DESIGN

EM Approach Sets New Speed Records

By using an enhanced interpolation method, the speed of multiple-frequency EM analyses increase while maintaining high accuracy.

Achieving ever-faster analysis speeds while maintaining accuracy has been the Holy Grail of electromagnetic (EM) software for some time. Modern EM modeling tools such as the em® software from Sonnet Software (Liverpool, NY) have enjoyed speed benefits due to the increasing performance of computers, but advances in the efficiency of EM software code have been relatively rare until now. With the release of Version 8.0 of the Sonnet Suite of EM tools, however, a one to two order-of-magnitude increase in speed has been realized for multiple-frequency analyses. The improvement in processing speed enhances a program that is already recognized as the most-accurate software available, and the fastest for a large class of planar circuits.

The gain in speed is achieved by enhancing a well-known interpolation technique.[1,2] By only analyzing a few frequencies, a detailed result over the entire frequency band can be obtained. For example, if four analyses strategically scattered over the passband of a filter are used to synthesize data at 300 frequencies, an increase in speed of 75 times is realized **(Fig. 1)**. This new approach to solving

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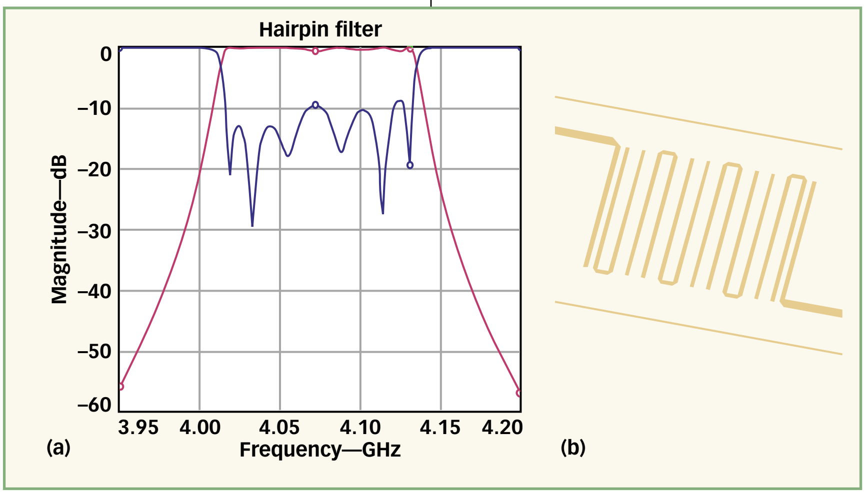


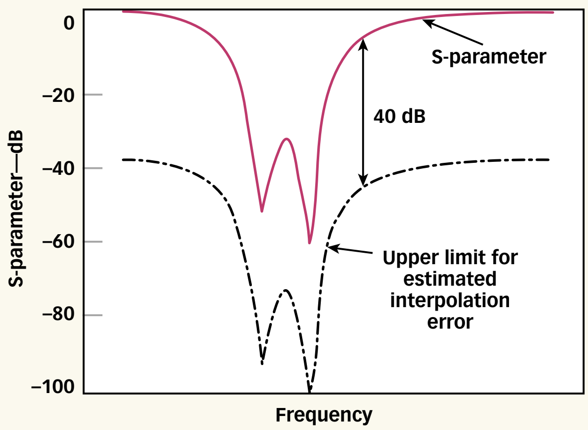
1. Sonnet ABS interpolation excels with complicated narrowband responses. This hairpin filter required only four analysis frequencies for the calculation of all 300 interpolated data points.

EM problems is known as Adaptive Band Synthesis (ABS).

