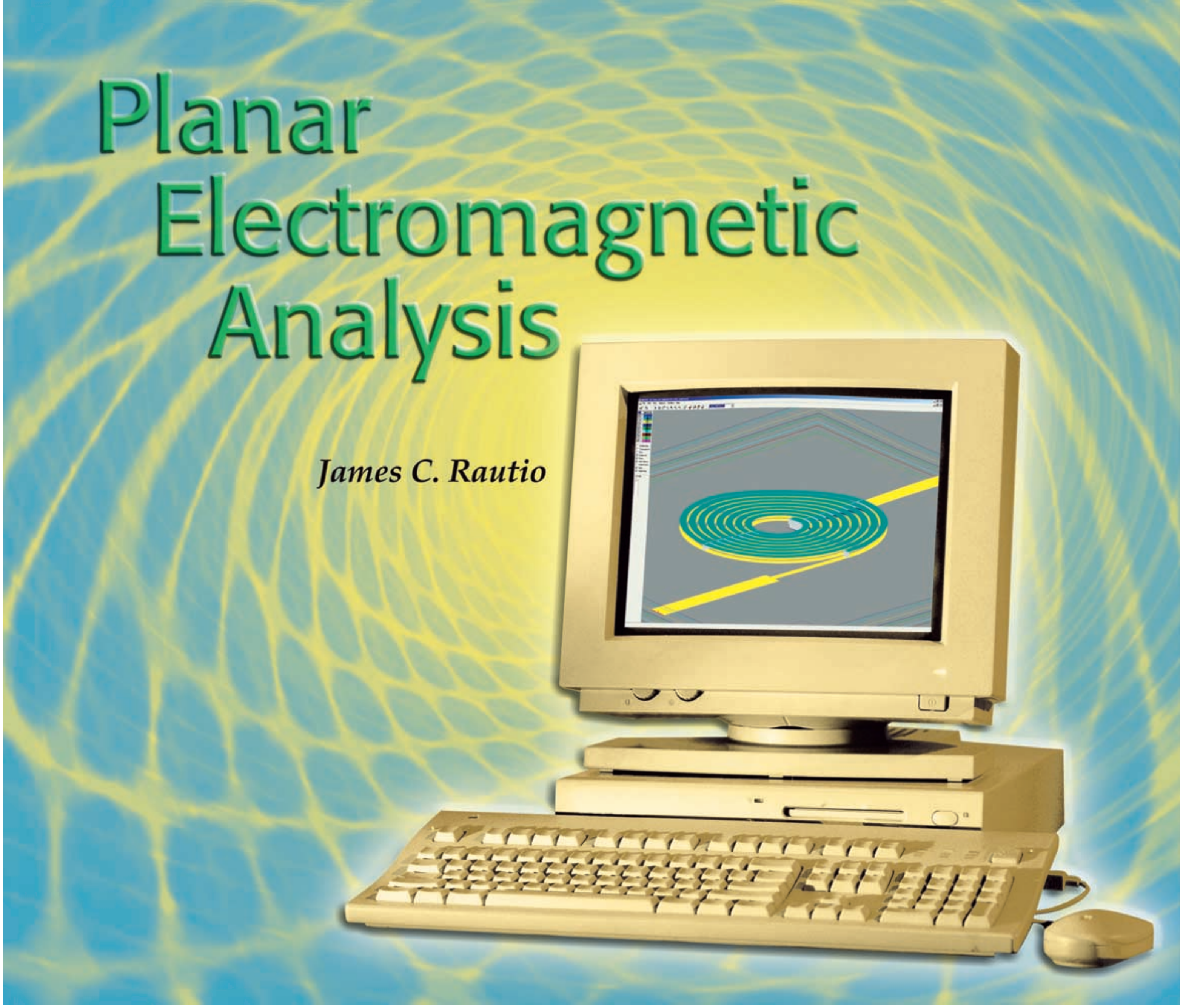
# Planar Electromagnetic Analysis

James C. Rautio



BACKGROUND; DIGITAL VISION, LTD; COMPUTER: COMSTOCK, INC. 1998;
COMPUTER SCREEN CAPTURE: CIRCULAR SPRIAL INDUCTOR MANUFACTURED USING MOTOROLA'S HIGH VOLTAGE IC (HVIC) SI IDMOS PROCESS

Electromagnetic (EM) analysis has been in regular use in the design of planar high-frequency and microwave circuits for well over a decade. This article provides a brief historical background of this development, a description of recent developments, and a speculative look at the future.

