Recent Technology Developments in the Sonnet Suites of Planar Electromagnetic Analysis Software

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***Abstract*—Sonnet is a high accuracy planar method of moments based electromagnetic analysis. Recent developments are described. These include multi-core CPU and cluster computing speed enhancement, full 64 bit addressing, enhanced lumped model extraction, modeling and measurement of dielectric anisotropy, a new empirical model of metal roughness, microvia array simplification, diagonal port de-embedding/calibration, interpolation, port tuning, and MATLAB interoperability.**

Keywords: Anisotropy, calibration, cluster computing, de-embedding, electromagnetics, interoperability, metal roughness, method of moments, microvia, multi-core, multi-thread, planar.

I. INTRODUCTION

The Sonnet® Suites of planar electromagnetic (EM) analysis tools have been under continuous commercial development since 1983. Over that period, both computer hardware and software technologies have increased in capability many fold. Below, we describe some of the more recent advances.

The Sonnet EM tools are based on a shielded (i.e., contained in a rectangular, shielding, conducting box) planar method of moments analysis [1]. The technique uses an exact (i.e., to within numerical precision) Green's function and an exact port calibration algorithm [2]-[4], yielding extremely high accuracy as cell (or mesh) size goes to zero. Primary use of Sonnet is for extremely high accuracy analysis of microwave circuits. Antenna analysis is achieved by setting the top and bottom covers of the box to the impedance of free space and by making sure that the conducting sidewalls (required to make sure all ports have exactly the same ground reference) are far enough from the antenna to have little influence on the result. An introduction to using Sonnet, and several other EM tools, for antenna analysis was recently translated from the original Japanese [5]. Several antenna applications are described in [6] and [7].

II. COMPUTATIONAL SPEED

Speed is often an important benchmark for electromagnetic analysis. This metric is most important for large circuits, for example, Fig. 1, which usually take the most time. There are now many commercial speed-enhanced EM tools that use various techniques (for example, an iterative matrix solve) to realize faster results. These tools have important applications, however, the necessary small increases in analysis error can be a problem for some applications, and analysis time for iterative techniques typically increases proportionally with the number of ports making them best suited for circuits with few ports.

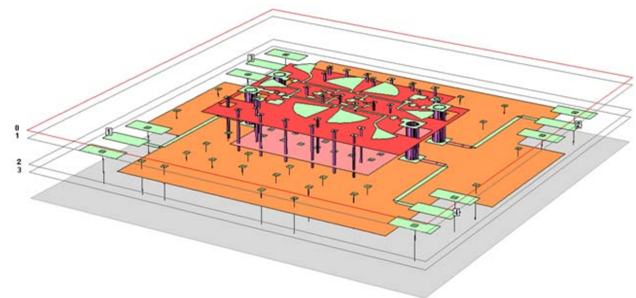

Figure 1. Typical complex RFIC circuit that can now be analyzed with a fine mesh for high accuracy using multi-core 64-bit computers.

A. Multi-core speed-up

Our emphasis is for high accuracy, often with large numbers of ports. Thus iterative approaches are not used. Instead, we emphasize enhancing the speed of algorithms like LU (Lower Upper) decomposition. For historical perspective, the first matrix we inverted using LU decomposition was in 1985 on one of the first IBM-PC's, using an 8088 CPU with an 8087 floating point co-processor (at that time, the co-processor was a separate chip). With hand-coded assembly language for the inner loop, we inverted a 100 × 100 matrix (i.e., 100 subsections) in about one hour. At that time, this was a world-class result for a US$2 000 desktop computer. The clock speed was 4.77 MHz.

One of the speed-enhancement techniques available for LU decomposition is parallel processing. This is especially useful now that multi-core CPU's are common. The main difficulty in realizing the maximum potential speed enhancement for LU decomposition is not the floating point performance. Rather, it is typically memory bandwidth. With N-processors, one would expect to see less than an N-factor speed-up due to memory bandwidth limitations. However, it appears that this is not an issue for modern multi-core CPU design. We measure speed-up for 1 to 16 cores and we find it to be almost exactly linear.

As for a specific benchmark, we now invert a 100 000 × 100 000 matrix (real, single precision) in under 3 hours on a 12-core ("dual hexa-core") computer costing US$3 000. Since LU decomposition is an N^3 process, this means that computer

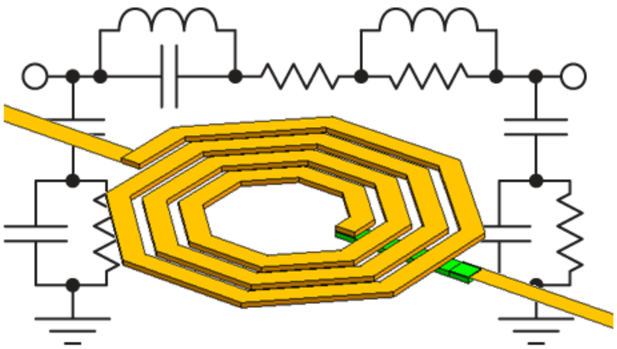

Figure 2. A pre-defined spiral inductor model, this one including skin effect resistance, can be extracted from EM analysis results.

hardware and software technology has improved by over 300 000 000 times in the last 28 years. This was not within even the wildest of imaginations back in 1985.

