3D-TLM Time Domain Electromagnetic Wave Simulator

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Printed on December 28, 2007.

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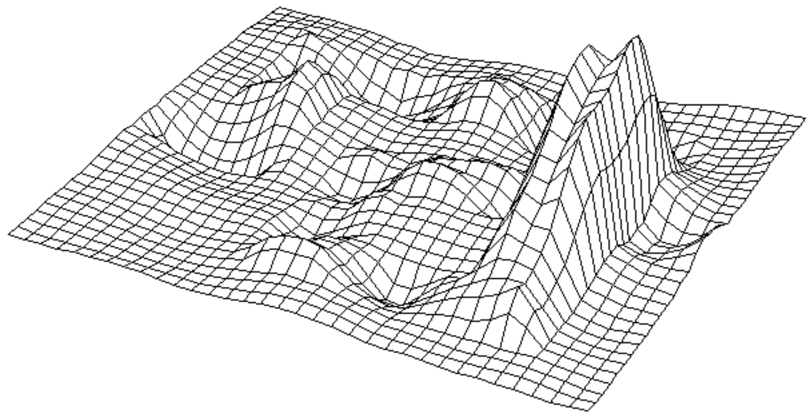


1.1 Introduction

This chapter is yet to be written. Instead, a list of references about the 3D-TLM method is given below. Reference 1 contains an extensive list of references on the method as well.

1.2 References

[1] W.J.R. Hoefer, *The Transmission Line Matrix (TLM) Method*, Chapter 8 of Numerical Techniques for Microwave and Millimeter-Wave Passive Structures, edited by Tatsuo Itoh, John Wiley & Sons, 1989.

[2] P.B. Johns, *A Symmetrical Condensed Node for the TLM Method*, IEEE Trans. Microwave Theory and Tech. vol. MTT-35, No.4, pp.370-377, April 1987.

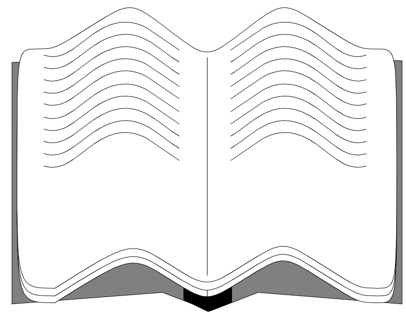
[3] R. Allen, A. Mallik and P.B. Johns, Numerical Results for the Symmetrical Condensed TLM Node, IEEE Trans. Microwave Theory and Tech. vol. MTT-35, No.4, pp.378-382, April 1987.

[4] D.A. Al-Mukhtar and J.E. Sitch, *Transmission-Line Matrix Method with Irregularly Graded Space*, IEE PROG. vol.128, Pt.H, No.6, pp.299-305, December 1981.

[5] C.E. Tong and Y. Fujino, *An Efficient Algorithm for Transmission Line Matrix Analysis of Electromagnetic Problems Using the Symmetrical Condensed Node*, IEEE Trans. Microwave Theory and Tech. vol. MTT-39, No.8, pp.1420-1424, August 1991.

[6] P. Naylor and R.A. Desai, *New Three Dimensional Symmetrical Condensed Lossy Node for Solution of Electromagnetic Wave Problems by TLM*, IEE Electronics Letters, vol.26, No.7, pp.492-494, March 1990.

CHAPTER 2 User Manual



2.1 Introduction

The 3D-TLM simulator is a general purpose three-dimensional transmission line matrix method program for the time domain analysis of three-dimensional electromagnetic structures of arbitrary shape. It computes the time response of such structures to arbitrary excitation in 3D space and time, and extracts their frequency characteristics, such as S-parameters and return loss, via discrete Fourier transform. In a field animation mode, it allows the time evolution of the field distribution to be visualized, both forward and backward in time.

2.2 General Features of the Simulator

The interface of the simulator is seamless and transparent to the user, allowing full interactive operation without requiring a long learning period. This is achieved by a carefully designed graphical user interface (GUI). A context sensitive help facility for all the important parts of the GUI is included.

The simulator has a main window and five types of subwindows: Editor, Generator, Scope, Analyzer and Animator. The main window has a menu bar which allows the user to enter commonly used commands by using *point-and-drag* style mouse actions. The other subwindows mimic various kinds of instruments that engineers would normally find in their laboratories, such as the drafting table, generator, scope and network analyzer, as well as a hard-to-find instrument — the field animator. The functionality of these windows and their associated gadgets are described in the following sections.

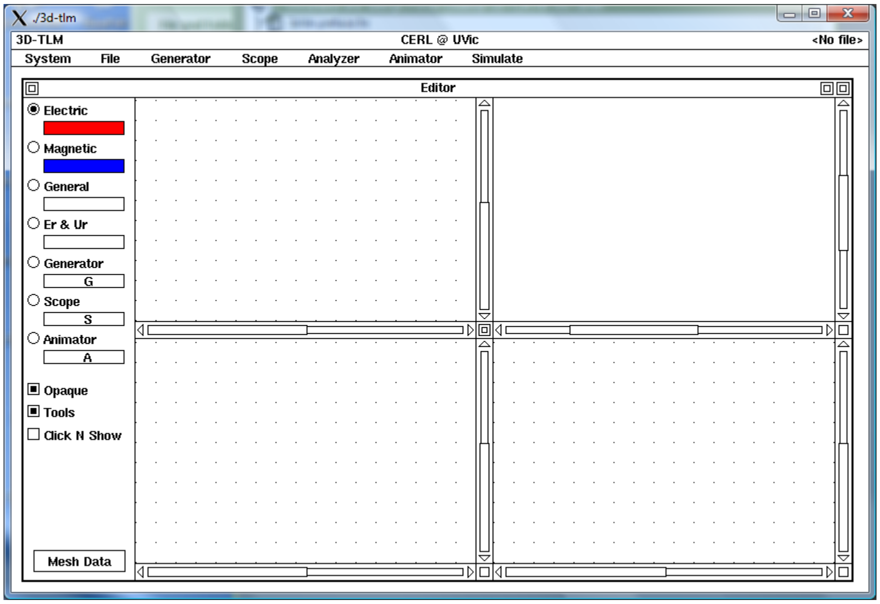


FIGURE 1 The main window of the 3D-TLM simulator.

2.3 The Main Window

The main window, Figure 1, has a menu bar which allows the user to enter commands by using *point-and-drag* style mouse actions. This menu bar has five pulldown menus: **System**, **File**, **Generator**, **Scope**, **Analyzer**, **Animator** and **Simulate**. The structure of this menu system is illustrated in Table 1.

2.3.1 The System Pulldown Menu

This pulldown menu contains three buttons: **Editor**, **Help** and **About**. The **Editor** button brings up the mesh editor window (see section 2.4) if it is not already visible on the screen. The **Help** button brings up a help window which describes all the important features of the simulator. It is a handy on-line help system that enables the users to find various information about the simulator by just a few simple keystrokes or mouse point-and-drag actions. The last button of this pulldown menu is the **About** button; this button brings up a dialogue box which shows copyright information of the simulator together with a few reference papers that contain the basic theory and algorithm of the 3D-TLM method.

System	File	Generator	Scope	Analyzer	Animator	Simulate
Editor	New	Generator 1	Scope 1	Analyzer 1	Animator 1	Data
Help	Open	Generator 2	Scope 2	Analyzer 2	Animator 2	Initialize
About	Save	Generator 3	Scope 3	-	Animator 3	Forward
-	Save As	-	-	-	-	Backward
-	Freq Res	-	-	-	-	-
-	Quit	-	-	-	-	-

TABLE 1 This table illustrates the menu system in the main window of the 3D-TLM simulator.

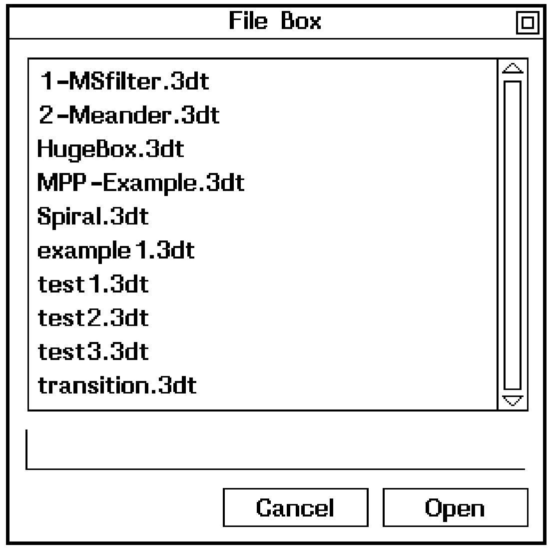


FIGURE 2 The file selection box is brought up by the `Open` button of the `File` pulldown menu. The user can open a file by either *double-clicking* on the file or *clicking* on it and then clicking on the `Open` button at the bottom of the file selection box.

2.3.2 The File Pulldown Menu

This pulldown Menu comprises six buttons: **New**, **Open**, **Save**, **Save As**, **Freq Res** and **Quit**. The **New** button deletes all the data in the simulator and prepares it for a fresh editing section. If the current data have not been saved, the simulator will bring up a dialogue box, to warn the user about the possible deletion of all data. The user can cancel the *New* operation by clicking on the **No** button, save the data, and then proceed to a new editing session.

The **Open**, **Save** and **Save As** buttons behave like buttons of similar names that one would find in other applications such as a word processor or mail handler. The **Open** button brings up a file selection box, Figure 2, enabling the user to select a 3D-TLM data file from a list of files. The **Save** button saves the data of the current edit-simulation section to a file. If a file name has not yet been specified then the action associated with the **Save As** button will be invoked, prompting the user for a file name and then save the data under that name. The **Freq Res** button save the generated frequency domain result to a file, 3d-tlm.rep, so that users can use other programs to process the data. The **Quit** button is for quitting the program — you have to use this button to quit the program, *DO NOT* use the window manager's *Close* command.

2.3.3 The Generator Pulldown Menu

This pulldown menu has 3 generator buttons: **Generator 1**, **Generator 2** and **Generator 3**. These buttons bring up the generator windows (see section 2.5) associated with them. These window model the signal generators usually found in microwave laboratories.