The field of electromagnetics began when James Clerk Maxwell [1] (Figure 1) put the known electric and magnetic phenomenon into mathematical form and, by trial and error, added the critical "displacement current" term that meant a changing electric field generates a magnetic field [2]. He then made an absolutely astounding observation [3], [4]:

> The velocity of transverse undulations in our hypothetical medium, calculated from the electromagnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau,

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> that we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena*. [Italics are original.]

The velocity calculated was 193,088 mi/s, the velocity observed was 195,647 mi/s. (Today, the speed of light is defined as exactly $2.99792458 \times 10^8$ m/s [5] or 186,282.4 mi/s.)

Although he is now widely viewed as the greatest physicist of the 19th century, Maxwell was modest about his achievements. One unfortunate side effect of his modesty is that it was not until several decades after his death that much attention was given to his "theory of electromagnetism."

Once the importance of Maxwell's equations was recognized, they were applied to the solutions of a large variety of problems. Their application was particularly important in the development of radar, having a significant influence on the outcome of World War II. However, at this time, most problems involved structures whose boundaries fall on constant coordinate surfaces. The coordinate system might be rectangular, cylindrical, or spherical, etc., but arbitrary structures with arbitrary surfaces were not easily approached.

World War II also initiated the serious development of electronic computers [6]. This development caused considerable excitement among a few far-sighted researchers in many fields. In electromagnetics, Roger Harrington (Figure 2) is one of those researchers and is today considered the father of the method of moments [7]. However, as with Maxwell, the work of many of these researchers was not immediately accepted. Harrington once related to me the comments of a reviewer of one of his first papers; it went something like this:

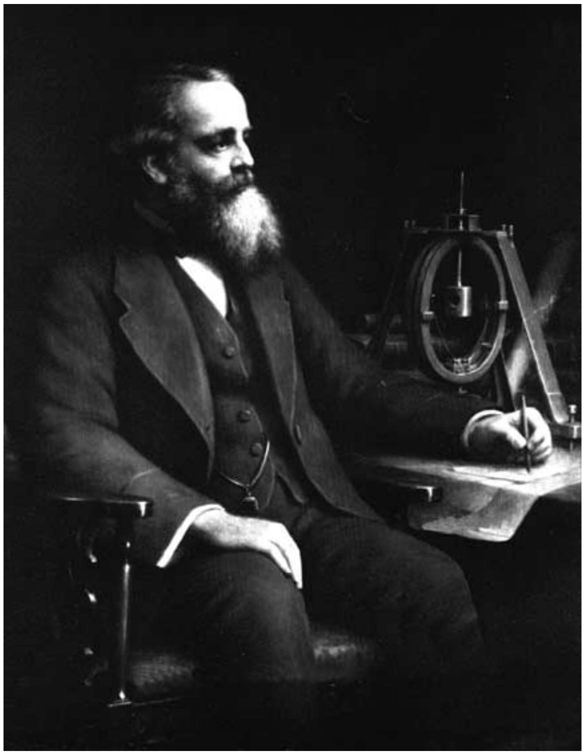

**Figure 1.** *James Maxwell from Sonnet's 1991 sales flyer. The apparatus might be a Helmholtz coil.*

> Your work is useless because it has been proven that it is impossible for a computer to invert even a 100 × 100 matrix because the magnetic tape would wear out going back and forth.

When I started working as a graduate student under Harrington, the IBM PC had just been introduced. In my office at Syracuse University, I had such a PC with an optional floating-point coprocessor (8088/8087). In 1984, I hand coded a matrix solve in assembly language and was able to invert a 100 × 100 real matrix in about one hour and was able to complete my dissertation [8], [9].

The acceptance of my continuing research by working microwave designers was slow, but, sometime around 1989, I was told by a well-known and skilled designer that he "used to think all the numerical EM stuff was strictly ivory tower, but now, it is actually becoming useful." It was then that I realized that the field of *applied* high-frequency numerical electromagnetics had begun.