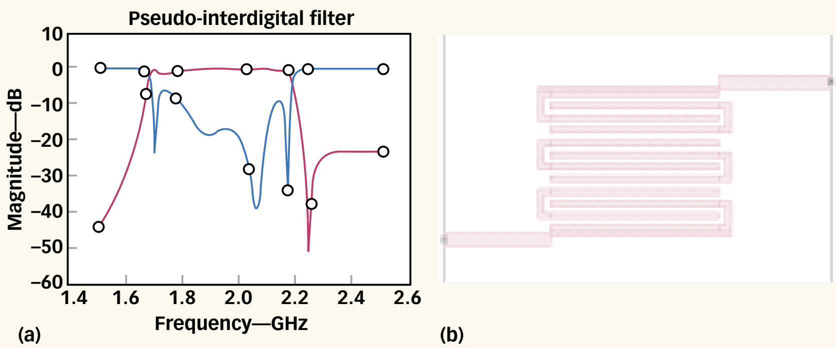
Basic interpolation techniques have been available for some time, but have not been incorporated into Sonnet's computer-aided-engineering (CAE) tools since the usual techniques do not provide the robustness and accuracy needed to meet Sonnet's quality standards. The usual approaches occasionally fail to converge (especially for large-bandwidth analyses) and inaccurate results are sometimes seen, even when convergence is thought to have occurred. But the enhanced interpolation technique that is used in Version 8.0 of the Sonnet Suite is exceptionally robust, efficient, and accurate.

The basic interpolation technique used by Sonnet is the Cauchy method. To understand how the technique works, first consider simple linear interpolation. In linear interpolation, a line drawn between two points is used to find additional points that lie between the two points. In the cubic spline approach, a cubic polynomial is used in the interpolation. The coefficients of the polynomial are set so that its curve passes through four known data points. Additional interpolated points for the cubic spline fall on the curve defined by the polynomial.

Unfortunately, a cubic spline is not quite up to the task of interpolating circuit responses. Except for narrow bands, the scattering (S)-parameters of a circuit, similar to a filter, tend not to fall on a smooth cubic spline-like curve. Rather, recalling Laplace transform theory, circuit responses fall on a curve well-represented by the ratio of two polynomials. This can work for a much wider bandwidth. Specifically, one polynomial is the numerator and a second polynomial is the denominator. The problem then becomes: provided with a set of calcu-



2. Sonnet ABS interpolation continues until the estimated error is more than 40 dB below the interpolated S-parameter at all frequencies, essentially eliminating interpolation error.



3. This specially modified hairpin filter requires a few more frequencies due to the octave bandwidth. Transmission and reflection zeros are preferentially selected.

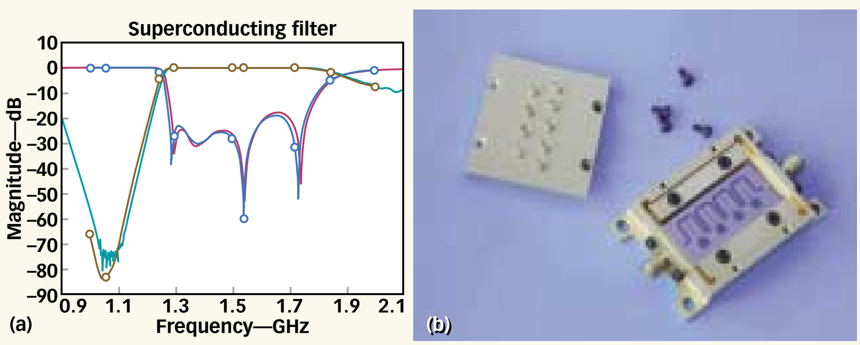
lated data, find the coefficients of the numerator and denominator polynomials so that the ratio of the two passes exactly through each data point. This ratio of polynomials is then used to interpolate the data.

The ratio of the polynomials is known as a Padé rational polynomial. A popular research area in EM studies for most of the last decade, there are several techniques for determining the polynomial coefficients of a Padé rational polynomial, and the Cauchy method is used here. There are some difficulties in using the Cauchy method (and any the other method) that must be addressed to achieve high reliability.