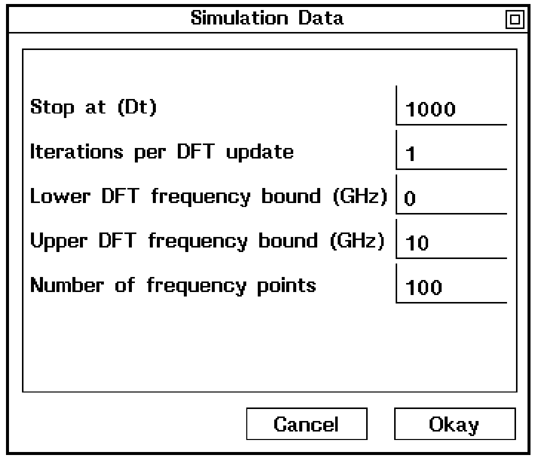


FIGURE 3 The dialogue box brought up by the Data button of the Simulate pulldown menu. These data are shared by all subwindows of the simulator.

2.3.4 The Scope Pulldown Menu

This pulldown menu has 3 buttons: **`Scope 1`**, **`Scope 2`** and **`Scope 3`**. These buttons bring up the scope windows (see section 2.6) associated with them. These windows model both the action of fast oscilloscopes and of spectrum analyzers found in microwave laboratories

2.3.5 The Analyzer Pulldown Menu

This pulldown menu has 2 buttons. **`S11`** and **`S21`**. These buttons bring up the analyzer windows (see section 2.7) associated with them. Together with the scope windows, they are used to compute the S-parameters of the structure under study. They model the functionality of microwave vector network analyzers.

2.3.6 The Animator Pulldown Menu

This pulldown menu has 3 buttons: **`Animator 1`**, **`Animator 2`** and **`Animator 3`**. These buttons bring up the animator windows (see section 2.8) associated with them. These windows are used for three-dimensional dynamic field animations in a direct-generated mode. No instrument resembling them can be found in a microwave laboratory.

2.3.7 The Simulate Pulldown Menu

This pulldown menu has four buttons: **`Data`**, **`Initialize`**, **`Forward`** and **`Backward`**. The **`Data`** button brings up a dialogue box, Figure 3, in which the user can enter some simulation data which are shared by all subwindows. The **`Initialize`** button deletes all simulation results so that editing of the structure in the editor window can begin again, or a fresh simulation can start from time zero. The **`Forward`** and **`Backward`** buttons cause simulation to march forward and backward in time, respectively.

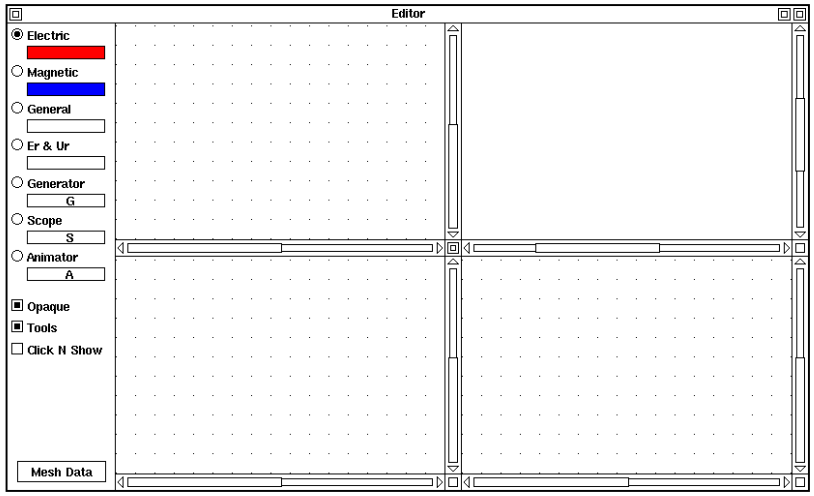


FIGURE 4 The Editor Window of the 3D-TLM simulator.

2.4 The Editor Window

The editor window, Figure 4, features a button panel on its left and four subwindows on its right. The button panel has 7 radio[1] buttons, 3 toggle[2] buttons and 1 push button. The radio buttons select the type of drawing primitive for the current drawing section. The toggle buttons toggle the states of the drawing windows, and the push button at the bottom is used to enter data shared by the drawing subwindows.

The subwindow at the top-right is a three-dimensional viewing area. It does not accept any mouse input. The subwindows at top-left, bottom-left and bottom-right are the *xy*, *xz* and *yz* planes (*xy*-plane means *x* is parallel to the horizontal axis and *y* is parallel to the vertical axis, and so on). There is a button at the center of these four subwindows; by *dragging* this button the sizes of the subwindows can be changed.

2.4.1 The Radio Buttons

The seven radio buttons are: **`Electric`**, **`Magnetic`**, **`Genera`**l, **`Er & Ur`**, **`Generator`**, **`Scope`** and **`Animator`**. Only one can be selected at a given time.

The first four buttons select structural primitives of the same names. The **`Electric`** and **`Magnetic`** primitives are electric and magnetic walls — boundaries with impulse reflection coefficients -1 and 1, respectively. The **`General`** primitive represents boundaries with arbitrary impulse reflection coefficients that must be input by the user. The **`Er & Ur`** primitive represents volumes with arbitrary user-definable permittivity and permeability values.

1. The buttons in a group of buttons to select one-out-of-many are called radio buttons. Only one of the buttons can be ON at a given time.
2. The buttons in a group of buttons to toggle the states of a group of parameters are called toggle buttons. More than one of the buttons can be ON at a given time.

The last three buttons select input/output tool primitives of the same names. The **Generator** primitives are used to enter the position and volume of the excitation regions. Although there are only three different generator windows (**Generator 1**, **Generator 2 and Generator 3**), there is no practical limit on the number of generators one can put into a structure. This is similar to a real situation in a laboratory: even though there may only be three signal generators, each of them can be connected to more than one input port at the same time. However, the electrical length of the connections between the generator and the input points is zero in the simulator. The **Scope** primitives are used to represent the position of the sampling (output) points. Since each output point must be associated with a scope window, and since there are only three scope windows, there can be only a maximum of three such primitives in a structure. The **Animator** primitives represent the position and size of output areas. Since there are only three animator windows, and since each output area must be associated with one of these windows, there cannot be more than three such primitives.

2.4.2 The Toggle Buttons

The three toggle buttons are: **Opaque**, **Tools** and **Click N Show**. More than one can be selected at a given time.

If the **Opaque** button is selected, the areas of the electric, magnetic and general wall sections in the projection plane will be filled with red, blue and white color, with hidden lines removed. In the 3D view, diagonal dashed lines of the corresponding colors will be drawn across these walls. Otherwise, only their perimeters will be drawn. If the **Tools** button is selected, the outline and location of the generators, scopes and animators in the structure will be drawn; otherwise, they will not be drawn. Unselecting the tool button facilitates the identification of primitives when there are many of them in the structure, and when the tool primitives are obscuring the primitives of interest. Selecting the **Click N Show** button turns ON another feature that helps to identify the primitives in the structure when the drawing gets complex. When this button is selected, *double-clicking* on any of the projection windows clears the window and causes only the deepest[1] primitive to be drawn on that window. Subsequent mouse clicks cause other primitives to be drawn in order of decreasing depth until all primitives are drawn.

2.4.3 The Mesh Data Button

The **Mesh Data** push button brings up a dialogue box which allows the user to input several parameters: **Relative Permittivity**, **Relative Permeability**, **Dimension Conversion Factor**, **Step Size** and **Pixel Per Step**. Relative permittivity and permeability are used by default in the simulation region where no **Er & Ur** primitive has been specified. The dimension conversion factor controls the unit of physical size and must be a power of 10, i.e. 0.001, 0.1, ..., etc.. The step size controls the spacings Δx, Δy and Δz between nodes. For example, if the dimension conversion factor is 0.001 and all step sizes are 1, then Δx, Δy and Δz are all 1 mm. The pixel per step measure is used to control the size of the drawing on the screen; smaller numbers give smaller drawings.

1. Deep means deep inside the screen surface. Take the *xy* plane as an example. The *z* axis is orthogonal to the screen with negative, zero and positive *z* values behind, on and outside the screen surface. Deepest means with the most negative *z* values.

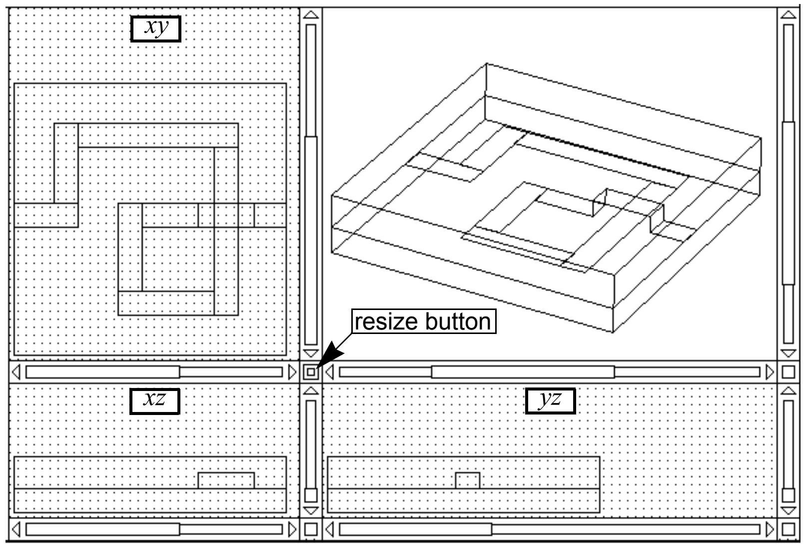


FIGURE 5 The drawing and viewing area of the editor window. The size of the subwindows can be changed by dragging the resize button.

2.4.4 The Drawing and Viewing Area

The drawing and viewing area of the editor window has four subwindows, Figure 5. The size of the subwindows can be changed by *dragging* the resize button. The default orientation in the 3D viewing window gives a very intuitive relationship between the 3D object and the projection images in the other subwindows — the *xy* subwindow shows the top-view of the object, the *xz* and *yz* subwindows show the front and side views. The 3D graphic attributes[1] of the viewing window can be changed interactively by *double clicking* on that window; this will bring up a dialogue box which allows the user to change the values of the 3D graphic parameters by using the keyboard.