## The Method of Moments

The method of moments is a general technique for converting a set of linear integrodifferential equations into an approximating set of simultaneous algebraic equations suitable for solution on a computer. The method is not limited to planar EM problems or even to electromagnetics. In fact, in the field of electromagnetics, special cases of the method of moments include Galerkin's method, the method of weighted residuals, point matching, and the Rayleigh-Ritz variational method.

As applied to the frequency-domain analysis of three-dimensional (3-D) planar circuits [i.e., circuits embedded in a layered dielectric (Figure 3) vias providing structure in the $z$-direction], a nonmathematical description of the method of moments, which I have developed over the years, follows.

First, we divide a circuit into small subsections. Then, we take one subsection at a time and calculate the electric field generated everywhere by the current on that one subsection. We do this for each subsection in turn. Then, we place current on all subsections simultaneously and adjust those currents so that the total tangential electric field goes to zero everywhere that there is a conductor, because you cannot have voltage across a conductor. The currents that give zero voltage across all conductors form the current distribution. Once we have the current distribution, the S-parameters follow immediately.

The specific current distribution we assume on each subsection is called a basis function. The "voltage" on each subsection is actually the electric field integrated over the area of the subsection (yielding the odd units of volt-meters) weighted by another function called a testing function. The method of moments allows the selection of any basis or testing function, however, solution quality and numerical efficiency are strongly dependent on these selections.

The calculation of the voltage generated by current requires evaluation of the Green's function [the EM equivalent of a linear system impulse response, it is a function of 3-D space coordinates rather than one-dimensional (1-D) time coordinates]. The result is the coupling between every pair of subsections and is stored in an $N \times N$ matrix, where $N$ is the number of subsections. The inversion of the matrix results in the current distribution, given that the voltage on one or more select subsections (the input and output ports) is nonzero. If the voltage absolutely everywhere in a circuit is zero, the current distribution is also zero. While we can obtain such a zero solution very quickly, it is not especially interesting.

## Initial Commercial Products

There was considerable research in numerical electromagnetics in the 1980s, sometimes even with limited commercial distribution. Examples include the Numerical Electromagnetics Code (NEC) and (related in name only) MiniNEC, both for analysis of wire antennas. LINMIC, written by Rolf Jansen, incorporated a planar method of moments analysis as part of a larger microwave circuit analysis tool.

The first planar method of moments tool to see widespread promotion was EMSim, developed by Y.L. Chow and distributed by EEsof from 1989-1993. My own efforts resulted in Sonnet, which started wide distribution later in 1989. This was quickly followed by HP (now Agilent) High-Frequency Structure Simulator (HFSS), a volume-meshing, finite-element code developed by Ansoft. It was intended for arbitrary structures but was also promoted for planar circuits. The final entry in the early planar market was Compact Explorer, whose distribution was terminated shortly after Ansoft acquired Compact. There was also a substantial amount of research published in this period that influenced but did not directly see commercialization.

A common misunderstanding during this period was that a volume-meshing code would be appropriate for planar circuits and would actually be faster than specialized planar codes for large circuits. Although this claim is still occasionally made, it has never been substantiated and can be considered discredited. Today, a more common view is that no single EM tool can solve all problems; an informed designer must select the appropriate tool for the appropriate problem.

Two misconceptions, still seen today, are that EM analysis cannot be trusted and that EM analysis is the ultimate truth. Today, all commercial tools have at least reasonable reliability, however, no EM tool should be trusted completely. A skilled designer always looks at EM results with a healthy skepticism; like a good jet fighter pilot, every high-frequency designer needs to know the limits of the tools, otherwise they might crash and burn.

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## Present Day Planar Tools

All of today's commercial planar tools can be divided into two groups: shielded and open. Shielded environment tools analyze planar circuits in an enclosing rectangular box. These tools include Sonnet, AWR EMSight, and Eagleware EMPOWER. Open environment tools have dielectric substrates going to infinity in all horizontal directions. These tools include Agilent Momentum, Zeland IE3D, and Ansoft Ensemble. Both approaches involve trade offs. The informed designer can select the appropriate tool based on design requirements.

