SPICE COMPATIBLE MODEL FOR MULTIPLE COUPLED NONUNIFORM TRANSMISSION LINES: APPLICATION IN TRANSIENT ANALYSIS OF VLSI CIRCUITS

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Abstract An SPICE compatible model for multiple coupled nonuniform lossless transmission lines (TL's) is presented. The method of the modeling is based on the steplines approximation of the nonuniform TLs and quasi-TEM assumptions. Using steplines approximation the system of coupled nonuniform TLs is subdivided into arbitrary large number of coupled uniform lines (steplines) with different characteristics. Then using modal decomposition method the system of coupled partial differential equations for each step is decomposed to a number of uncoupled ordinary wave equations describing uncoupled uniform TLs in each step. To satisfy the boundary conditions at the discontinuities a new model is developed. Therefore each step of the system can be modeled in SPICE using a set of ideal delay lines representing uncoupled TLs and some linear-dependent voltage and current sources. Finally some examples are given to show the validity and usefulness of the model.

Key Words VLSI Circuits, Interconnect, Transient Analysis, SPICE Model

چکیده در این مقاله یک مدل سازگار با خطوط انتقال غیرهمگن چند تایی تزویج شده بدون تلف ارائه شده است. این مدل بر پایه فرض انتشار شبه TEM و روش تقریب پله ای برای خطوط غیرهمگن بنا نهاده شده است. با استفاده از تقریب پله ای سیستم خطوط انتقال غیر همگن تزویج شده به تعداد دلخواهی خطوط انتقال همگن تزویج شده که دارای مشخصات متفاوتی هستند، تقسیم می‌شود. سپس با استفاده از روش تفکیک مودال معادلات دیفرانسیل با مشخصات جزئی مربوط به هر پله ای به صورت تعدادی معادله موج توصیف کننده خط انتقال تفکیک شده، در می آید. برای اغنای شرایط مرزی موجود در گسستگی‌های موجود روش جدیدی ایجاد شده است. به همین دلیل می‌توان هر پله سیستم را در نرم افزار SPICE با خطوط تاخیر ایده الی که توصیف کننده خطوط انتقال تفکیک شده مورد بحث می‌باشند و همچنین تعدادی منابع ولتاژ و جریان وابسته توصیف کرد. در نهایت تعدادی مثال که شاهدی بر صحت و مفید بودن روش هستند، ارائه شده است.

1. INTRODUCTION

The analysis and modeling of multiple coupled micro strip and other TLs and interconnects has been a topic of considerable interest in VLSI design and microwave integrated circuit technologies. As clock rates increase and inter-line spacing decrease, an accurate analysis of pulse propagation in multiconductor, coupled TL's becomes more important. A considerable amount of work has been done on the applications, analysis, and simulation of multiple coupled TLs [1-36]. For example authors of [3] used iteration-perturbation approach in spatial domain. Also the same problem was considered in [4,5] using Chebyshev expansion in time-and frequency-domain respectively. Time-domain perturbational method [6] and the method of convolution characteristics [7] have also been used previously to treat such problem. In [8] a nonuniform multiple coupled TL's systems are considered as a cascaded chain of short uniform line sections (steps). Then the ABCD matrices of the sub networks were obtained using some first terms of the matrix series expansion of the analytical expression. This caused (as the authors stated) an additional errors in the results except when the number of the steps are large, which is then increased the computation time. Also several SPICE compatible [11-19], and other circuit simulation-models [20-36] has been presented by several authors. For example for the case of lossless uniform lines with frequency-independent line constants, a SPICE model based on modal decomposition method was proposed in [11]. This model leads to a circuit model consisting of linear-dependent sources and ideal delay elements representing uncoupled TLs. Almost the same principle has been used by several authors to obtain a SPICE model for different applications [12-16]. The principles of configuration-oriented SPICE model for homogeneous and inhomogeneous medium were presented in [16, 17]. Authors of [18] present a new SPICE compatible model for almost all types of TLs But the authors do not give computed example for the case of nonuniform TLs. This makes it difficult to decide whether the presented method in [18] is computationally efficient for multiple coupled nonuniform TLs.