Primitives can be entered into the editor with just a few simple mouse operations. Dimensionally speaking, there are two kinds of primitives — 2D and 3D. 2D primitives are **`Electric`**, **`Magnetic`** and **`General`**. These primitives must lie on a plane orthogonal to one of the main axes. 3D primitives are **`Er & Ur`**, **`Generator`**, **`Scope`** and **`Animator`**. These primitives occupy cubical volumes. To enter primitives into the editor, the coordinate parameters — (x_1,y_1,z_1) and (x_2,y_2,z_2) — of the primitives must be specified by using mouse *point-and-click* and *dragging* actions. For the 2D primitives, the coordinate parameters on one of the axes must be the same[2]; this is enforced by the editor.

The following steps define an electric wall of $10 \times 10\ \Delta l^2$ in the *xy* plane at z=0.5 Δl. Note that nodes are situated at 0, 1, 2, ... and therefore, boundaries must be at 0.5, 1.5, 2.5, ...

1. Projection point, magnification factors, rotation angles, rotation center, etc..
2. That is either $x_1 = x_2$ or $y_1 = y_2$ or $z_1 = z_2$.

- Select the **`Electric`** radio button on the button panel.
- Place the mouse pointer at *z*=0.5 anywhere in the *xz* window. Depress the left mouse button to read the coordinate (just depressing the left mouse button without dragging the mouse pointer will not enter anything into the editor. After a few trials you will be able to locate the *z*=0.5 position. This action specifies z_1=z_2=0.5.
- Using the technique described above, place the mouse pointer at (*x*,*y*)=(0,0) in the *xy* window. Press and hold the right mouse button, then drag the pointer to (*x*,*y*)=(10,10). A counter will appear to facilitate this operation; the value displayed in it during the dragging operation is the displacement of the pointer from the initial location. Therefore, when the value in the counter is (10,10), the pointer is in the desired location. This action specifies (x_1,y_1)=(0,0) and (x_2,y_2)=(10,10).

The above input procedure applies to the **`Magnetic`** and **`General`** drawing primitives as well. The difference resides in the first step — **`Magnetic`** or **`General`** must be selected instead of **`Electric`**.

Entering 3D drawing primitives is similar but not exactly identical. Step 2 above only specifies z_1. This step must be repeated once to specify z_2. If this step is repeated more than once, then only the last two actions are taken into account. That is, the second last action specifies z_1 and the last one specifies z_2.

The above procedure only specifies the coordinate parameters of the primitives; for the **`Electric`** and **`Magnetic`** primitives, these are the only data the user needs to enter. The remaining primitives all require additional data from the user in order to complete the input operation. If additional data are needed, the editor will bring up a dialogue box to prompt the user to enter the required data. Some dialogue boxes require the user to enter numbers through the keyboard, some require the user to select one item out of a few by using the mouse only. Table 2 lists the input data for all the drawing primitives.

Once a structure is entered into the editor by drawing on one of the projection windows, its three-dimensional drawing will appear on the 3D viewing window immediately. This 3D window usually gives a better view than three 2D projection images.

Primitives	**Data**
Electric	None
Magnetic	None
General	Impulse reflection coefficient
Er & Ur	Relative Permittivity and Permeability
Generator	Select a generator window out of three
Scope	Select a scope window from the remaining scope windows
Animator	Select an animator window from the remaining animator windows

TABLE 2 Input data for drawing primitives.

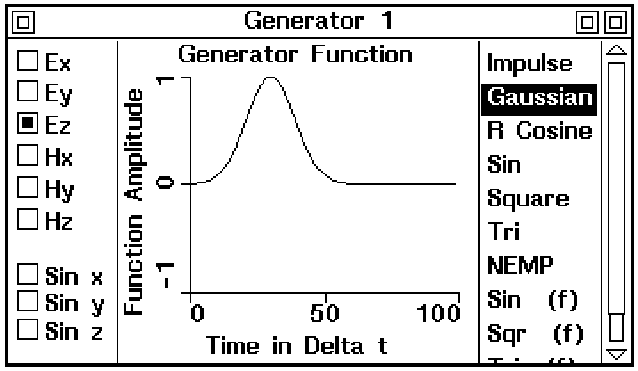


FIGURE 6 The generator window.

2.5 The Generator Window

The generator window, Figure 6, has three regions: a button panel on its left, a graphic area in the center, and a list box on its right. It has more features than the traditional sweep generator one could find in the microwave laboratory.

2.5.1 The Button Panel

The button panel has two groups of toggle buttons. The first group is for field components: **`Ex`**, **`Ey`**, **`Ez`**, **`Hx`**, **`H`**y, **`Hz`**; the second group is for the spatial distribution of the fields: **`Sin x`**, **`Sin y`**, and **`Sin z`**. Any or all of these butons can be selected at a time. The field output of the generator is the vector sum of the field components selected. The states of these buttons can only be changed before the simulation has begun; once it has started, their states cannot be changed. To change their states again the user must start a new simulation by selecting the **`Initialize`** button (see section 2.3.7) first.

2.5.2 The Graphic Area

The graphic area displays the excitation function in the time domain. The nature of the excitation function can be changed by using the list box on the right (see section 2.5.3). The attributes of the selected function can be changed by *double-clicking* on the curve. The graph attributes[1] can be changed interactively by *double-clicking* on one of the axis labels. In all cases, *double-clicking* will bring up a dialogue box for data entry.

2.5.3 The List Box

The list box has a number of build-in functions, and the user can select one of them by *clicking* on it. *Double-clicking* on the desired function will select it and bring up a dialogue box to enter function specific data such as amplitude and frequency.

1. The graph title, x-axis and y-axis labels etc. are collectively called graph attributes.

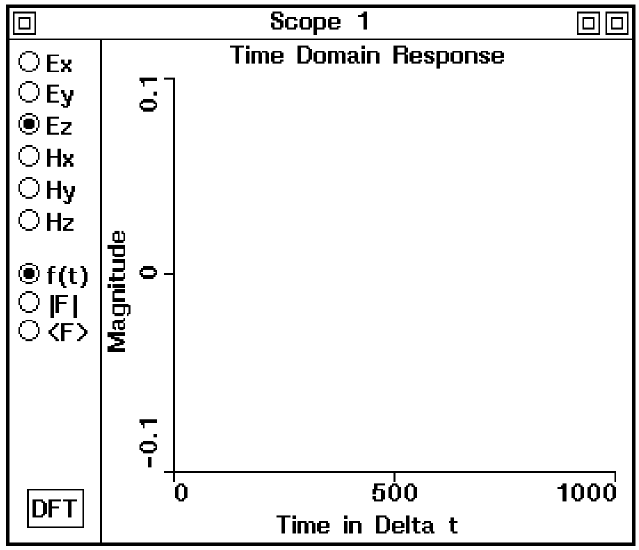


FIGURE 7 The scope window.

2.6 The Scope Window

The scope window, Figure 7, has two regions: a button panel at the left and a graphic area at the right. It models both fast oscilloscopes and spectrum analyzers normally found in a microwave laboratory.

2.6.1 The Button Panel

The button panel contains three groups of buttons. The first group is for field component selection: **`Ex`**, **`Ey`**, **`Ez`**, **`Hx`**, **`Hy`** and **`Hz`**. It enables the user to select one of the six field components to be sensed at the output point associated with the scope window. The state of these radio buttons cannot be changed once simulation has begun. To change their states, the user must initialize the system by selecting the **`Initialize`** button (see section 2.3.7) first. The second group of buttons is for output function selection: **`f(t)`**, $|\mathbf{F}|$ and $\langle\mathbf{F}\rangle$. **`f(t)`** is the time domain response; $|\mathbf{F}|$ and $\langle\mathbf{F}\rangle$ are the magnitude and angle (in degree) of the frequency domain response, respectively. The state of these radio buttons can be changed at any time. The push button, **`DFT`**, at the bottom of the panel is for recalculation of the discrete Fourier transform. Normally, the user would not have to recalculate the discrete Fourier transform if the desired frequency range and the number of frequency points were specified at the beginning of the simulation by using the **`Data`** button (see section 2.3.7).

2.6.2 The Graphic Area

This graphic area is similar to the one in the editor window (see section 2.5.2). Instead of displaying the excitation function, this graphic area shows the response of the structure to a selected excitation. The graph attributes can be changed interactively by *double-clicking* on one of the labels in the graphic area.

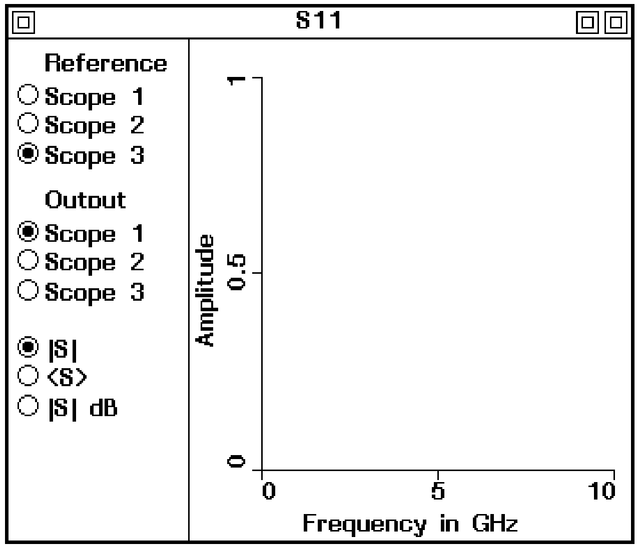


FIGURE 8 The analyzer window.

2.7 The Analyzer Window

Like the scope window, the analyzer window, Figure 8, contains a button panel and a graphic area. The S11 and S21 analyzer windows look similar, differing only in title and function. For an analyzer window to appear on the screen, the structure under study must have at least one **`Scope`** primitive (see section 2.4.1) referenced to a scope window. In most cases, a reference structure is needed as well (see Chapter 3).

2.7.1 The Button Panel

The button panel contains three groups of radio buttons. The first two groups both have three buttons of the same names: **`Scope 1`**, **`Scope 2`** and **`Scope 3`**. In order to compute S-parameters, a reference signal and an output signal are needed. (The reference signal is the time domain voltage *incident* upon the excited port). These buttons select the desired reference and output signal from the scope window referenced by the appropriate **`Scope`** primitives. In most cases, the buttons selected under **`Reference`** and **`Output`** should be different in order to yield meaningful results. The function of the last three radio buttons is self-explanatory. The states of these three groups of radio buttons can be changed at any time.

2.7.2 The Graphic Area

This graphic area is similar to the one in the scope window (see section 2.6.2). Instead of displaying the response of the structure to a selected excitation, it shows the S-Parameters of the structure based on the response from two scope windows. The graph attributes can be changed interactively by *double-clicking* on one of the labels in the graphic area.

