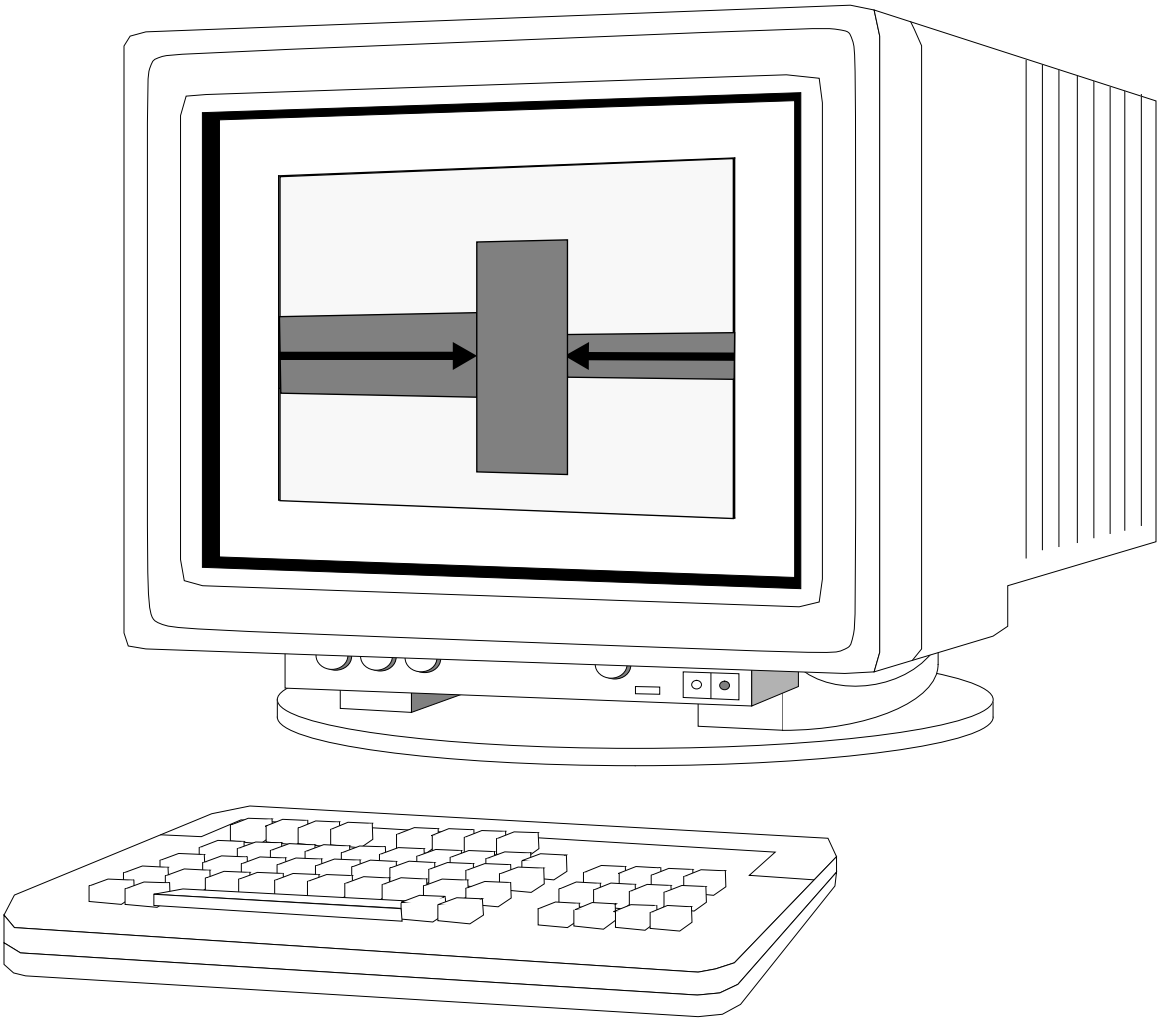
Em User's Manual



Em User's Manual

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Chapter 1 Introduction

Em is an electromagnetic analysis which calculates S-parameters for arbitrary predominantly planar (e.g., microstrip, coplanar, etc.) geometries. ***Em*** maintains full accuracy at all microwave frequencies. ***Em*** is a "full-wave" analysis in that it takes into account all possible coupling mechanisms. The analysis inherently includes dispersion, stray coupling, discontinuities, surface waves, moding, metallization loss, dielectric loss, radiation loss; in short, it is a complete electromagnetic analysis. Since ***em*** uses a surface meshing technique (it meshes only the surface of the circuit metallization), ***em*** can analyze predominately planar circuits much faster than volume meshing techniques.

Em is also a full three dimensional analysis in that both 3-D fields and 3-D currents are included in the analysis. ***Em*** analyzes such 3-D structures embedded in planar multilayered dielectric, thus ***em*** is optimized for "predominately planar" circuits. For this class of circuits, ***em*** can use the FFT (Fast Fourier Transform) to efficiently calculate the electromagnetic coupling on each dielectric surface. This is what provides ***em*** with its several orders of magnitude of speed increase over volume meshing techniques.

Em performs an electromagnetic analysis of a microstrip circuit (see Figure 1) by solving for the current distribution in the microstrip metallization using the Method of Moments.

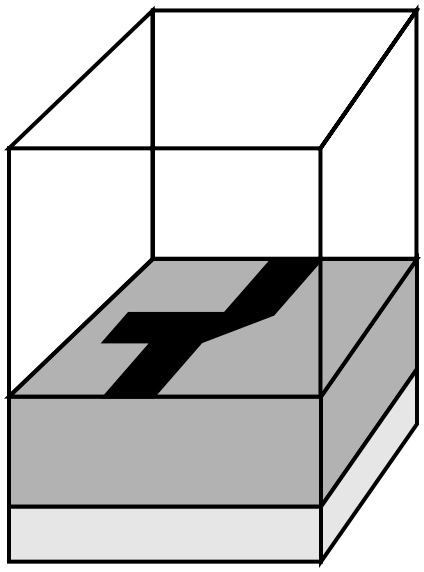

Figure 1 ***Em*** analyzes microstrip structures inside a shielding box. Port connections are made at the box sidewalls.

♦ What Can *Em* Do?

As we mentioned, ***em*** is an analysis of arbitrary 3-D structures embedded in planar dielectrics. While ***em*** is optimized for predominately planar structures, vias (to ground and between layers) are allowed, providing the third dimension. The via capability allows analysis of air bridges, wire bonds, spiral inductors, wafer probes and internal ports as well as the more usual ground vias.

It is appropriate to use ***em*** for:

- Evaluation of specific discontinuities or groups of interacting discontinuities to assist in the design of a microstrip circuit. ***Em*** provides ultra-precise S-parameters for microstrip discontinuities allowing designers to work with confidence.
- Design validation. This effectively eliminates expensive design iterations (i.e., “tweak”, refabricate, etc.) of the passive, planar portion of a circuit. At present, because ***em*** makes no compromise in accuracy, performing an

analysis of, say, an entire amplifier with a single electromagnetic analysis on a mid-range workstation is probably not feasible. However, validation of large portions of an amplifier design is reasonable. If a circuit is designed from the start with electromagnetic analysis in mind, much larger circuits can be done (the analysis works best with tightly packed, rectangular circuits).

- Microwave package evaluation. What happens when the lid goes on? ***Em*** analyzes a circuit inside a conducting box. If the box (acting as a dielectric loaded resonator) is resonant at a frequency where the circuits still have gain, bad things happen. ***Em***, under the assumption of uniform dielectric within each layer of dielectric, provides an analysis of a package prior to fabrication. Resonances can then be dealt with on the computer rather than in a machine shop.
- Certain microstrip antennas. The "top" of ***em***'s box can be effectively removed by setting the cover resistivity to 377 ohms/square. While radiation is outside of ***em***'s primary thrust, a wide variety of microstrip antennas and radiating discontinuities can be evaluated.

Em is not appropriate for doing an initial design. Rather, the faster circuit theory simulators (which do not include stray coupling) should be used for the first cut. ***Em*** can then enhance the simulator performance by providing custom, ultra-precise discontinuity data and for validating large portions of the final circuit, including all stray interactions. Consistent with our philosophy at Sonnet Software, ***em*** is designed to work with your existing CAE software, enhancing your capability, in a "win-win" relationship.

Em does not yet include graphical presentation of S-parameters. Since the output data is in Touchstone or Compact (at your discretion), you can use the S-parameter plotting capability of whatever microwave CAE tool you are already familiar with.

♦ Software Un-Limits

Another part of our philosophy at Sonnet Software is to develop software which does not artificially restrict creative abilities, that is, software which knows no limits.

For example, ***em*** can handle any number of ports, any number of layers, any number of subsections, any number of frequencies and over any frequency range. The list of limitless parameters is, itself, almost limitless. Such software is more difficult to develop, but it is worth it, because it sets you free to explore with your creativity unrestricted by any arbitrary, programmer specified limits.

Em is limited only by the hardware on which it is running. If you need better performance, just get a faster computer or more memory. The full version of ***em***, itself, will never limit you to, for example, “No More Than 4 ports”. (Note: The demo version of ***em*** is limited by the password file to circuits with less than 120 subsections.)

♦ Where Did *Em* Come From?

The technique used in ***em*** was developed at Syracuse University in 1986 by Rautio and Harrington [1]. It was originally developed as an extension of an analysis of planar waveguide probes [2]. The technique expresses the fields inside the box as a sum of waveguide modes and is thus closely related to the spectral domain approach. A full bibliography of relevant papers is presented at the end of this chapter.

♦ The *Em* User

The ***em*** user should have a good working knowledge of microwave design. In order to make use of ***em***’s results, access to a microwave circuit theory based analysis program is desirable. The user should also have at least some familiarity with computers including a minimal working knowledge of a text editor (which can be acquired in 15 minutes, Appendix V, "A Very Brief Introduction to Vi").

In the next section, a brief outline of ***em***’s theory provides background for using ***em***. A description of the environment expected by ***em*** follows. Then we dive into a series of examples illustrating ***em***’s capabilities. A detailed reference for ***em***’s command line and file formats provides the appendices.

♦ Enhancements since Release 2.1

Release 2.1 provided speed enhancement. This release provides functionality enhancements. The enhancements are a direct result of suggestions our customers have taken the time to make. We thank you for doing so. We didn’t have a chance to implement all suggestions, but you may recognize one or more of your suggestions in the following list.

For example, arbitrary cross-section transmission lines (with thickness) are now easily analyzed. In addition, ***em*** can use “push-pull” ports, useful for coplanar and slot line transmission line structures.

A new subsectioning algorithm has been developed which allows the user more control, for example, using large subsections on large polygons and small subsections on fine structures. In addition, all restrictions on placement of polygon edges for proper via connection have been removed.

A subtle effect associated with skin effect has now been included. It is well known in electromagnetics that the surface impedance of a conductor has a real part equal to the imaginary part when in the skin effect region. Only the real part was included prior to release 2.2. With this release, we now include both real and imaginary parts automatically. You need take no further action after having input the skin effect coefficient (R_{RF}). Differences in results are slight but noticeable. To the best of our knowledge, this is the first time both real and imaginary parts of the surface impedance have been included in any commercial program, whether based on circuit theory or on electromagnetics. As before, additional reactive surface impedance may be included to simulate super conducting kinetic inductance, for example.

Em now includes a box resonance mode detector and/or remover. If box modes are a problem, you can find out by invoking the "-b" option. To remove the box modes, use the "-B" option.

When ***em*** is started with the verbose ("-v") option, a rough estimate of the amount of memory required will be printed out (in Mbytes, 1 Mbyte is the minimum number which will print out, even if much less is used). If you run into memory limitations, don't forget the memory saver option ("-m"), which kicks the calculations over into single precision, cutting memory requirements by almost half. Most work requires no more than 8 Mbytes, however if you start pushing the limits (up to about 2,000 subsections), as much as 32 Mbytes can be useful.

Em is now compatible with release 3.0 of Touchstone which allows more than four ports. You will notice that the format of the output from ***em*** for more than four ports has been changed slightly to remain compatible with Touchstone.

Em has never limited you on the number of ports in your circuit.

With an eye to the future, this release of ***em*** also includes output of a ".jxy" file which contains all the current distribution information. This data will be used to allow viewing of the current distribution.

♦ References

[1] J. C. Rautio and R. F. Harrington, "An Electromagnetic Time-Harmonic Analysis of Shielded Microstrip Circuits", IEEE MTT Transactions, Aug. 1987, Vol. MTT-35, No. 8, pp. 726-730.

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[13] J. C. Rautio, “A Time-Harmonic Electromagnetic Analysis of Shielded Microstrip Circuits,” Ph. D. Dissertation, Syracuse University, Syracuse, NY, 1986.

[14] J. C. Rautio, “Preliminary Results of a Time-Harmonic Electromagnetic Analysis of Shielded Microstrip Circuits,” ARFTG Conference Digest, Baltimore, pp. 121-134, June 1986. (Voted best paper at the conference.)

[15] J. C. Rautio, “Techniques for Correcting Scattering Parameter Data of an Imperfectly Terminated Multiport When Measured with a Two-Port Network Analyzer,” IEEE Trans. Microwave Theory Tech., Vol. MTT-31, pp. 407-412, May 1983.

Chapter 2 A Simple Outline of the Theory

Another part of the Sonnet Software philosophy is to inform, rather than merely impress. There has been much written (especially in electromagnetics) with the primary intent of impressing the reader, while conveying minimal useful information. We feel that such "content free" text has no place in engineering. Thus, we present a description of ***em***'s theory with the intent to inform. A full set of references is at the end of Chapter 1.

♦ Subsectioning the Circuit

The analysis starts by subdividing the microstrip metallization into small rectangular subsections. ***Em*** then evaluates the electric field everywhere due to the current in a single subsection. In an actual subsectioning, see Figure 2, small subsections are used where needed and larger subsections where the analysis does not need small subsections. Triangular subsections can be used to fill in the diagonal "staircase", at the user's discretion.

Next, ***em*** repeats the calculation for every subsection in the circuit, one at a time. In so doing, ***em*** effectively calculates the "coupling" between each possible pair of subsections in the circuit.

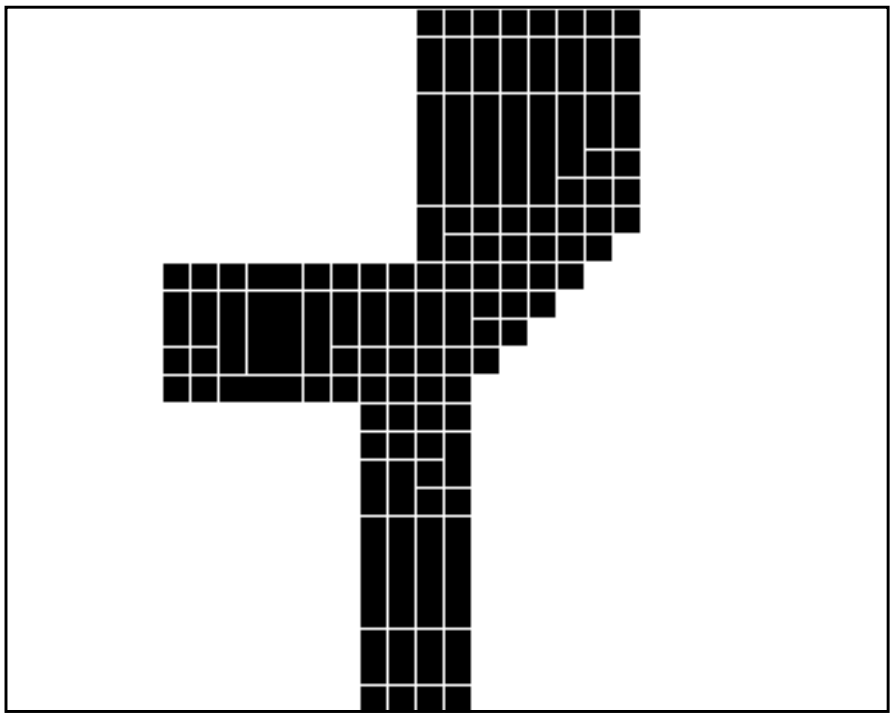


Figure 2 ***Em*** calculates the tangential electric field on all subsections, given current on one subsection. This figure shows the actual subsectioning for an example circuit.

♦ Voltage Across a Conductor is Zero

Each subsection generates electric field everywhere on the surface of the substrate, but we know that the total tangential electric field must be zero on the surface of any conductor (this is the boundary condition, no voltage allowed across a perfect conductor).

The problem is solved by assuming current on all subsections simultaneously. ***Em*** adjusts these currents so that the total tangential electric field (i.e., the sum of all the individual electric fields just calculated) goes to zero everywhere that there is conductor. The currents that do this form the current distribution on the metallization. Once we have the currents, the S-parameters (or Y, or Z, etc.) follow immediately.

If there is metallization loss, we modify the boundary condition. Rather than zero tangential electric field (zero voltage), we make the tangential electric field (the voltage on each subsection) proportional to the current in the subsection. The constant of proportionality is the metallization surface resistivity (in ohms/square). Sound familiar? It's Ohm's Law!

♦ An Alternate Description

We hope our intent to inform has been successful. In contrast, if our intent had been only to impress, the analysis would have been described in the following "content free" format:

> *This analytical full-wave numerical approach invokes a Galerkin method of moments technique which develops the dyadic Green's function operator as a bi-dimensional infinite vectorial summation of homogeneous rectangular waveguide eigenfunctions resulting in a subsectional technique using roof-top expansion and testing functions closely related to spectral domain techniques.*

Both descriptions, by the way, are accurate.

Chapter 3 The Environment Expected by *Em*

If ***em*** has not yet been installed on your system, refer to the **Sonnet Installation Manual** for installation information.

Em is computation and memory intensive. As much real memory as possible is recommended. If more real memory is required than is installed, the program starts swapping out to disk, increasing execution time substantially. We recommend a minimum of 8 Mbytes, up to 32 Mbytes (and occasionally even more) can be useful

There are no special display or peripheral requirements. Unlike ***xgeom***, the X Window System is not required.

♦ The Input and Output Files

Em does four things:

- Reads an ASCII ".geo" file describing the circuit.
- Reads an ASCII ".an" file specifying the analysis frequencies.
- Number crunches.
- Outputs an ASCII ".rsp" file with the S-parameters of the circuit.

There are three files associated with ***em***: a file which controls the analysis (default name “ctl.an”), a file which specifies the circuit geometry (from ***xgeom***, default name “cir.geo”), and a circuit response file (default name “cir.rsp”). The default file names are used if there is no file name with the appropriate extension (the characters following the period in the file name) in the command line.

The analysis control file determines the frequencies for analysis. Its other uses are detailed in Appendix II, "The Analysis Control File Format". An example file is given in the next section. If a name other than “ctl.an” is selected, a name ending with “.an” is recommended.

The circuit geometry file is generated with a geometry capture program such as ***xgeom***. It specifies the size of the box containing the circuit, the number of layers and the dielectric constant of each layer as well as a polygonal description of the metallization outline. The format of the file is specified in Appendix III, "The Circuit Geometry File Format". Experienced users may wish to make minor changes directly to the file rather than going through the geometry capture program. A geometry file name ending with “.geo” is recommended.

The format of the geometry file is simple. In fact several users have written simple programs to convert output from their favorite CAD program (for example, AutoCad) into .geo format. ***Xgeom*** will presently take output in GDSII format or from Cadence.