In this paper a simple SPICE compatible model for multiple coupled nonuniform loss less TL's is presented. The geometry under considerations includes M (arbitrary number) of coupled nonuniform planar TLs each with different tapering in width and spacing. The method is based on the quasi-TEM assumptions for the coupled TLs and step lines approximation. Using step lines approximation, the system of coupled nonuniform TLs is decomposed into (N) arbitrary large number of coupled uniform step lines with different characteristics. Then using modal decomposition method the system of coupled partial differential equations for each step are decomposed to M uncoupled ordinary wave equations which are then modeled using ideal delay lines in SPICE and linear-dependent voltage and current sources. To satisfy the boundary conditions at the discontinuities, the continuity condition for the voltages and currents are imposed using a proposed linear model, which can be simulated using some linear-dependent voltage and current sources. The step line approximation is the only source of error in this paper. The method proposed here has been verified by comparing its results, with those obtained by other methods. It is a fast and convenient method for investigating time-domain near- and far-end cross talks and other related quantities that are of utmost importance in interconnect performance analysis.

2. REVIEW OF MODAL DECOMPOSITION METHOD

Consider a system of M-coupled nonuniform transmission lines with equal lengths, terminated by arbitrary complex loads as shown in Figure 1. This can be considered as a circuit model for typical high speed digital interconnects. To find the model of this configuration, the total length of the coupled lines d is subdivided to N equal (without loss of generality) intervals Δz . The inductance, capacitance, resistance, and conductance matrices of the coupled TLs over each subinterval are taken to be independent of z. The partial differential equations, which describe the system in the n-th step, are given by

$$\frac{\partial\,[v_k(z,t)]_n}{\partial z}+[L]_n\frac{\partial\,[i_k(z,t)]_n}{\partial z}=0 \tag{1}$$

$$\frac{\partial\,[i_k(z,t)]_n}{\partial z}+[C]_n\frac{\partial\,[v_k(z,t)]_n}{\partial z}=0 \tag{2}$$

Where $[v_k(t,z)]_n$, $[i_k(t,z)]_n$, $[C]_n$ and $[L]_n$ are $M\times 1$ voltage and current vectors, and $M\times M$ capacitance and inductance matrices of the coupled TLs at the n-th step respectively. Note that the matrices $[L]_n$ and $[C]_n$ are symmetric as a consequence of the reciprocity properties for the electromagnetic fields. Furthermore, they are assumed to be strictly positive definite.

Using the "modal decomposition" method [1], one may decouple [1,2] by simultaneously diagonal zing $[L]_n$ and $[C]_n$ matrices. The modal variables are defined by

$$[v_k^m(z,t)]_n=[T_v]_n\;[v_k(z,t)]_n \tag{3}$$

$$[i_k^m(z,t)]_n=[T_i]_n\;[i_k(z,t)]_n \tag{4}$$

In which $[T_v]_n$ and $[T_i]_n$ are constant "Transfer" matrices, for the n-th step. In 3 and 4

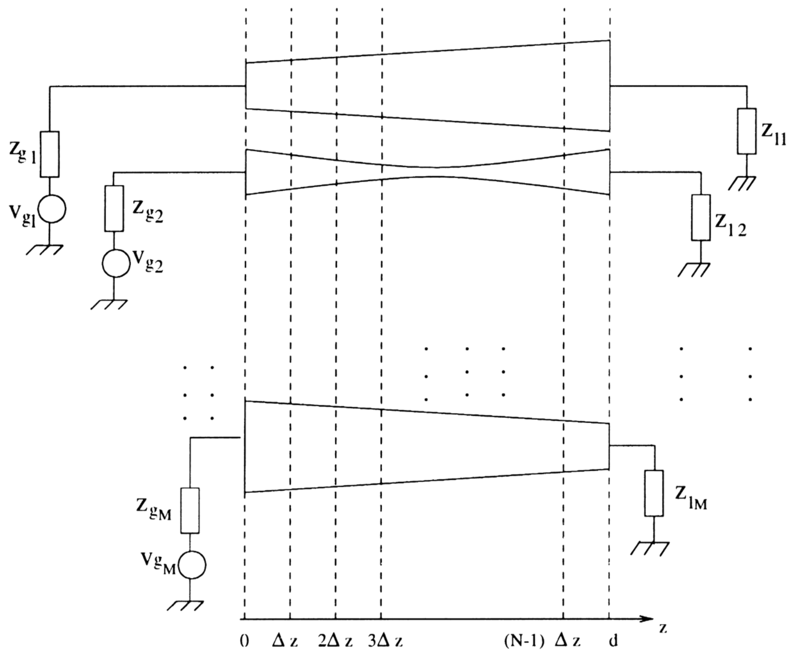

Figure 1. Multiple nonuniform-coupled *TLs*.