B. *Multi-CPU speed-up*

The multi-core speed-up described above takes an analysis at a single frequency and breaks it into multiple smaller pieces, one for each core. The maximum memory required is the memory required for analysis at one frequency.

Another approach, given that analysis is required at, say, 10 frequencies, is to use a cluster of 10 computers, one for each frequency. The disadvantage of this approach is that 10 computers, each with the full memory required for analysis at one frequency, are required. However, now the analysis is 10 times faster. For applications where cost is a secondary issue and large problems must be analyzed as rapidly as possible, then a cluster of multi-core computers becomes viable. A cluster of 10 computers, each being a 12-core machine achieves very close to the theoretical 120 times speed-up.

C. *Memory Address Space Speed-up*

Back in 1985, who could have imagined anyone needing more than a 32 bit address space, which could address up to 4 GB. In fact, Bill Gates was widely quoted as asking who would ever want more than the 640 kB address space of the first IBM-PC. Today problems requiring more than 4 GB of memory are common.

Converting a large program (remember, we have been doing intense development for over a quarter century) from a 32-bit address space to 64-bit is a lengthy process. We have recently completed the final stage of that process, making the entire analysis engine 64-bit, realizing an additional three times faster analysis for large circuits like that of Fig. 1, which requires 18 GB of memory. Note that our observed speed up is due to increased memory bandwidth, and elimination of data conversion overhead. A 64-bit computer is not inherently faster than a 32-bit computer.

III. Lumped Model Extraction

A major application of Sonnet is for RFIC (Radio Frequency Integrated Circuit) modeling. By far, the most interest for RFICs on silicon is spiral inductor modeling. An integral part of most RFIC modeling is time domain simulation. For this, a lumped equivalent circuit is required; a simple list of S-parameters is insufficient. As an additional problem, it is absolutely critical that the lumped models be causal (not violate speed-of-light), passive, and stable. Sonnet excels in this application because of the high accuracy yielded by the perfect port calibration, the perfect Green's function (both to within numerical precision), and a causal dielectric loss model. Very small, non-physical analysis error results in a model that might be non-causal, non-stable, or non-passive.

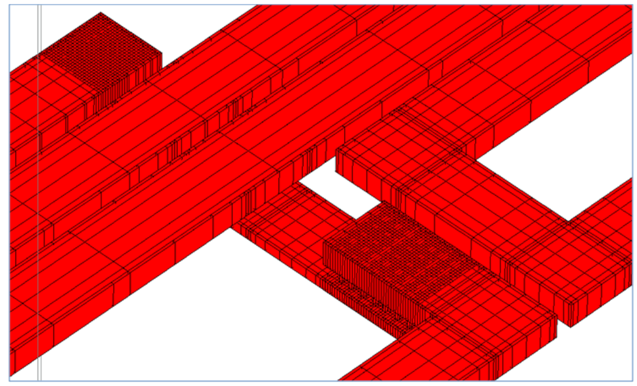

Figure 3. The two regions of extremely fine meshing are the result of microvia arrays connecting metal levels. Microvia arrays are now automatically simplified so that normal meshing is used in these regions.

Up to now, Sonnet has emphasized synthesis of arbitrary compact lumped models. However, many RFIC designers require a best fit of a specific model that has been set in advance. Our most recent development addresses this need, Fig. 2.

IV. Micro-Via Arrays

Silicon RFIC designs now frequently include "micro-via arrays". These are arrays of very large numbers of very tiny vias used to connect metal from one level to metal in another level. For example, this might allow connecting two levels of metal together in parallel to reduce loss.

In the usual RFIC design process, several hundred custom inductors might be analyzed, with only one selected for the final design. Thus, fast analysis is highly desirable. However, meshing micro-via arrays, as they are provided to an EM analysis, results in an excessively fine mesh. The mesh required to analyze geometries with this kind of detail is much finer than is required by the desired accuracy, Fig. 3. To realize the desired speed, a designer can manually remove the micro-via array and substitute a few large vias that give the same result, only much faster. Performing this layout modification manually on several hundred layouts is both tedious and error prone. Thus, we have automated this simplification process.