The circuit response file format can be selected on the command line for compatibility with popular microwave circuit analysis programs. The circuit response file contains automatically generated comment lines as well as copies of any comment lines in the analysis control and geometry files. A file name ending with “.rsp” is recommended.

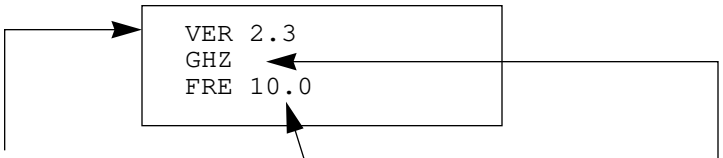
Chapter 4 The First Example -- Cascaded Steps

The circuit for the first example is described in the ***Xgeom* User's Manual**, starting in section "Specifying Box Parameters" on page 13 and ending with section "Saving the Circuit on Disk" on page 33. If you followed the tutorial example there, the circuit should now be stored in the file "steps.geo". If not, use the file "$SONNET_DIR/examples/steps.geo" in its place.

♦ Creating the Analysis Control File

Before doing an analysis, we create an analysis control file. Edit a new file named "ctl.an". If you are not familiar with an editor, we recommend the vi editor, it takes about 15 minutes to learn the four or five commands needed for this example as de-

scribed in Appendix V, "A Very Brief Introduction to Vi". Enter the following text (be sure to use upper case!). The Vi editor is not the world's best editor, however, it is very functional, and you will find it on *every* UNIX computer you ever use.



The first line is the ***em*** version number. It is not needed now, but we strongly recommend including it for compatibility with future versions.

The second line indicates the units for frequency. The only other choice is "MHZ" which is the default. Switching between MHZ and GHZ is permitted at any point in the file.

The third line indicates that we will do the analysis at 10 GHz only. A line like

```
FRE 1 10 2
```

starts the analysis at 1 GHz and ends it at 10 GHz with a step of 2 GHz. You can enter in as many FRE lines as you like in any order.

Other than the amount of time you are willing to wait for an analysis to complete, there is no limit on the number of frequencies.

The ctl.an file and the steps.geo file are used for the example runs of ***em*** in this section.

♦ Baseline Run of Steps.geo

To run ***em*** for the first example, type:

time em -v steps.geo

and press return.

The steps.geo file, as displayed by ***xgeom***, is shown in Figure 3. The "time" command is optional. When included, execution time is output after the program finishes executing.

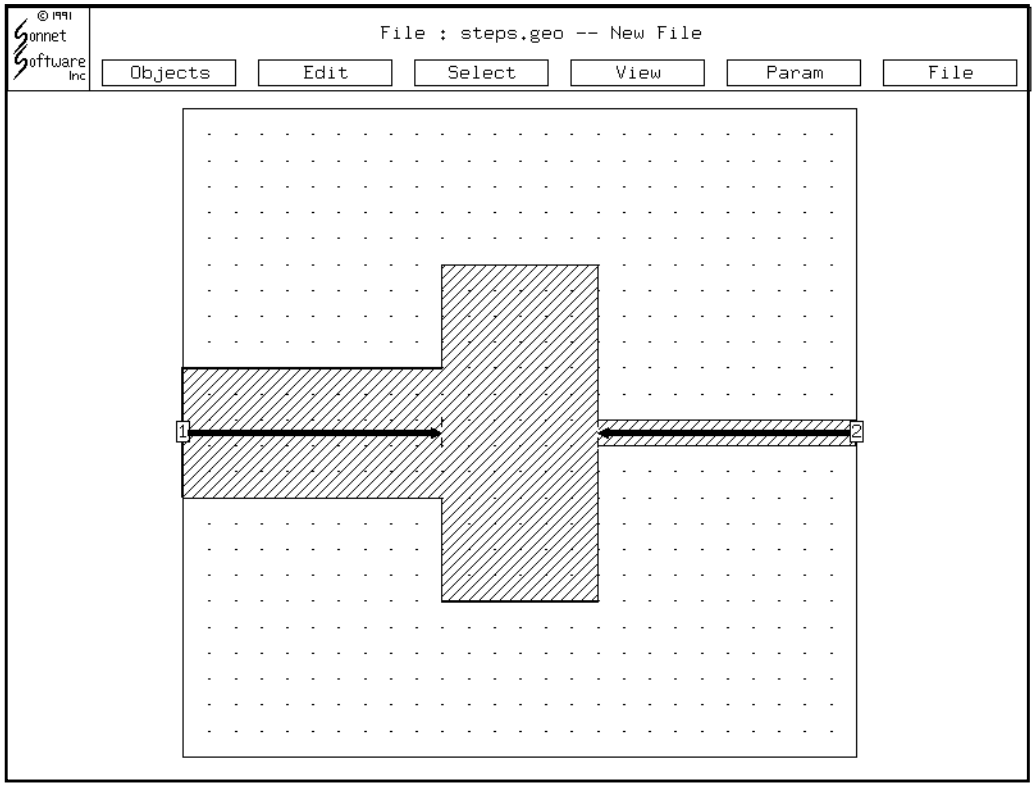


Figure 3 Our first example, in the file "steps.geo", is a cascade of two steps. The arrows indicate reference planes. Reference planes are ignored until de-embedding is used in a subsequent chapter.

If you did not create the ctl.an file, ***em*** asks for a start, stop and step frequency in MHz. Unlike using an analysis control file, all three numbers must be given, they must be in MHz and only one set of start, stop and step frequencies may be specified.

♦ *Em*'s Output to the Screen

The "-v" (verbose mode) in the command line causes the program to print out its status as the analysis proceeds, as shown below:

```
Circuit geometry file -- steps.geo --
Analysis control file -- ctl.an --
Circuit response file -- cir.rsp --


                    A TIME-HARMONIC ELECTROMAGNETIC ANALYSIS
                        OF SHIELDED MICROSTRIP CIRCUITS

                                    Version 2.3

               (C) Copyright 1987,1989,1991 Sonnet Software, Inc.
                                All rights reserved.


Circuit uses 100 subsections, 1 Mbyte.
Analyzing 10.000000 GHz.
 Loading matrix, source level 0, field level 0.
 Reducing matrix.

       2.8 real         1.7 user         0.2 sys
```

The first three lines indicate the files which are being used for the analysis. For example, the circuit response file is "cir.rsp". This is the default file name and it contains the S-parameters of the "steps.geo" file at the frequencies specified by "ctl.an". The "cir.rsp" file may be used just like measured data in the usual microwave circuit theory programs.

The file information is followed by the title page. At this point, you may notice a slight pause. ***Em*** is now subsectioning the circuit. Large circuits can take several minutes to complete subsectioning.

When finished subsectioning, ***em*** prints out the number of subsections required for the circuit given the cell size specified in ***xgeom***. This gives a good indication of how long the analysis will take. As you do different circuits, you will get a good feel for what is

a reasonable number and what is not. On a Sun SPARCstation 2, the above example of about a hundred subsections is fast. A circuit of 2,000 subsections will likely require several hours per frequency and 4,000 subsections would be totally out of the question. This line also indicates that 1 Mbyte of memory is estimated to be required.The estimate of memory required is usually within 1 Mbyte of that actually used. (Actually the estimate given is the amount of memory needed for the matrix that em builds to solve the circuit.)

When finished with the automatic subsectioning, ***em*** displays the first frequency of analysis and then starts the analysis. At this time, ***em*** is setting parameters for the analysis.

When complete, ***em*** states that it is loading the matrix. This is where ***em*** calculates the electric field generated by current in each subsection. For this circuit there is only one metallization level, level 0. ***Em*** calculates the electric field induced in level 0 which is due to current in each level 0 subsection. With more levels, each level-to-level coupling is calculated separately.

The final line of ***em*** output indicates that it is reducing the matrix. ***Em*** is now effectively adjusting the current in each subsection for zero tangential electric field on all metallization. Matrix reduction is about one half of a matrix inversion. A custom LU decomposition algorithm (which takes advantage of the special characteristics of our problem) is used.

The last line of the output is due to the “time” command we used. Of the three times given in our example, the middle one, “user”, is of interest, showing the execution time (in seconds) required by ***em***. If you were running Csh, your output might look more like this:

```
1.6u 0.1s 0:01 99% 0+676k 2+1io 0pf+0w
```

In this case, the first time (“u”) is the one of interest. This time is compared with the remaining runs in this section. The examples in this manual were run on a Sun SPARCstation 2 with 32 Mbytes of main memory. Since this problem required only 1 Mbyte, an 8 Mbyte SPARCstation would have generated the same statistics. You can expect your timings to be different from those given here.

Note that the System Time (“sys”, or “s”) is very small. If this time is large, it suggests that there is a great deal of swapping going on because ***em*** requires more memory than the machine has. When this happens, check to see if the computer has a window system running or if there are other users on the computer. If not, then your circuit is probably too large. See Chapter 5, "Tricks to Get a Faster Analysis".

♦ The Circuit Response File

When complete, the output is stored in the file “cir.rsp”:

```
! ************************************************
! em -v steps.geo  -- Wed Oct 11 09:23:53 1991
! Em version 2.3
! License id sonnet.101
! Last time steps.geo was updated - Mon Oct 7 15:40:41 1991
! Example of 1) two cascaded steps, or
! 2) a cross junction and two short stubs.
! With em, there is no need to decide which way to model it.
! At least 20 subsections/wavelength.
! All dimensions are in mils.
!   A = 260.000000(26), B = 250.000000(25), C = 1025.000000, with 2 layers.
!   Layer  H( mils)      Erel    tan(d)     Murel    tan(d)  subs
!     0    1000.000  1.000000       0.0  1.000000       0.0  100
!     1    25.00000  9.800000       0.0  1.000000       0.0  0
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
# GHZ S MA
10.0000000 0.7715488 -4.288 0.698625 92.401 0.698625 92.401 0.715488 9.0911
```

An easy way to view the file is by using the Unix “cat” command (concatenate). Type:

cat cir .rsp

If you only want the end of the file listed out, Type:

tail cir .rsp

If you want to list, say, the last 24 lines of a file, type:

tail -24 cir .rsp

The first automatically generated comment in the file (see below) contains the command line that was typed to start the run and the time and date that the run started.

```
! em -v steps.geo  -- Wed Oct 11 09:23:53 1991
```

The next two lines specify the version of ***em*** used, the license identification and the last time the steps.geo file was updated.

```
! Em version 2.3
! License id sonnet.101
! Last time steps.geo was updated - Mon Oct 7 15:40:41 1991
```

The next three lines are user provided comments entered when ***xgeom*** saved the "steps.geo" file to disk.

```
! Example of 1) two cascaded steps, or
! 2) a cross junction and two short stubs.
! With em, there is no need to decide which way to model it.
```

The next line (see below) informs us that the maximum subsection size provides at least 20 subsections per wavelength. Not only does ***em*** automatically subsection the circuit for you, the subsectioning algorithm divides the circuit into variable sized subsections. Small subsections are used where needed with larger subsections filling less critical areas. The upper limit on subsection size was set in ***xgeom*** and is repeated here for future reference.

```
! At least 20 subsections/wavelength.
```

The length units in use (mils) is then displayed, followed by box dimensions. The A dimension (260 mils) is along the X-axis (horizontal in the ***xgeom*** display) and the B dimension (250 mils) is along the Y axis (vertical in the ***xgeom*** display). The A dimension is divided into 26 cells while the B dimension is divided into 25 cells as is also indicated on the line. The C dimension is the height of the box, the sum of the thicknesses of each dielectric layer in the box.

```
! All dimensions are in mils.
!   A = 260.000000(26), B = 250.000000(25), C = 1025.000000, with 2 layers.
```

Following the box dimensions is one line for each dielectric layer in the box. The parameters of each layer are listed in labeled columns. At the end of each line (except the last) the number of subsections generated by ***em*** is listed for the metallization located between that dielectric layer and the next lower layer.

```
!   Layer  H( mils)      Erel    tan(d)     Murel    tan(d)  subs
!     0    1000.000  1.000000       0.0  1.000000       0.0  100
!     1    25.00000  9.800000       0.0  1.000000       0.0  0
```

Next comes a comment stating the kind of data stored (S-Parameters), a vendor specific data line and finally the data itself. The data consists of frequency followed by the four S-parameters in magnitude, angle format.

```
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
# GHZ S MA
10.0000000 0.715488 -4.288 0.698625 92.401 0.698625 92.401 0.715488 9.0911
```

The S-Parameters shown above are Touchstone compatible. Use the "-C" option if you want the S-Parameters to be Super-Compact compatible.

Since we did not invoke ***em***'s automatic de-embedding (which is covered in a subsequent chapter), the S-parameters are for the entire structure, not just the discontinuity all by itself (see Figure 3 on page 15).

Before we get to the automatic de-embedding example, the next example shows how to get the same results as this example, only faster.

Chapter 5 Tricks to Get a Faster Analysis

♦ Symmetry Provides a Faster Analysis

The microstrip circuit in steps.geo (see Figure 3 on page 15) is symmetric about the horizontal center line. ***Em*** can take advantage of this, provided all ports are also on the center line. This second condition is important. If there is a port off the center line, ***em*** creates the port's image on the other side of the center line and shorts the two together, a result usually not desired.

If you want to short two symmetrical ports together (see section "The Coplanar Short" on page 62), make sure you remove the port below the line of symmetry. Whenever you see an error message stating that there are no subsections for a given port, check for ports below the axis of symmetry.

To permit ***em*** to take advantage of the symmetry, run ***xgeom*** and modify steps.geo using *Param* ⇒ *Box* ⇒ *Symm.* When you click on the "Symm." button, it toggles from "No" to "Yes" and a dashed center line is drawn on the circuit. Visually check to make sure the circuit really is centered on the center line. If not, move the circuit until it is centered.

When finished, save the file under the new name “steps_sym.geo”. You may want to add a comment or two indicating the modification as you store the file.

If you are using the “$SONNET_DIR/examples/steps.geo” file, just use “$SONNET_DIR/examples/steps_sym.geo” file instead (likewise for all subsequent examples).

Run the analysis with “time em -v steps_sym.geo”. The output to the screen should be the same as the previous section, with one exception, the time. This is how the time came out on our computer:

```
1.7 real         0.9 user         0.1 sys
```

We see a large percentage improvement in speed by taking advantage of the circuit symmetry (1.7 seconds of user time without the use of symmetry versus 0.9 seconds with the use of symmetry. Your results may differ). The result of this analysis is very slightly different from the previous run due to a slightly different subsectioning with symmetry. For any conceivable microwave design requirements, the results are identical and well worth the two times improvement in speed, especially for large circuits whose analysis times are measured in hours instead of seconds.

The example in the next chapter builds on this one by adding automatic de-embedding.

♦ Invoking Single Precision for More Speed

Em normally works with double precision. In many cases, a single precision matrix reduction is all that is needed. To invoke a single precision matrix, run ***em*** with the memory saver “-m” option. Keep in mind that the matrix elements are still calculated in double precision because of potential numerical difficulties. Once calculated, they are then stored in single precision format.

By invoking single precision, you cut the memory required by a factor of two. This has a significant effect if your problem is large enough to cause ***em*** to swap out to disk. For big problems, this can result in an order of magnitude increase in speed.

On some machines the floating point speed is also increased because single precision calculations can be done faster than double precision. The Sun SPARCstation machines are such. Unfortunately, compilers on many other computers perform single precision arithmetic by first converting to double precision, performing the operation and then converting back to single precision. If such a machine is not memory swapping in double precision, no increase in speed will be seen in single precision. It may even be slightly slower.

In general, use the memory saver option on large circuits (800 subsections or more), it is not needed on small circuits. The memory saver option can result in slightly different results. At extremely low frequencies, when the subsections size is on the order of 0.0001 wavelength or smaller, single precision may not be enough to allow the matrix to be properly inverted. In this case, very strange results are generated. For example, S_{21} may be different from S_{12}. In such a case, eliminate the -m option and re-analyze.

♦ Adjusting the Subsectioning Limits

The biggest way to get more speed is to reduce the number of subsections. A reduction in number of subsections by half can result in one, or even two, orders of magnitude increase in speed. The most direct means of reducing subsection count is to reduce the amount of metal. Any metal which is unlikely to carry current should be religiously removed. This includes distant ground plane regions in coplanar waveguide and long, unneeded lengths of connecting transmission line.

A second way to reduce the number of subsections is to cut the circuit into pieces and analyze each piece separately. For example, instead of analyzing an entire bandpass filter, analyze half of it. Then, if both halves are identical, just use a circuit theory program to cascade the half filter analysis with itself. Most filters, and other structures as well, can be broken down into a number of small circuits which can be easily analyzed. In fact, a pure circuit theory analysis takes this “breaking down” to the limit.

A third way to reduce subsection count is to simply use a larger cell size. It can be surprising how little a larger cell size changes results on many circuits. Be careful not to become blinded to viable options because of the length units in use. For example, if you want to analyze a line 7.0 microns wide. The obvious potential cell dimensions are 1 micron (for a seven cell wide line) and 7 microns (for a one cell wide line). There are other options too! For example, the cell size can be specified to be 7/3 = 2.33333 microns for a three cell wide line.

Also, try not to get mesmerized by the n-th decimal place on dimensions. If a 7.1 micron wide line is called for, and you use a 7 micron cell size, the error introduced is probably less than the manufacturing tolerances.

However, there are circuits which have very fine geometries combined with very large geometries. The fine geometry determines the cell size and the large geometry unnecessarily uses a large number of cells.

Addressing this problem, release 2.2 and above allows a minimum and maximum subsection size, in terms of cells, to be specified for each polygon. For example, in a large polygon, one could specify, say, the smallest subsection to be 10 cells in the x direction and 5 cells in the y direction. The large polygon will no longer use such a large number of cells and you can still use the small subsections in any region of fine geometry.

If the maximum subsection size happens to be greater than the subsections per wavelength (lambda) parameter, the subsections per wavelength takes priority.

To work best, the large polygon should have a rectangular geometry. Diagonal geometries can negate the beneficial effect of the large subsection size.

These subsectioning limits can be set using *Objects* $\Rightarrow$ *Polygons* $\Rightarrow$ *Param* as described in ***Xgeom*** **User's Manual**.

Chapter 6 Automatically De-embedding the Discontinuity

The ***em*** analysis is very physical and complete. All the effects that are seen in an actual measurement (with the exception of thermal noise) are also seen in the ***em*** analysis. This includes things like box resonances, dispersion, loss, higher order microstrip modes and port discontinuities.

How ***em*** handles port discontinuities is dealt with in this section. When a physical device is measured, it is often first placed in a microstrip-to-coaxial fixture (see Figure 1). In order to get accurate measurement of the device, two things must be removed from the measured data:

- The microstrip-to-coaxial transition (connector) discontinuity.
- The length of interconnecting transmission line (reference plane shift).

The process of doing this is called “de-embedding”.