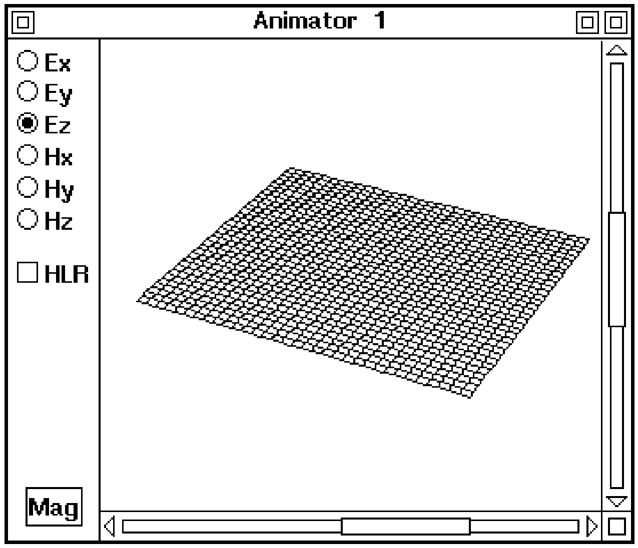


FIGURE 9 The animator window.

2.8 The Animator Window

The animator window, Figure 9, has a button panel on its left and a 3D graphic area on its right. It is used to visualize field evolution — there is nothing like it in a normal microwave laboratory.

2.8.1 The Button Panel

The first group of radio buttons — **`Ex`**, **`Ey`**, **`Ez`**, **`Hx`**, **`Hy`** and **`Hz`** — has functions similar to those in the scope window (see section 2.6.1). The user can select only one at a time, but unlike those in the scope window, the states of these buttons can be changed at any time. Therefore, all six field components are available for animation at all times. The user just interrupts the simulation process, changes the field selection, and continues the simulation. The **`HLR`** button toggles the hidden line removal feature. It should be off if simulation speed it important. The last button, **`Mag`**, allows the user to change the field strength magnification[1] factor.

2.8.2 The 3D Graphic Area

This 3D graphic area is similar to the one in the editor window (see section 2.4.4). Instead of displaying the geometry of the structure under study it shows the field distribution in an area specified by the user. The 3D graphic attributes can be changed interactively by *double-clicking* on the window; this will bring up a dialogue box which allows the user to change the values of the 3D graphic parameters through the keyboard.

1. This magnification factor is different from the one in the dialogue box in the 3D Graphic Area (see section 2.8.2).

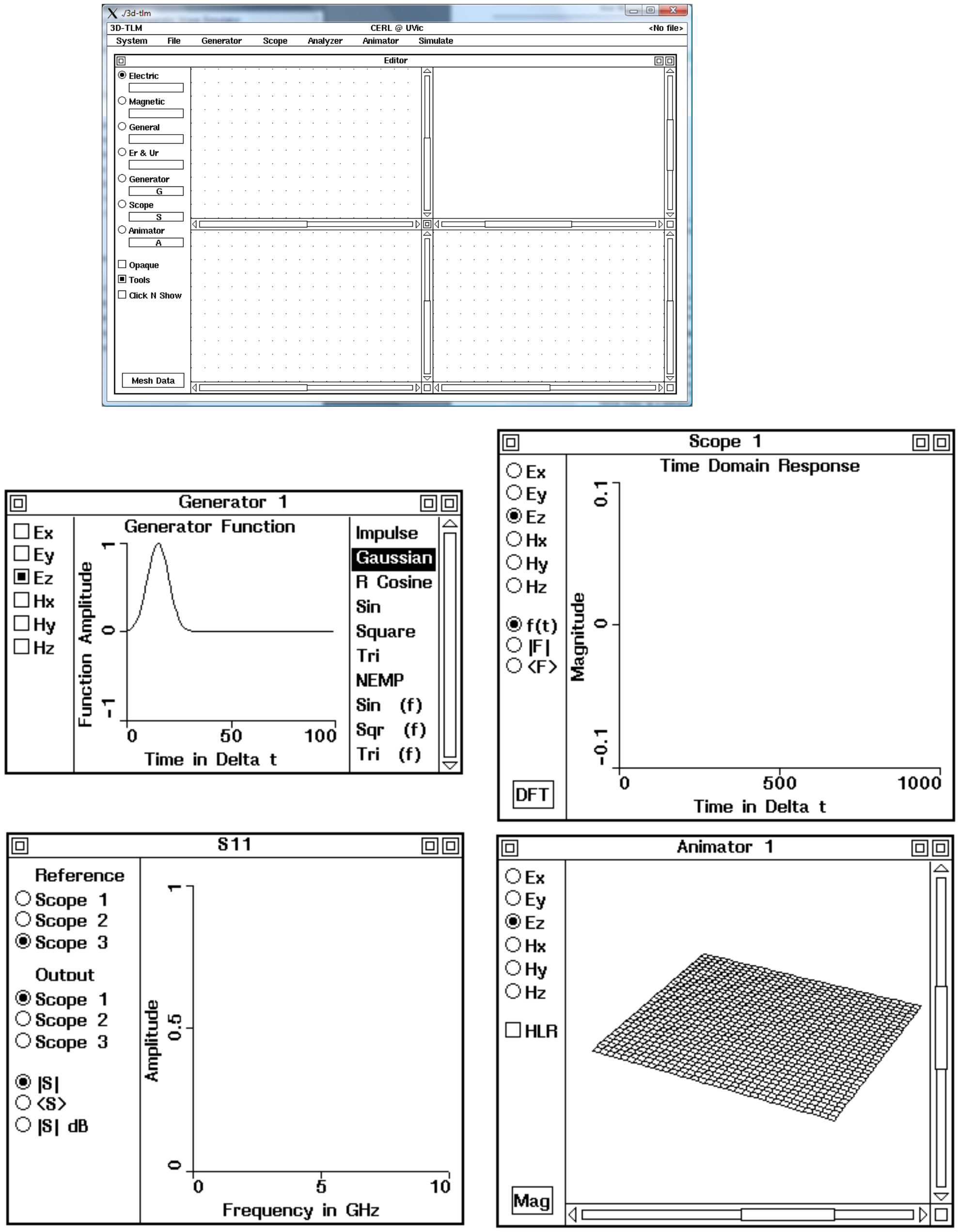


FIGURE 10 The window hierarchy of the simulator.

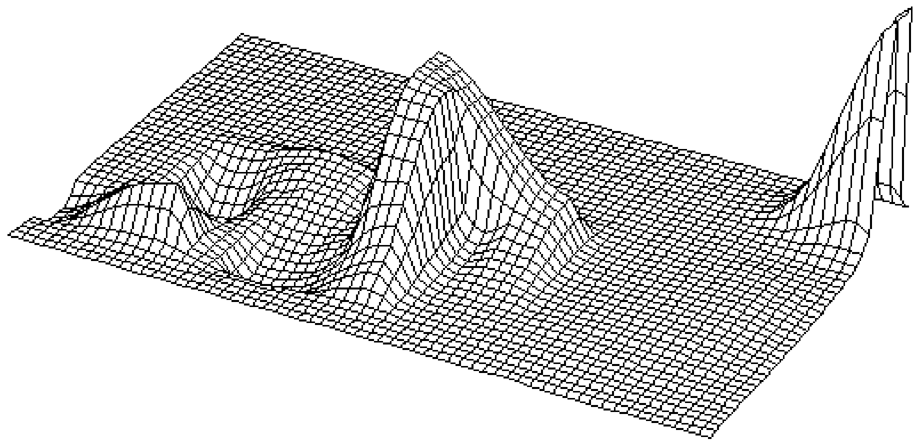
2.9 Summary

The interface of the simulator has been described in detail. Figure 10 summarizes the window hierarchy of the simulator.

2.10 Conclusion

The 3D-TLM Time Domain Electromagnetic Wave Simulator is a very complex piece of software. To use it effectively one must know both the 3D-TLM method itself (see *Chapter 1 3D-TLM Method*) and the features of this simulator well. Some ideas, such as S-parameters calculation, are easier to illustrate through examples than through plain manual-style explanations. The users are encouraged to read *Chapter 3 Simulation Tutorial* for a step-by-step introduction to the simulator.

CHAPTER 3 Simulation Tutorial



3.1 Introduction

The 3D-TLM Time Domain Electromagnetic Wave Simulator is a very complex piece of software. To use it effectively one needs to know both the 3D-TLM method itself and the features of this simulator well. Therefore, the users are encouraged to read both *Chapter 1 3D-TLM Method* and *Chapter 2 User Manual* first before trying to following this tutorial.

After reading this tutorial, users should be able to model electromagnetic structures with realistic approximations. The essential steps are:

- Sketch the structure of interest on a sheet of paper; note down all the dimensions in SI unit.
- Discretize all dimensions into integer multiples of Δl. (This may not always be possible; in this case the closest integer value should be used).
- Enter the structure into the simulator by using the editor window.
- Specify the excitation regions, excited field components and excitation functions by using the editor and generator windows.
- Specify the sampling regions and sampled field components by using the editor and scope window.
- If field animation is needed, specify the animation regions and field components to be visualized by using the editor and animator windows.
- Specify some simulation parameters, then start the simulation.
- If S-parameters are needed, they can be computed by using the analyzer windows.

The following sections illustrate the above steps in detail.

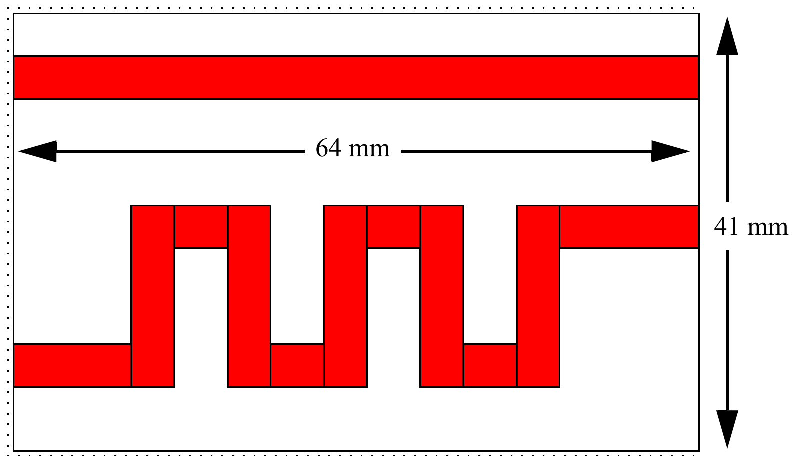


FIGURE 1 The topview of a microstrip structure to be modeled in this tutorial. The upper straight line is a reference line, and the lower structure is a meander line. The reference line is needed to generate the reference signal for the calculation of the S-parameters of the meander line.