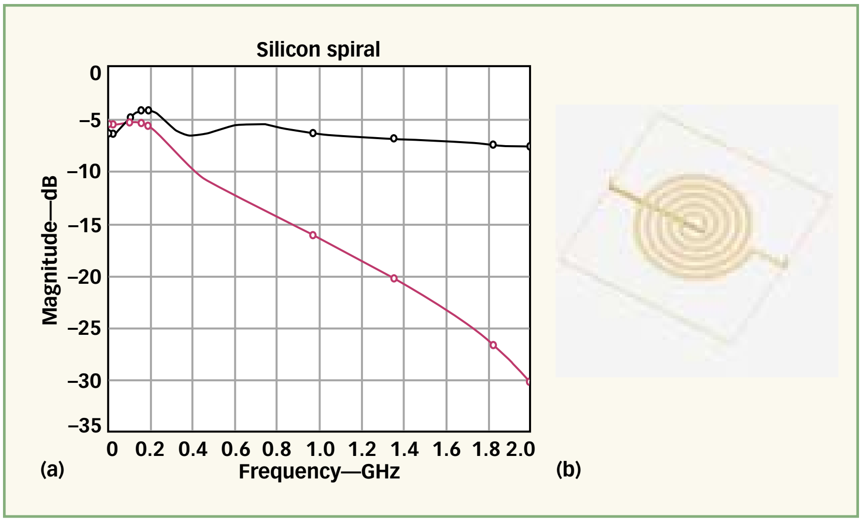
For example, the order of the numerator and denominator polynomials must be properly determined. Additionally, the calculation of the polynomial coefficients requires the inversion of a matrix with elements involving frequency raised to the Nth power. For example, if there are 20 data points, N might be as high as 20. Numbers this large can easily cause numerical-precision problems during matrix inversion.

It is important to have some way to determine the quality of the resulting interpolation. There are several ways to estimate interpolation error. The estimated interpolation error is then used to determine if the analysis has converged and, if not, what frequency is most advantageously analyzed next. Provision must be made for the fact that this estimate of interpolation error may, itself, be off by a considerable amount.

Finally, it should be remembered that distributed circuits are being analyzed, rather than the lumped circuits that have always been analyzed with the Laplace transform. Since certain planar circuits can only be presented over a narrow band by the Padé rational polynomial, there can be a failure to converge in some cases.



4. A superconducting filter provides the best agreement between measured and calculated data of four different EM tools sampled by the designer.



5. For this spiral inductor on Si, ABS interpolation goes to very low frequencies.

The way Sonnet improves the ability of the Padé polynomial to represent a distributed circuit is by taking advantage of information internal to the method-of-moments (MoM) matrix that is used by the Sonnet EM analysis. This matrix consists of the EM coupling between all subsections in a circuit. Certain select aspects of this matrix are then extracted, allowing a more sophisticated polynomial model to be adaptively synthesized.

This approach supports a large increase in robustness combined with a decrease in the number of frequencies that must otherwise be analyzed. Typically, narrowband results can be obtained with one-half to one-quarter the number of analysis frequencies. Wideband results usually require seven to 15 data points, compared to alternate techniques which often fail to converge at all. The Padé polynomial is still not perfect for representing distributed circuits, but the Sonnet ABS approach does speed the analysis of filters and many other structures.

Part of the information extracted from the MoM matrix is the approximate frequency of transmission and reflection zeros (i.e., frequencies at which the S-parameters go to zero). It has been found that giving priority to analysis at these frequencies results in a significant reduction in the number of required analysis frequencies.

For example, returning to Fig. 1, small circles indicate frequencies that have actually been analyzed. The entire filter response was calculated from analysis at only four frequencies. Both ends of the passband were analyzed first. The interpolation then decides that the best frequency for the next analysis is in the middle of the band. With the information extracted from the moment matrix at only these three frequencies, ABS preferentially places the last analysis exactly on the highest-frequency S11 zero. With these four data points, the estimated interpolation error is now low enough and the algorithm terminates. Full calculation over the entire range yields visually identical results.

The estimation of interpolation error is critical. This is often accomplished by comparing the results of two similar but distinct interpolations, perhaps one with five data points, and a second with six data points. The difference between the two tends to approximate the interpolation error. After running experiments on a large number of circuits, it was found that the actual interpolation error must be at least 20 dB below the magnitude of the S-parameter being interpolated for a plot of the interpolated data to exactly overlay a plot of the actual data visually. In addition, it was found that even the best estimate of error (from comparing two different interpolations) could be off by up to an additional 20 dB. Thus, to be assured of good results, the estimated error must be at least 40 dB below the magnitude of the S-parameter that is being estimated.