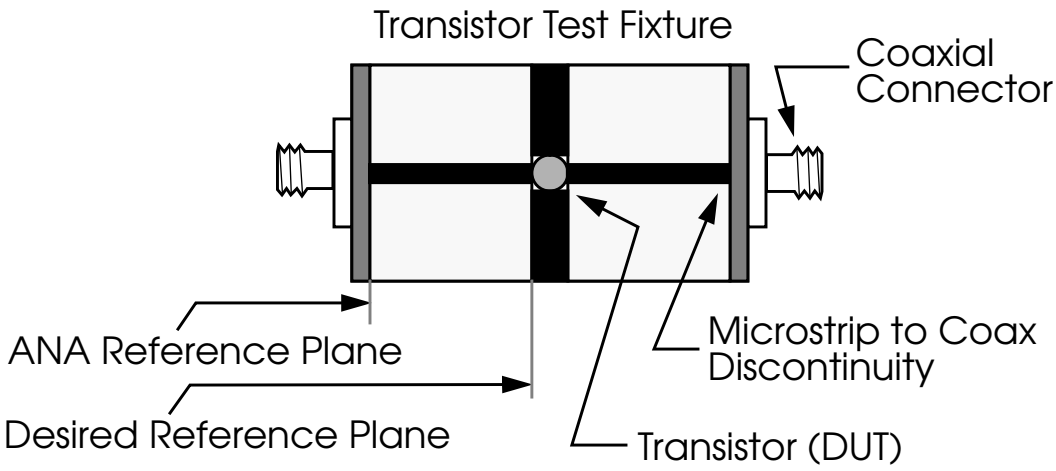


Figure 4 In order to get accurate data from a physical measurement, we must remove the port discontinuities and shift the reference planes to the face of the structure of interest.

In order to get accurate data on our device (frequently a discontinuity) from ***em***, we use very much the same kind of de-embedding. Instead of a physical connector, ***em*** uses what is called a “source” in electromagnetics. Any source, in any electromagnetic microstrip analysis, introduces its own discontinuity. The source discontinuity is analogous to the connector discontinuity of a physical measurement. It is something which corrupts the desired data and is to be removed.

To put the problem in microwave terms, we call the source discontinuity a “port discontinuity”. In an actual physical measurement, the connector discontinuity must be removed. In the ***em*** analysis (and all other electromagnetic microstrip analyses) we must remove the port discontinuity. Once done, we may also shift the reference plane right up to the face of the device (discontinuity).

The complete theory of the de-embedding algorithm used is presented in [5] (see the references at the end of the first chapter) and an abbreviated summary is presented in [4].

♦ A De-embedding Example

Em’s entire de-embedding process is enabled by simply adding “-d” to the command line. The “steps_sym.geo” file has the reference planes already set to the face of the discontinuity, as indicated by the reference plane arrows (see Figure 3 on page 15). The reference planes are ignored until we invoke the automatic de-embedding.

To run ***em***, using both the circuit symmetry and automatic de-embedding, as well as measuring the execution time, type:

time em -vd steps_sym.geo

Note that the "-v -d" options have been combined to the equivalent "-vd". The resulting output to the computer screen is:

```
Circuit geometry file -- steps_sym.geo --
Analysis control file -- ctl.an --
Circuit response file -- cir.rsp --


                  A TIME-HARMONIC ELECTROMAGNETIC ANALYSIS

                      OF SHIELDED MICROSTRIP CIRCUITS

                                Version 2.3


              (C) Copyright 1987,1989,1991 Sonnet Software, Inc.
                                All rights reserved.


Circuit uses 55 subsections, 1 Mbyte.
Primary structure -- Analyzing  10.000000 GHz.
  Loading matrix, source level 0, field level 0.
  Reducing matrix.
De-embedding matrix, side 0.
First standard, 23 subs, 100.000000 mils -- Analyzing  10.000000 GHz.
  Loading matrix, source level 0, field level 0.
  Reducing matrix.
Second standard, 43 subsections -- Analyzing  10.000000 GHz.
  Loading matrix, source level 0, field level 0.
  Reducing matrix.
De-embedding matrix, side 1.
First standard, 6 subs, 100.000000 mils -- Analyzing  10.000000 GHz.
  Loading matrix, source level 0, field level 0.
  Reducing matrix.
Second standard, 11 subsections -- Analyzing  10.000000 GHz.
  Loading matrix, source level 0, field level 0.
  Reducing matrix.

       3.2 real        2.9 user         0.1 sys
```

The main difference between the output from this example and the previous one is the extra lines at the end. There are two ports in “steps_sym.geo”, one on the left (side 0) and the other on the right (side 1). In order to de-embed the left side, ***em*** automatically creates two standards (analogous to ANA measurement standards) and analyzes each one. The same is done for the right side. The number of subsections is listed for each standard as well as the physical length for the first standard. The second standard is always double the length of the first standard (both standards are through lines).

♦ The De-embedded Result

When complete, both ports are de-embedded (port discontinuity removed and reference plane shifted) and the resulting discontinuity data is saved to disk. As an added benefit, ***em*** also calculates and saves to disk the effective dielectric constant (Eeff) and the TEM Equivalent characteristic impedance of each port connecting transmission line (Zo), as shown in the circuit response file:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 120.000000 120.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 0.758856 -165.0 0.651258 -79.39 0.651258 -79.39 0.758856 -173.8
! Eeff = (  7.35), Z0 = (   33.60).
! Eeff = (  6.32), Z0 = (   73.80).
```

If loss is included, Eeff and Zo both become complex.

Results such as the above can be used directly in the popular microwave circuit simulators, just treat it as if it were measured data. If you need a different file format, see Appendix I, "The Em Command Line" describing the ***em*** command line.

De-embedding is where some microwave design background is useful in properly interpreting the results as described in the next chapter.

♦ Specifying Port Normalizing Impedances

Whenever results are to be incorporated in a circuit in a circuit theory based analysis program, the normalizing impedance for each port should be 50.0 ohms and the information in this section should be ignored. In some cases, S-parameters normalized to some other impedance is desired.

For example, you may want to see what the reflection coefficient of a structure is when port 2 is connected to a 1.0 pF capacitor in parallel with a 10 ohm resistor (a power fet input model), while the input is being driven with a source which has a 35 ohm internal impedance. In this case, normalize port 1 to 35 ohms and port 2 to 10 ohms plus 1.0 pF.

In another example, pure electromagnetics is frequently carried out using S-parameters normalized to the characteristic impedance of each connecting transmission line. In the de-embedded steps, above, the researcher would want S-parameters normalized to 33.6 ohms on port 1 and 76.8 ohms on the output. These are often called “generalized” S-Parameters, in spite of the fact that the line impedance is usually not known, thus precluding conversion to 50 ohms for use in circuit theory software.

To understand the physical meaning of normalized S-parameters, recall that our standard 50 Ohm S-parameters are measured by terminating all ports in 50 Ohms and then measuring ratios of incident to reflected (or transmitted) wave amplitudes. If we were to use 60 Ohm terminations, instead of 50 Ohm terminations, the resulting measurements of traveling wave ratios would yield S-parameters normalized to 60 Ohms. If we were then to take the S-parameters which had been measured using 60 Ohm port terminations and use it in a circuit theory program (which expects you to use 50 Ohm terminations), we would get incorrect results.

For what would the 60 Ohm S-parameters be useful? Say you wanted to know what percentage of power would be absorbed by a 60 Ohm load terminating port 2 of a two port. That would simply be one minus the magnitude squared of S_{11}, using the 60 Ohm S-parameters. If you are interested in a different load, use a different normalizing impedance.

S-Parameters can be renormalized to any real impedance by using a circuit theory based program to cascade appropriate transformers on each port. This technique can not be used with a complex impedance, as is the case with a lossy line or complex load.

In ***em***, the default normalizing impedance is 50.0 ohms. If you would like a different normalization, refer to the section "Menu: Objects - Ports" on page 64 of the ***Xgeom*** **User’s Manual** on how to specify the normalizing impedance for each port.

The normalizing impedance is represented by four numbers. First is the real part in ohms. Next comes the imaginary part in ohms. Third is the inductive part in Henrys. The last number is the capacitive part in Farads. The inductive and capacitive part modify only the reactive portion of the load, they are included so you don’t have to manually re-calculate the reactive part at each frequency.

The resistance, reactance and inductance are all connected in series when the specific normalizing impedance is calculated at each frequency of analysis. The capacitance is connected in parallel with the result and then the final normalizing impedance at the frequency of analysis is calculated. The normalizing impedances are ignored if Z- or Y-parameters are specified for output.

This capability should be used only by the most advanced users. If the above discussion is not clear, seek assistance. Under no circumstances should this capability be used on data which is to be incorporated in a circuit in a standard circuit theory program. Such programs assume S-parameters normalized to exactly 50 Ohms.

For example, the 50 Ohm S-parameters of a microstrip step junction look like a very small shunt capacitance and a very small series inductance. In other words, the reflection coefficient is almost zero and the transmission coefficient is almost unity with a couple degrees of phase. If, instead of 50 Ohm S-parameters, we were to use S-parameters normalized to the characteristic impedances of the lines connecting to each of the two ports (this is common in electromagnetics), the S-parameters would look like a transformer between the two impedances. This causes the circuit theory programs, which are expecting 50 Ohm S-parameters, to give grossly incorrect results.

Chapter 7 Automatic De-embedding Limitations

Care should be taken when making use of de-embedded results. With some experience in microwave design, the parallel between potential difficulties in de-embedding and actual, physical microwave measurements are easily seen.

♦ Higher Order Microstrip Modes

The de-embedding removes the port discontinuity and the connecting length of transmission line. The de-embedding assumes that the only mode propagating on the connecting transmission line is the fundamental quasi-TEM mode. If higher order modes are propagating, the de-embedded results are not valid (the same is true for actual, physical measurements). If this is the case, we strongly recommend using a thinner substrate, unless, for some reason, multi-mode operation is desired.

Even when higher order microstrip modes are evanescent, there can still be problems. If the port is so close to the discontinuity of interest that their fringing (evanescent) fields interact, the de-embedding looses validity. Again, this is a problem which would also arise in an actual physical measurement if the device to be de-embedded is close enough to the fixture connector. This problem is explored in a subsequent section.

Another related difficulty is that the resulting data, when it is used in a microwave circuit analysis program, should not be connected so close to another discontinuity that there is interaction (again, via evanescent fringing fields) between the discontinuities. Circuit analysis programs do not account for this interaction, invalidating the results. For a detailed description see [8] in the references at the end of the first chapter.

If there are two discontinuities close enough to interact, put both (all) of them in ***em*** where the interaction is completely included. In fact that is just what we did for the cascade of two steps.

♦ Box Resonances

A problem which affects actual measurements, as well as the ***em*** analysis, is box resonances. If present, resonances put glitches into the de-embedded data. To remove box resonances, just take the box lid off. How? A good approximation is to set the cover resistivity to 377 ohms per square, the impedance of free space. This solution, and its limitations, is demonstrated in a subsequent section.

Em also has the ability to detect and/or remove box resonances. Use the “-b” to detect resonances and “-B” to both detect and remove. All detected resonances are listed in the .rsp file just before the S-parameters for the frequency. This is described in detail in section "Verifying the Box Resonance Problem" on page 40.

♦ Potential Reference Plane Difficulties

Em allows one reference plane per box side, no matter how many ports are on that side. All the ports on a side are de-embedded with a single pass through the de-embedding algorithm. Thus, no matter how many ports there are on a circuit, there are never more than four passes (for four sides) through the de-embedding algorithm. In the above example, there were ports on only two sides resulting in only two passes through the algorithm.

If there is more than one port per side, we have coupled lines and Zo and Eeff are not calculated. The de-embedded data is still accurate. The multiple ports may be as close to each other as desired, all interactions on any given side are taken into account.

Note that if the reference plane is close to zero electrical length (at very low frequency) or is close to a multiple of one half wavelength, the values of Zo and Eeff are not valid (and are usually not printed out). However the de-embedded data is still just fine. An example of this is provided later.

If the length of the reference plane is more than one wavelength, incorrect results might be seen. ***Em***'s calculation of Eeff is based on phase length. If the reference plane is, say, 365 degrees long, the Eeff calculation is based on a phase length of 5 degrees. But ***em*** has some "smarts" built in. If a non-physical result is seen, *em* increases the calculated phase length by 360 degrees at a time until physical (i.e., Eeff >= 1.0) results are seen.

Thus it takes a particularly long reference plane before the Eeff calculation fails. When it does fail, it suddenly jumps down to a value just above 1.0. Zo and the de-embedded data still have full validity. This failure mode is rarely seen.

♦ *Em*'s Intelligent De-embedding Algorithm

Em's de-embedding has even more "smarts" built in. It checks to see if two opposite sides of a circuit are identical (including reference plane length and the order of the port numbering). If so, it cancels the second (identical) pass through the de-embedding and simply uses the results from the first de-embedding. This can save a lot of time on structures like the gap or cross discontinuity.

♦ Why Box Sidewalls are Important

The box sidewalls can, on occasion, be frustrating, especially in regards to box resonances. This is true both with ***em*** and with actual circuits. However, the sidewalls also provide an invaluable service, they provide an unambiguous ground reference.

Microwave ports consist of two terminals. One terminal carries signal (e.g., the center conductor of a coaxial connector) and the other terminal is ground. When incorporating measured or calculated N-port S-parameter data into a circuit theory based analysis, all ports are assumed to have exactly the same ground reference.

Now let's say we incorporate loss in the sidewalls, in an attempt to kill box resonances. When current flows in the sidewalls, that current will generate a tangential electric field, a voltage. Thus the grounds at any two ports can have a voltage between them, violating the circuit theory assumption of all ground terminals being at the same potential. This effect is also known as a ground loop.

If we were to use an analysis that had no sidewalls at all, we would now have to integrate electric field through the substrate to calculate the circuit voltage. While such a voltage depends on the path taken to get to the ground plane, it can be done. In fact, if you use a via port in ***em***, this is just what is done. Now the problem that is introduced

is a port discontinuity that includes a series inductance as well as a shunt capacitance. And in this case, as is pointed out in [4] and [5] (references are at the end of the first chapter), it is impossible to de-embed internal S-parameters based on external current-voltage relationships. In addition, with sidewalls forming a perfect ground an infinitesimal distance from the signal line, there is no ambiguity as to what the voltage is.

Thus, the box sidewalls are frustrating on occasion, but they really are useful.

Chapter 8 De-embedding Situations

The following sections show what happens when unexpected results are encountered, how to recognize a problem, and what to do (if anything) when a problem is present.

Remember, ***em*** is a very physical analysis. If problems are encountered using ***em***, the same problems will be seen if the circuit were actually built.

♦ De-embedding Reference Plane Length -- How Close is Too Close?

As mentioned previously, if the port (which is, itself, a discontinuity) is too close to the discontinuity we are trying to de-embed, the resulting data is in error. This is because the fringing fields of the discontinuity interact with the fringing fields of the port. The de-embedding algorithm (which is virtually identical to algorithms used in de-embedding ANA measured data), being based on circuit theory, cannot handle fringing field interaction. See [8] in the references at the end of the first chapter for a detailed description of this problem.

As an experiment, we changed the circuit in “steps.geo” into an open end discontinuity. To do this, we first changed the X (horizontal) dimension of the box from 260 mils to 300 mils and from 26 cells to 30 cells long. Then we deleted port 2 (*Objects* ⇒ *Ports* ⇒ *Delete*) and most of the points in the original metallization outline with the result shown in Figure 5. All other box parameters are the same.

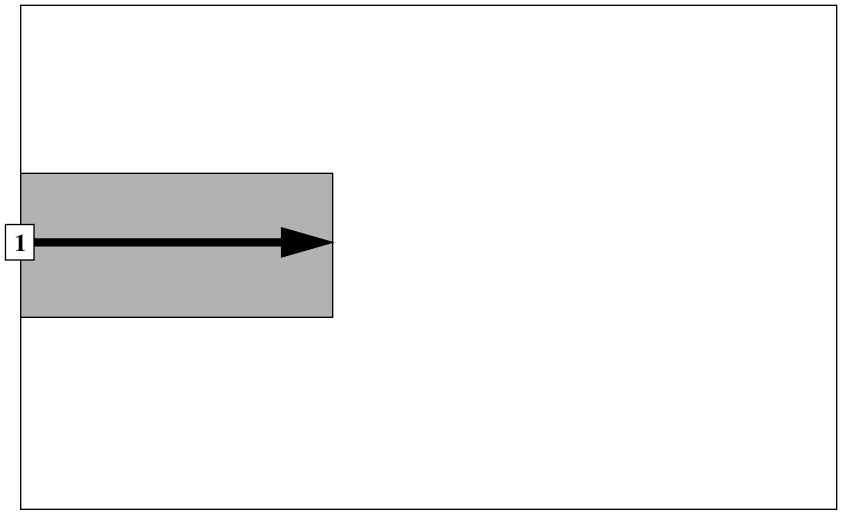


Figure 5 The open end discontinuity (“open_120.geo”) is used to check de-embedding interaction between the discontinuity and the port.

Both the line length and reference plane are 120 mils and we saved the result in file “open_120.geo”. We also shortened the line to 40 mils and 20 mils and used *Objects* ⇒ *Ref. Planes* to move the reference plane. Those circuits were saved in files “open_40.geo” and “open_20.geo” respectively. In order to make the reference plane four cells long (the minimum length allowed), open_20.geo cell size was changed from 10 mils to 5 mils.

The result of each analysis (using the -d option) is:

```
120 mils between port and open end:
10.0000000 1.000000 -17.97
! Eeff = (  7.39), Z0 = (   33.78).

40 mils between port and open end:
10.0000000 1.000000 -19.51
! Eeff = (  7.26), Z0 = (   33.57).

20 mils between port and open end:
10.0000000 1.000000 -17.69
! Eeff = (  8.50), Z0 = (   31.39).
```

We see that, even with a reference plane on the order of the substrate thickness, there is only a moderate effect. At 40 mils, even that effect is almost gone with the Zo, Eeff and reflection phase very close to their values at 120 mils.

From this, we can suggest (this is not a rigorous conclusion!) that a reference plane equal to one substrate thickness or more is reasonable provided the transmission line is not over-moded. For reference planes shorter than one substrate thickness, the error introduced by fringing field interaction increases rapidly.

Zero length reference plane is a special case. Recall that de-embedding is a two step process. First, the port discontinuity is removed, then the reference plane shifted. A zero length reference plane is realized by simply skipping the second step and is entirely valid.

♦ Reference Plane Length at Multiples of a Half Wavelength

Eeff and Zo are not available when the length of the reference plane is an integral multiple of a half wavelength. For example, at an extremely low frequency the electrical length of the reference plane may be a fraction of a degree (i.e., zero half wavelengths). In this case, the analysis is unable to accurately evaluate the electrical length and, especially, the characteristic impedance.

If it gets bad enough, the analysis refuses to make the calculated values available. Occasionally, inaccurate values do get through and it is important to recognize the situation. It is also important to realize that only Eeff and Zo are affected. The de-embedded data is still available to full accuracy.

As an example, modify your “ctl.an” file to the following:

```
Ver 2.3
GHZ
FRE 16.0 19.0 0.5
```

Next run ***em*** with the command “em -vd open_120.geo”, thus using the 120 mil reference plane set up in the previous example. This reference plane is precisely 180 degrees long at 17.5 GHz. The results are:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 120.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
16.0000000 1.000000 -27.11
! Eeff = (  7.90), Z0 = (   38.90).
16.5000000 1.000000 -28.03
! Eeff = (  7.94), Z0 = (   42.01).
17.0000000 1.000000 -29.00
! Eeff = (  7.99), Z0 = (   54.82).
17.5000000 1.000000 -30.03
! Eeff = (  --  ), Z0 = (  --  ).
18.0000000 1.000000 -31.12
! Eeff = (  7.98), Z0 = (   25.90).
18.5000000 1.000000 -32.28
! Eeff = (  8.01), Z0 = (   30.25).
19.0000000 1.000000 -33.51
! Eeff = (  8.03), Z0 = (   32.14).
```

No results are printed out for Eeff and Zo at 17.5 GHz. Even so, we can see that the data (S11 phase) is completely reasonable at all frequencies, including 17.5 GHz. At frequencies around 17.5 GHz we can see that Eeff is affected a small amount, while Zo is obviously “walking” into and out of the (Zo) singularity.