$[v_k^m(t,z)]_n$ and $[i_k^m(t,z)]_n$ represent voltage and current modal vectors. A simple method to obtain $[T_v]_n$ and $[T_i]_n$ is given in several references [1, 2]. Substituting 3 and 4 in 1 and 2 leads to the uncoupled set of partial differential equations as

$$\frac{\partial\,[v_k^m(z,t)]_n}{\partial z}+[L^m]_n\frac{\partial\,[i_k^m(z,t)]_n}{\partial z}=0 \qquad (5)$$

$$\frac{\partial\,[i_k^m(z,t)]_n}{\partial z}+[C^m]_n\frac{\partial\,[v_k^m(z,t)]_n}{\partial z}=0 \qquad (6)$$

In which $[L^m]_n$ and $[C^m]_n$ arc diagonal matrices defined for the n-th step as:

$$[L^m]_n=[T_v]_n\;[L^m]_n\;[T_i]_n^{-1} \qquad (7)$$

$$[C^m]_n=[T_i]_n\;[L^m]_n\;[T_v]_n^{-1} \qquad (8)$$

Therefore by using proper transfer matrices $[T_v]_n$ and $[T_i]_n$ for the n-th step, the coupled equations [1,2] arc now decoupled to *M* uncoupled wave equation in terms of modal variables.

3. EQUIVALENT SPICE MODELS FOR UNIFORM COUPLED TL's STEP

Consider n-th uniform coupled transmission lines step with length Δz. Note that the distance for the n-th step is measured from $z=(n-1)\Delta z$. From [3,4] one can relate the voltages and currents of the modal and main lines as (for $0\le z\le\Delta z$)

$$v_{kn}^m=\sum_{r=1}^{M}s_{kr}^n\,v_{rn}(z,t) \qquad (9)$$

$$v_{kn}=\sum_{r=1}^{M}p_{kr}^n\,v_{rn}^m(z,t) \qquad (10)$$

$$i_{kn}^m=\sum_{r=1}^{M}t_{kr}^n\,i_{rn}(z,t) \qquad (11)$$

$$v_{kn}=\sum_{r=1}^{M}q_{kr}^n\,i_{rn}^m(z,t) \qquad (12)$$

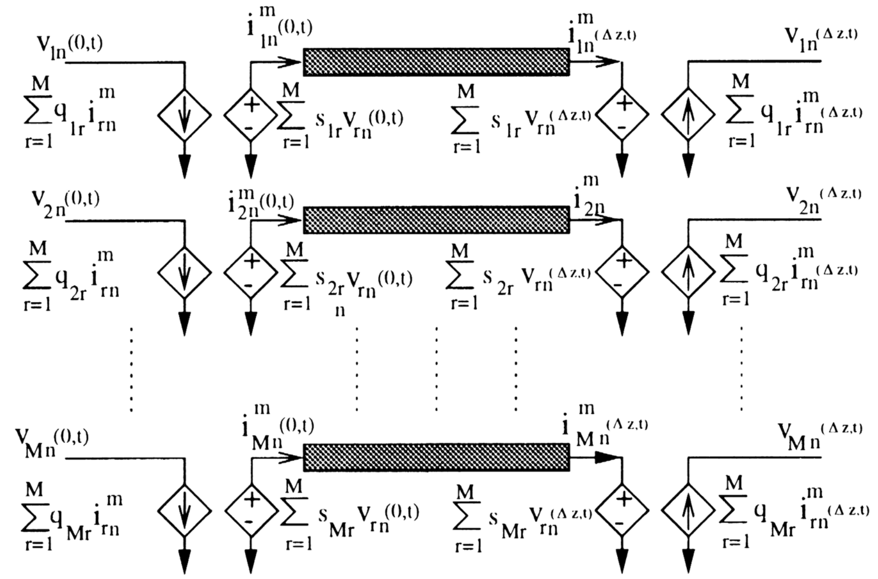

Figure 2. SPICE Model of the n-th Uniform Coupled TLs Step.

