3-D TLM Time Domain Electromagnetic Wave Simulator for Microwave Circuit Modeling

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Abstract

A novel 3-D TLM time domain simulator for electromagnetic waves in structures of arbitrary geometry is described. It computes their response to arbitrary excitation in 3-D space and time, and extracts their frequency characteristics via discrete Fourier transform. It also visualizes the field propagation in a generated-solution mode (field animation). Furthermore it permits time reversal for inverse problem simulation. It has been implemented on RISC workstations and 386 micro-computers.

1 Introduction

While most algorithms and procedures for three-dimensional TLM modeling of electromagnetic fields have been published [1] - [3], no comprehensive implementation of all these concepts in a single 3-D simulator has been available to date. Only a 2-D TLM simulator has been reported sofar [4]. To realize such a simulator as a useful tool for microwave engineers, we have developed a sophisticated interface which allows to graphically input the geometry and electrical composition of a three-dimensional structure, and to extract meaningful engineering data in the appropriate form.

The 3-D TLM method is highly suitable for electromagnetic modeling in the time domain. It is flexible and versatile because it incorporates all the properties of the propagation space and the interaction of the field with the boundaries and materials. Hence, it is not necessary to reformulate the electromagnetic problem for every new structure; its parameters are simply entered by the user through the graphics interface and automatically translated into codes for boundaries, losses, permeability and permittivity, and the excitation of the fields. Furthermore, by solving the problem in discrete time steps the solution of large numbers of simultaneous equations is avoided. Nonlinear as well as dispersive material properties are readily modeled in the time domain as well. Another advantage of the TLM method resides in the large amount of information generated in one single computation using impulse excitation. Through subsequent processing of the impulse response, all frequency domain characteristics of the structure can be extracted and displayed over a wide frequency range. At the same time, by visualizing the field response during a simulation, wave propagation can be observed directly on the computer screen. In this process, the characteristics of a given structure are directly translated into the field behaviour, which allows the designer to better understand its function and to fully engage the intuitive qualities of the mind.

2 The Principal Functions of the 3-D TLM Simulator

The principal functions of the Simulator can be summarized as follows:

- The topology of an electromagnetic structure, including its boundaries, dielectric and magnetic properties, losses, special subregions, source configuration and output points/regions are entered with the mouse like in a standard 3-D drafting program. This is done using the **Editor** window.
- The excitation function is selected from a number of available waveforms (Dirac, sine, raised cosine, rectangular and triangular pulse, NEMP, Gaussian pulse) or specified by a user-generated ASCII file. This is done using a **Source** window.
- The time response at any point in the structure can be observed and displayed together with its discrete Fourier transform (frequency response in magnitude and phase). This is done using a **Analyzer** window.
- All six components of the electromagnetic field can be visualized in any plane along the main axes inside the structure for dynamic field animation in a generated-solution mode. This is done using a **Animator** window.
- Scattering parameters, time and frequency responses, excitation functions, and field pictures can be displayed and printed. Data can be stored in output files for later simulation, modification, or continuation of a task at a later time.
- Advanced features include the modeling of dispersive boundaries, in particular non-TEM absorbing boundary conditions and field partitioning in the time domain using Johns Matrix techniques and Diakoptics [4], the recursive generation of absorbing Johns Matrix boundaries, variable mesh size [3], and the reversal of an electromagnetic process in time.

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3 Description of the Principal Simulator Functions

In order to ensure that the 3-D TLM simulator can be used effectively without highly specialized knowledge of discrete mathematics and numerical modeling, much effort has been concentrated on the user interface. It is seamless and transparent to the user, featuring multiple windows and a functionally structured menu systems consisting of both pulldown menus and submenus with clearly defined functions. The main functions of the interface are described below.

3.1 The Editor Window

The **Editor** window allows the user to graphically input the structure. It has four quadrants. The first displays the structure in a 3-D perspective projection which can be rotated arbitrarily. Quadrants 2, 3, and 4 represent the x-y, x-z, and y-z planes, respectively. Boundaries and subregions (including sources, output points and planes of field visualization) are drawn in any of the three Cartesian planes and appear automatically in all four quadrants. By activating one of the items in the window margin, the user selects the type of boundary and the input/output devices.