The main point of this section is that if your results show a rapidly changing Zo, check the electrical length of the reference plane. If it is a multiple of a half wavelength, the de-embedded data is still correct. Disregard Zo.

♦ Box Resonances and De-embedding

Being based on circuit theory, ***em***'s de-embedding algorithm (like all de-embedding algorithms) is unable to de-embed a structure contained inside a resonant cavity (box). This section shows the effect of a box resonance and its resolution.

Modify the "ctl.an" file to the following:

```
VER 2.3
GHZ
FRE 24.0 24.6 0.1
```

Run ***em*** with the command "em -vd open_120.geo", thus using the same ".geo" file as in the previous section. The results are:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 120.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
24.0000000 1.000000 -53.53
! Eeff = (  8.14), Z0 = (   36.44).
24.1000000 1.000000 -55.49
! Eeff = (  8.13), Z0 = (   36.20).
24.2000000 1.000000 -60.21
! Eeff = (  8.10), Z0 = (   35.53).
24.3000000 1.000000 -172.8
! Eeff = (  7.70), Z0 = (   29.29).
24.4000000 1.000000 -42.01
! Eeff = (  8.25), Z0 = (   39.61).
24.5000000 1.000000 -47.89
! Eeff = (  8.21), Z0 = (   38.19).
24.6000000 1.000000 -50.09
! Eeff = (  8.19), Z0 = (   37.80).
```

Here we see the effects of a box resonance with the jump in phase (at 23.4 GHz) of the de-embedded open end. Note that Eeff and Zo are also affected. This is because there is also a resonance in at least one of the standards that ***em*** creates for de-embedding.

In some cases, the standards do not have a box resonance and Zo and Eeff are unaffected. To see an example of this, reduce the top layer thickness from 1000 mils to 50 mils. The box resonance moves to 24.85 GHz while the Zo and Eeff calculations remain smooth.

A box resonance is not directly related to the length of the reference plane. Thus, it is easily distinguished from the problem described in the previous section where the reference plane is precisely a multiple of a half wavelength long. Notice that the box resonance is also a much more narrow band problem, at least for a lossless box. Compare the above results with those of the previous section.

♦ Verifying the Box Resonance Problem

When you see a "glitch" in the S-parameter data or in the characteristic impedance, you can verify whether or not it is a box mode. To do this, invoke the "-b" option to detect box resonances: "em -vbd open_120.geo". The output at 24.3 GHz is:

```
! Box resonances, primary structure.
! TE: (0,1,*)
! Box resonances, first standard, side 0.
! TE: (0,1,*)
! Box resonances, second standard, side 0.
! TE: (0,1,*)
24.3000000 1.000000 -172.8
! Eeff = (  7.70), Z0 = (   29.29).
```

Notice that the resonance detection information is printed out before the frequency of analysis, not after. Also note that the S-parameters are the same, the resonance has not been removed. We see box resonances listed for the primary structure (the open end) and for both standards.

The box resonance information tells us that the resonance is Transverse Electric (TE), i.e., there is no Z directed electric field (perpendicular to the substrate surface). The modes are (0,1,*) indicating that there is no variation (first digit) of field in the X direction (the direction of the open stub) and a half sine wave of variation (second digit) in the Y direction. All three resonances are the same because the three structures (primary and two standards) differ only in the X dimension, and there is no variation of the field in the X direction.

The "*" in the mode number indicates that the variation in the Z direction is unknown. Since we generally have several different dielectrics as we go along the Z axis, a mode number here is not always clear. However, we can deduce that there is something resembling a half a sine wave variation in fields along the Z axis as a resonant mode can not have more than one mode number equal to zero.

♦ Removing Box Resonances Artificially

To remove (as well as detect) box resonances, use the "-B" option. This option reduces the effect of the offending waveguide mode(s) in the calculation of coupling. There is a problem in doing this. We have now created a non-physical problem where all boundary conditions are no longer exactly met. The nature of this problem is such that if a mode is removed in one of the standards during analysis, the de-embedding becomes very confused and bad data can result. The bad data is usually obviously bad and, on top of that, ***em*** also prints out a warning message if both -B and -d are used on the same command line. You can see this by using -Bd on the open_120.geo file.

The -B option works reasonably well when not using de-embedding. Compare the output of "em -vb open_120.geo" with the output from "em -vB open_120.geo". The data with the box mode is still several degrees off, however it is much improved from the case without box modes removed.

On rare occasions, the box mode detection function "detects" a resonant mode which does not exist, this is called "false-ing". In some cases, these are actually modes which could exist, but are simply not excited by the specific circuit you are analyzing.

♦ Removing Box Resonances Naturally

The box is a resonator because it is completely enclosed. To keep it from resonating, just take off the top cover. We can use a close approximation to this by setting the top cover resistivity to 377 ohms/square, the impedance of free space. This is an accurate approximation provided the cover is not so close that it interacts with the evanescent fringing fields surrounding the circuit.

If you wish to model a sheet of resistive material in the box, rather than removal of the top cover, setting the top cover to that resistivity is accurate no matter how close the cover is to the circuit. It is an approximation only when used to model the removal of the top cover.

Modify the file "open_120.geo" using ***xgeom*** to set the top cover resistivity to 377 ohms/square. This is the DC resistivity. Leaving the skin effect resistivity (which has a square root of frequency dependence) at 0.0, the DC resistivity is used at all frequencies. Use the ***xgeom*** option P*aram* ⇒ *Metallization* ⇒ *Param* to accomplish the modification and save the result in "open_loss.geo"

Run ***em*** with the command line “em -vd open_loss.geo”. The results are:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 120.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
24.0000000 0.989850 -53.29
! Eeff = (  8.15+j 0.00472), Z0 = (   36.39+j 0.09712).
24.1000000 0.975852 -54.83
! Eeff = (  8.15+j 0.01108), Z0 = (   36.21+j 0.22926).
24.2000000 0.930987 -56.56
! Eeff = (  8.14+j 0.03062), Z0 = (   35.96+j 0.66193).
24.3000000 0.855130 -53.16
! Eeff = (  8.17+j 0.06718), Z0 = (   36.42+j 1.67372).
24.4000000 0.907590 -48.77
! Eeff = (  8.21+j 0.04222), Z0 = (   37.59+j 1.29206).
24.5000000 0.951697 -49.522
! Eeff = (  8.21+j 0.01961), Z0 = (   37.66+j 0.68442).
24.6000000 0.969420 -50.69
! Eeff = (  8.21+j 0.01094), Z0 = (   37.55+j 0.43596).
```

Most of the resonance has been removed. To remove the resonance more completely, the top cover can be moved closer to the substrate surface. In fact, if the cover is moved to within 50 mils, there is absolutely no indication of a resonance (now approaching 24.85 GHz) left. Another solution to the problem is to change the size of the box, larger or smaller, to move the resonant frequency.

With the top cover off, ***em*** is also including radiation loss in the de-embedded discontinuity (see the S11 magnitude). The loss has a second effect in making Eeff and Zo complex as well.

Taking the top cover off works, provided the sidewalls of the box are large enough to form a propagating waveguide up to the top cover, or you can place the top cover close enough to the substrate surface to catch the fields in the box mode. Some high order “box” modes are confined primarily to the substrate and will be difficult to remove in this manner. As you make the box bigger by increasing the substrate surface areas, the modes “loosen up” so that they can propagate to the top cover and become absorbed.

To completely absorb any single waveguide mode, set the surface impedance of the top cover equal to the impedance of the waveguide mode. If you have multiple modes to absorb, setting the impedance to 377 ohms/square is a nice compromise, because some modes are above 377 ohms and others are below.

Chapter 9 Vias and 3-D Structures

Up to this point, most of the consideration has been with two-dimensional (2-D) structures, i. e., only X and Y current has been needed. However, ***em*** can also handle full 3-D current as well. The third (Z) dimension of current is handled by a special kind of subsection called a via.

♦ Adding Vias to the Circuit

Vias, as used in ***em***, are actually more general than the vias generally used in microwave design. In microwave design, vias connect metal on the substrate surface to the groundplane beneath the substrate, a ground via. In ***em*** vias can connect metallization between any substrate or dielectric layer, not just bottom layer to ground. We call these "level-to-level" vias, they can connect any two adjacent metallization levels.

Thus, ***em***'s vias can be used in air bridges, spiral inductors, wire bonds, and probes as well as the standard ground via. ***Em***'s vias use a uniform distribution of current along their length and thus are not intended to be used to model resonant length vertical structures. Keep the via lengths small with respect to a wavelength.

To use vias, use ***xgeom*** to specify one or more polygon edges as edge-vias (see Chapter 12, "Using Vias" in the ***Xgeom*** **User's Manual** for details). ***Em*** places subsectional vias (called "via-posts") along the entire length of all edge-vias. Vias always go up from the selected polygon edge with the length of the via equal to exactly the thickness of the dielectric layer. The via-posts are rectangular cylinders with a horizontal cross-sectional area equal to one cell. If you make the cell size smaller, the vias will be smaller with more of them along the edge-via. Of course, the length of the edge-via is unchanged. Current in a subsectional via is uniform through out the body of the via and is Z directed. Via loss is determined by the polygon from which the via originates.

An edge-via may also be specified as a port (using ***xgeom***). This allows ports to be placed at other than the substrate edge. For example, in an amplifier design, one may wish to have three or four ports on the interior of a circuit in which to insert the measured S-parameters of an FET. To do this, put ground edge-vias at the points where you wish to place the FET terminals. Then specify the bottom (ground) edge-via as a port. The file "SONNET_DIR/examples/patch.geo" has an example of a via-port.

♦ Restrictions on Vias

With the present version of ***em***, automatic de-embedding is not available for via ports so do not use the -d option if you have specified any vias to be ports. There is a small series inductance and shunt capacitance associated with a via port. The port discontinuity is small compared to a typical FET. However, if you are using the port via to include, say, a small measured capacitor (say, 0.1 pF), the port discontinuity may be of comparable magnitude, be careful!

The via ports can also be used as models of coaxial feed for microstrip antennas. In this case the port discontinuity is desired, as it will approximate what is actually seen.

Another factor to keep in mind is that the height of the via should be a small fraction of a wavelength. The via height is the same as the thickness of the substrate or dielectric layer it penetrates. So, for ground vias, this is usually no problem. If a microstrip substrate were a significant fraction of a wavelength thick, over-moding also becomes a major problem. If one is using vias to form, say a septum, or an interior wall, keep an eye on the potential problem. A via which happens to be a half wavelength long will not give reasonable results.

♦ Simple Via Example

A simple via is stored in the file $SONNET_DIR/examples/via.geo. This file was generated by simply adding a via to ground at the end of the stub in open_120.geo, converting an open circuited stub to a short circuited stub, see Figure 7. In this Figure, the via subsections are indicated by small triangles pointed down, indicating metal going into the screen. Triangles pointing up indicate metal coming out of the screen.

The vias were captured by placing a polygon on the ground level indicating the periphery of the ground via. A square was used to model a via that is actually round. Such a model gives surprisingly accurate results. If an even more accurate model is needed, an octagon can be used.

After the polygon is in place at the base of the via, each side of the base polygon is converted into vias going up. You may want to change the snap grid to get the via-posts to fall in the precise cells that you want. See Chapter 12, "Using Vias" in the ***Xgeom*** **User's Manual** for details

Note that the top end of the via (see Figure 7) is a "hat" which is larger than the via itself. Beginning with release 2.2 of ***em***, there are no longer any restrictions on the polygons at the top of a via.

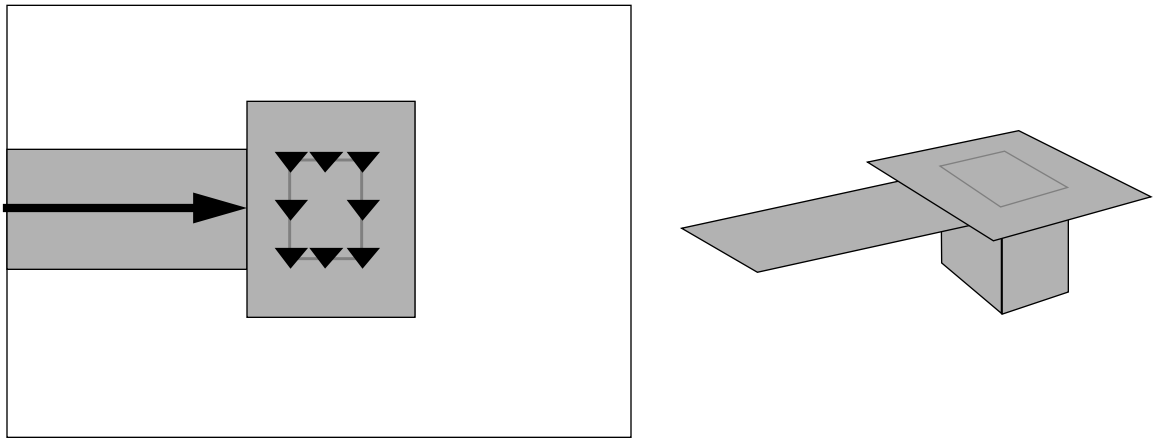


Figure 6 A simple via to ground. On the left, as it would appear in ***xgeom*** (top view). On the right, a view in perspective.

An analysis of the above via at 10 GHz with de-embedding gives a phase of 148.27 degrees, a perfect short circuit is 180 degrees. This means the via has an inductive phase of about 32 degrees.

♦ A Conical Via

One may simulate a conical ground via with a staircase approximation. Simply divide, say, a 100 μM GaAs substrate into four 25 μM substrates. Then put polygons (and specify edge-vias) at appropriate places to form the step approximation to the via sides. For an example, see the file "cvia.geo" in the examples directory. This circuit is a conical via to ground placed in the center of a through line, the purpose being to measure the via inductance. To look at the cvia.geo file type:

xgeom $SONNET_DIR/examples/cvia.geo &

The cvia.geo file is a very detailed model of a conical via. If you are modeling a large circuit (say, an inter-stage matching network) with multiple vias, you may want to use a simpler model for faster analysis.

Another, more complex circuit (see Figure 7), which uses a simple via, shows a 20 µM

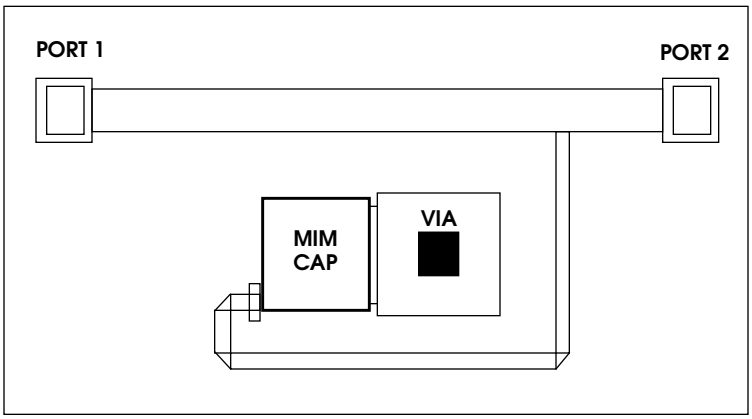


Figure 7 The coupling between the 20 µM wide stub and the via/capacitor combination requires an electromagnetic analysis.

wide stub shunted across a 50 ohm line on 100 µM GaAs (courtesy Raytheon Research Division). The stub is so close to the via/capacitor combination that there is significant coupling, causing the error seen in the circuit theory calculation (see Figure 8).

The ***em*** analysis includes the coupling and would have eliminated a re-design and re-fabrication cycle. The circuit theory analysis requires only a fraction of a second per frequency while ***em*** requires just under one minute per frequency (SPARCstation 2). But, in this case, the circuit theory analysis, because it gives the wrong answer, is a very expensive way to do the analysis!

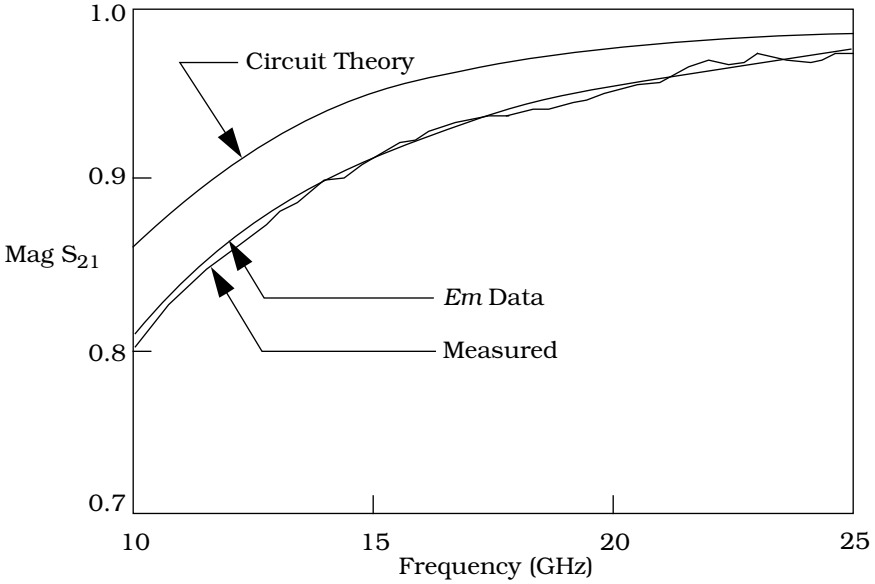


Figure 8 The ***em*** calculated data, which required a minute per frequency to analyze, accurately predicts the measured data, which required fabrication of a GaAs MMIC wafer.

If the circuit had been spread out (the stub straightened out and kept at least 100 µM from any other components), the circuit theory would probably have provided an accurate analysis, and electromagnetic analysis would be unneeded. This illustrates the point that we should use a combination of circuit theory and electromagnetic analysis, either one alone will compromise the quality of resulting designs.

This circuit is also in the examples directory as “raystub.geo”. As the file stands, we recommend using a workstation with a performance of at least 1 MFLOP and 8 (preferably 16) Mbytes of memory. Otherwise, double the cell size and/or remove the metallization loss for a faster analysis.

Chapter 10 Metallization Loss and Super Conductor Surface Reactance

Metallization loss is specified in ***xgeom*** by using the *Param* ⇒ *Metallization* option, see section "Menu: Param - Metallization" on page 79 in the ***Xgeom*** **User's Manual** for details.

A common misconception is that only one type of metallization is allowed on any given level. In fact, different metallizations (i.e., different losses) can be mixed together on any and all levels. It is possible to have, say, a thin film resistor right next to a superconductor all on the same level.

♦ Surface Resistance

The metallization loss is based on surface resistance. Two numbers are required. The R_{DC} determines loss at low frequency (where the conductor is much thinner than the skin depth). Surprisingly, electromagnetic analyses often predict zero loss at low frequency because they assume R_{DC} is zero. R_{DC} is useful for thin film resistors as well as low frequency metal loss.