The trade offs stem from how the Green's function, used to fill the moment matrix, is calculated. In shielded environment tools, the Green's function is just a sum of sines and cosines. This sum is calculated very efficiently by the fast Fourier transform (FFT).

The Green's function is integrated four times to calculate each subsection-to-subsection coupling to fill the $N \times N$ moment matrix. One two-dimensional (2-D) integration is over the $x$-$y$ area of the subsection with current on it. This calculates the electric field generated by the current. A second 2-D integration is over the subsection being coupled to. This yields the total induced voltage. This 4-D integration is repeated for every element in the matrix.

**Figure 2.** *Roger Harrington in his office at Syracuse University, 1985.*

With the shielded Green's function, integration is easy; each term is a just a sine or cosine that can be integrated with pencil and paper by any college freshman.

> **Every high-frequency designer needs to know the limits of the tools, otherwise they might crash and burn.**

The bottom line is: shielded analyses use the FFT to quickly calculate the Moment matrix to full numerical precision; absolutely no numerical integration or other approximation is required.

In open environment analyses, the Green's function is a Sommerfeld integral. The Sommerfeld integral is highly singular, and numerical integration must proceed carefully. Once the Green's function is obtained by a combination of numerical and analytical integration, sometimes combined with appropriate approximations, the four integrations described above are performed numerically for each matrix element. The tremendous progress realized in this area over the last decade has allowed the generation of useful open environment tools.

There has been very little published comparing the two approaches quantitatively. However, we have seen anecdotal results suggesting that open environment analyses can work down as far as –80 dB, while shielded tools can push down to –180 dB. However, keep in mind that dynamic range is highly variable from circuit to circuit. Based on extensive experience with the Sonnet shielded analysis, the dynamic range might degrade to as low as 100 dB down, especially for more complex circuits. Thus, it is important to consider the *minimum* dynamic range seen in an analysis rather than the maximum.

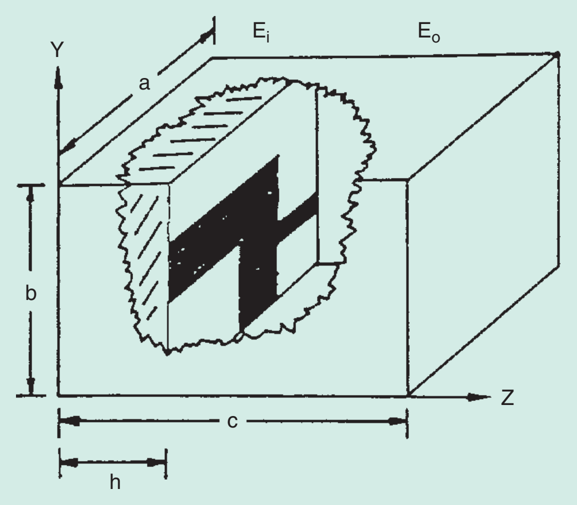

**Figure 3.** *Planar geometry as shown in [9], 1987. This was before vias (z-directed current) were added.*

Except for the dynamic range, looking at current distributions frequently reveals numerical problems. A good result will have a smoothly varying current distribution with very strong current close to the edges of the conductor. When numerical problems start to occur, current distribution quickly becomes ragged, and the high edge current becomes indistinct. A skilled designer always checks the current distribution to find incipient numerical problems.

An example is shown in Figure 4. At 10 GHz (left), the spiral inductor shows a good current distribution. There is a very narrow region (red) of high current at the edge of the lines. The current distribution varies smoothly as we go along the line. The line width is 500 µm and the cell size is 50 µm.

Even though the FFT approach is extremely robust, if we take the analysis down to 1 Hz and analyze in single precision, we can see the effect of numerical precision on the current distribution (Figure 4). Numerical precision problems are emphasized by this combination of single precision, very low frequency, and very small cell size. The current distribution provides an excellent early warning for many numerical problems.

Note that a faster (in fact, nearly instantaneous) analysis could be realized by using large 500-µm subsections, and, while numerical precision problems would be reduced, the ultimate accuracy would also degrade. This is especially true for loss as most of the loss is near the conductor edges with the high current. A large subsection size artificially spreads the narrow edge current out, resulting in an optimistic calculation of loss.