Over the years of working with various meshing tasks (including development of roof-top-like basis functions that curve to follow curving lines), we have come to realize that meshing algorithms are often much more difficult to develop than even the most complicated electromagnetic algorithm. Maxwell's equations provide no help for meshing problems.

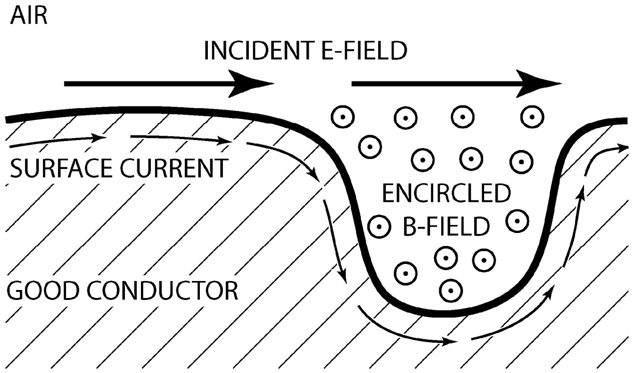

Figure 4. The new metal roughness model includes substantial excess surface inductance generated by the roughness forming many small surface inductors (encircled B-field).

V. Conductor Roughness Modeling

We always like to look at the difference between measured and calculated. So-called "good agreement" is boring. When we start thinking about the difference, even a small difference, we can start finding some really interesting things. For example, recently while working with Rogers Corporation, we saw strange results where measurement showed the substrate dielectric constant seemed to depend on both the substrate thickness and the roughness of the copper foil.

It turned out [8] that all the results are explained by a single substrate dielectric constant as long as we include excess inductance in the surface impedance of the copper foil. We all recall that skin depth results in a surface resistance. Sometimes we forget that there is an equal amount (in terms of Ohms/square) of inductive surface reactance. Roughness magnifies this surface inductance many times, Fig. 4, from [9].

This roughness model is now included in Sonnet. If the measured resonant frequency for a patch antenna is a bit lower than EM analysis predicts, it might be due to metal roughness. We have experimentally observed the effective dielectric constant of microstrip lines increase by 15% due to roughness.

VI. Dielectric Anisotropy Modeling

Another reason measured and calculated results might be different is anisotropy. Most substrates, including ceramic substrates (due to non-spherical grains) and all composite materials are anisotropic. We deal with uniaxial anisotropy, where there is one dielectric constant for horizontal (parallel to the substrate surface) electric field and a different dielectric constant for vertical electric field.

Note that modeling an inhomogeneous substrate (e.g., an epoxy-fiberglass weave like FR-4) as anisotropic is an approximation. The most accurate model would be to model the exact inhomogeneous nature of the substrate. Due to the complexity of the problem, that approach is rarely practical.

To measure anisotropy, we use a very long dual mode microstrip resonator [10]. The resonator is typically 25 or more wave lengths long. The resonator is formed from a pair of microstrip lines, giving us a pair of both even and odd mode resonances every half wavelength. Each pair of resonant frequencies is converted into the equivalent horizontal and vertical dielectric constant. Over a typical band, say, 0.5 to 16 GHz, we can evaluate nearly 50 pairs of uniaxial dielectric constants, Fig. 5, from [11].

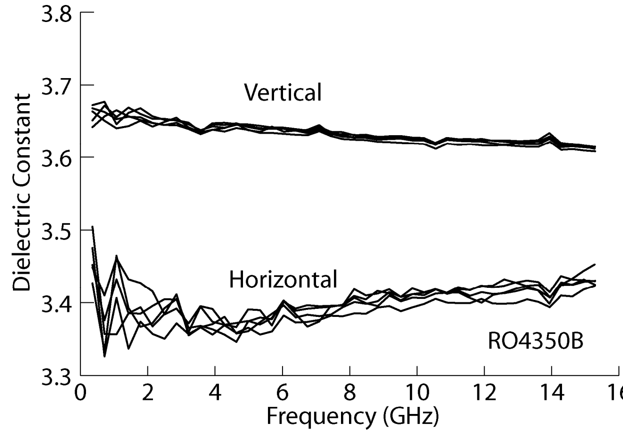

Figure 5. Measured values of anisotropic dielectric constant for five samples of Rogers RO4350B. This sort of anisotropy is present in all inhomogenous substrates.

The dielectric constants are determined by comparison to resonances expected based on EM analysis of similar resonators. EM analyzing a resonator that is 25 wavelengths long to the required accuracy of better than ±0.001% is a non-trivial EM problem. The only way we have found to successfully EM analyze such a resonator is by dividing it into many small pieces (many of which are identical and need be analyzed only once), using a very fine meshing (for accuracy), and then connecting the pieces back together with circuit theory. The difficulty of this problem is increased by the fact that we typically need a frequency sweep with around 100 000 data points. This approach requires the perfect Green's function, the perfect port calibration, and the perfect port ground reference available in Sonnet.