The second required number is R_{RF}. ***Em*** multiplies this number by the square root of the frequency (in Hertz) to yield the ohms/square at high frequency. ***Em*** also properly models the transition between electrically thin (low frequency) and electrically thick (high frequency) conductors. See the section "Menu: Param - Metallization" on page 79 in the ***Xgeom*** **User's Manual** for examples. The equations for R_{DC} and R_{RF} are repeated here (σ is the bulk conductivity in mhos/meter, t is the metallization thickness):

$$R_{DC} = \frac{1}{\sigma t} \qquad R_{RF} = \sqrt{\pi \frac{\mu}{\sigma}} \qquad \mu = 4\pi \times 10^{-7}$$

Typical values for R_{DC} and R_{RF} are 0.004 and 3e-7. If you start getting very strange results, check R_{RF} especially to make sure it didn't slip an exponent!

The transition frequency, from R_{DC} to R_{RF} is the square root of R_{DC}/R_{RF}. At this frequency, and a relatively narrow band around it, both coefficients are important.

If an extremely precise evaluation of loss is needed, we recommend building and measuring a simple structure of the desired metallization. Then adjust the values of R_{DC} (at low frequency) and R_{RF} (at high frequency) until the calculated loss matches the measured loss. Then you can use these values for any circuit which uses the same metallization. You are now effectively using measured values for R_{DC} and R_{RF}. The typical values given above usually work well as a first approximation.

It is well known in electromagnetics that the surface impedance of a good conductor has an imaginary part which is equal to the real part. This reactive surface impedance is physically due to the increased surface inductance caused by the current being confined closer and closer to the surface of the conductor. This surface reactance is now included. The effect is small but potentially significant in certain cases.

Some electromagnetic analyses use a "perturbational" approach for loss. This means that they assume the current flowing everywhere is the same as the lossless case. This approximation works for low loss (good conductor). However for thin film resistors (high loss), the lossless (short circuit) current is not the same as the lossy current and a perturbational approach fails.

Em's loss analysis is not perturbational. It works just as well for 100 ohms/square resistor material as it does for 0.004 ohms/square good conductor.

♦ Surface Reactance

Until recently, the only surface resistivities of practical interest were pure real, i. e., pure loss. With the growing application of super-conductors in high frequency work, a reactive (inductive) surface impedance may see actual application. A super conductive effect known as "kinetic inductance" slows the velocity of the electrons with no loss of energy. This can be modeled as a surface inductance.

The effect of the surface inductance is to make ε_{eff} larger, i. e., the velocity of propagation slower. For normal conductors, ε_{eff} can never be larger than ε_{rel}. In a super conductor, this is no longer true. This unusual effect becomes significant for very thin substrates. As an example (data provided by Miter Corporation), take Niobium at 4^{o} Kelvin, line width of 80 μM, substrate thickness 0.7 μM (!), $\varepsilon_{rel} = 8.0$ has a surface impedance of 2.65e-5 + j 0.00678 ohms/square at 10 GHz. Z_0 (as determined by ***em*** using the -d option on a through line) is 1.27 ohms and $\varepsilon_{eff} = 9.65$ with very low loss. What can a creative microwave designer do with such a transmission line? Only time will tell.

Surface reactance is included in ***em*** by using the *Param* ⇒ *Metallization* option and specifying the surface reactance in ohms/square. ***Em*** uses the same reactance at all frequencies. As more is understood about kinetic inductance, a more sophisticated model will be used. We presently plan to include a surface resistance which is proportional to the frequency squared and a surface reactance which is proportional to frequency (i.e., an inductance) specifically for super conductors. This will be available on the next release. Any comments are welcome.

As an added side light, the surface resistance can be used to include lumped resistors (just make a square patch and set the ohms/square to the desired resistance). In addition, the surface reactance can be used to make a lumped reactance. Since the reactance of an inductor and capacitor both change with frequency, one must manually change the reactance as the frequency changes, but at least lumped reactive components can be used.

The surface reactance effect can also be seen in normal conductors.

Chapter 11 Corner Fill and Triangular Subsections

Corner fill places a special kind of subsection in the vicinity of all small gap discontinuities. These subsections accurately model the corner singularity in the current distribution and allow more accurate results to be generated. Using corner fill increases the number of subsections used. If there are no gap discontinuities, corner fill has no effect.

Microstrip structures with diagonal edges may benefit from including triangular subsections. The edges of such structures are frequently much better approximated with the diagonal edges allowed by triangular subsections. Triangle fill must be selected manually. Include it only on polygons with diagonal edges that also carry significant current. See [6] in the references at the end of the first chapter for a detailed description of triangle subsections.

Both of these options involve additional computation time. However, depending on the circuit, using these options may allow a given level of precision to be achieved more quickly. The alternative to using corner fill and triangular subsections is to increase the resolution (smaller cell size).

An example of each option is given next.

♦ The Effect of Corner Fill on a Gap

There are two example circuits to show the effect of corner fill, “gap20.geo” and “gap20_noco.geo” The first circuit uses corner fill. The second circuit is identical to the first except it does not use corner fill.

Set the “ctl.an” file to 1.2 GHz and analyze the first circuit by typing:

em -vd gap20.geo

The resulting S21 magnitude is 0.06 or -24.2 dB. When the above command line is used with the file “gap20_noco.geo”, the result is 0.05 or -25.8 dB. for a total of 1.6 dB difference. The use of corner fill increases the number of subsections but also increases the accuracy of the analysis.

Beginning with release 2.2 of ***em***, corner subsections are included only when there is a gap of two cells or less.

♦ The Triangle Fill Option Applied to a Coupled Open-Miter

To demonstrate the triangle subsections, run ***xgeom***, again, on "open_120.geo". This time, we shall analyze a right angle mitered bend which is closely interacting with an open end. Attempts to model this discontinuity using a circuit theory based program do not include the fringing field interaction between the two discontinuities.

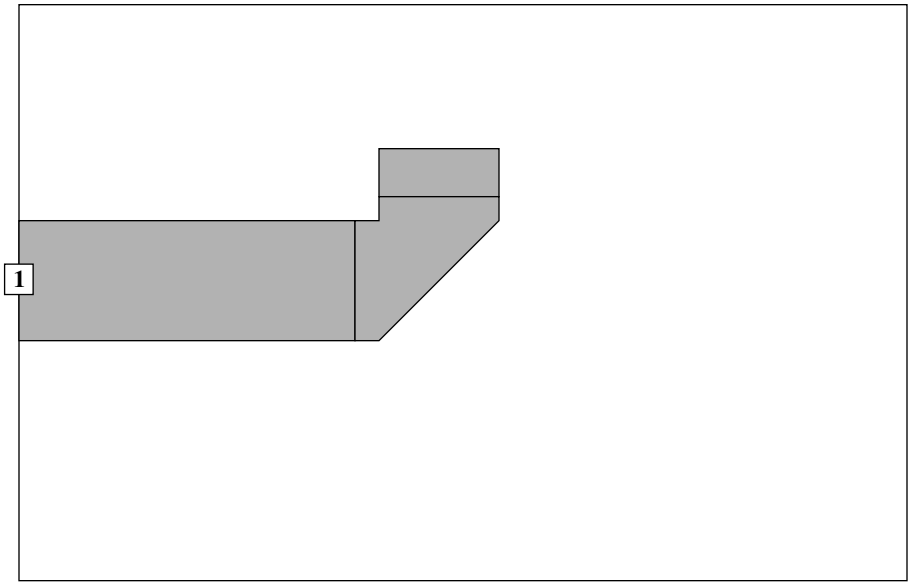


Figure 9 A closely interacting mitered bend and open end discontinuity.

The circuit (see Figure 9) is a multi-polygon circuit. The transmission line connected to port 1 is the original stub from "open_120.geo". It is unchanged and forms the first polygon. The mitered region is the second polygon with the new open end forming the third polygon. Polygons with edges in common are electrically connected together along those edges.

To capture the circuit, use *Objects* ⇒ *Polygons* ⇒ *Add.* After the circuit is drawn, select *Objects* ⇒ *Polygons* ⇒ *Param* and change the miter polygon fill mode to "Diagonal" and leave the open end polygon as "Staircase".

Be sure to click on *Param* ⇒ *Box* ⇒ *Symm*. to turn off symmetry. With the miter included, the circuit no longer has symmetry. Save the file under "open_miter.geo".

With “ctl.an” set to 10 GHz, use the command line “em -vd open_miter.geo”. The result is:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 120.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 1.000000 -150.9
! Eeff = (  7.39), Z0 = (   33.64).
```

You may notice that the miter polygon has “tabs” prior to attachment to both the port connecting line and the open end polygon. These tabs are required because all acute interior angles are removed prior to subsectioning. If the tabs are not there, little notches appear at each corner of the miter.

This analysis required more time. The analysis time is sensitive to whether or not triangle subsections are included. Once included, however, the ***em*** analysis time is relatively insensitive to the number of triangle subsections.

Chapter 12 A Multi-Port Discontinuity for Microstrip Coupled Line Filters

Em can handle circuits (with complete de-embedding) of any number of ports, without limit. In this section we look at the junction between two sections in the classic microstrip bandpass filter.

This junction (see Figure 10) is usually accounted for by adding a microstrip open end model at the end of each resonator. This model often takes the form of a simple length extension. In reality, the open end discontinuity is modified by the close proximity of

the adjacent resonator. In addition, the fringing fields also generate coupling between the open end and the adjacent resonator. There is even coupling between the open end of the port 1 resonator and the open end of the port 4 (non-adjacent) resonator!

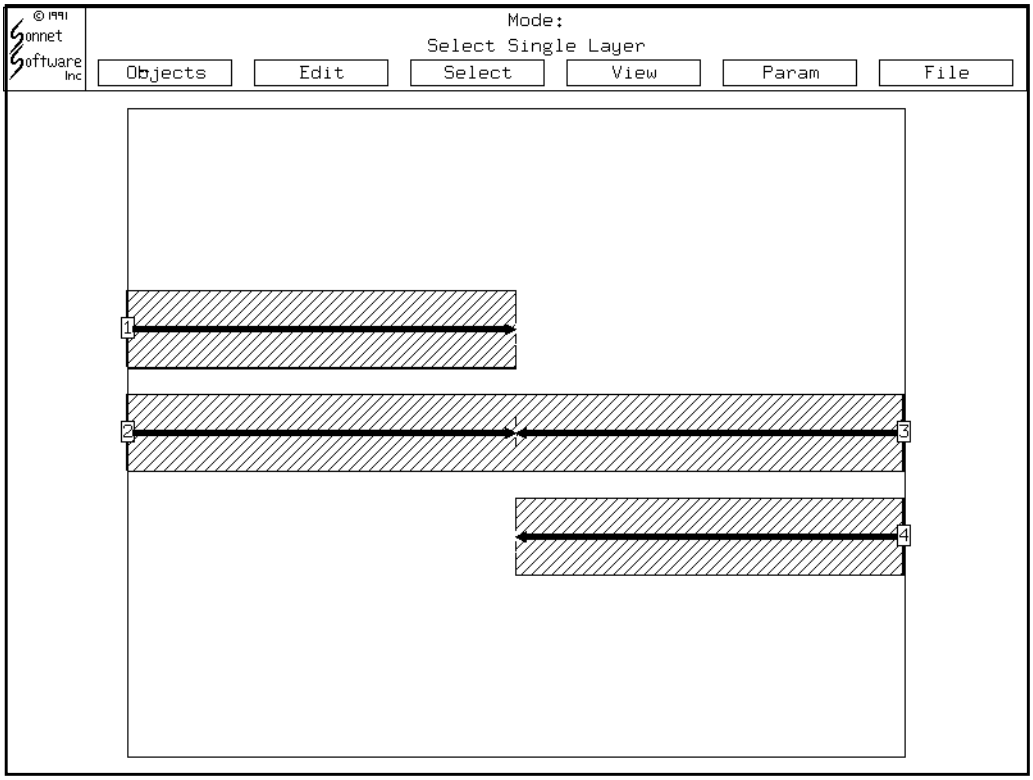


Figure 10 A four-port discontinuity is formed at the point where two sections of a coupled line filter join.

All of these couplings are precisely evaluated by ***em***. To demonstrate, capture the circuit shown in Figure 10, or use $SONNET_DIR/examples/coup_end.geo. This circuit uses the same box and dielectrics as "open_120.geo", just load the file and use *File* ⇒ *Clear* to remove the existing circuit. Don't forget to also click on *Param* ⇒ *Box* ⇒ *Symm.* to turn off symmetry. This circuit is not symmetric.

Save the file as “coup_end.geo”. Run the analysis with “em -vd coup_end.geo” for the results (listed in matrix order using magnitude, angle format):

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 150.000000 150.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 0.998745 -16.04 0.035238 89.979 0.035390 72.291 0.003731 -124.6
           0.035238 89.979 0.010670 -97.32 0.998695 -0.920 0.035390 72.291
           0.035390 72.291 0.998695 -0.920 0.010670 -97.32 0.035238 89.979
           0.003731 -124.6 0.035391 72.284 0.035239 89.986 0.998745 -16.04
! Eeff = (  --  ), Z0 = (  --  ).
! Eeff = (  --  ), Z0 = (  --  ).
! Eeff = (  --  ), Z0 = (  --  ).
! Eeff = (  --  ), Z0 = (  --  ).
```

♦ Using *Em*’s Results in a Filter Design

As an example of the use of ***em*** in a filter design, one would do the first cut of the microstrip filter with conventional circuit theory based programs. With the resulting approximate final dimensions, calculate the above discontinuity. You may want to include radiation loss (as described in a previous section) and metallization loss. Dielectric loss can even be included in the discontinuity.

Incorporate the discontinuity (as though it were measured data) between ideal circuit theory coupled lines in the circuit theory based software. Now, the lengths of the coupled lines can be adjusted to account for the effects of the junction discontinuity. The resonator couplings (gap widths) can even be modified slightly since the junction discontinuity is insensitive to the gap width.

If desired, even the coupled lines can be done using ***em*** (and the automatic de-embedding). A small section of line can be calculated with no loss of precision relative to a large section. Just analyze a section of line longer than one or two substrate thicknesses and set the reference planes for, say, a one cell length of line.

In the circuit theory program, this short length of line may be cascaded as needed to build any desired length of line.

The obvious approach to the problem is to analyze the entire filter with ***em***. Given sufficient computing power (a very small cell size is needed to accurately position the edges of a typical filter), this is a viable alternative. You may want to select several frequency points to validate the design, say the 3 dB points and one or two other points, and restrict the analysis to just those points. This approach takes into account coupling between all resonators and discontinuities in the entire filter.

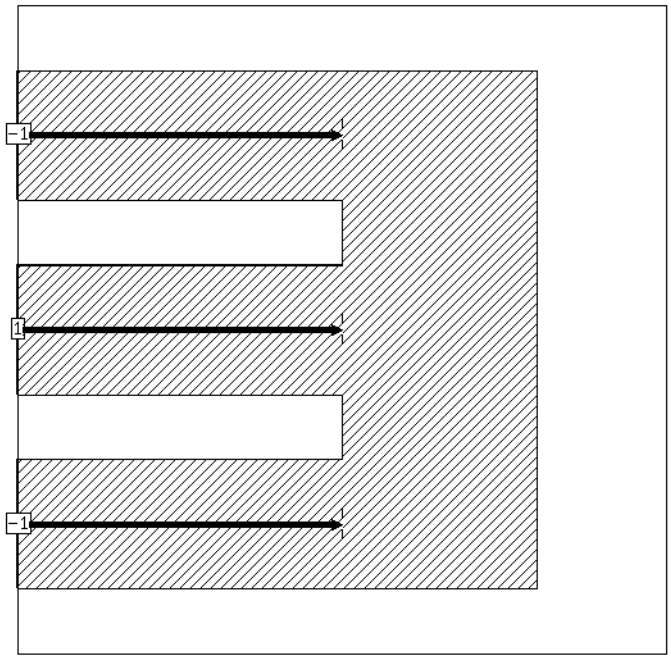
Yet another approach is to take a symmetric filter and split it in half (midway between the input and output). Analyze the half filter (typically a 3-port) and then use a circuit theory program to cascade it with itself to form the complete filter.

Chapter 13 Co-Planar Waveguide Discontinuities and Balanced Ports

Em also handles coplanar waveguide well because ground planes and dielectric layer thicknesses can be made any value while still maintaining full accuracy and without compromise in speed. This section describes a very simple, yet important, coplanar waveguide discontinuity, the short circuit. A second example is the coplanar cross junction. This discontinuity also illustrates the use of level-to-level vias to form air bridges (which suppress the slot line mode).

♦ The Coplanar Short

The coplanar short (see Figure 11) finds wide use as a measurement calibration standard.



Notice that both ground ports have been labeled “-1”, while the signal port is labeled “1”. This represents a balanced port. Any number of ports can have the same positive or negative labels (this is done in ***xgeom***). ***Em*** sums the total current going into all the positive ports with the same port number and sets that equal to the total current going out of all the ports with that same negative port number. Thus the name “balanced”, or “push-pull” port. Both coplanar and slot line can be represented with balanced ports.

Note that we end the width of the ground lines just before they would have touched the sidewall. If the side of the ground line touches the side wall, it will short out to the sidewall, thus allowing ground current to return via the sidewall instead of via the ground line. This defeats the purpose of the balanced port. Be sure that your ground lines touch the sidewall only at the location of negative port numbers when using balanced ports.

When using balanced ports, restrictions on the distance between the outer edge of the ground lines and the sidewalls have been removed as of release 2.2. The close proximity shown above is entirely acceptable.

The above circuit does not have symmetry. This issue is addressed at the end of this section.