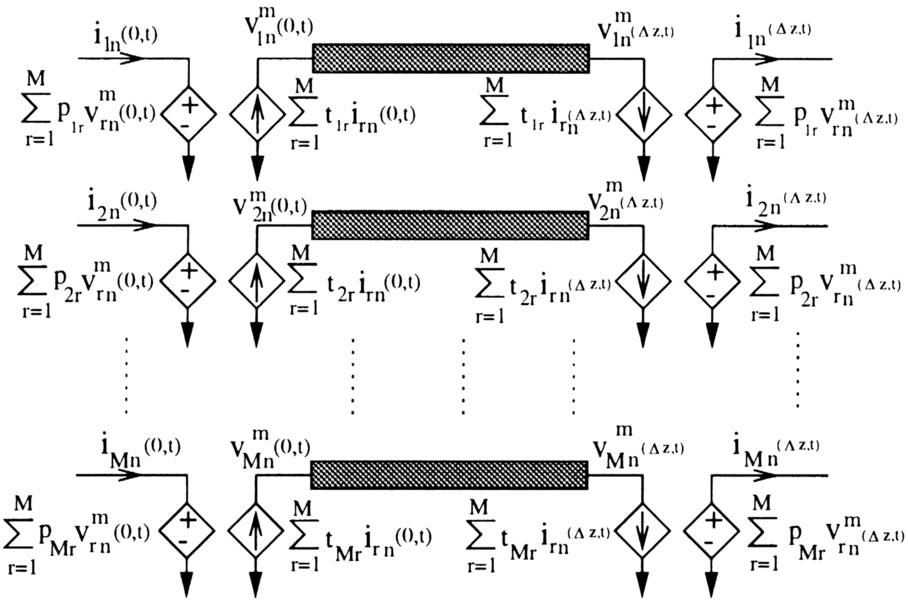

Figure 3. SPICE Model of the; n-th uniform Coupled TLs Step.

In which s^n_{kr}, p^n_{kr}, t^n_{kr} and, q^n_{kr} are elements of the k-th row and r-th column of $[T_v]_n$, $[T_v]_n^{-1}$, $[T_i]_n$ and $[T_i]_n^{-1}$ respectively, and v^m_{kn}, v_{kn}, i^m_{kn} and i_{kn} represent the modal and main voltages and currents of the k-th line and n-th step. According to these equations and based on modal decomposition method discussed briefly in previous section several equivalent models for uniform coupled lines can be derived. Two equivalent SPICE models for the uniform coupled TL's structure are shown in Figures 2 and 3. It is simple to show that these two models are equivalent.

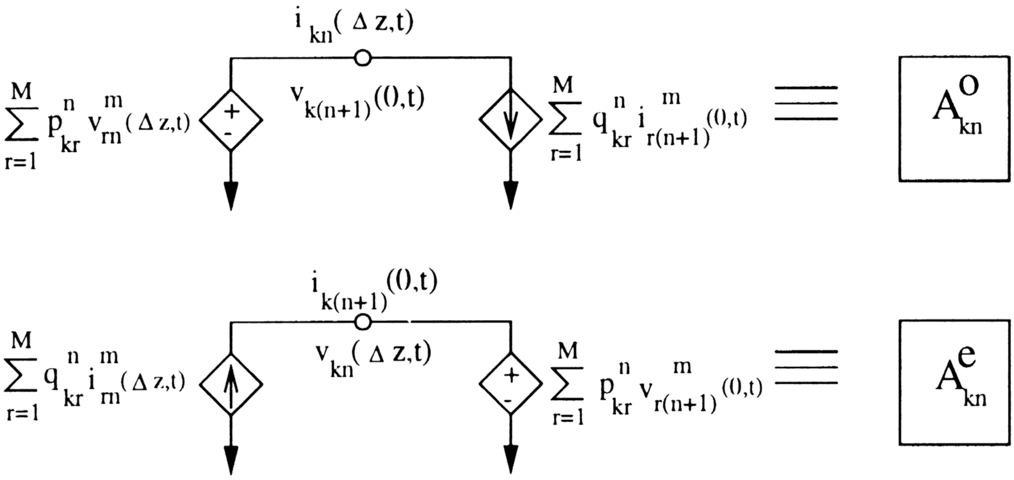

Figure 4. SPICE model of boundary conditions.

4. SPICE MODEL FOR NONUNIFORM COUPLED TRANSMISSION LINES

To find a suitable SPICE model first we have to impose the boundary conditions at the discontinuities of the adjacent steps. Boundary conditions at the discontinuity of the n-th and (n+l)-th steps are given by:

$$[v_k(\Delta z,t)]_n = [v_k(0,t)]_{n+1} \tag{13}$$

$$[i_k(\Delta z,t)]_n = [i_k(0,t)]_{n+1} \tag{14}$$

To impose these boundary conditions for the k-th line of the n-th step we use the following SPICE models (see Figure 4). Note that in this paper the model shown in Figure 2 is used for the first step, and A_{kn}^{o} and v_{kn}^{e} are used when n is an odd or even number, respectively. Finally the SPICE compatible model for nonuniform coupled TLs structure is obtained as shown in Figure5.