3.2 The Structure to be Modeled

The structure to be modeled in this tutorial is shown in Figure 1. It consists of two microstrip lines. The upper is a reference line, and the lower is a meander line. The former is needed to generate the reference signal for the calculation of the S-parameters of the meander line. This structure is very simple so that a step-by-step illustration of its simulation can be given easily. To speed up the simulation and to make the editing procedure easier, let us arbitrarily choose the thickness of the substrate to be 1 Δl, and let us place a cover at 2 Δl above the ships. Hence the total height of the mesh is 3 Δl.

Good absorbing boundaries are needed to model the side walls of the structures properly. If one is mainly interested in the low frequency response, simple reflective boundaries with zero impulse reflection coefficients are sufficient (see *Chapter 1 3D-TLM Method* for details).

3.3 Editing the Structure

The first step is to break down the meander line into small rectangles as shown in Figure 2 then discretize their dimensions and positions. This procedure is trivial and the result, with elements numbered from left to right, is given in Table 1. Note that neither Figure 2 nor Table 1 show the reference line; the position of this line is immaterial as long as its width is the same as that of the meander line and there is sufficient isolation between them; this can be achieved be placing an absorbing boundary at y=29 Δl. This value gives lateral symmetries to both the reference and the meander lines. If better results are desired, the physical separation between the structures and the absorbing boundaries should be a few times larger. But the chosen value will serve the purpose of this tutorial well enough.

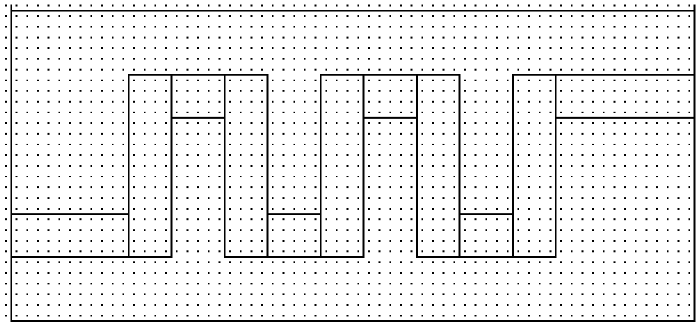


FIGURE 2 The rectangular sections that make up the meander line in Figure 1

Element	z1	x1	z2	x2
1	0	6	11	10
2	11	6	15	23
3	15	19	20	23
4	20	6	24	23
5	24	6	29	10
6	29	6	33	23
7	33	19	38	23
8	38	6	42	23
9	42	6	47	10
10	47	6	51	23
11	51	19	64	23

TABLE 1 The discretized coordinates of the elements show in Figure 2.

Now we are ready to enter the elements. Type ‘3d-tlm’ from the command prompt. This will bring up the simulator with an empty editor window. Click on the **`Mesh Data`** push button to bring up a dialogue box and enter the parameters as shown in Figure 3. Note that the value of ‘**`Pixels Per Step – Z`**’ is larger than that of the ‘**`Pixels Per Step – X`**’ and ‘**`Pixels Per Step – Y`**’, this changes the aspect ratios of the *xz* and *yz* subwindows of the editor window. It is not necessary to use different aspect ratios, one of the reasons for using it in this tutorial is to demonstrate the flexibility of the editor; another one is to stretch the z-axis so that it is easier to edit as well as to view the structure.

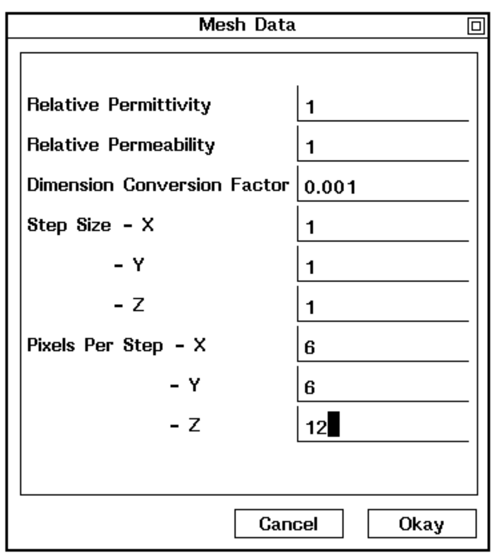


FIGURE 3 Mesh data for this simulation tutorial. The value of ‘**`Pixels Per Step - Z`**’ is larger than that of the ‘**`Pixels Per Step – X`**’ and ‘**`Pixels Per Step - Y`**’, this changes the aspect ratios of the *xz* and *yz* subwindows of the editor window.

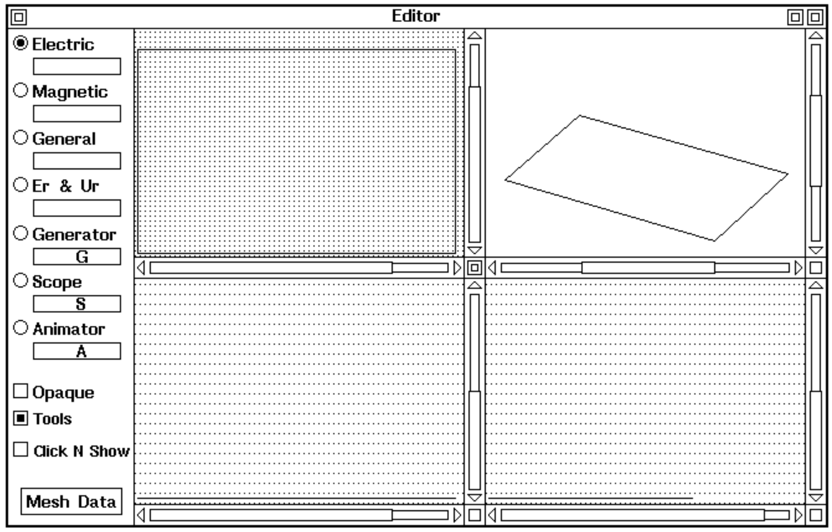


FIGURE 4 The editor window showing the ground plane of the structure

3.3.1 Entering the Ground Plane

The ground plane of the microstrip structure should be entered first into the editor because it serves as a reference frame for the other elements. Follow these steps:

- Select the Electric drawing primitive by *clicking* on the **`Electric`** radio button.
- Put the cursor at (0.5,0.5)[1] in the *xz*-window.
- Put the cursor at (0.5,0.5) in the *xy*-window. Press and hold the right mouse button; this will bring up a coordinate meter. You can use the left button as well. The coordinate meter shows the cursor position when a button is pressed. If the mouse is dragged with the left button, the coordinate meter shows the new cursor position, otherwise it shows the cursor's displacement from the initial position.
- Make sure the value of the coordinate meter is (0.5,0.5); drag the mouse upward and rightward until the value in the coordinate meter is (64,41), then release the mouse button.

If you entered an element with either a wrong position or size, simply overdrawn the element with an identical one to remove it. If everything was done correctly, your editor window should look similar to Figure 4. The drawing in your 3D viewing subwindow is not the same as that of Figure 4. To make your 3D drawing look similar, *double-click* on the 3D viewing window to bring up a dialogue box. Change the magnification factor to a smaller value and hit the return key. The drawing in the 3D viewing window will be updated with the new magnification factor[2]. Once you feel satisfied with the drawing, *click* on the **`Okay`** button to dismiss the dialogue box. If you think you have messed up the values, *click* on the **`Cancel`** button and start the process again.

1. Pressing a mouse button without dragging the mouse will bring up a coordinate meter showing the position of the cursor. If the value is not (0.5,0.5), simply release the mouse button and select another location.
2. If the dialogue box happens to obscure the 3D viewing subwindow, simply move the dialogue box to a new position by dragging its title bar.

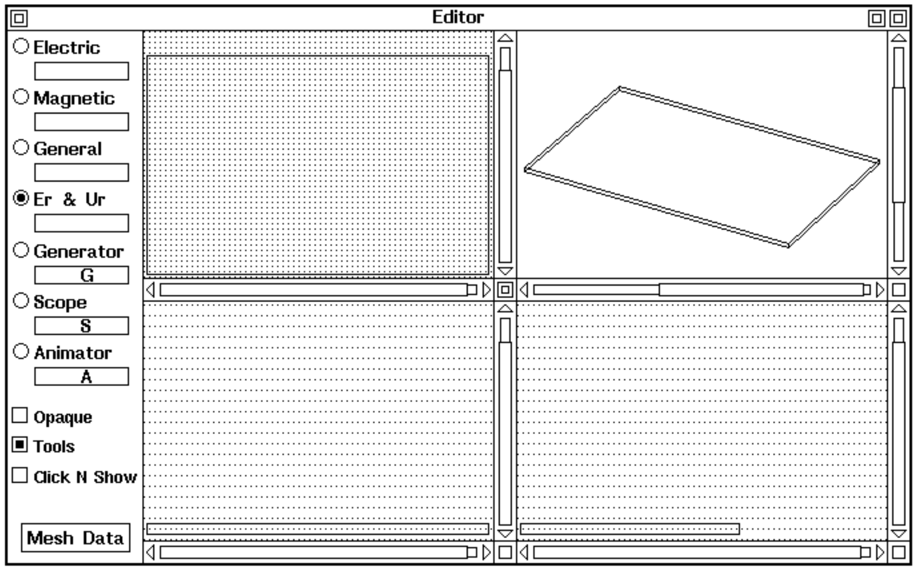


FIGURE 5 The editor window showing the ground plane and the substrate. Turn on the **`Opaque`** and **`Click N Show`** toggle buttons, then double-click on the xy-window to display only the ground plane in red color. Another mouse click on the xy-window displays the substrate.