To analyze the coplanar short, type “em -vd coshort.geo”, use $SONNET_DIR/examples/coshort.geo if you did not capture your own geometry. The result is

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 50.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 1.000000 168.49
! Eeff = (  5.22), Z0 = (   58.11).
```

A perfect short is 180 degrees, thus we have a short that is about 11 degrees inductive.

It is possible to get the same result, only much faster. Notice that the circuit is symmetric. To add in symmetry, use ***xgeom***. If this were the only change we were to make before analyzing the circuit, it would not work.

The reason for this is that when a circuit is symmetric, ***em*** does not subsection any part of the circuit below the center line. After subsectioning the circuit, ***em*** checks to make sure all ports have at least one subsection associated with it. But notice that the “-1” port below the center line is still there. This port would not have any subsections and ***em*** would print an error message to that effect and terminate. So also remove the lower of the two “-1” ports and save the circuit under “coshort_sy.geo”. An analysis of this circuit provides almost identical data in much less time.

Whenever you see an error message stating that there are no subsections for a given port, check for ports below the axis of symmetry, assuming symmetry is turned on.

♦ The Coplanar Cross Junction

The coplanar cross junction (see Figure 13) illustrates the analysis of coplanar waveguide structures as including the effect of air bridges as an integral part of the coplanar discontinuity. The air bridges are needed in order to suppress the slot line mode which would otherwise propagate in the coplanar transmission line. In the case of the cross junction, the air bridges are needed for a second purpose, to provide a return path

for ground current. The ground conductor on both sides must be continuous between all ports, otherwise the ground current on one side is interrupted. If so, very strange results will be seen, both in the ***em*** analysis and in actual measurements.

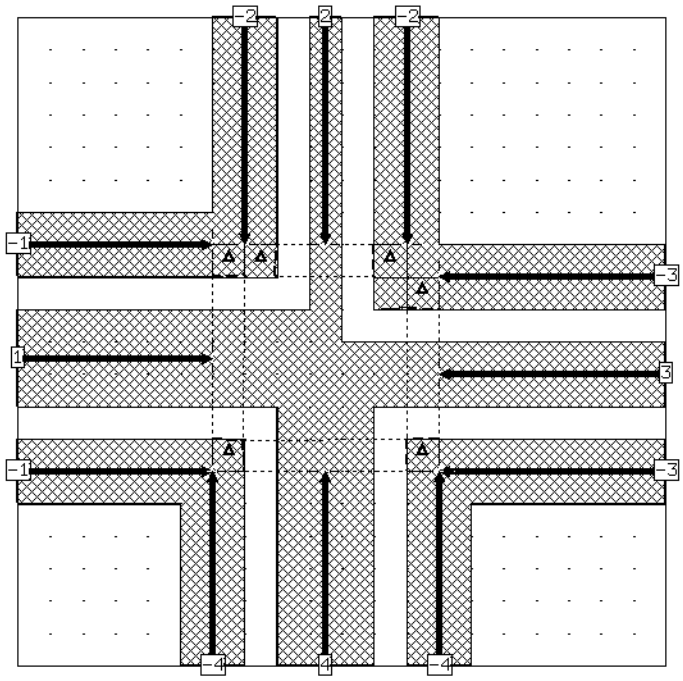


Figure 12 A coplanar cross junction with airbridges (dotted lines) to short out slot line modes and to provide a return path for current.

The air bridges are indicated by dashed lines. Both ends of each air bridge are supported by a via (indicated by the up triangle) which also provides electrical connection to the ground conductors. The air bridges are 1.5 μM above the GaAs.

This circuit is stored in the file “cocross.geo” in the examples directory.

Chapter 14 Thick Metal with Arbitrary Cross-Section

The previous chapter discussed balanced or “push-pull” ports. In this section, we will use “push-push” ports to create thick metal lines where the vertical cross-section has an arbitrary geometry.

For demonstrating this capability, we will do a simple trapezoidal geometry, the cross section shown in Figure 13.

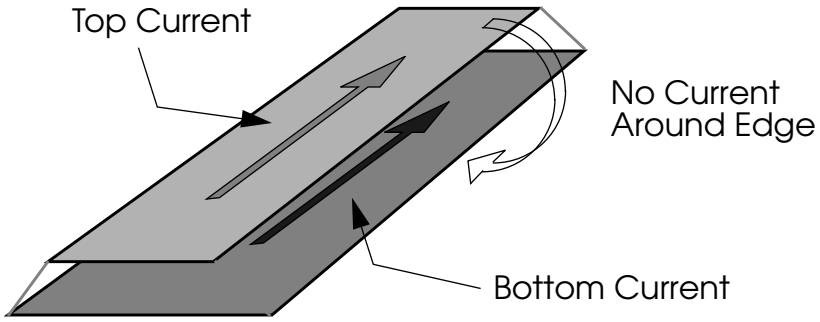


Figure 13 A trapezoidal cross-section transmission line viewed in perspective. If the line has no current going around the edge, it can be modeled, as shown, as two infinitely thin sheets of current, one at the top and the other at the bottom of the actual metal.

For the simplest possible model, we can assume that there is no current flowing around the edge of the line, orthogonal to the direction of the transmission line. In this case, there will be no need for vias to attach the top and bottom metal (shown as light and dark shaded in the figure).

Previous to release 2.2, the above model would have to have been analyzed as a four port, two ports (one for top and one for bottom metal) at each end. Then the top and bottom metal on each end would be connected together in a circuit theory based program.

Beiginning with release 2.2, just label the two ports on one side both port 1 and on the other side as both port 2. ***Em*** then automatically connects the ports together and outputs, in this case, two port S-parameters. As many physical ports as desired may be given the same numeric label, and all ports with the same label are automatically connected together. Such ports can be called “push-push”, in contrast with the “push-pull” ports of the previous chapter.

A circuit implementing the above transmission line is stored in $SONNET_DIR/examples/thkthru.geo. An analysis, using "em -vd thkthru.geo" (if the .geo file is in your current directory) yields:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 0.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 0.311259 -125,5 0.950325 144.54 0.950325 144.54 0.311259 -125.5
! Eeff = (  7.62), Z0 = (   26.47).
! Eeff = (  7.62), Z0 = (   26.47).
```

For extremely thick lines, where the assumption that there is no current wrapping around the edge might not be valid, vias must be included along the edges of the line so that current flowing there is included. Note that vias, representing Z-directed current, are not needed to represent current flowing along the edge of the line. They are only needed for current which flows over and around the edge of the line, a rare and unusual situation.

If a more detailed, "arbitrary" cross-section is desired, one can use more than two levels of infinitely thin metal to model the cross-section. Don't place metal on the interior (i.e., metal which is not on the top, bottom or edge) of the thick line, there is no current inside a good conductor and there is no need to waste subsections there.

When a discontinuity is encountered in thick metal, vias probably should be included between the top and bottom metal as current may need to flow up or down at that point. Also if a line is longer than about an eighth wavelength, it would be a good idea to "tack" the top and bottom together with vias periodically to prevent unexpected resonances.

The example directory contains an example of a thick step junction, file thkstep.geo. An analysis of that file with de-embedding gives:

```
.
.
.
! S-Parameters, Magnitude/Angle, Matrix order, Normalized to 50 Ohms.
! AUTOMATIC DE-EMBEDDING IN EFFECT
! Reference plane offsets: 0.000000 0.000000 0.000000 0.000000 (mils)
# GHZ S MA
10.0000000 0.252715 -107.8 0.967549 -19.64 0.967549 -19.64 0.252715 -111.5
! Eeff = (  7.70), Z0 = (   26.67).
! Eeff = (  8.24), Z0 = (   16.60).
```

Chapter 15 Determination of Package Resonances

The microwave circuit is designed, fabricated and meets all specifications. So put it in the package, button it up and ship it. Right?

Of course not. The circuit has to work in the package. Once the lid goes on, it must be tested. What could possibly go wrong? Package resonances and chip-to-chip coupling could go wrong. And when you are just about to ship is the wrong time for something to go wrong.

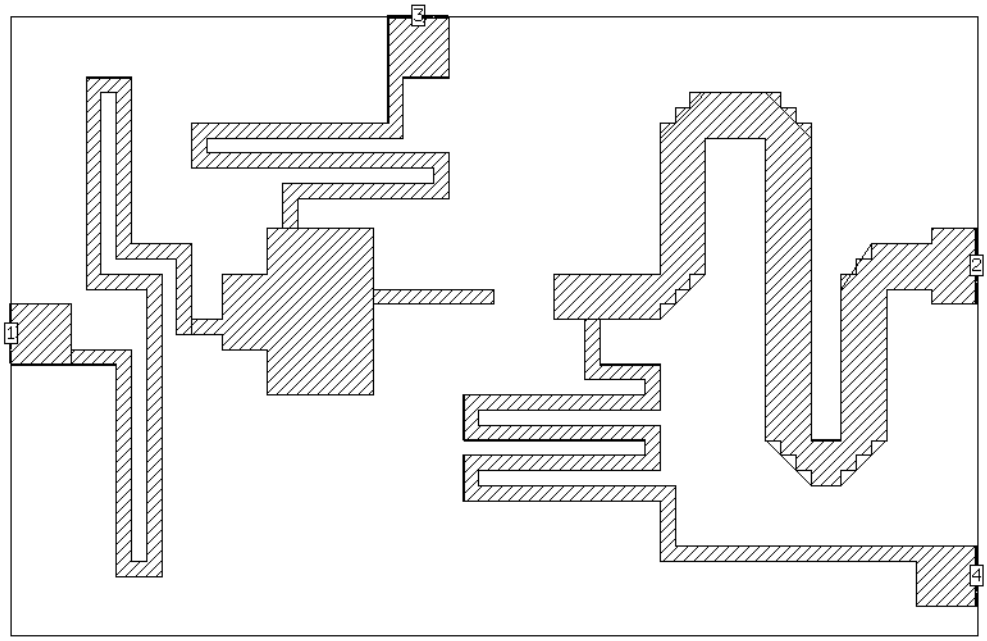


Figure 14 A model of an amplifier to check for package resonances.

Em can help with the package design. You can find out, on the computer, early in the design cycle, if the package is going to have resonances that are of any concern. As an example, we analyzed a model of an amplifier (see Figure 14). The circuit is stored in the file "package.geo" in $SONNET_DIR/examples directory.

We have left the transistor location open in this circuit for two reasons. First, ***em*** can not do active devices (if you want to use a circuit theory program to include a transistor, place via ports here). Second, if there is a resonance, it will show up as a value of S21 approaching unity. This indicates a strong, package resonance induced, coupling between input and output. And this means problems!

We have also included the bias lines (ports 3 and 4) to make sure that a package resonance doesn't kill the bias isolation. Feedback through bias leads is a significant cause of low frequency oscillations and smoked devices!

The amplifier model is only approximate, we don't need exact line widths and precise layout. The purpose of this analysis is only to check for resonances. The detail used in this case is probably more than is needed. A simpler circuit should be sufficient for a package resonance search.

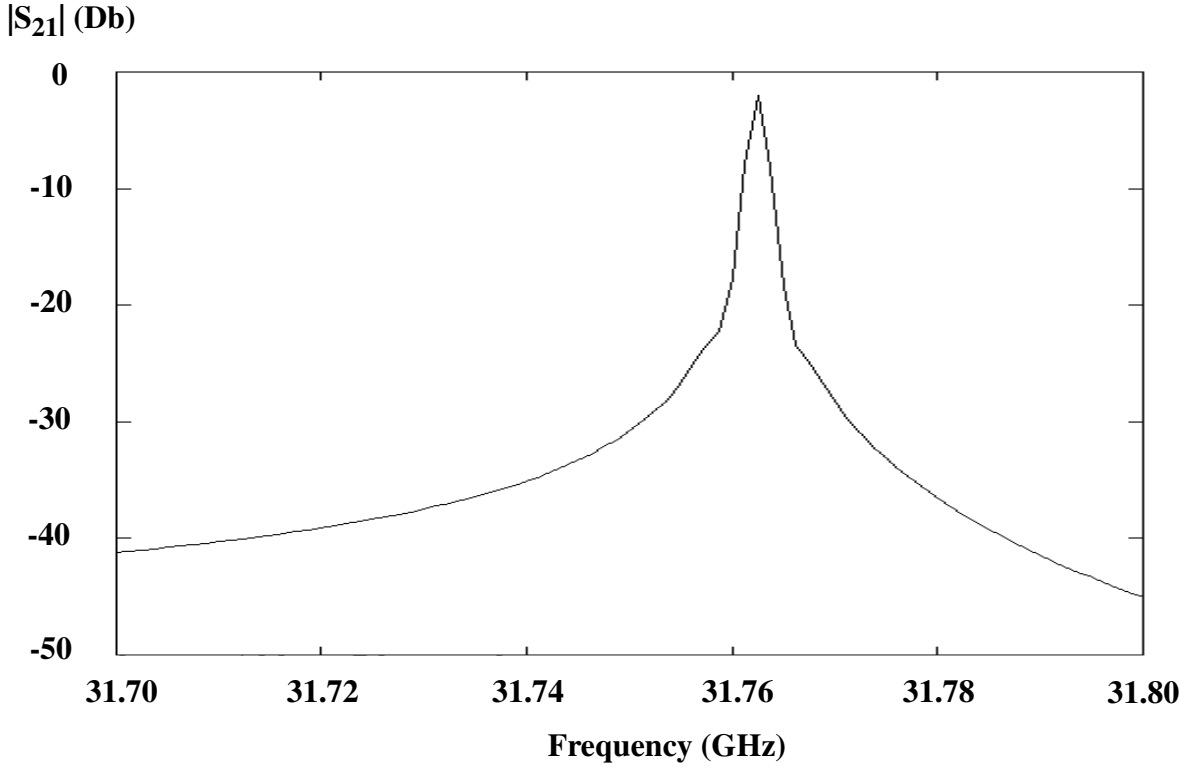


Figure 15 Results of a search for package resonances shows strong coupling between input and output at 31.7625 GHz.

The lowest resonance found was at 31.7625 GHz (see Figure 15). There may be other resonances, the search was not exhaustive. Coupling between bias ports (not shown) also becomes large at resonance, making instability a virtual certainty. In addition to searching for resonances by looking at the S-parameters, as we have done here, we can also search for resonances by invoking the "-b" option. The "-b" option is described in section "Verifying the Box Resonance Problem" on page 40.

This package has big problems at resonance. Fortunately, with the ***em*** analysis in hand, modifications can be made and tested before costly fabrication.

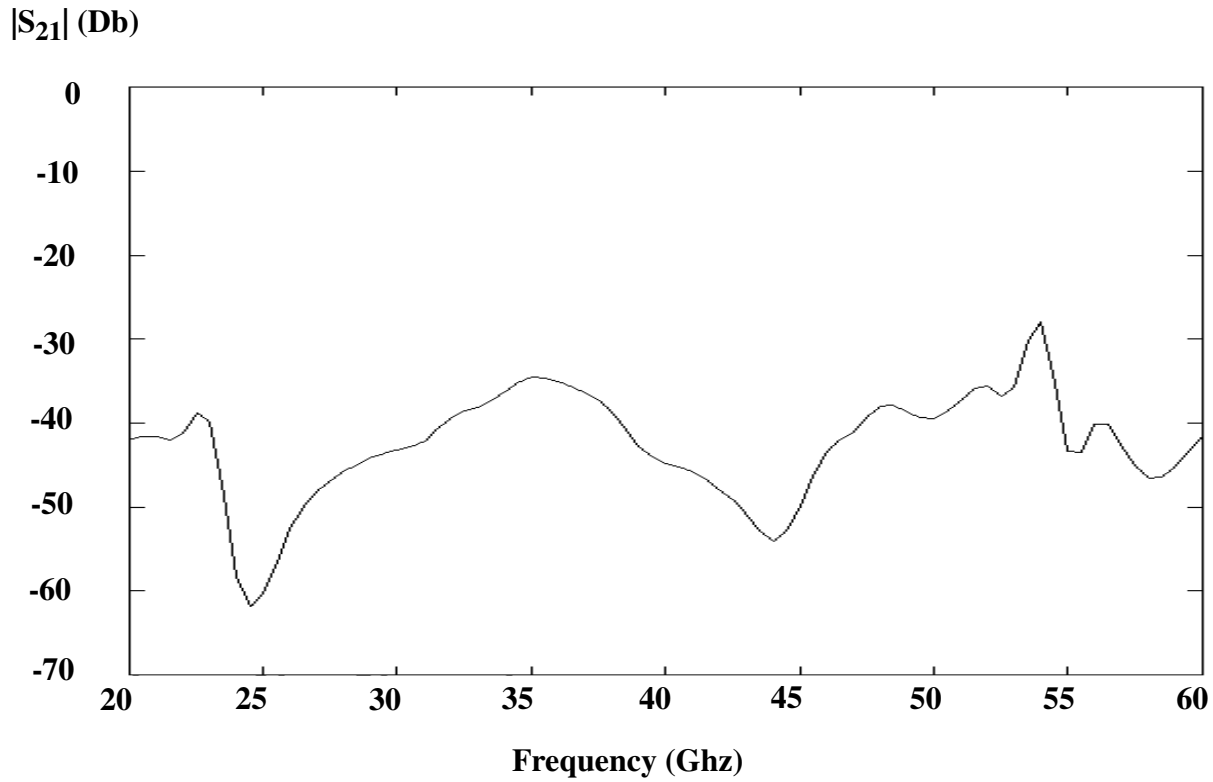


Figure 16 The package resonances disappear when the top cover is removed.

A second analysis was performed from 30 GHz to 60 GHz with the top cover removed (i.e., resistivity set to 377 ohms/square). This analysis showed several low Q (wide bandwidth) resonances, none of which exceeded 35 dB down (see Figure 16).

To aid the user in finding box resonances, you may also invoke the “-b” option discussed in the section "Verifying the Box Resonance Problem" on page 40. With this option, box resonances are detected and listed in the output file.

A related application of this analysis is to use the circuit package as the resonant, frequency determining element in an oscillator design.

Chapter 16 Antennas and Radiation

Analysis of radiation is not the primary thrust of ***em***, however, there are several classes of radiation problems that can be solved reasonably well using ***em***. The presence of sidewalls in the analysis determines the class of radiation problems that ***em*** can handle. If radiation is by means of a surface wave, traveling along the substrate, the surface wave is reflected by the sidewall. It may be possible to achieve some degree of analysis of surface wave radiators by placing a resistive screen of subsections and vias just in front of a sidewall. This technique has not yet been explored.

♦ Resistive Top Cover Technique

However, if the sidewall is placed a significant distance from the antenna (so that the sidewall does not influence radiation) and most of the radiation is by a space wave, ***em*** can provide reasonable results.

The sidewall effect is actually desired in another class of problems, waveguide simulators. A waveguide simulator uses the images from the sidewalls of a waveguide to simulate an infinite array. For this class of problems, use the sidewalls of the box as the

waveguide and place the top cover at a large distance from the substrate surface. Set the top cover surface impedance equal to the excited waveguide mode impedance. This simulates an infinite waveguide.

For non-surface wave radiators, the sidewalls must be moved far from the antenna. This has two effects. First, the influence of the sidewalls on the antenna are reduced. Second, it allows the sidewalls to form a propagating waveguide for a large number of waveguide modes.

The “radiation” is accomplished by setting the top cover to 377 ohms/square. (the impedance of free space). This is the technique used in the previous section to reduce the waveguide modes. The 377 ohms/square approximates an open ended waveguide (which is *not* a perfect radiator!). Since some waveguide modes have an impedance greater than 377 and others are less than 377, this forms a nice compromise. As the dimensions of the waveguide become very large with respect to wavelength (the desired situation), all waveguide modes, in air, approach 377 ohms. This technique fails if the sidewalls of the box are so close that they form a cut-off waveguide.

Make sure that the top cover is not too close to the radiator. As the resistive top cover becomes involved in the reactive fringing fields of the radiator, it changes the reactive input impedance into resistive input impedance, an undesired situation. Keep the top cover at least one substrate thickness away from the radiator.

♦ Lossy Dielectric Technique

A modification of this approach, which can cause the complete absorption of all the propagating (quasi-radiating) waveguide modes is to place an extremely thick layer of slightly lossy dielectric starting about one substrate thickness above the radiator and ending at the resistive top cover. This is the technique used in $SONNET_DIR/examples/patch.geo. This is a double patch antenna (see Figure 16).