To demonstrate the characteristics of the **Editor**, Fig. 1 shows a simple example: a groove guide resonator short-circuited at both ends by an electric wall, and bounded at the top and bottom by absorbing walls. One mesh unit Δl corresponde to 1 mm in this example. The E_z component of that mode is injected and picked up at the center of the cavity. The input and output boxes are not shown in Fig. 1 to avoid crowding the picture.

The functions of the **Editor** are similar to that of a lab facility for drafting and realizing a physical microwave structure.

3.2 The Source Window

The **Source** window allows the user to specify the field component(s) to be injected in the source region, the excitation function and its characteristic parameters. An arbitrary number of distinct sources with the same characteristics can be used in a given structure, and three different source characteristics can be specified in three **Source** windows. Fig. 2 shows the **Source** window displaying the Gaussian impulse injected into the groove guide cavity to determine its eigenfrequencies in the 20 to 50 GHz range.

The functions of the **Source** are similar to that of a programmable function generator and synthesizer.

3.3 The Analyzer Window

The **Analyzer** window allows the user to display either the time domain response or the frequency domain response of a structure, the latter being computed with the complex discrete Fourier transform. The output signal can be picked up at any node in the structure and can be any of the six field components at the output node. The parameters of the time and frequency domain displays can be adaped to the user's particular needs. Up to three **Analyzer** windows displaying the output at three different output nodes may be active at the same time. The **Analyzer** output also allows the computation and display of complex S-parameters.

Fig. 3 shows the **Analyzer** window for the groove guide resonator, displaying its eigenspectrum in response to the Gaussian impulse excitation of Fig. 2. The lowest spectral peak corresponds to the dominant TE_{11} mode resonance, while the other peaks are higher order mode resonances.

The functions of the **Analyzer** are similar to that of a combined oscilloscope and spectrum analyzer.

3.1 The Animator Window

The **Animator** window allows the user to visualize the distribution of any of the six field components in any plane parallel to the main axes. Three independent **Animator** windows can be open at the same time. The plane(s) of visualization must be specified in the **Editor** window. During a simulation, the field values are displayed immediately after any desired number of computation steps, resulting in a generated-solution mode field animation which visualizes the propagation of the fields in the structure.

Fig. 4 demonstrates the field animation feature by showing three snapshots of a Gaussian impulse which travels across a 90^o crossing (overpass) of two microstrip lines. The plane of visualization lies 1 Δl beneath the strips, and the distribution of the E-field component perpendicular to that plane (E_z) is shown. The scattering of the impulse at the overpass and the coupling of energy into the crossing line is clearly visible.

The functions of the **Animator** are similar to that of a facility for visualizing field and wave phenomena in space and time.

4 Conclusion

In summary, the simulator presented and described in this paper combines the functions of a time domain analyzer, a microwave/millimeter-wave vector network analyzer, a spectrum analyzer, a signal processor, and a field animation machine. By combining the most advanced concepts of TLM modeling with interactive computer graphics, this simulator allows the user not only to generate the traditional engineering characteristics of a structure, but also to observe dynamic electromagnetic processes which could only be imagined until now. It thus enriches the perception to an extent rarely achieved by any other tool in science or engineering. In graphical representation, most electromagnetic processes can be comprehended in their full complexity by intuition. New ideas and associations are stimulated, and the creative potential of all those who think in pictures is awakened.

The 3-D TLM simulator has been implemented both on RISC workstations and 386 micro-computers, and will be demonstrated during the Open Forum presentation.