Shielded analyses have a significant dynamic range advantage over open analysis tools, and, because of the FFT, they can also handle much larger numbers of subsections and many more dielectric layers than open tools. However, open tools also have an advantage. Because of the numerical integration, it is easy to integrate the Green's function over any arbitrary area. Thus, adding arbitrary triangle and different size rectangle subsections is relatively easy.

In contrast, shielded environment tools use the FFT, thus restricting the subsection boundaries to a fine underlying uniform mesh. This is exactly analogous to using uniform time sampling in digital signal processing prior to applying an FFT. The requirement for a uniform underlying mesh makes FFT tools best for circuits with a more rectangular (i.e., "Manhattan") layout. While open tools cannot handle the large subsection count of shielded tools, they can analyze a more arbitrary circuit with fewer, larger subsections.

Most open environment tools can approximate the effect of a shielding box, and shielded tools can remove the top cover of the shield to approximate radiation. However, due to the necessary speed and accuracy trade offs, a designer should use these tools in these extended configurations only if the appropriate tool is unavailable.

A skilled designer considers factors including required dynamic range, circuit layout, circuit complexity, and open/shielded nature of the circuit in selecting the appropriate tool for a particular circuit. At least one open and one shielded tool is required to handle a full spectrum of planar problems.

## Commercializing Software

In developing any kind of technology, there comes a time when a researcher must decide whether or not to commercialize. In my case, I first approached several high-frequency software vendors and, sooner or later, received rejections from all of them. This meant that I had to commercialize the tool myself or let the issue drop and get on with life. With financial help from GE, HP, and David Sarnoff Research Labs, I decided to commercialize.

Now, nearly 20 years later, I would rate the total effort devoted to the underlying theory at about 10%, getting the tool ready for market at about 30%, and marketing and sales at about 60%. I now occasionally receive proposals from researchers to market software that they have developed, sometimes with a comment like, “It’s 90% complete, only 10% left to do!” to which I might reply, “I think you have the right numbers, they are just in the wrong order.”

The biggest obstacle to commercialization is in not realizing the full magnitude of the task. Getting funding is an important but, clearly, secondary issue. After overcoming these first two problems, one must put in place a rigorous software development and testing capability. Without development structure, deadlines will never be met, the resulting product will be inappropriate for customer needs, documentation will not be in sync with the product, and introduction of the product will be delayed. The sales force will be telling customers that the release will be out next month, for 12 to 24 months in a row. Without extensive and automated testing exercised throughout the development process, tools full of bugs will be placed in the customer’s hands, destroying the company’s reputation and leaving an overworked support staff unable to respond in a timely manner.

In addition to development and testing, there are business issues, like hiring employees, setting up payroll and benefits, and dealing with all the government paperwork. Then, there is marketing and sales for the final 60% of the total effort. Commercialization is a difficult and time-consuming task.

## Recent Developments

Over the last few years, there has been substantial research into taking EM data at a few frequencies and interpolating that data, in some intelligent way, to a large number of frequencies. Without any kind of interpolation, an analysis must be performed at, for example, 100 frequencies in order to get a good plot of the circuit response. That number can be reduced substantially by means of interpolation.

We are all familiar with linear interpolation: draw a straight line between two points and the interpolated points fall on that line. For a cubic spline, the same thing is done with a cubic polynomial and four data points from which a smooth curve results.

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Recent work has concentrated on extending this idea to a ratio of two polynomials, called a Padé rational polynomial [10], [11]. To apply this type of interpolation, one needs as many data points as there are undetermined coefficients in the ratio of two polynomials. In addition, some way of estimating error is required so as to set the frequency for the next analysis to generate an even better interpolation model.

This kind of interpolation is inspired by the Laplace transform, which, for lumped circuits, is a ratio of two polynomials. However, we are not dealing with lumped circuits, we are dealing with distributed circuits. Thus, the Padé polynomial is band limited. For example, a filter with six resonators has a reflection response with six zeros, but a simple application of this type of interpolation might require 20 or more frequencies to calculate 20 or more poles and zeros for a good answer. In some cases, the approach might not converge at all.