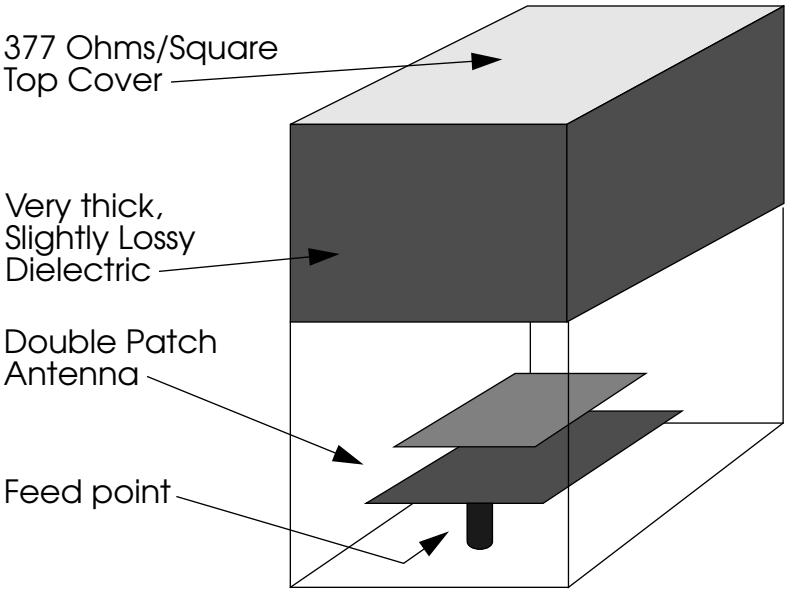


Figure 17 Radiation can be simulated by including a lossy top cover, a lossy dielectric layer and by placing the sidewalls far from the radiator (drawing not to scale!).

The antenna in patch.geo has two patches, one directly above the other. The lower patch is fed with a via port while the upper patch is capacitively coupled to the lower patch. The intent is to obtain a double resonance.

Only the top half of the antenna was captured. Since it is symmetrical and symmetry is turned on, this is acceptable. ***Em*** ignores the bottom half when subsectioning a symmetric circuit.

The antenna is fed by a via. To add the via, position a polygon directly on the ground level. We used a polygon smaller than the cell size but the results would be the same for a polygon as large as one cell. The ground polygon is not subsectioned, because there is already metal covering the entire ground level. However the polygon provides a polygon edge which can be changed to an edge-via. Use *Objects* ⇒ *Vias* ⇒ *Add* to add an edge-via to an edge of the polygon. Then also add a port to the same polygon edge. You now have a via port which feeds the patch antenna.

To make sure we have radiation, the antenna, with a largest dimension of 32 mm, is placed no closer than 30 mm to any sidewall. If more accuracy is desired, larger distances may be advisable. The two substrates are each about 0.5 mm thick. The lossy dielectric layer starts at 4.0 mm above the top patch and is a full 100 meters thick with a loss tangent of 0.001. The large thickness has no impact on analysis time, it simply changes the argument to a tangent function. This thick layer, topped with a 377 ohms per square cover, forms a dummy load, absorbing any “radiation”.

The antenna was described in May 1990, AP Transactions, pp. 612-614. Measured versus calculated is shown in Figure 16.

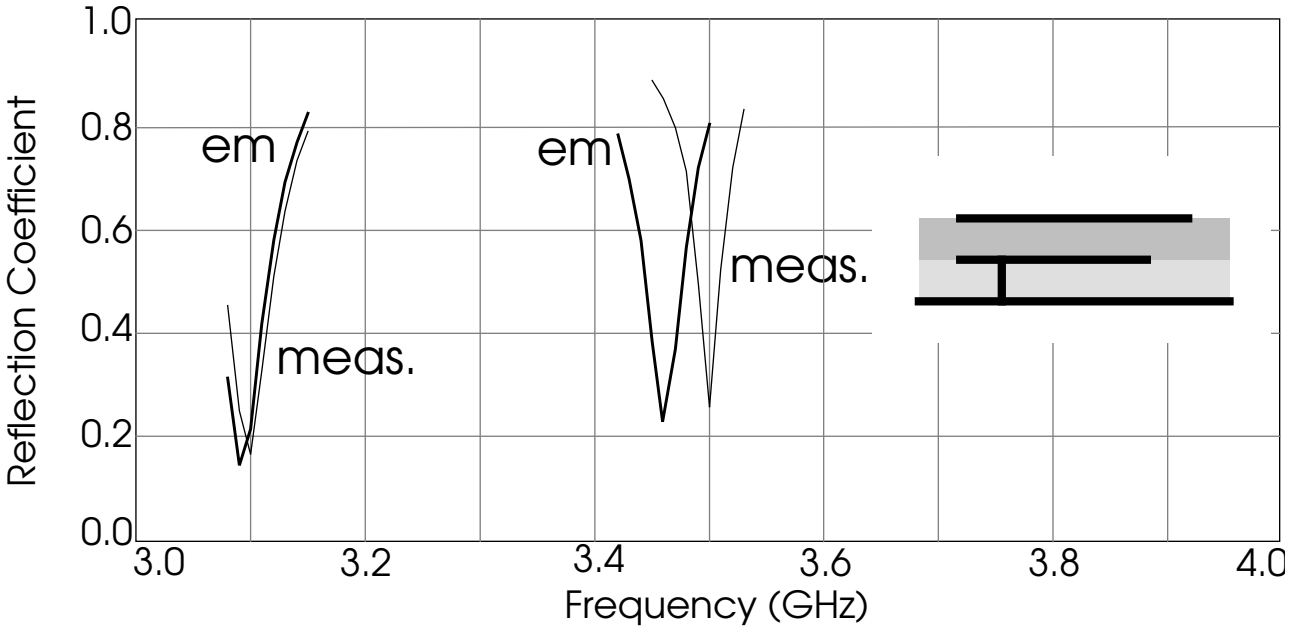


Figure 18 Measured versus calculated for a dual patch antenna. For the higher resonance, the difference is about 2%.

The authors of the above paper mention that adhesive layers are included in the actual antenna, however no details are given so they could not be included above. In addition, the amount of shunt capacitance in the feed connector was not measured and, thus, could not be corrected in the analysis. Since ***em*** can not presently de-embed via ports, de-embedding was not used for this analysis.

Radiation from discontinuities can, with care, also be evaluated in the same manner as radiation from antennas.

Chapter 17 A Simple Accuracy Test

The file "$SONNET_DIR/examples/cal_thru.geo" provides a simple but very precise test of ***em***'s accuracy. It is just a thru connection de-embedded with zero reference plane length. The reason it is precise is that it uses an air dielectric everywhere. Thus the velocity of propagation is precisely the speed of light (2.997925×10^{10} cm/S).

The length of the line is set to 7.494812 mm so that it is exactly 90 degrees long at 10 GHz. This is long enough that the ports do not interact. The line width is set to 1.0 mm with the "substrate" thickness adjusted for 50 ohms (zero reflection) at low frequency, 0.206 mm. Automatic de-embedding (the "-d" option) is invoked in the ***em*** analysis run.

Since the dielectric is homogeneous (air everywhere), there can be no dispersion. Thus any variation in characteristic impedance is error. We also know exactly (to seven places) what the phase of S_{21} should be. Any deviation is error. Further, we have all this information without any measurements and far more accurately than could possibly be obtained by the usual microwave measurement techniques.

At 10 GHz, the phase error is 0.1 percent which is typical up to 40 GHz. Above that frequency, error increases to about 1 percent as we encounter box resonances (which may be removed using the technique described in a previous section). Zo is within 0.3 ohm (0.6 percent error) of 50 ohms over most of the range.

A similar test for vias may be realized by constructing a vertical microstrip line with the above dimensions, 0.206 mm from a sidewall. The box sidewall becomes the ground plane. Set one end of the via line to be a port. There is a small shunt capacitance associated with the port which, for horizontal lines, is normally removed by the automatic de-embedding. There is no automatic de-embedding for via ports (yet), so just analyze two different lengths and plot the phase versus length. The slope of the line is the speed of light. Answers are typically within 0.1%.

One might suspect that this is an overly simple test, not indicative of true microstrip performance. We point out that this is a necessary test (no test is sufficient) for validation of microstrip performance. An air substrate is a special case of microstrip.

That this is not a trivial test becomes apparent when applied to several other well known electromagnetic microstrip analysis programs. They can fail the test dramatically. We recommend you try this test on any such program to which you have access. The results may be surprising.

Chapter 18 Range of Analysis Validity

There are only two approximations used by ***em***. First, ***em*** subdivides the metallization into small subsections. Second, the coupling between subsections is an infinite summation which ***em*** truncates. The user has full control over both approximations.

The number of terms taken in the infinite summation has little impact on execution time (try it!). In addition, nearly full accuracy is obtained, even at minimum setting. ***Em***'s -c option determines the number of terms taken. For example, -c2 takes four times the number of terms over -c1, while -c3 includes nine times the number of terms. Default is -c2. The -c option is of little concern.

In contrast, the cell size is important. By using a smaller cell size, metal edges can be more accurately defined and the microstrip current distribution is better represented. Both effects improve the accuracy of the result. The trade-off is increased execution time.

The trade-off between execution time and accuracy increases the degrees of freedom available to the microwave design engineer. With previous software, if additional accuracy is needed (and when is it not needed?), the designer is stymied. With such software, the accuracy you get is what you have to take. Period.

♦ Subsection Size

There are actually two limits on subsection size, a minimum and a maximum. When we refer to a cell, we have in mind the minimum limit. For example, a circuit may cover 10,000 cells. ***Em*** can use variable size cells, which we refer to as subsections. That same 10,000 cell circuit could be subsectioned into only 200 variable sized subsections. The maximum limit determines the size of the largest subsection (which may cover many cells).

With a maximum frequency in mind, the cell size should be set so that a single cell is no more than a fraction of a wavelength at the maximum frequency of analysis.

The maximum subsection size is usually specified in terms of subsections per wavelength. For most circuits 10 or 20 subsections per wavelength provide good results. A large value, say 40,000 per wavelength assures that the cell size and subsection size are everywhere the same. If the cell size is larger than the specified number of subsections per wavelength, the subsections per wavelength specification is ignored.

In the limit, as subsection size (both maximum and minimum) is made smaller, the ***em*** analysis is asymptotically exact. Given sufficient computer resources, an arbitrarily accurate answer may be achieved. The convergence of the answer, as a function of cell size, is extremely fast.

♦ Metallization and Dielectric Thickness

The analysis assumes zero metallization thickness. This could result in some discrepancy for thick lines which are tightly coupled. An approximation for metallization thickness is to have two zero thickness metallization levels, one at the top and the other at the bottom of the actual metallization. Layer to layer vias may be used to form the sides of the thick lines.

Dielectric layer thickness and dielectric constant have no impact on the accuracy. The substrate area also has no impact on accuracy, however, it does have a secondary impact on analysis time.

All coupling between all subsections is calculated and included in the analysis, even coupling between patches of metallization which are not connected to anything.

♦ Numerical Precision

Em will experience a numerical precision problem (difference between two large numbers) if the subsection size gets too small. For example, if the subsection size is several microns and the frequency is a few kiloHertz, there will be precision problems. The results quickly become obviously bad. A higher frequency of analysis solves the problem. The subsection becomes larger, in terms of wavelengths.

The precision problem also arises with vias. This is especially true if, in addition to the small cell size, if the via is in a thin layer, say a micron or less, unreasonable results are seen as high as several hundred MHz, or even 1 GHz. The net effect of the loss of precision makes the via appear to have a very long phase length. These problems become worse if the -m (single precision) is used.

Em is a complete electromagnetic analysis, all electromagnetic effects, such as dispersion, loss, stray coupling, etc., are included.

Chapter 19 Time Required for Analysis

Em is a memory and computation intensive program. Small circuits are analyzed quickly while large circuits can require a considerable amount of time. In some cases, it may be desirable to run the program in background (i.e., under Unix, end the command line with an ampersand, "&").

There is no simple rule for calculating the time required for a particular analysis so some guidelines are presented.

The amount of time required is closely related to the number of subsections, which is printed out when ***em*** is run with the -v option. After a few trials, you will have a good idea of whether an analysis is a few seconds, a few hours, or just totally hopeless by looking at the number of subsections.

The most important factor in the execution time required is the amount of memory required by ***em*** compared with the amount of memory you have. This is also printed out by ***em*** if you use the-v option. If ***em*** says you need 36 Mbytes and you have 16 Mbytes installed, kill the run quickly! You can reduce the memory required by using the -m, memory saver, option, which makes the analysis single precision. You can also try to reduce the area of metallization in the circuit. Try to eliminate any metal that is not carrying current and make connecting lines as short as possible (but not too short, see the chapters on de-embedding).

Another approach, if your memory requirement is right on the edge, is to free up some of your computer's memory. Make sure no one else is also running a big number cruncher at the same time. Also, if you have a window system running, take it down before starting your job.

The estimate of required memory printed out by ***em*** is just an estimate. It is usually within 1 Mbyte or so, but could be off by more. To get both the memory estimate and the number of subsections without going on to actually analyze the circuit, use the -N option.

You can check the memory actually used by typing the "ps" (process status) command. Consult your system administrator or UNIX manuals for details on the "ps" command.

♦ The "Wall"

When using circuit theory analysis, an increase in circuit complexity gradually produces an increase in analysis time. With an electromagnetic analysis, the increase happens suddenly. A mere doubling of circuit complexity (say, by using a smaller subsection size) can result in one, or even two, orders of magnitude longer analysis. We call this the "Wall" (see Figure 19).

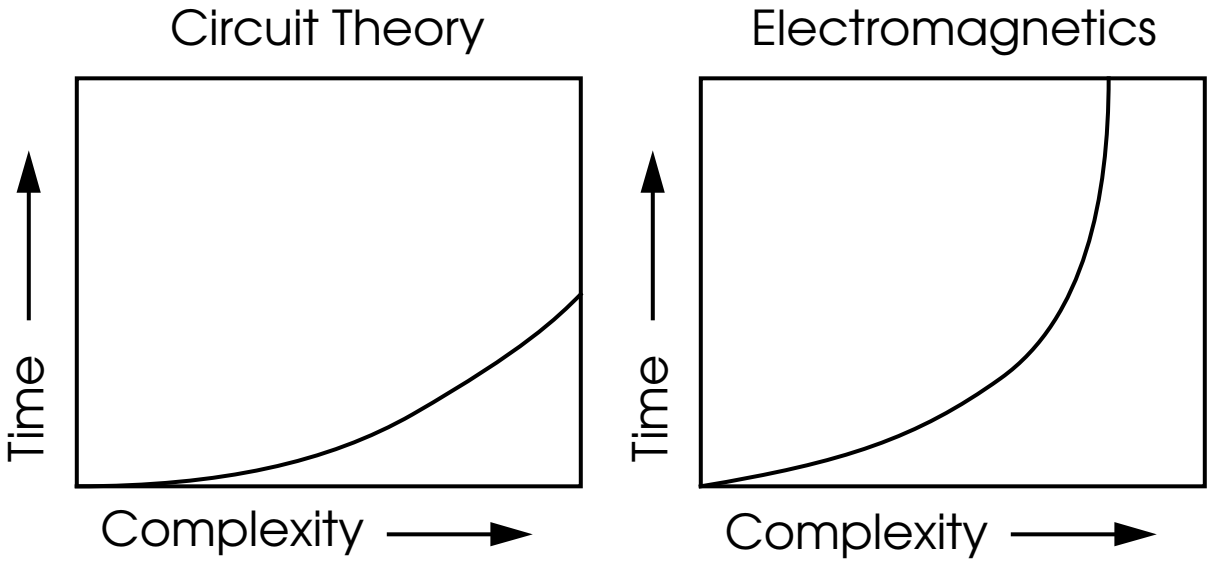


Figure 19 Circuit theory analysis time increases slowly with respect to circuit complexity. Electromagnetic analyses run into the "Wall" at some point.

The Wall is frequently encountered when ***em*** runs out of real memory, as described above, and is forced to start swapping out to disk. Execution time can quickly go from a few minutes to a few hours. Either get more memory or modify the circuit so that there are fewer subsections.

To avoid the wall, *start with no loss (metal or dielectric) and use a large subsection size*. Perform the first analysis at a single frequency to evaluate how long an analysis will take. Then, provided you get fast results, try adding loss or making subsection size smaller. Keep going until the analysis is as long as you can tolerate and then let it run over a full range of frequencies, perhaps overnight.

The main factor in an analysis time is the number of subsections. ***Em*** prints out the number of subsections if the "-v" option is used. As you gain experience with ***em***, you will get a good feel for what can be tolerated. For example, on a Sun SPARCstation 1 with16 Mbytes of memory, up to 1700 subsections (lossless) or 1200 subsections (with loss) can be calculated in an hour or so. At this point the computer runs out of memory and starts swapping to disk, resulting in huge increases in time. As you gain experience, you will have a good feel for what your computer can do.

To avoid the frustrations of getting on the slow side of the wall, *start lossless with big subsections*. You may find the big subsections provide all the accuracy you need!

♦ Detailed Parameter Dependencies

How do changes in the various input parameters affect the analysis time?

First, keep in mind that ***em*** has two stages in the analysis. In the first stage, ***em*** fills a large matrix. The matrix has one row/column for each subsection. This is where ***em*** is calculating the coupling between every possible pair of subsections. In the second stage, ***em*** is solving the matrix. Here, ***em*** is performing matrix inversion-like functions and is calculating the currents which allow all boundary conditions to be met. The different parameters affect each stage of the analysis differently.

Parameters which have no effect include the substrate thickness, cover height and number of ports. Each of these parameters is unlimited and have no impact on speed while still maintaining complete accuracy.

Including metallization loss increases the execution time of the final matrix reduction only. And this is only if the rest of the structure is lossless. If there is any dielectric loss or ground plane (or top cover) loss, there is virtually no additional impact from also including metallization loss (the whole calculation is already full complex). The matrix solution time is increased by about a factor of four (it becomes complex). Metallization loss has no impact on any other segment of the analysis.

Including dielectric loss, or ground plane or top cover loss, makes the entire calculation complex. The matrix solution time is increased by about a factor of four, while the rest of the analysis is increased by about a factor of two.

In calculating the values for the matrix elements during the matrix fill, several two dimensional DFT's (Discrete Fourier Transform) must be calculated. The size of the DFT's are the same size as the substrate in terms of cells. If a substrate is 128 x 64 cell, each DFT is 128 x 64 elements. Memory storage is required for only one DFT at a time and this is usually much smaller than the matrix being filled.

For large substrate dimensions (as measured in terms of cells), it is best to use a power of two. With a substrate dimension of 32 cells, little difference will be noticed if a power of two is not used. However if the substrate dimension is 512 cells, noticeably slower execution results if one were to use 500 cells. With a power of two, the FFT algorithm is automatically used to evaluate the DFT

Normally there are three DFT's performed. One for X current to X current coupling. A second for Y current to Y current coupling. The third is for X to Y current coupling. If there is more than one layer, the coupling between every possible pair of layers is also calculated, with another three DFT's for each coupling. If corner fill is used, there are now four kinds of subsections between which coupling must be calculated (10 DFT's). If triangle fill is used, there are another two kinds of subsections and vias require one more kind subsection.

For all the above detail, keep in mind that, unless the substrate is large (greater than 256x256 cells), the FFT time is of little consequence.

The matrix load time is proportional to the number of subsections squared for large circuits.

The matrix load time is also proportional to the square of the number of metallization levels which actually have metallization on them. Levels with no metallization have virtually no impact on analysis time.

The number of subsections, for a given cell size, can be reduced by minimizing the number of vertices and the number of diagonal lines in the polygonal description of the circuit. If the circuit is symmetric with no more than two ports, with both ports on the axis of symmetry, invoke the symmetry option for a significant memory and time savings.

The matrix reduction goes with the number of subsections cubed and is the main limitation on the analysis at this time. A practical limit for typical workstations (SPARCstation 1 class) is about 2,000 subsections.