Acknowledgements

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References

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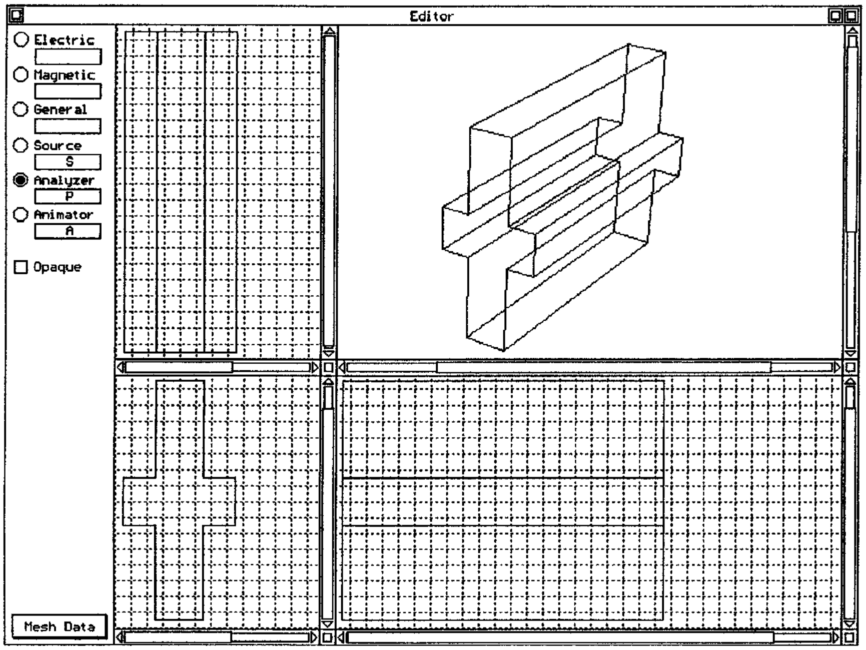

Fig. 1
The four quadrants of the **Editor** window. The example shows a groove guide resonator short-circuited at both ends by electric walls.

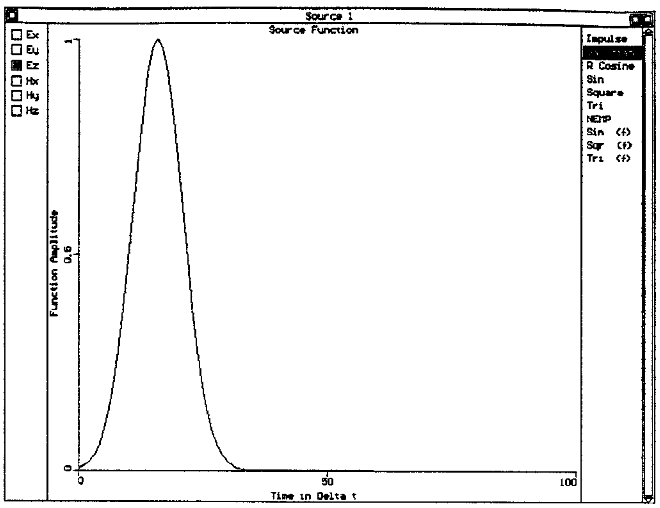

Fig. 2 The **Source** window displaying the Gaussian impulse injected into the groove guide cavity to determine its eigenfrequencies.

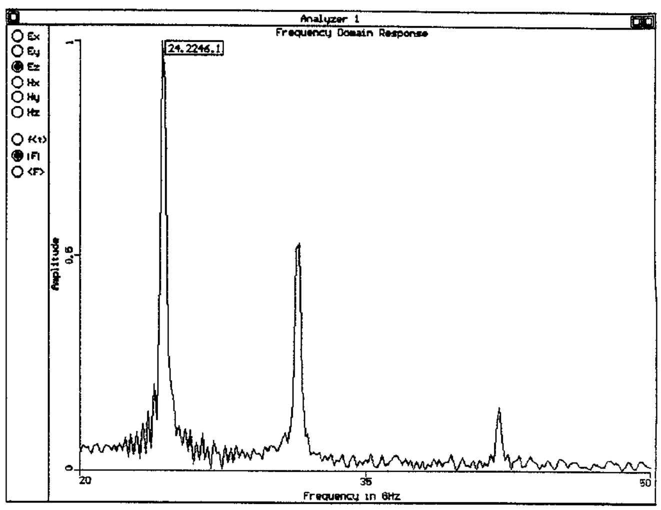

Fig. 3 The **Analyzer** window showing the eigenspectrum of the groove guide resonator excited by the Gaussian impulse of Fig. 2. The lowest spectral peak corresponds to the dominant TE_{11} mode resonance, while the other peaks are higher order mode resonances.

