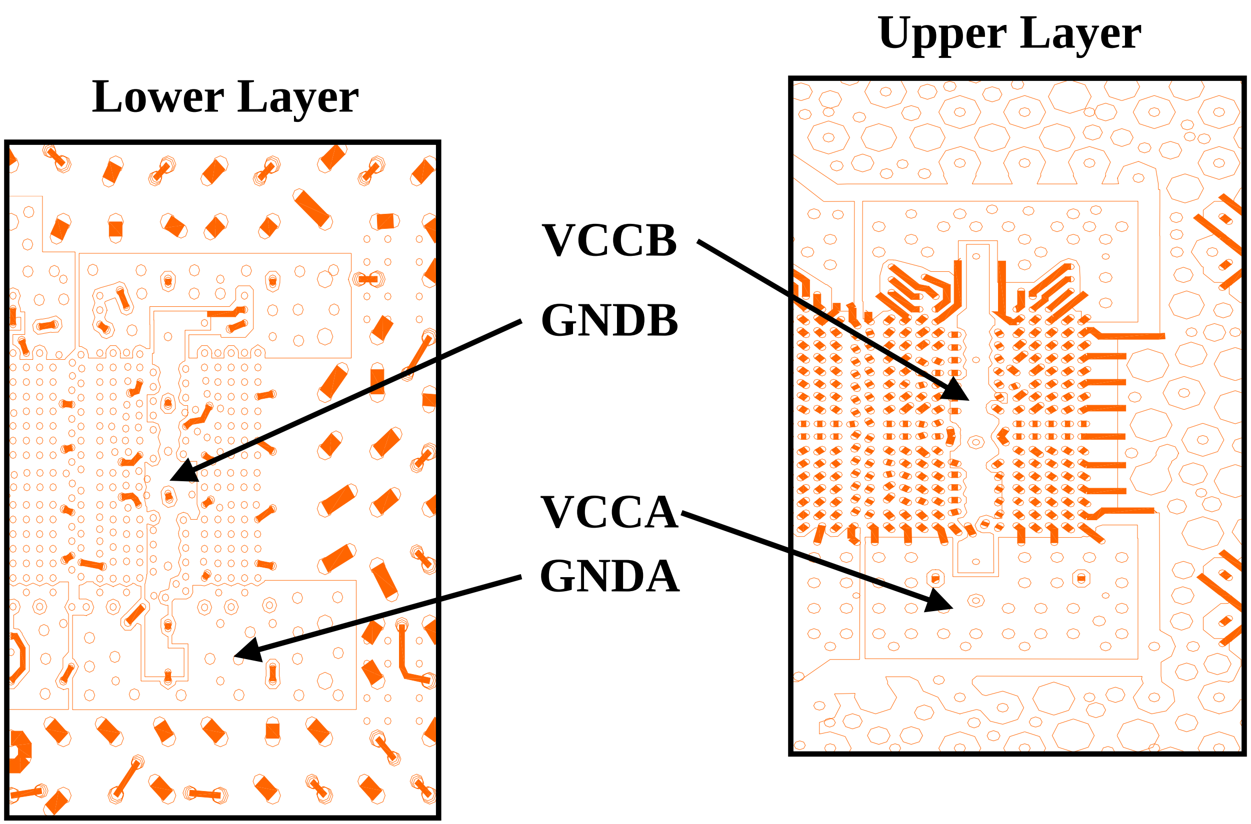
75K Unknowns
64 point freq sweep in 15min

740K Unknowns
64 point freq sweep in <3hrs

- Generally we require frequency sweeps, not single frequency solutions.
- To increase efficiency (decrease solve time) frequencies are distributed over groups of processors, in addition to each frequency being solved in parallel.
  - Allows selection of optimum number of processors per frequency
- Peak true efficiency >85% obtainable when number RC blocks ~ number of processors.