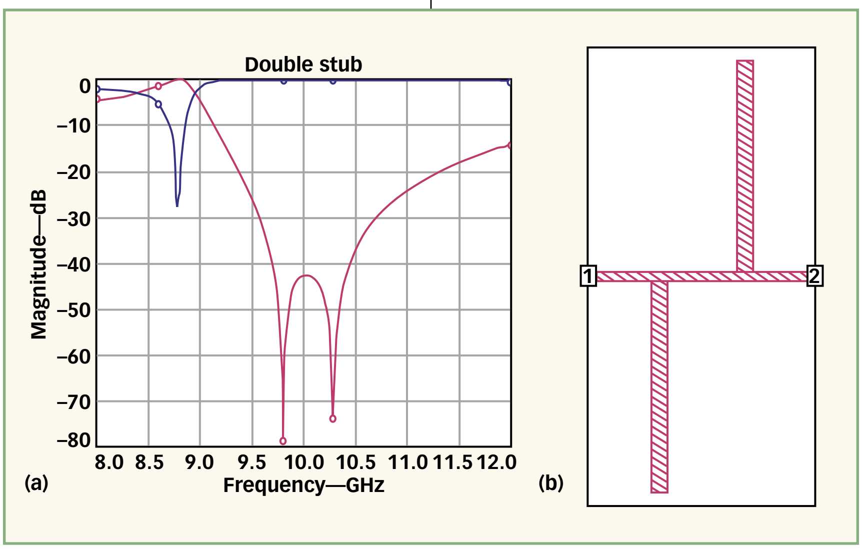
Figure 2 shows this approach to evaluation of interpolation error. If the interpolated S-parameter is, for example, −60 dB, then the estimated error must be less than −100 dB or the interpolation is not considered converged. When all estimated error is more than 40 dB below the interpolated S-parameters at every frequency, then the interpolation terminates. Since Sonnet uses a Fast Fourier Transform (FFT), and the moment matrix is calculated to full precision, achieving estimated error as low as −140 dB is reasonable. This yields a usable noise floor of approximately −100 dB on interpolated S-parameters.

In contrast, previous techniques might set a uniform limit for estimated interpolation error regardless of how big or small the value of the S-parameter. For example, if a uniform limit of −60 dB is set for the estimated error, the actual error could be up to −40 dB. This means that S-parameters below −20 dB might start to have noticeable interpolation error. Thus, such an interpolation approach has only a −20 dB assured noise floor, often an unacceptable situation. Returning to Fig. 1 once more, note that a −20-dB noise floor could significantly compromise the result. The actual −100-dB noise floor assures a robust result.

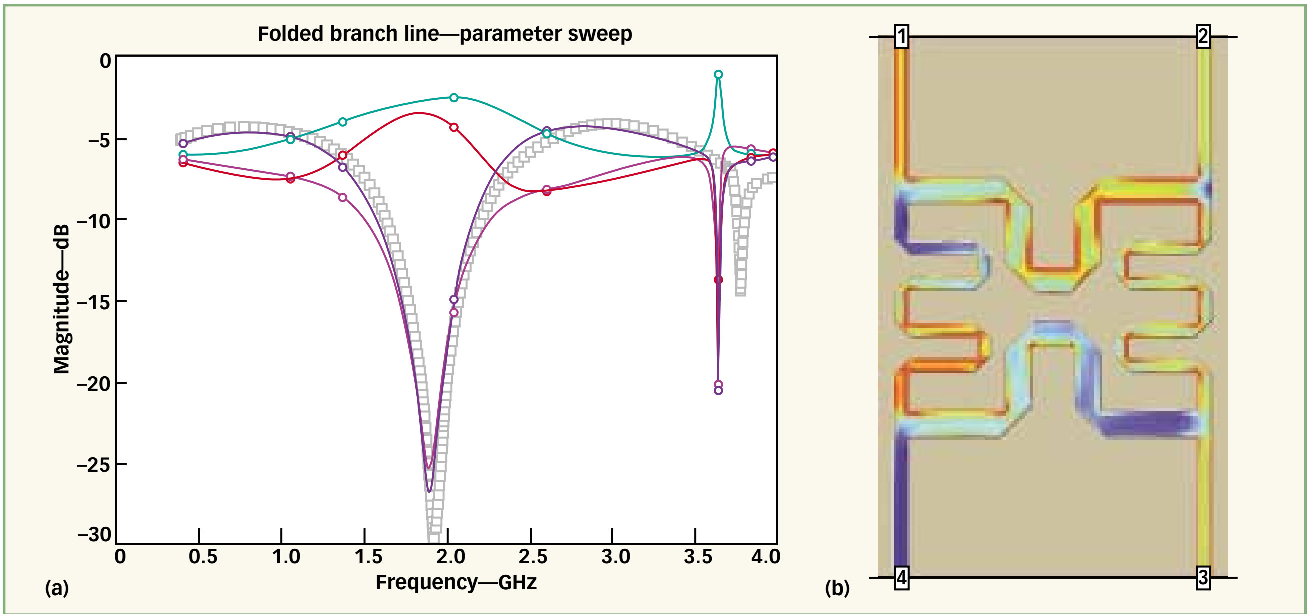
The Sonnet ABS interpolation begins with two analyses, one at each end of the band of interest. Then, a preliminary interpolation is attempted and the frequency with maximum estimated interpolation error is determined. If the estimated error is 40 dB or more below the S-parameter magnitude at each frequency, the analysis terminates. Otherwise, the worst interpolated frequency is selected for analysis and the procedure continues. Even after applying this approach to more than 150 trial circuits, no failures have been found. Robustness is a very important goal, and it appears inherent in the ABS technique.