5. EXAMPLES AND RESULTES

In the first example consider two conductor nonuniform TLs as shown in Figure 6. This transmission system is considered in [4]. Terminations are considered to be 50Q pure resistive. The total length of the nonuniform section of the lines is subdivided to 6 steps. Parameters of the lines for each step are given in [4]. The voltage waveforms at some points of the excited (active) and parasitic (passive) lines using SPICE model of this system are shown in Figures 7 and 8.

As the second example consider the same structure as shown in Figure 6. Now we want to investigate the effect of the rise and fall times of the input signal on the signal propagation and crosstalk. Figures [9-10] show the voltage at various points of the lines for a signal with 0.01 Ps rise and fall times. As it is clear the magnitude of the crosstalk signal is magnified for this case. In the third example we put two coupled systems as shown in Figure 6 in cascade to form the structure shown in Figure 11. This structure is now modeled using the proposed SPICE compatible model. The voltage waveforms at some points of the excited (active) and parasitic (passive) lines are shown in Figures12 and 13.

6. CONCLUSIONS

An efficient SPICE compatible model of lossless

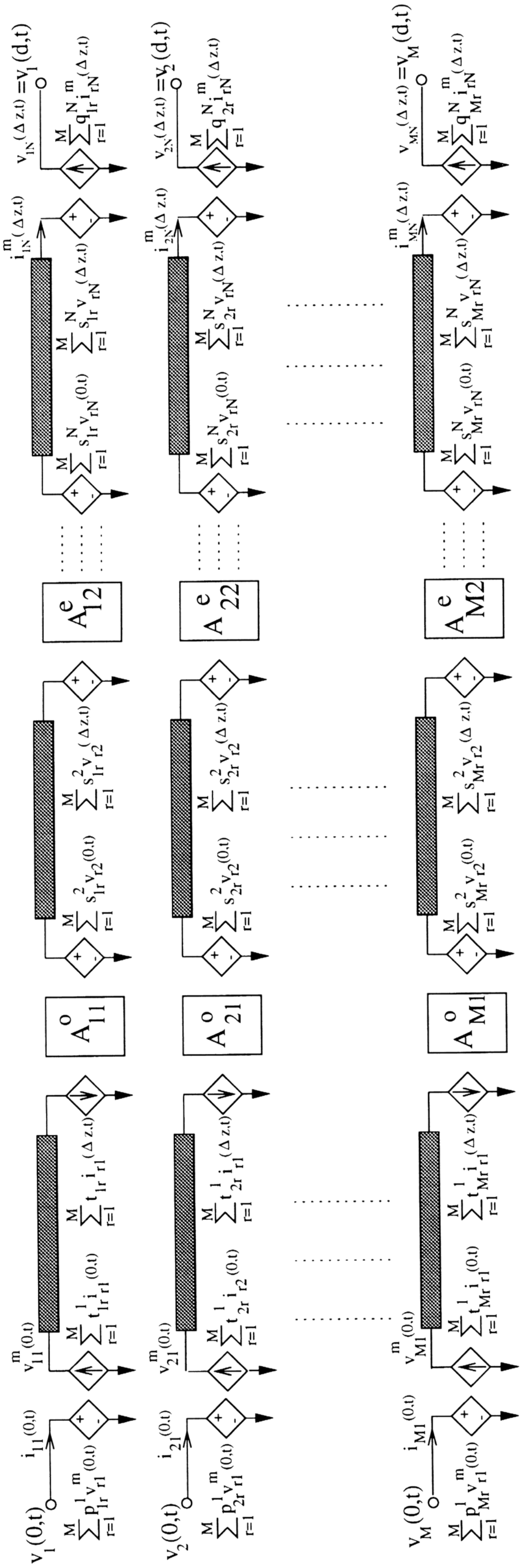

Figure 5. SPICE Compatible Model for nonuniform Coupled TL's Structure.