Appendix I The *Em* Command Line

NAME: ***em*** - Electromagnetic analysis of microstrip circuits.

SYNOPSIS: ***em*** [-options] [files]

DESCRIPTION: ***Em*** performs an electromagnetic analysis of shielded microstrip circuits. The circuit geometry is subdivided into small rectangles. The analysis calculates the N-port circuit parameters (e.g., S-parameters) and is described in the "***Em* User's Manual**". The circuit geometry is stored in a file which can be created by a geometry capture program such as ***xgeom*** (see the ***Xgeom* User's Manual**).

♦ Options

-c Followed by an integer, 1-5, to indicate the number of cycles to be used in the modal summation. Values outside the valid range are limited to within the range. Larger numbers give slightly more precise answers. Default is 2.

-m Memory saver option. The system matrix is filled in single precision which reduces memory requirements for storing the matrix to one half of that of double precision. On Sun SPARCstations, matrix solution time is twice as fast. On Cray computers, this option has no effect. If this option is not used, the matrix is stored in double precision.

-s
-y
-z
N-port circuit parameters are stored in S, Y or Z parameter form. The default is -s. The Y and Z parameters may be normalized to 50.00 Ohms depending on the microwave circuit analysis software vendor (see -CT).

-G
-M
Select GHz or MHz for the circuit response file listing. If neither option is used, the frequency units default to those last used in the analysis file. If no frequency units were explicitly specified in the analysis control file, MHz is used. This option has no effect on information specified in the analysis control file.

-C
-T
Store the circuit response information in Super-Compact (-C) or Touchstone (-T) format. Default for this option is Touchstone.

-n
Specify a name for the circuit file (used with -C). For example, -nfilter.

-r
Specify the file for circuit response (usually S-parameter) data. Default file is “cir.rsp”. Specifying a command line file name which ends with a period followed by “rsp” is equivalent to specifying the option. This option is usually used when the desired response file does not end with “.rsp” or “.d”, for example, -ranswer.s2p.

-g
Specify the file for circuit geometry. Default file is “cir.geo”. Specifying a command line file name which ends with a period followed by “geo” is equivalent to specifying the option.

-a
Specify the file for the analysis parameters (usually frequencies for analysis). Default file is “ctl.an”. Specifying a command line file name which ends with a period followed by “an” is equivalent to specifying the option. Similar to -r except the file “stdin” may be specified. If the option “-astdin” is specified or if the analysis control file does not exist, the user is prompted for a start stop and step frequency in MHz.

-v
Verbose mode, display messages during program execution describing the current state of the analysis.

-j
Outputs current density information for the entire circuit. Default file name is cir.jxy. Specifying a command line file name which ends with a period followed by “jxy” is equivalent to specifying the option.

-N
Calculates the number of subsections followed by an estimate of the number of Mbytes of memory required. The analysis is not performed.

-Q
Suppress printing of the license. Use of this option indicates that you agree to the terms of the license.

-d
The circuit is automatically de-embedded to the specified reference planes (see the geometry file description). This is the only case in which the reference plane information is used and is called automatic de-embedding. Specifying a command line file name which ends with a

period followed by “d” is equivalent to specifying the option. For example, “em -vd thru.geo” places the automatically de-embedded S-parameters in “cir.rsp” while “em -v thru.geo thru.d” places the same results in “thru.d”.

-b Detects potential box resonances, prints out warning message just before S-parameter data in .rsp file.

-B Same as -b except, in addition, it tries to remove the offending waveguide mode. Bad data may result if used in conjunction with the -d option.

-Ver Prints out the current version of ***em*** and license id and exits. Must be the first option on the command line. All other options are ignored.

The following files may be specified on the command line:

Analysis Control File:

Default name “ctl.an”, the file name should end with “.an”, otherwise, the file name must be specified with the -a option. This file can set the frequencies for analysis, among other things. If the file does not exist, the user is prompted for a start, stop and step frequency in MHz.

Circuit Geometry File:

Default name “cir.geo”, the file name should end with “.geo”, otherwise, the file name must be specified with the -g option. The circuit geometry file can be created with a geometry capture program such as ***xgeom***, see the ***Xgeom*** **User’s Manual**. If the circuit geometry file does not exist, ***em*** terminates.

Circuit Response File:

Default name “cir.rsp”, the file name should end with “.rsp”. If the file ends with “.d”, automatic de-embedding is enabled. Otherwise, the file name must be specified with the -r option. This file contains the N-port circuit parameters (e.g., S-parameters) of the circuit being analyzed. This file can be used for input directly to any of a number of microwave circuit analysis programs.

Current Density File:

Default name “cir.jxy”, the file name should end with “.jxy”. This file stores current density information on the file for later viewing. Analysis time is increased by this option and the file can take up a large amount of disc space if the circuit is large with many ports.

EXAMPLES:

em -v sscross.geo

Analyze the circuit in sscross.geo and append the result to file cir.rsp using the analysis control parameters in ctl.an. Print out the status of the analysis as it executes.

em -r../cap.mim -yd

Analyze the circuit in cir.geo with the answer going to cap.mim in the directory one level up using the analysis control information in ctl.an. The output is to be in y parameters and automatic de-embedding is invoked.

Appendix II The Analysis Control File Format

The analysis control file controls the frequencies used for analysis as well as other analysis parameters. The file may have any name ending with ".an". If the analysis control file name does not end with ".an", the file name must be specified with the -a option, for example: ***em*** -aanalysis.file. If no file name is specified in the command line, ***em*** looks for "ctl.an" in the current directory. If that file is not found or if the file is specified as "stdin" (with the ***em*** -a option), ***Em*** interactively asks the user for the frequencies of analysis.

Any line with a first non-space character of "!" is ignored. Any blank line is also ignored. Comments following any complete line of data are allowed.

In the keywords that follow, only the first three letters are significant. Additional letters may be used but they do not alter the program's execution. For example, "VER", "VERSION", and "VERTRFGH" all have the same effect. There may be no more than 255 characters per line.

VER Any line with the first three characters "VER" is taken to specify the ***em*** version number. Up to five characters following the end of the first space characters following "VER" are read into ***em***. This information is required for compatibility with future versions. The VER line should be the first non-comment line in the file.

ANN When the response file is created, the analysis parameter file is searched for any lines beginning with ANN. The remainder of any lines found are listed in the heading of the circuit response file. This is useful for the automatic documentation of the ***em*** analysis output.

CYC The number of cycles for the modal summation may be specified on a line starting with "CYC". Default is 2. The number of cycles (1-5) must follow on the same line. If the number of cycles is outside of the proper range, it is limited to within that range. The analysis is slightly more precise with more cycles. The number of cycles can also be specified on the command line and if it is, it will take precedence over the specification in the analysis file.

GHZ
MHZ Frequency units can be specified by a line with "MHZ" or "GHZ". The frequency units can be changed as often as desired within the same analysis file. All frequencies specified on a FRE line must be in the units most recently specified. If no units have been specified, MHz is assumed. If no frequency units were specified in the command line, the frequency units in effect at the end of the analysis file is used for the circuit response file. Frequency units specified in the command line have no effect on how the analysis file is read.

FRE A line starting with FRE specifies a list of analysis frequencies. FRE may be followed by one, two or three numbers. One or two numbers specify one or two frequencies. Three numbers specify a start, stop and step. The start, stop and step are all checked for error conditions. When the file is complete, the frequency list is sorted. As many FRE lines may be used as is needed. Duplicate frequencies are not removed. There is no limit on the number of frequencies.

Appendix III The Circuit Geometry File Format

The circuit geometry file specifies the circuit geometry to be analyzed by ***em***. The geometry of the metallization is represented in terms of polygons. Any part of a polygon outside the box is ignored by ***em***. The coordinates of the polygon vertices are called out in terms of actual dimensions using floating point values. The polygons are automatically subsectioned by ***em*** for analysis. Polygons with dimensions smaller than the selected resolution can provide unreliable results.

The file can be created by means of a geometry capture program such as ***xgeom*** (see the ***Xgeom*** **User's Manual**). Other information, including the box dimensions and substrate parameters, are also specified. The experienced user may want to make minor modifications to a specific geometry file without going thru the geometry capture program. With this in mind, the file format has been set up to be as forgiving as possible, but keep in mind that it is still possible to corrupt the file in a manner which will not be detected by the analysis software. For this reason, only experienced users should attempt any modification.

The file may have any name ending with ".geo". Otherwise, the file name must be specified with the -g option, for example: "em -gcircuit.file". If no file name is specified in the command line, ***em*** looks for "cir.geo" in the current directory. If that file is not found, ***em*** terminates with an error message directed to standard error (which is usually your computer screen).

Any line with a first non-space character of "!" is ignored. Any blank line is also ignored. Comments following any complete line of data are allowed. Comments are not allowed in the polygon vertex lists.

In the keywords that follow, only the first three letters are significant. Additional letters may be used but they do not alter the program's execution. For example, "VER", "VERSION", and "VERTRFGH" all have the same effect. There may be no more than 255 characters per line. The following description is for version 2.2.

VER Any line with the first three characters "VER" will be taken to specify the ***em*** version number. Up to five characters following the end of the first space characters following "VER" are read into ***Em***. This information is required for compatibility with future versions. The VER line should be the first non-comment line in the file.

LIC Followed by a string representing the license id number. This string is output to the heading of the circuit response file. If the value is unknown, then ***xgeom*** uses the string "UNKNOWN".

DAT Followed by a string the last date the file was changed. This string is output to the heading of the circuit response file.

ANN When the circuit response file is created, the circuit geometry file is searched for any lines beginning with ANN. The remainder of any lines found are listed in the heading of the circuit response file. This is useful for the automatic documentation of the ***em*** analysis output.

LEN The length units used in the file (see BOX below) are specified by a line beginning with LEN followed by two items. The first is up to six letters representing the unit. The last item is a conversion constant which, when multiplied by a length in the specified units yields meters. For example -- LEN mm 0.001. Only one LEN line is allowed per file and, if present, it must be before the BOX line. If not present, LEN mils 0.0000254 is assumed.

BOX The dimensions of the box and the parameters of the enclosed substrates are described starting with a line whose first non-space characters are "BOX". BOX is followed by at least five numbers with one more optional. First is the number of metallization levels (= 1, if using standard microstrip). Next come the A and B dimensions of the substrate surface given in the units specified by the LEN statement. These are followed by the integer size of the substrate along the A and B dimensions. These integers must be even. The smallest possible subsection dimension (i.e., the resolution) is equal to two units in each dimension. The final number is optional. It is an integer which sets the minimum density of subsections per wavelength. Default is 20 subsections per wavelength, with anything below 6 set to 6. The wavelength

used is a simple average of the dielectric constant (and magnetic permeability) over all dielectric layers (i.e., constants are summed and divided by the number of layers, air included).

The next lines provide information on each of the dielectric layers in the box. Each line has the thickness of the layer (in the units previously specified) followed by the relative dielectric constant followed by the relative permeability of the layer. The dielectric loss tangent and the magnetic loss tangent follow. All items except the substrate thickness are optional. Default is lossless free space. Only one dielectric layer per line is allowed.

SYM If the circuit AND excitation are symmetric about the center line parallel to the X axis, a significant reduction in computation time can be realized. To indicate this, include a line with "SYM" as the first non-space characters. In this case, a mirror image of the geometry of the half substrate with Y coordinate less than the center line is used on both halves of the substrate. Even though the data for the large Y coordinate half of the substrate is ignored, it is recommended that the data be consistent with the small Y coordinate half of the substrate so that the automatic subsectioning may proceed correctly.

REF Each side of the Box may have a reference plane offset associated with it. REF, followed by up to four numbers, indicates the reference plane offset for each side. All ports on a given side have the same offset. The first number is the offset for the x=0 side followed by the x=A, y=0 and y=B side. The offset information is used ONLY if ***em***'s "-d" option (automatic de-embedding) is used. Reference planes not specified default to zero. The reference planes are floating point numbers, in the units specified by LEN. The actual reference plane is moved to the nearest even integer coordinate (see BOX).

RES Needed if metallization loss is to be included. Followed by up to three real numbers, the first is the resistivity (Ohms/square) at zero frequency (equals one over the bulk conductivity times metallization thickness). The second number (if present) represents the skin effect coefficient which is multiplied by the square root of frequency in Hertz to obtain the resistivity. For example, for ideal copper, 3 mils thick, use: "RES 0.0002 2.6e-7". For equations to calculate these numbers, see section "Menu: Param - Metallization" on page 79 in the ***Xgeom*** **User's Manual**. The third, if present, is the surface reactance in Ohms/square. There is one RES line per metallization type. An index is assigned to each metallization type starting with zero and increasing according to their order of occurrence in the file.

TOP
BOT

Same as a RES line (above) except that the top or bottom plate resistivity is specified. Up to one TOP and one BOT line is allowed per file.

REN
TON
BON

Specifies the name of a RES, TOP or BOT resistivity specification. The first item is an integer representing the pattern to be used in drawing any polygon assigned to the metallization. The entire remainder of the line is used as the name of the most recent RES, TOP or BOT line. For example: “RES 0 Cap bottom plate”.

POR

Followed by three required integers. The first is the polygon number within a specific level (see NUM), starting with zero. Count only polygons on the same level as the port. The port is located along the entire length of one line segment of that polygon, the second integer indicates the number of the first vertex of that line segment in the polygon (again, starting with zero). The third integer is the metallization level on which the port is located, starting with zero. A port is usually placed at the edge of the substrate so that a connection to ground is readily available (the sidewall). Otherwise a port is placed at the junction of two polygons (each polygon has a line segment colinear with the other). In this case, the two terminals of the port are formed by the two polygons. If there is no second polygon, ***em*** terminates stating that the port has no subsections.

The ports are numbered according to their order of appearance in the file unless an optional fourth integer follows which lists the number by which the port will be known. This number cannot be zero, but may be any other value. It need not be consecutive. If the index is the same as the index of any other port, the ports will be connected together. If the index is negative, it will be connected together with any other negative indices of the same value and be used as the ground terminal for that port. Four optional floating point numbers follow representing the impedance to which the port S-parameters will be normalized. The first is resistance (ohms), the second is reactance (siemens), the third is inductance (henries) and the fourth is capacitance (farads).

VIA

Followed by three required integers. A VIA line points to a polygon edge to which ***em*** will attach vias starting on the indicated metallization level and going up exactly one layer to the next metallization level. Polygons on the bottom cover (ground plane) are used only for vias attached to ground. A edge-via on the top metallization level attaches to the top cover. The three integers are identical to those for the POR line. The same polygon edge may be both a edge-via and a port. If a via is a port, it should be attached to bottom (or top) cover.

NUM Followed on the same line by a single required number, the total number of polygons in the file. The next line (blank lines and comments not allowed) describes the first polygon. The first number is the metallization level number (starting with zero). The second is the number of x,y point pairs. The third item is the metallization index, default is lossless (= -1). The fourth item is optional and indicates the edge fill mode. Default (or "N" or "n") results in a staircase fit to the edge of the given polygon. Specifying "T" or "t" allows diagonal edges (i.e., triangle subsections). "C" or "c" includes subsections which improve the representation of current at corners, important for gaps. A value of "B" or "b" includes both "T" and "C" above. Other values result in the default. Next, an integer follows, it is used for GDSII bug tracing. Four more numbers terminate the line, xmin, ymin, xmax, ymax. These integers indicate the smallest and largest subsection size for the polygon in terms of cells. Default is min = 1, max = 100.

The proper number of x,y point pairs follow, one pair per line and separated by blanks. The data are floating point numbers in the previously specified units (see LEN). The last point must be identical to the first point. Immediately following the last line is an END statement. Subsequent polygons are presented in an identical manner, no blank lines allowed.

Once a NUM line is encountered, the other keywords, described above, are not recognized.

Polygons which have edges in common are electrically connected. Polygons with an edge in common with the edge of the substrate are automatically shorted to ground on that edge. The polygons may overlap, however it is recommended that they do not. Likewise, a polygon may be complex (it crosses over itself), however this is of little utility.

Appendix IV Summary of Unix Commands

The following is a summary of some basic Unix commands. This chart is intended for the user who has no experience with Unix. We have included a list of MSDOS equivalent commands.

UNIX	MSDOS	MEANING
ls	dir	Print the names of all the files in the directory
ls -l	dir	Print the names of all the files in the directory and gives the last time the file was modified
cat *file*	type *file*	Print a file on the screen
tail *file*	-	Print the last 10 lines of a file
rm *file*	del f*ile*	Delete a file
mkdir *directory*	mkdir *directory*	Make a new directory
rmdir *directory*	rmdir *directory*	Delete a new directory
cd *directory*	cd *directory*	Change the default directory.
pwd	cd	Print working directory.

Notes:

1. Unix file names use “/” not “\”, which is used in MSDOS.
2. Command and file names are case sensitive, so the file “filter.geo” and “FILTER.GEO” are different.

Appendix V A Very Brief Introduction to Vi

The vi (visual) editor is a screen based editor available on all Unix systems. While there are certainly better editors (vi is still very good), once one knows vi, it may be used on any Unix system whatever.

In this appendix, we provide a minimal tutorial on the vi editor so that one may create a "ctl.an" file for ***em***. Vi is much more flexible than suggested here. If you find yourself doing significant work on Unix systems, we recommend learning vi in more detail.

To start, type:

```
vi ctl.an
```

If the file exists, it will be displayed at the top of your screen. In any case, lines on your screen which are past the end of the file are displayed with a "~" in the first character position.

Vi has an input mode and a command mode. Vi starts in command mode, any letters typed at the keyboard are treated as commands, not text. In command mode, input from the keyboard is not displayed on the screen.

Some of the commands (which are usually just single letters) place vi into input mode. In input mode, text typed at the keyboard goes into the file and is displayed on screen. When finished with input mode, pressing “ESC” returns vi to command mode. Pressing “ESC” in command mode makes a beep. If you forget which mode you are in, press “ESC” and you can be certain vi is in command mode.

With vi running, type “i”. This command places vi in input mode. Now type the following text (be sure to use upper case!):

```
VER 2.2
GHZ
FRE 10.0
```

To correct errors while still on the same line, try “backspace” or control-H. If you have already pressed return, just keep going for now.

When finished typing, press “ESC”. You are now back in command mode. If you used the caps lock key, be sure to take it out of caps lock. The commands are very case sensitive. A command typed in upper case has a different function from lower case. The problem is especially confusing because commands are not typically displayed on the screen.

To make corrections, in command mode, move the cursor to the point you want to correct. Try any arrow keys which may be on your keyboard. If you have no arrow keys or they don’t work as expected, you can use the commands “h” (left), “j” (down), “k” (up) and “l” (right). If you make a mistake in typing a command, press “ESC” and start over.

To remove an unwanted character, type “x”. To replace a single character, type “r” followed by the new character. To insert text before the cursor, type “i” (sound familiar?) and press “ESC” when finished. To delete an entire line, type “dd”.

There are a lot more commands, but these should be enough for very simple editing. Before we end the description, one final command. To save your file and exit vi, type “:wq”.

SUMMARY OF VI COMMANDS

i	Insert (enter input mode)
ESC	Leave input mode
h	Move cursor left one character
l	Move cursor right one character
j	Move cursor up one line
k	Move cursor down one line
x	Delete a character
dd	Delete a line
r	Replace a single character
:wq	Write out the file, then quit the editor
:q!	Quit the editor without making any changes to the file

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