Figure 3 shows a special kind of hairpin filter similar to that described in refs. 3 and 4, with nonstandard positioning of each resonator. This positioning introduces coupling between nonadjacent resonators, which can cause transmission zeros. Properly positioned, in this case just above the passband, such transmission zeros can significantly increase the filter skirt steepness and reduce in-band group-delay variation. Provided with a second zero below the passband, an "elliptical" filter response would result.

In this case, Sonnet ABS requires

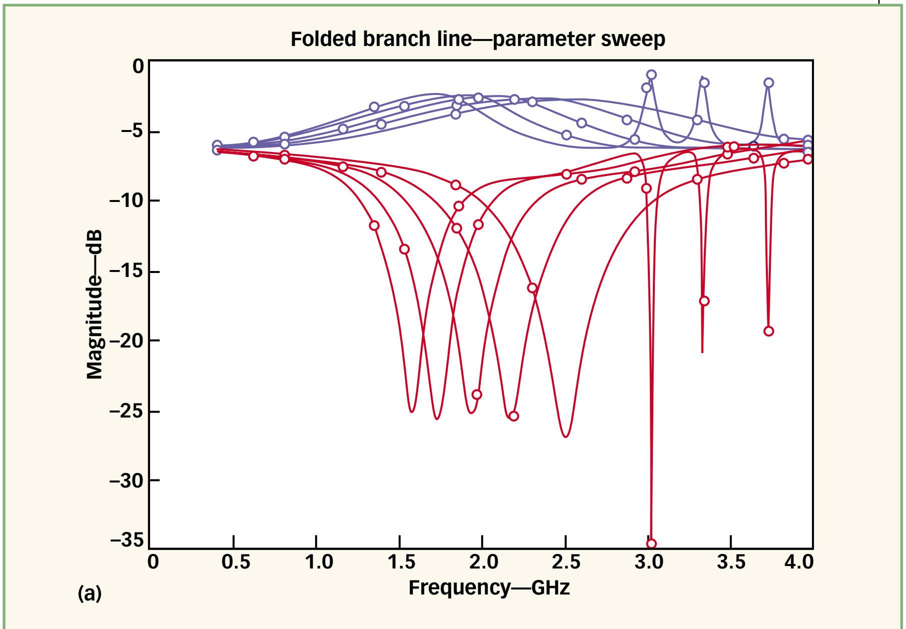


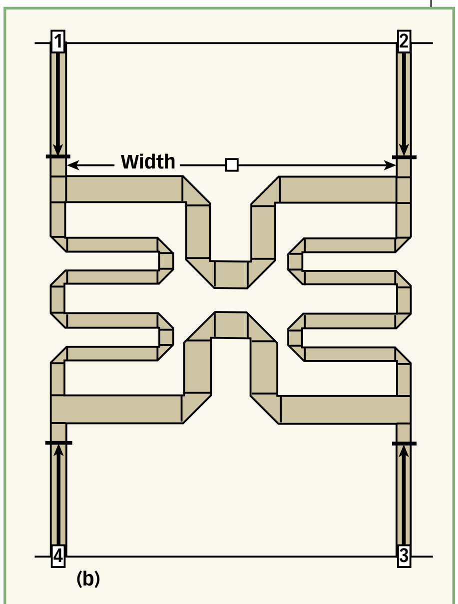
6. The classic double-stub benchmark (b) introduced by Texas Instruments/Raytheon around 1989 has a double transmission zero due to coupling between identical stubs (a). The two end frequencies and one frequency at each of the three zeros are all that is required to interpolate the entire frequency response.



seven analysis frequencies. In addition to the first and last frequencies, five frequencies are scattered through the passband, each getting closer to filter zeros as the interpolation successively extracts better information about the zeros. The reason more data is needed, as compared with the previous filter, is that this analysis covers a one-octave (factor of two) bandwidth. The analysis in Fig. 1 covers slightly less than a 10-percent bandwidth. As is true for ABS and all the other

7. The folded branch-line coupler requires only eight frequency points to cover a decade bandwidth. The first four S-parameters are shown along with the worst-case measured data (for S11).





8. The width (distance between two input ports) has been parameterized and swept over five values (a), with the widest case shown in (b). Each case required only seven or eight analysis.

techniques, larger bandwidths require more data points.

Figure 4 shows a superconducting filter designed to remove clutter in a radio astronomy application. Nine data points were required for the analysis of the filter's passband. Constraints in budget and time limited the designers to only one fabrication, so first-pass success was a critical design requirement. This filter was analyzed using four different EM CAD tools. Sonnet, with an analysis time of 5 min. per frequency was the fastest and also provided data closest to the measured results (also plotted in Fig. 4).

For this filter, Sonnet's 5-min. analysis time was achieved by a relatively new user. In the hands of an expert Sonnet user, analysis time was reduced to 30 s/frequency (having a faster computer also helped). As an indication of the cell size used, the narrow vertical lines are subsectioned six cells across.