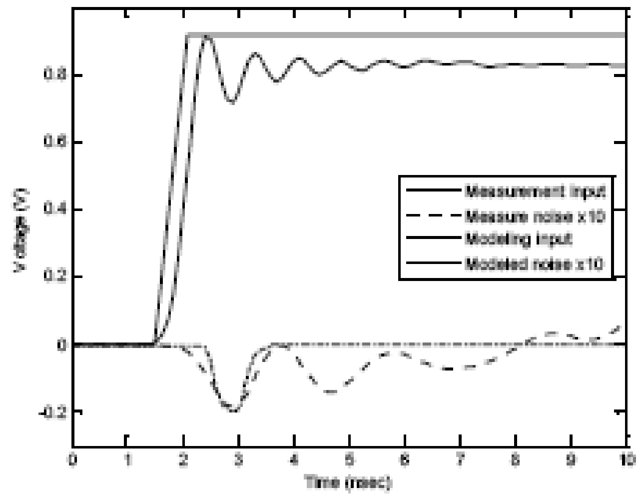
Precorrected FFT Example

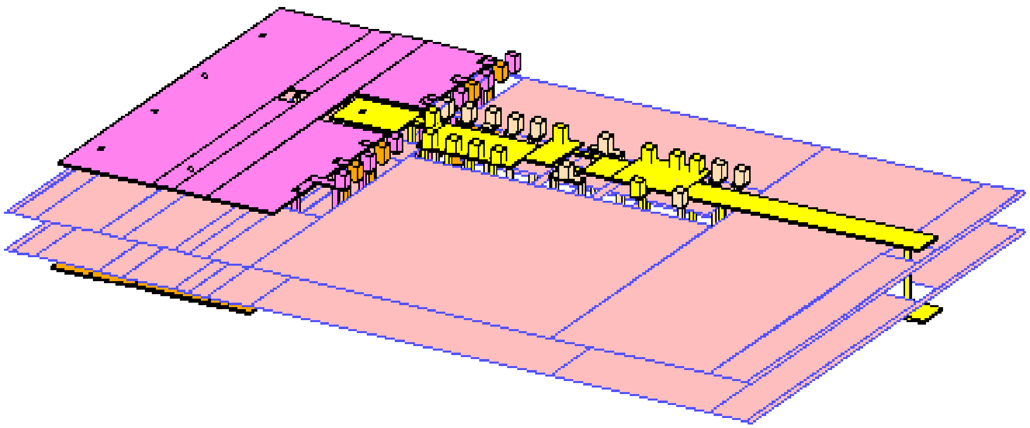
- Reduced Coupling works best when a clear return path for the current is apparent.
- For problems where Reduced Coupling is not sufficient to produce adequate results, the reduced coupling matrix can be used as a preconditioner for the PFFT algorithm.
- The below example shows two layers from an Allegro file with analog and digital ground/voltage islands. The desired solution is the coupling between the separated power islands.

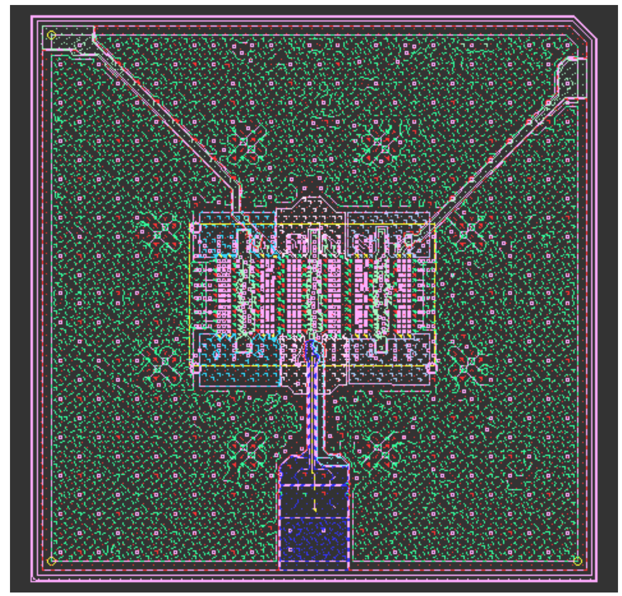


Precorrected FFT Example

- Model and comparison to measurement of coupling from island A into island B.
- Results in plot are time shifted and coupling is multiplied for ease of viewing. Only first coupling peak captured due to difference in time domain measurement and modeling input signal.







75K surface unknowns – 35 minutes per frequency point, Direct matrix solution would take 80 hours and 64 Gbytes –

Conclusion

- MoM has the advantage of being able to handle extreme aspect ratios, which reduces the number of mesh elements.
- MoM can also be structured to handle very low frequencies, down to MHz or KHz for typical packaging structures, which effectively solves for the DC solution.
- Some fast algorithms (Reduced Coupling and PFFT) were demonstrated to show how MoM can gain additional efficiency advantages using state of the art algorithms.
- Reduced Coupling was demonstrated in parallel, showing parallel efficiencies of 85% for a single frequency point running on 84 processors. Running massively parallel, up to 16384 processors, when distributing the frequency sweep as well.