However, when we extract additional information from the Moment matrix to build a more sophisticated interpolation model, convergence can be seen with far

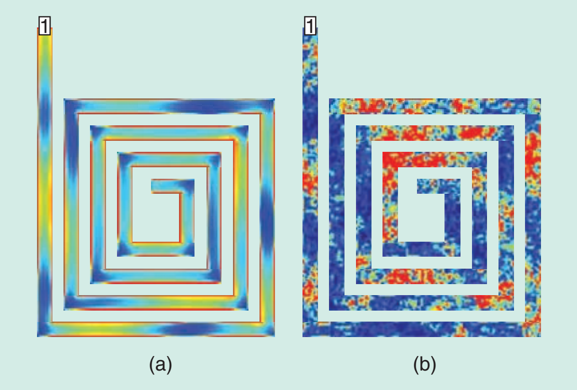

**Figure 4.** *At 10 GHz (a), this spiral inductor (line width 500 μm) shows a smooth current distribution with high (red) edge current. At 1 Hz (b), and with single precision, numerical precision problems are obvious.*

fewer data points [12] (Figure 5). This hairpin band-pass filter has six reflection zeros. Analysis was performed only at the start and stop frequencies, and two additional automatically selected frequencies (indicated). Because additional information is extracted from the moment matrix at each of the four frequencies, a high-order interpolation model can be synthesized, yielding data at 300 frequencies as plotted. When the filter is calculated directly at all 300 frequencies and then plotted, the data is visually identical to the interpolation result. The interpolation and the full calculation fall exactly on top of each other, as they do for all of the 1,500 circuits that we tested.

**Ease of interoperability in a multivendor environment, even between competitive vendors, is becoming critically important.**

The idea of how to extract this additional information came to me in December 2000. The idea achieved proof-of-concept almost immediately. Prototype software was then developed on Microsoft Excel over the next six months or so.

An initial regression test (a sequence of analyses all automatically performed with results compared to known correct answers) involved 36 circuits. Alternative approaches were run through the regression test with the best overall approach selected for use. It is important to use a large number of circuits for regression testing. This is because comparing algorithms based on results from just one or two circuits "tunes" the algorithm just for those circuits. The tuned algorithm might then work poorly for a general range of circuits.

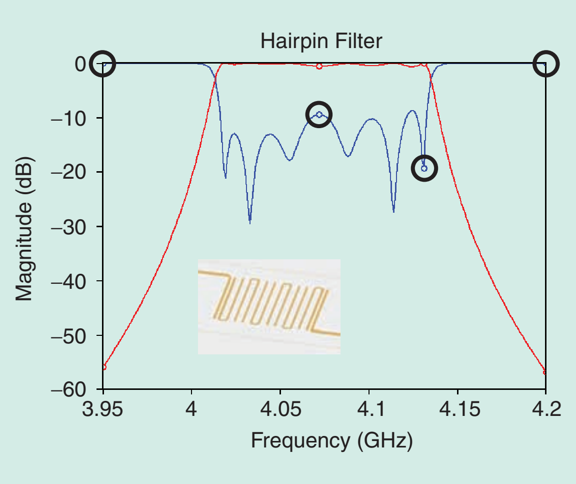

**Figure 5.** *Interpolation can take advantage of information in the moment matrix to yield a high-order model with only a few analyses. In this case, a six-resonator filter is completely characterized after analysis at only the four indicated frequencies.*

About one year was then spent defining the user interface, implementing the algorithm into our core software, testing on about 1,500 circuits and at several beta sites, and documenting the interpolation. In every single one of the 1,500 circuits, the algorithm converges to give results visually identical to an overlaid plot of a complete analysis for all S-parameters above –100 dB and occasionally down as far as –160 dB.

The software started shipping in August 2002, just over a year and half after the initial 1% flash of inspiration. Thomas Edison had it right about perspiration.

Another recent development has been an iterative matrix solution for very large matrices. A normal lower/upper (LU) decomposition time increases with the cube of $N$, the number of subsections. Iterative techniques increase with a lower power of $N$, so, in spite of their increased overhead, for some large value of $N$, such approaches are faster. In fact, extremely large matrices can be inverted that are simply impossible with today's hardware using LU decomposition.