3.3.2 Entering the Substrate

The substrate on which the metallization is deposited can be entered in a similar manner. The steps are:

- Select the Er & Ur drawing primitive by *clicking* on the **`Er & Ur`** radio button.
- Use the ground plane as the coordinate reference, put the cursor at (0.5,0.5) on the *xz*-window; click a mouse button and make sure that the value displayed in the coordinate meter is (0.5,0.5). Then put the cursor at (64.5,1.5) on the *xz*-window; click a mouse button and make sure that the value displayed in the coordinate meter is (64.5,1.5). These two mouse clicks MUST happen one after the other because the editor uses the two most recent mouse click coordinates to compute z_1 and z_2. Therefore, repeat this step until you have successfully entered (0.5,0.5) and (64.5,1.5) in two continuous mouse clicks.
- Put the cursor at (0.5,0.5) on the xy-window; hold the right mouse button and drag the cursor upward and rightward until the values in the coordinate meter are (64,41), then release the mouse button.
- The above step will bring up a dialogue box which allows you to enter the relative permittivity and permeability of the region. For this tutorial, just *click* on the **`Okay`** button to use the default values. If you click on the **`Cancel`** button then the Er & Ur primitive that you have just drawn will be deleted from the editor.

If you have entered everything properly, your editor window should look similar to Figure 5. If the position or size of your Er & Ur primitive is different from that of what it supposed to be, you could remove it by overdrawing it with an identical Er & Ur primitive.

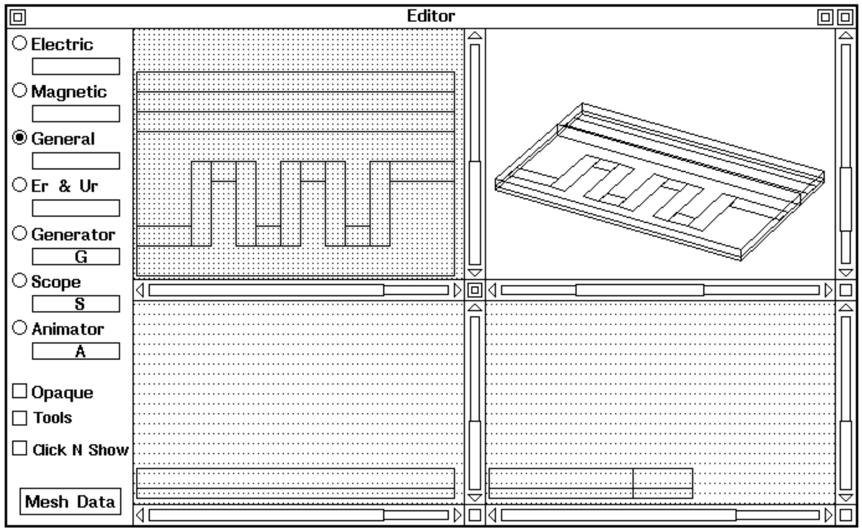


FIGURE 6 The complete structure for this tutorial.

3.3.3 Entering the Structure

The reference and the meander lines can be entered into the editor by first clicking at (0.5,1.5) in the xz-window. With the help of Table 1, and by following the steps in *Entering the Ground Plane* the structure can be entered into the editor in a straightforward manner.

3.3.4 Entering the Remaining Boundaries

Six more elements must be entered into the editor — 1 electric wall and 5 absorbing boundaries[1]. The electric wall, as mentioned in section *The Structure to be Modeled*, is 2 Δl above the substrate. Four of the five absorbing boundaries are to be placed along the *xy* perimeter of the mesh, i.e. at x=0, x=64, y=0 and y=41 Δl. The fifth absorbing boundary must be placed between the reference and the meander lines; this boundary is used to suppress possible interactions between these two lines. It has been determined earlier (See ?$paratext>? on page 18.) that this absorbing boundary should be placed at y=29 Δl.

The steps for entering an electric wall should be familiar by now. Absorbing walls are entered in the same manner after clicking on the **`General`** instead of the **`Electric`** radio button.

If you have entered everything correctly, your editor window should look similar to Figure 6. Try to turn on the **`Opaque`** and **`Slow Show`** toggle buttons and double click on any one of the drafting windows if you have not already done so; this is a very useful feature for checking your structure.

1. In this example, the impulse reflection coefficient is 0. For a general discussion about absorbing boundaries see *Chapter 1 3D-TLM Method.*

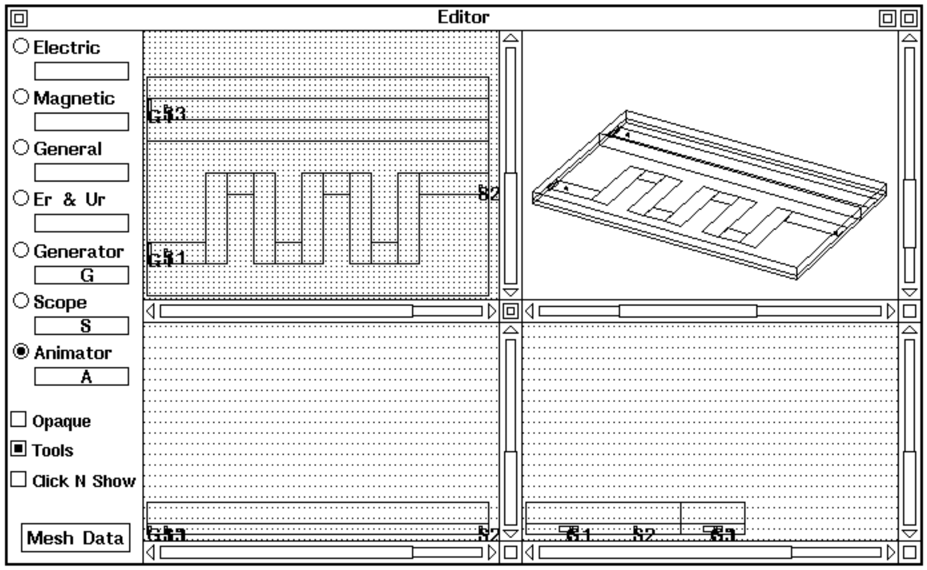


FIGURE 7 The dimensions, positions and orientations of the generator and scope primitives. The generator primitives at the inputs of the meander line and the reference line (left-hand side) are both G1. The scope primitives at the input and output of the meander line and at the input of the reference line are S1, S2 and S3, respectively.

3.3.5 Entering Generator, Scope and Animator Primitives

Entering the generator, scope and animator primitives is very similar to entering the Er & Ur drawing primitive. Click first on the appropriate radio button, then specify z_1 and z_2 in the *xz* window, and finally (x1,y1) and (x2,y2) in the *xy* window. A step-by-step procedure has already been given in an earlier section *Entering the Substrate*. After you have specified the volume enclosed by these primitives, a dialogue box will appear if it is necessary to associate the primitives with a corresponding window. Simply click on the button of your choice to dismiss the dialogue box.

We have entered two generator, three scope and one animator primitives.

The generator primitives at the inputs of the meander line and the reference structure are both associated with the Generator 1 window. These primitives are marked as G1 in the editor's drafting windows. Similarly the scope primitives at the input and output of the meander line and at the input of the reference line are S1, S2 and S3, respectively. The dimensions, positions and orientations of these primitives are shown in Figure 7.

The animator primitive is just beneath the metallization and encloses one layer of nodes, the only layer of nodes inside the substrate. This primitive is removed on purpose from Figure 7 because it would obscure the other primitives. Animator primitives are different from other primitives — they can be entered or removed from the structure at any time, while all other primitives must be entered before the start of a simulation.

3.4 Simulation Set Up

We need to do a few more things before we can start a 3D-TLM simulation. The following steps will guide you in the setup of the generator, scope, analyzer and animator windows as well as in entering some parameters shared by more than one window. The order in which the windows are set up is not important as long as you follow the steps outlined below.

3.4.1 Set up the Generator

The generator primitives entered into the structure are associated with the same generator window, **`Generator 1`**. Therefore, the inputs to the meander line and the reference line have the identical field component(s) and function[1]. Therefore, field component(s) and function injected into both lines are the same. The following steps guide you to step up this function.

- Bring up the generator window by selecting the **`Generator 1`** button in the **`Generator`** pulldown menu.
- Unselect the **`Ex`** toggle button and select the **`Ez`** toggle button[2]. This selects only the E_z field component.
- Double click on the **`Gaussian`** item in the list box. This will bring up a dialogue box; enter 1, 9 and 30 for amplitude, sigma and mean, then click on the **`Okay`** button.

If you entered everything as mentioned above your **`Generator 1`** window should look like Figure 8. Feel free to select other time functions and see how the generator window responds to these changes; change it back to the Gaussian function before you leave this section, otherwise your simulation result will not be in agreement with this tutorial.

3.4.2 Set up the Scopes

There are three scope primitives in this example; each of them is associated with a scope window. The field component to be sampled as well as the kind of output response to be displayed can be different in each scope. In this example (in general, when you need to compute S-parameters), the field component in all the scopes are set to **`Ez`**. This reason is that in order to compute S-parameters in this example, all the scopes must have the same field component[3]. The type of signal to be displayed does not matter because it

1. The spatial distribution of the input function of these two primitives may not be the same if their size and/or orientation are not the same.
2. You don't have to unselect the **`Ex`** toggle button if you want to inject both the E_x and E_z field components.
3. You could select a different field component in each scope, yet the analyzer windows would still compute S-parameters. This is meaningful only if you have a structure where the input is E_z and the output is E_x. In every case you must know what you are doing and sample the proper field component with each scope.

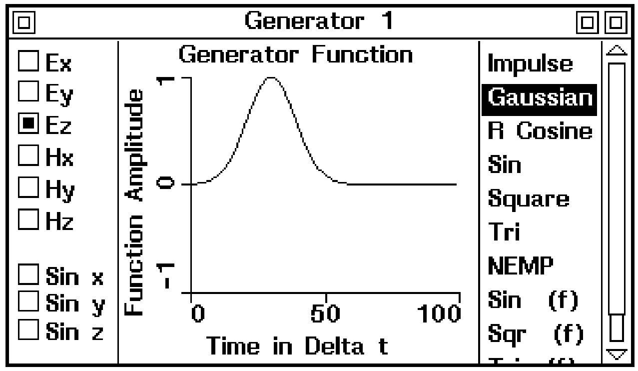


FIGURE 8 Generator 1 displaying a Gaussian pulse with amplitufe=1, sigma=9 and mean=30. The E_z field component is selected as well.

can be changed at any time. The following steps set up your scopes to match the data used in our simulation:

- Bring up all three scope windows if you have not already done so.
- Select the **`Ez`** and $|$**`F`**$|$ radio buttons on all scope windows.
- Click on the **`DFT`** push button (of the graphic area) in one of the scopes to bring up a dialogue box. Enter 0 and 20 for the lower and upper frequency bounds and 100 for the number of frequency points, then click on the **`Okay`** push button. Notice that the *x*-axis labels on all three scopes are updated to the same frequency range, since this operation affects all the scope windows[1].