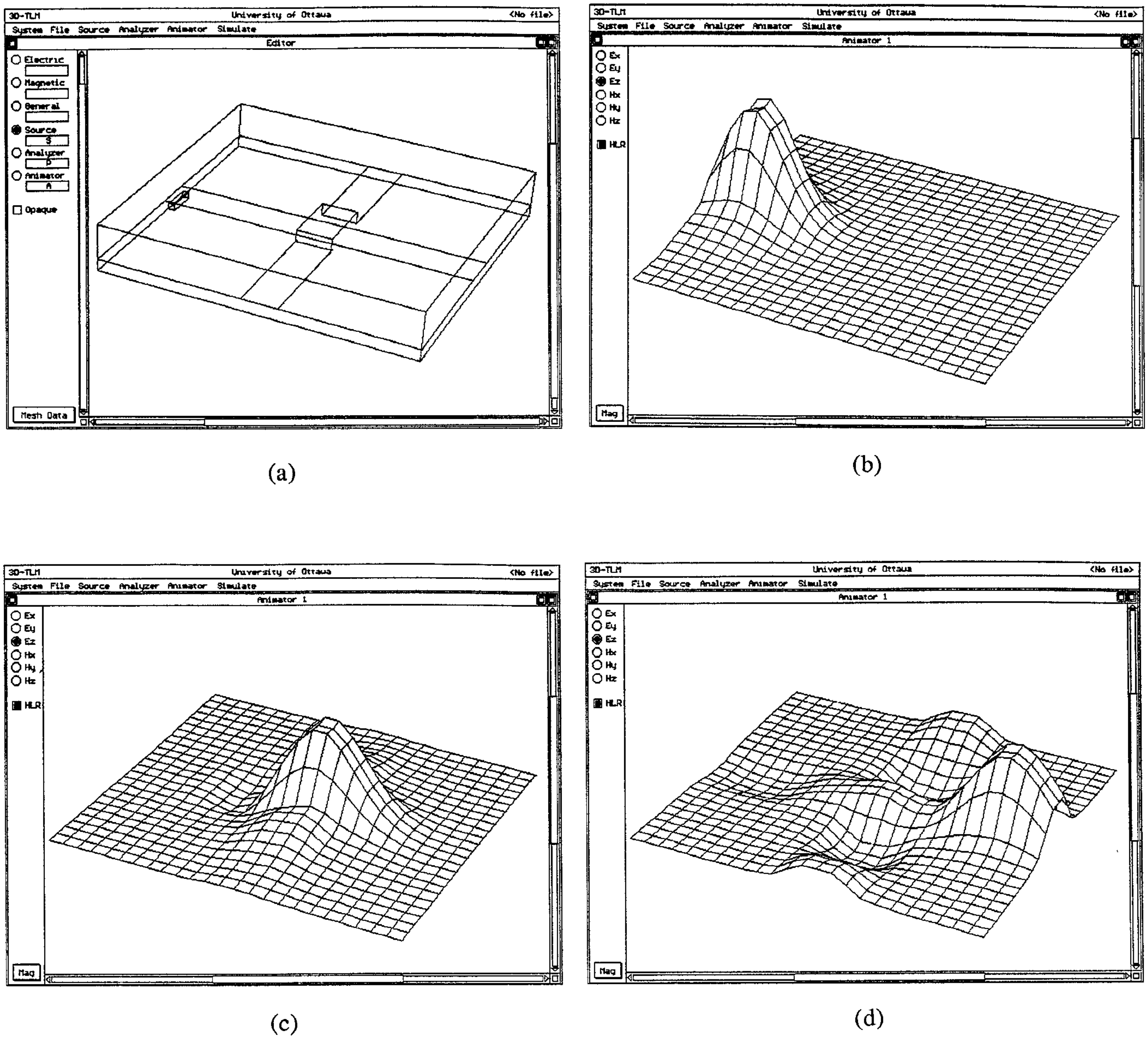

Fig. 4 The **Animator** window. (a) $90°$ crossing (overpass) of two microstrip lines. (b) to (d) Three snapshots of a Gaussian impulse which travels across the overpass. The plane of visualization lies 1 Δl beneath the strips, and the distribution of the E-field component perpendicular to that plane (E_z) is shown. The scattering of the impulse at the overpass and the coupling of energy into the crossing line is clearly visible.