VII. Diagonal Port De-embedding

Connections to microwave circuits and antennas are made by use of ports. Each port generates fringing fields that appear in the resulting S-parameters, typically, as a small amount of shunt-to-ground capacitance and resistance. For high accuracy analysis, this port discontinuity must be characterized and removed. Sonnet characterizes the port discontinuity, including multiple coupled ports, perfectly [2] - [4]. Groups of coupled internal ports are also perfectly calibrated [3]. "Perfect" means to within numerical precision provided the port connecting lines are not over-moded.

For some problems, port calibration is not needed at all. In many cases, approximate port calibration is sufficient, as in, for example, when not all the ports are referenced to exactly the same ground potential. In other cases, as in analysis of the dual mode resonator described above, perfect port calibration is required.

Perfect port calibration requires using one of the perfectly conducting box sidewalls as a perfect short circuit calibration standard. Thus all such ports had to be oriented parallel to one of the box sidewalls. We have now extended perfect port calibration to ports that are at an arbitrary angle with respect to the box sidewalls, Fig. 6.

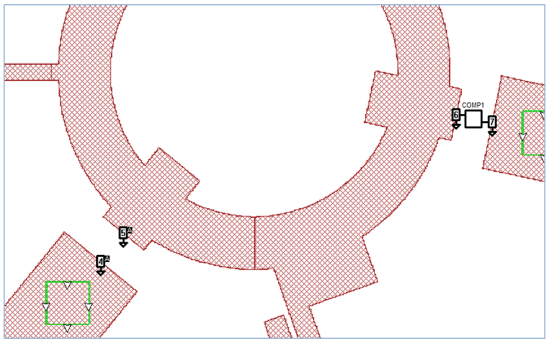

Figure 6. Perfectly calibrated internal ports that are at an arbitrary angle to the box sidewalls are now possible.

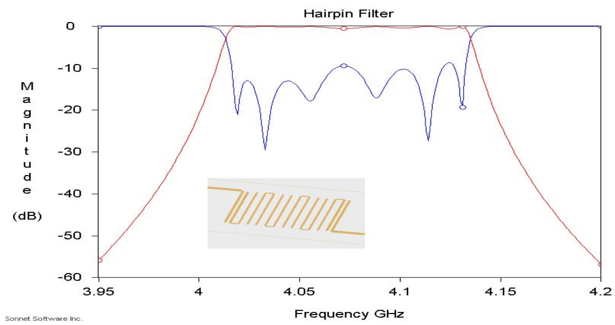

Figure 7. Actual EM analysis was performed only at the four frequencies marked with small circles. The rest of the data is interpolated.

VIII. Interpolation

Although it does not fall under the category of "recent", Sonnet has developed a world class interpolation capability. Based on the well known Padé rational polynomial interpolation, our approach creates a very high order polynomial based not on the S-parameters at a few frequencies, but rather based on information extracted from the entire moment matrix. A typical result, Fig. 7, from [12], shows a filter response interpolated from analysis at four frequencies. EM analysis results evaluated at all frequencies are visually identical at this plotting scale.

IX. Port Tuning.

Groups of perfectly calibrated internal ports can be used to provide access points in a circuit so that small circuit theory elements can be introduced for rapid tuning purposes. For example, very short circuit theory transmission lines can be connected between pairs of closely spaced ports placed across a gap cut in the center of a resonator. Then, the lengths of those transmission lines are adjusted in real time to tune the lengths of each resonator [13]. We have also developed methodology for tuning the separations between resonators in real time [14]. Most of the circuit is analyzed to full EM accuracy, but it is tuned at circuit theory speed.

X. Interoperability

Sonnet has spent several decades developing and updating interfaces with Agilent ADS, Cadence Virtuoso, and AWR. Sonnet projects can flow easily and seamlessly to and from these popular frameworks. Most recently, Sonnet has developed an extensive MATLAB API (Application Programming Interface). All data structures inside Sonnet, including, for example, the moment matrix, current distribution, etc., appear as data structures inside MATLAB.

XI. Conclusion

We describe recent advances in Sonnet technology including substantial speed-up taking advantage of multi-core CPUs, cluster computing, and 64 bit computing. We also describe a new lumped model extraction and automatic micro-via simplification intended for spiral inductors, a new conductor roughness model, the ability to measure and analyze uniaxial substrate anisotropy, a new diagonal port calibration/de-embedding capability, and our existing world-class interpolation capability. Finally, we summarize a recently developed port tuning methodology.

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