All your scope windows should now look like Figure 9.

3.4.3 Set up the Analyzers

The editor window contains no analyzer drawing primitive. In order to compute S-parameters, you must enter the scope primitives at the appropriate locations and then bring up the analyzer windows from the main menu bar (see section 2.3.5).

The frequency range in the analyzer windows are set automatically to the range in the reference scope. Therefore, if you want to extract S-parameters in a different frequency range you cannot change it in the analyzer windows; you must change it either via the commands under the scope windows (see section 3.4.2) or by following the steps outlined in the section *Final Preparation*.

Follow the steps below to set up your analyzer windows for computing the S-parameters in this example.

- Bring up the **`S11`** and **`S21`** analyzer windows[2].

1. In fact, this operation sets the frequency bounds for all the scope and analyzer windows.
2. Notice that the frequency ranges in the analyzer windows were already set to 0 to 20 GHz in the previous section.

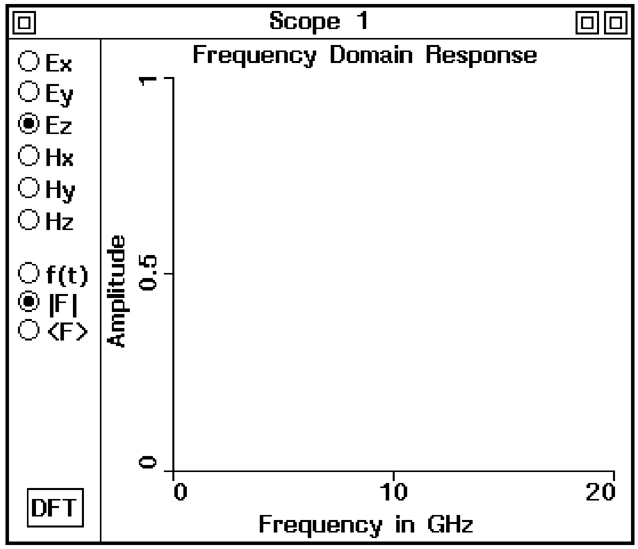


FIGURE 9 `Scope 1` shows that the field component to be sampled is `Ez` and the output response to be displayed is |`F`|; the frequency range is 0 to 20 GHz.

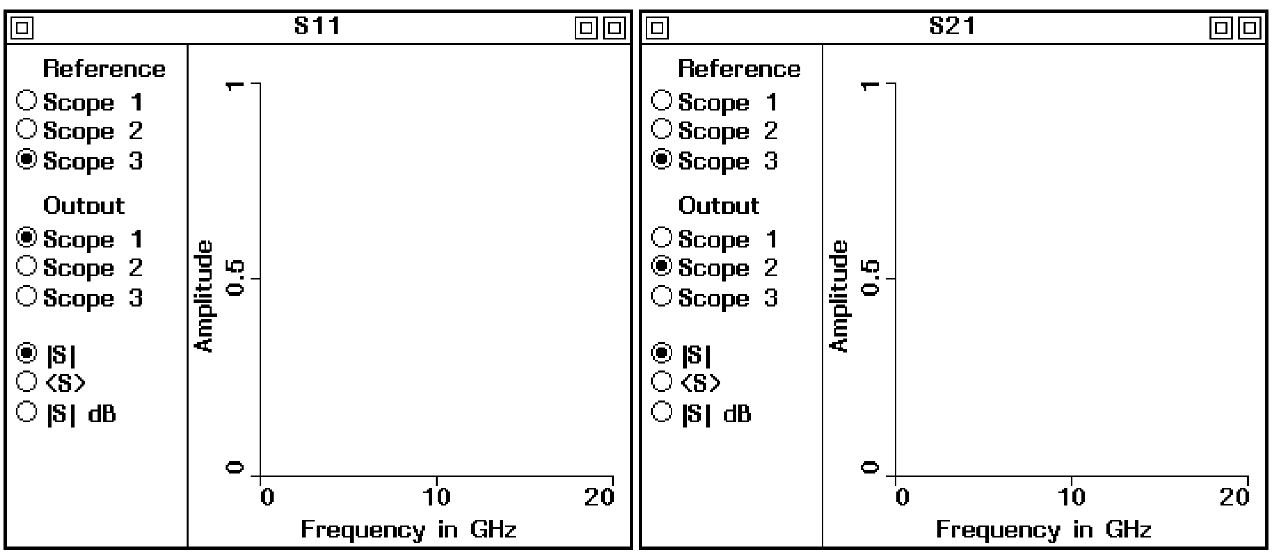


FIGURE 10 The `S11` and `S21` analyzer windows show the proper setting for computing S-parameters for this tutorial.

- Select **`Scope 3`** as the reference scope in both analyzer windows
- Select **`Scope 1`** and **`Scope 2`** as the output scopes in the **`S11`** and **`S21`** analyzer windows, respectively.
- Select |**`S`**| in both analyzer windows.

Your analyzer windows should now look like those in Figure 10.

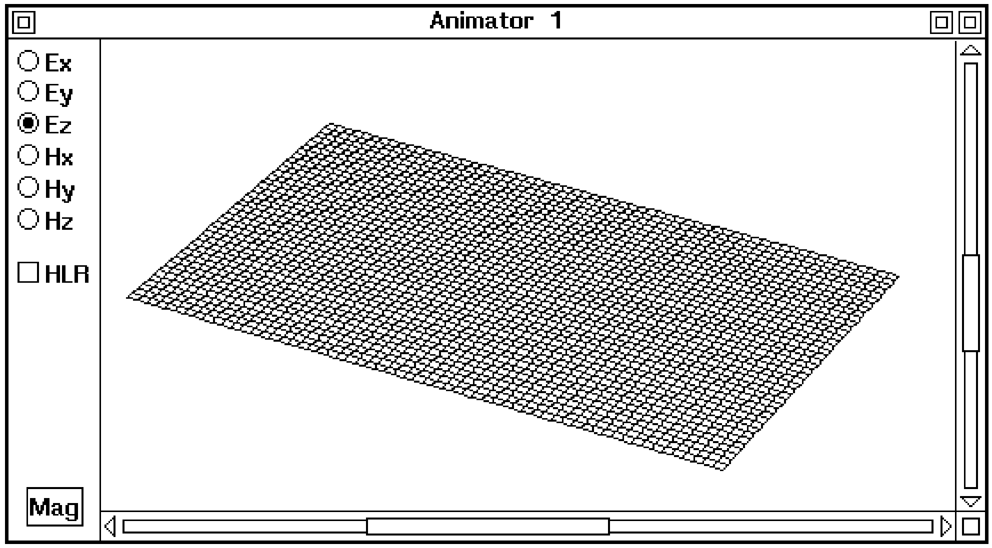


FIGURE 11 `Animator 1` displaying the setting and initial field values in the area of interest.

3.4.4 Set up the Animator

The animator primitive is associated with the **`Animator 1`** window. It is not necessary to set it now because setting may be changed at any time during the simulation. However, we recommend that you follow the following steps so that your simulation output will look like that in this tutorial. The steps are:

- Bring up the **`Animator 1`** window.
- Select the **`Ez`** radio button.
- Unselect the **`HLR`** button if it is selected[1].
- *Click* the **`Mag`** push button to bring up a dialogue box and enter 30 for the magnification factor. Since this dialogue box has only one item, pressing the return key on the keyboard is equivalent to clicking the **`Okay`** button in the dialogue box.
- *Double-click* the 3D graphic area to bring up a dialogue box and enter 300 for the **`Projection Point`**[2] parameter, then *click* the Okay button.

Now, your **`Animator 1`** should look like Figure 11. If not resize the window and use the scrollbars to center the 3D drawing. If your drawing is too big to fit in the drawing area, *double-click* on the drawing area to bring up a dialogue box which allows you to resize the drawing.

1. This turns off the hidden line removal option. As a result the field animation process will run faster. However, if picture quality rather than speed is your main concern, turn the **`HLR`** button on.
2. In this tutorial the other parameter values are not set. Simply use the default setting of the simulator. If your 3D drawing is too big to fit into the drawing area, reduce the value of the **`magnification`** parameter in this dialogue box as well.

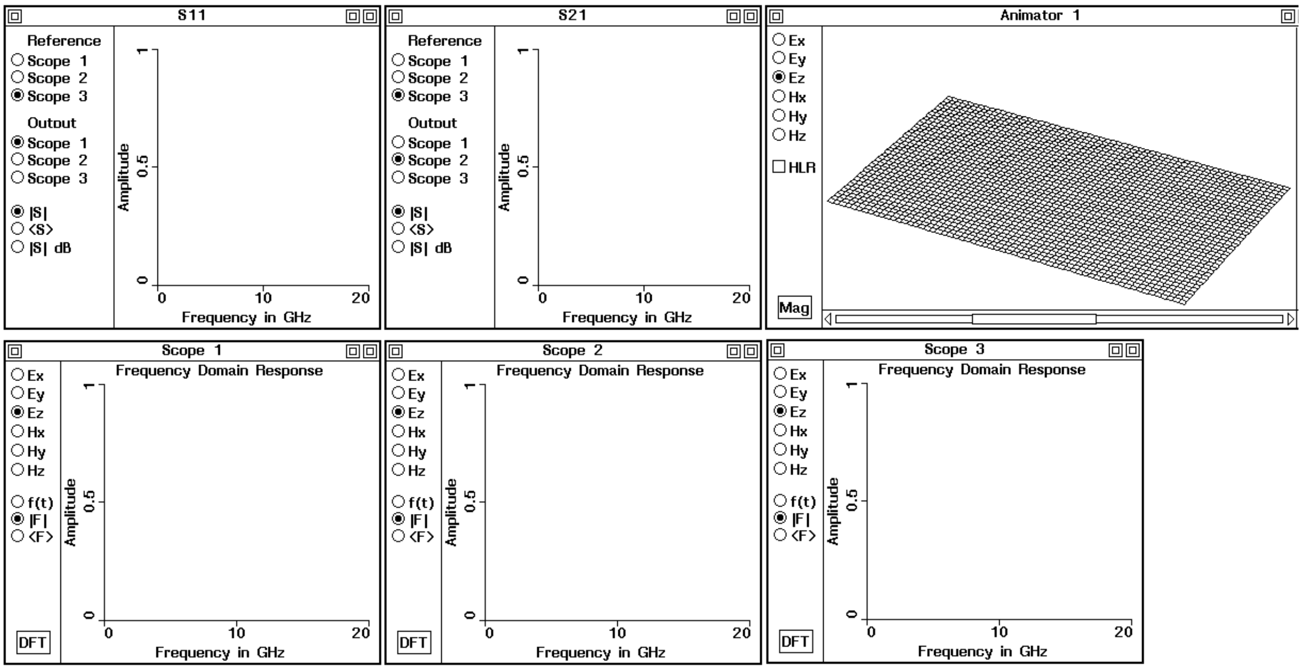


FIGURE 12 We recommend that you organize the subwindows of the simulator so that the subwindows shown in this diagram can all be seen together. This allows you to visualize the changes in all the subwindows simultaneously.