While a number of vendors have this kind of capability, such approaches seem to have had little impact in the marketplace. I can only draw on my own limited experience with iterative matrix solve techniques, which I found (at least as I implemented them) to lack the extremely high level of robustness required for the kind of problems we like to solve. Would today's algorithms work for 100% of 1,500 randomly selected circuits? Whatever the answer, iterative matrix solve approaches do not, as yet, seem to have had much influence.

The "seamless interface" between multiple tools from a single vendor has been available from nearly all multiple-tool vendors for quite a while. A recent development has been the increasing importance of interoperability of tools from different vendors. This is especially important from the Sonnet point of view because we provide only one of the many different tools needed by a high-frequency software designer. Thus, we have developed interfaces to all major vendors. However, we have found that some vendors are willing to make it easy to interface. For others, it can be difficult. Since it is clear that no single vendor can provide a total solution, ease of interoperability in a multivendor environment, even between competitive vendors, is becoming critically important.

## Future Speculation

Crystal ball gazing is always dangerous, but I shall make an attempt anyway; if half of my predictions are true 20 years from now, I will be pleased. In that vein, my first prediction is simple: if you flip a coin right now, it will come up heads.

More seriously, computer power will continue to increase until we can invert a 100,000 × 100,000 matrix in about 1 h on a desktop computer that costs about US$2,000. (Today, we can almost do 20,000 × 20,000.)

After that, if the widespread speculation that Moore's Law will break down is true, and computer complexity stops its rapid increase, then we will see only incremental improvement…unless, of course, something other than the transistor proves to be practical.

Artificial neural networks (ANNs) and space mapping will both see continued research and have a chance of wide application if their model development and use can be made efficient and essentially transparent to the user. ANNs take data from a set of analyses (for example, a microwave structure with various geometrical parameters being varied) and, by "training" a neural network, a model of the device is developed.

Space mapping takes a few very precise but lengthy analyses of a structure and finds a mapping from the parameters of the precise analysis to the parameters of a similar but faster "coarse" analysis. The fast, coarse analysis is then quickly optimized to the desired result with space mapping, yielding the correct parameters for the precise analysis. Many designers already do this manually without realizing it. For example, a designer might notice that, by modifying the specified substrate thickness and dielectric constant, a circuit theory analysis gives the same result as a full EM analysis (this is quite common). The designer optimizes the circuit theory model quickly and then transfers the optimized dimensions into the EM analysis for a single final analysis.

As mentioned above, interoperability is becoming an important issue. I predict that it will become the dominant issue in high-frequency software in the next few years. Further, the vendor that can find a way to allow easy interoperability and make that solution open to everyone, including competitors, will find an overwhelming competitive advantage. Soon, the venerable "seamless interface" among tools of a single vendor will simply not be enough to be competitive.

The importance of educating users will increase as well. There are too many new designers who are not even sure just exactly what characteristic impedance is. These designers must be educated, both by rebuilding the remnants of our university programs and by means of post-degree training. The free versions of EM software introduced, first by Sonnet and later by Ansoft, are important steps facilitating this effort.

The quality of experimental validation will gradually increase. Researchers are slowly becoming sensitive to the fact that a plot of measured versus calculated that lacks even a suggestion of an error analysis is just so much road-kill. Even now, error bars are more often included in high-frequency research validation plots (see, for example, [13]).

Finally, the rapid proliferation of EM tools seen in the 1990s is over. There will still be occasional new introductions, but the high cost of commercializing a tool combined with the advanced state of development and entrenched market position of existing tools makes new introductions difficult.

## Conclusion

The field of electromagnetics started with Maxwell's genius. Widespread use of numerical solutions to Maxwell's equations waited for the advent of inexpensive and powerful desktop computing. Today, numerical electromagnetics is considered a necessary part of nearly all high frequency design. Multiple EM tools are required in order to efficiently solve a broad spectrum of problems. Even just within the field of planar circuits, two main tools (open and shielded environment) are needed. Since no one vendor can supply all required tools, interoperability is rapidly becoming an overwhelming issue. Maxwell would be pleased with our progress over the last 130 years.

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