Figure 5 shows a spiral inductor on a silicon (Si) substrate. Sonnet typically shows exceptional accuracy when analyzing this kind of inductor. Due to use of the FFT (which provides the accuracy), circular spirals such as the one in Fig. 5 take several minutes per frequency for analysis. In comparison, equivalent square spirals can be analyzed in only seconds. In this case, analysis at nine frequencies provides enough information for the 300 data points plotted. The approach sometimes tends to cluster data points at low frequencies. If the bottom 10 percent of the frequency range is not needed, however, the number of data points could be cut in half.

Figure 6 shows a classic microstrip double stub. This circuit was one of the first benchmarks used to validate Sonnet in 1989. Generated by Texas Instruments/Raytheon, the two identical stubs couple enough to produce two deep transmission zeros. With the very small cell size used in Fig. 6 (the stubs are subsectioned eight cells across) this problem was too large for 1989 technology and hardware (the validation was completed by switching to a larger cell size). Today, this analysis requires 1 s/frequency.

Figure 7 shows the first four S-parameters of a folded branch-line coupler. The measured data, which shows the worst agreement with calculated data (S11), is also plotted. The ABS approach required analysis at only eight frequencies, generating 300 data points and covering an entire decade of bandwidth. The narrowest lines are 20 cells wide.

Sonnet can also automatically sweep parameters and optimize. **Figure 8** shows the result of sweeping the width (distance between the two input ports) of the folded branch-line over five values. The widest case is shown in Fig. 8(b). With Sonnet ABS, only seven or eight data points are needed for each case. A total of 38 frequencies were analyzed, providing 300 frequency data points for each of five coupler widths.

The ABS technology is available this summer in the company's Sonnet Suite of EM tools, as well as in the free SonnetLite package (available at www.sonnetusa.com starting June 3). Sonnet and ABS are both trademarks of Sonnet Software, Inc. MRF

ACKNOWLEDGMENTS

The author gratefully acknowledges the Max-Planck-Institute fur Radioastronomie for the design and measurement of the superconducting radio-astronomy filter. The author also gratefully acknowledges John Sevic for the design and measurement of the folded branch-line coupler.

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