3.4.5 Final Preparation

One last thing that must be done before the simulation can start is to bring up a dialogue box and enter some parameters which control the behaviour of the simulator during the simulation process:

- Bring up the **`Simulate`** pulldown menu.
- Select the **`Data`** button. This will bring up the required dialogue box.
- Enter 1000 and 1 for **`Stop at (Dt)`** and **`Iterations per DFT update`**[1] then click the **`Okay`** button.

That is all for the set up task; the system is now ready for an exciting simulation!

3.5 Simulation Process

We suggest that the subwindows of the simulator be organized as shown in Figure 12. It is not necessary to bring up the generator window, **`Generator 1`**, because it's graph does not change as the simulation proceeds.

1. The other values are related to the frequency bounds and resolution for the discrete Fourier transform. They have been specified earlier in section *Set up the Scopes*. They can be changed here as well; the changes will be dispatched to all the scope and analyzer windows.

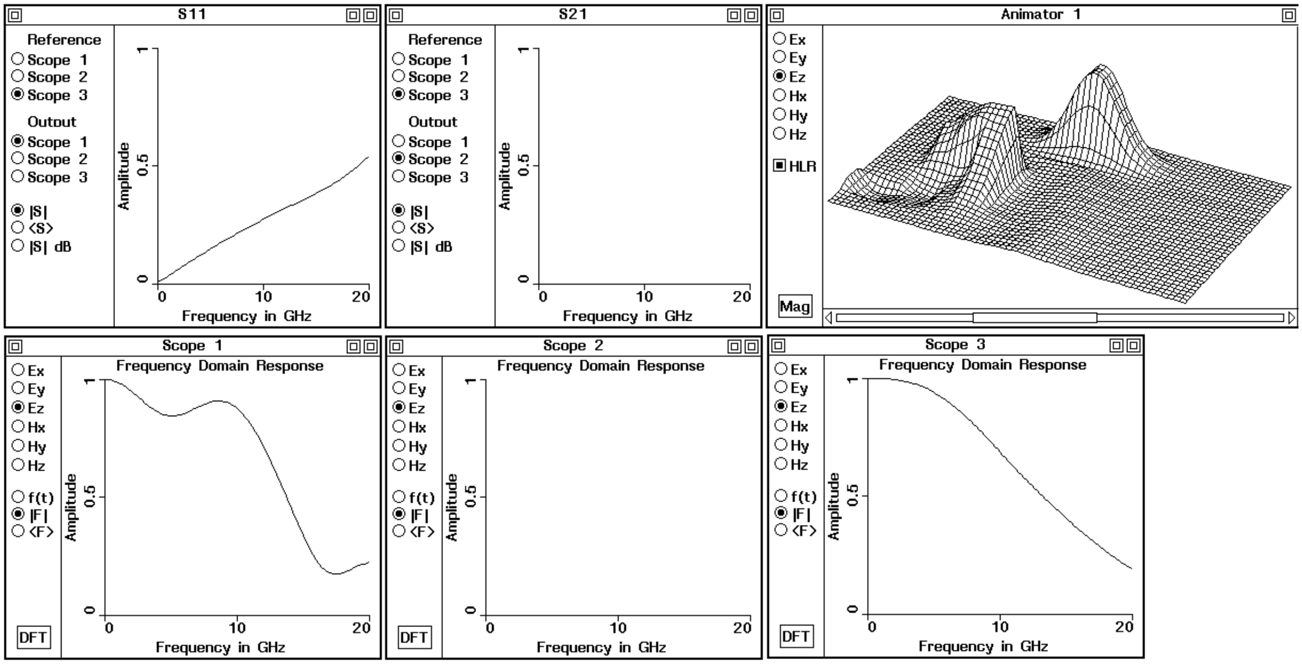


FIGURE 13 Intermediate simulation results at 100 Δt. **`Scope 2`** and **`S21`** have no output yet because the wave has not reached **`Scope 2`** which is at the right end of the structure, see Figure 7.

To start the simulation, select **`Forward`** from the **`Simulate`** pulldown menu. Try that and see how the various subwindows change as the simulation proceeds. You may interrupt the simulation process at any time by just clicking a mouse button; the simulation process will stop after the current simulation has been completed.

Figure 13 shows the intermediate simulation result at 100 Δt. **`Scope 2`** and **`S21`** have no output yet because the wave has not reached **`Scope 2`** which is at the right end of the structure, see Figure 7.

Once you have interrupted the simulation process, you can actually reverse the time flow by selecting **`Backward`** form the **`Simulate`** pulldown menu. This is something you cannot do in your laboratory, but this simulator shows you what you would see if you could return back into the past!

You can also ask **`Animator 1`** to display a different field component, or ask the scope windows to display the time domain response by simply selecting the appropriate radio buttons in these windows. You can also change the reference scopes in the analyzer windows. Another thing you can do at this point is to select the **`Initialize`** button from the **`Simulate`** pulldown menu. This will throw away the simulation result; you could then modify the structure and start a new simulation again! This is like tweaking your structure and measuring its response again. The difference is that you can do it much faster here than in the laboratory! Feel free to experiment and to explore "...what happens if..." Have fun and try all these things but remember to restore the simulator to the state shown in Figure 13 before you go on to the next section.

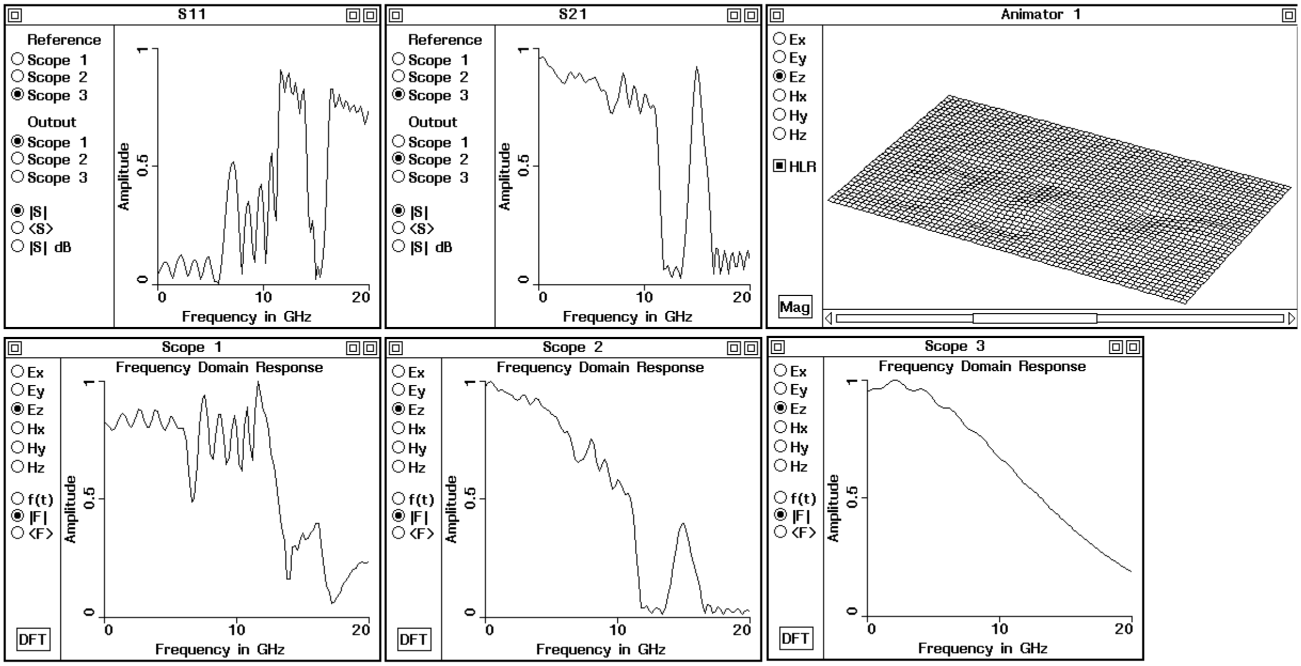


FIGURE 14 The simulation result of this tutorial. This is not a definitive result for the structure due to the very coarse discretization, but it demonstrates all the features described in section *Simulation Results*.

3.6 Simulation Results

If you let the simulation run for 1000 iterations, your result should be the same as that shown in Figure 14. The result in Figure 14 is not what a typical good result should look like due to the rather coarse discretization (for more accurate results, refine the mesh at least three times and use three times as many time steps), but it shows you some important 3D-TLM concepts.

- The output at **Scope 3** is taken from a reference line. One would expect to see a flat frequency response, but **Scope 3** shows something very different. The reason is that the excitation signal used in the generator is a Gaussian function, hence we got a Gaussian frequency response. There is some ripple in the output signal which is due to the discrete nature of the mesh and the truncation of the response (Gibbs effect).
- In spite of Gaussian excitations, the signal in Scope 1 and Scope 2 can still be used to compute S-parameters because they will be normalized to a signal which is obtained from the same Gaussian excitation.
- The animator window shows clearly that there is still some residual signal in the meander line. This ringing is due to multiple reflections of the signal at the bend discontinuities, leading to parasitic resonances. During the simulation you can also observe the semi-circular surface wave that is launched at the input points (to avoid this surface wave, a mode template would have to be implemented). The time domain output of this example is not shown in Figure 14. Try to figure out why the signals behave in certain ways. It is an interesting and rewarding exercise to compare and contrast the time domain signals in the various scope windows.

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