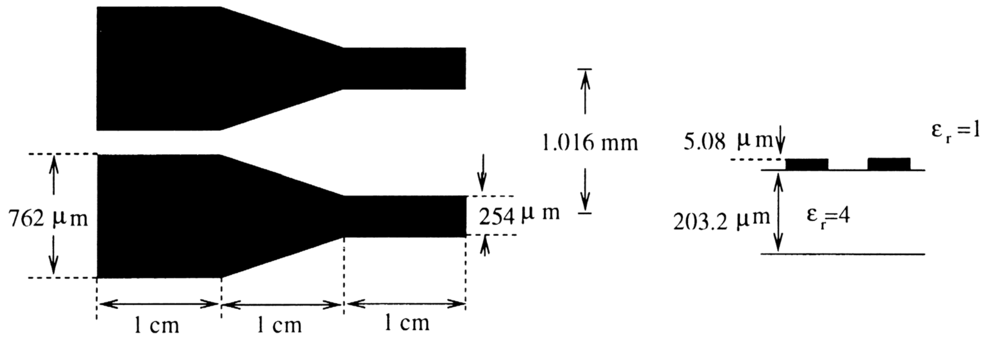

Figure 6. The transmission system in Example 1.

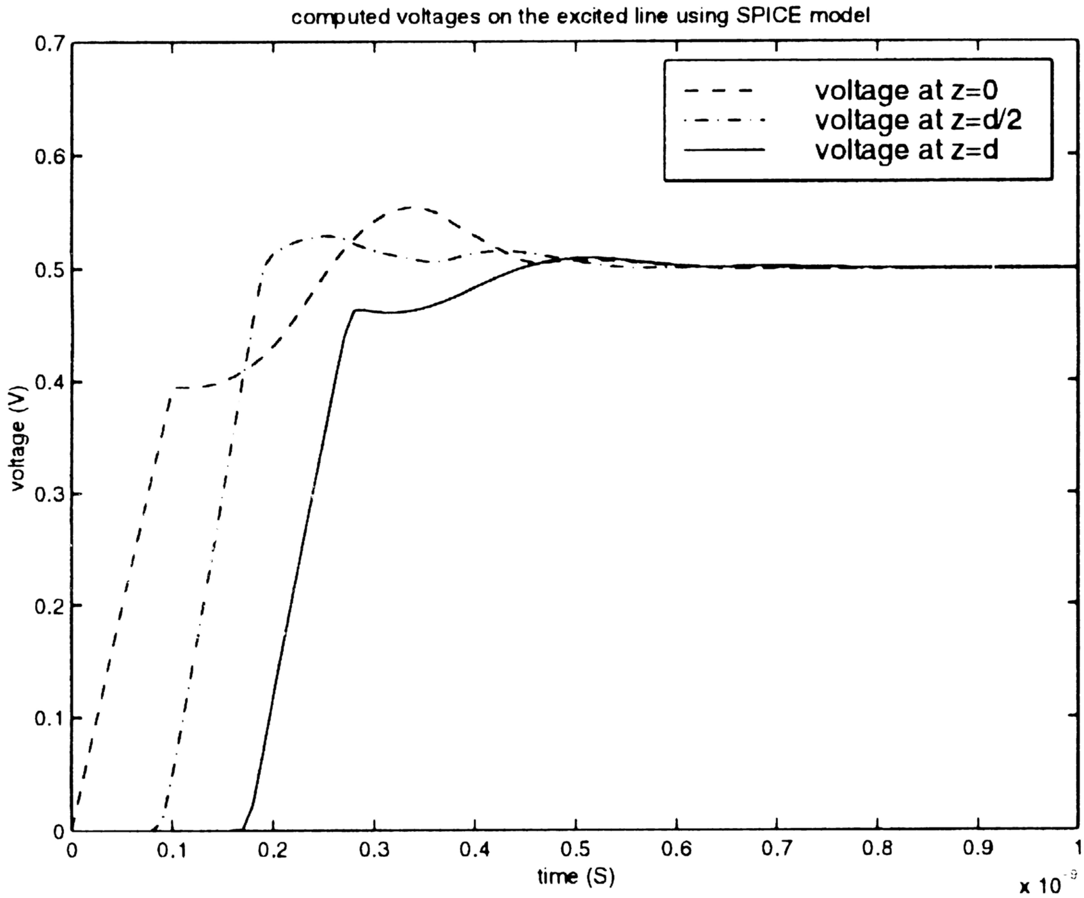

Figure 7. Input voltage waveform and voltages for the various points of the excited line (Compare the voltage at $z = 0$ and $z = d$ with Figure 9).

coupled TLs for evaluating the transient response was presented. It can he used for VLSI nonuniform interconnect analysis and design. The accuracy of the present model has been verified by comparing its results with those obtained using other methods. The most advantage of such modeling scheme is that each physical point of the system can be easily accessed. So the voltage and current at arbitrary

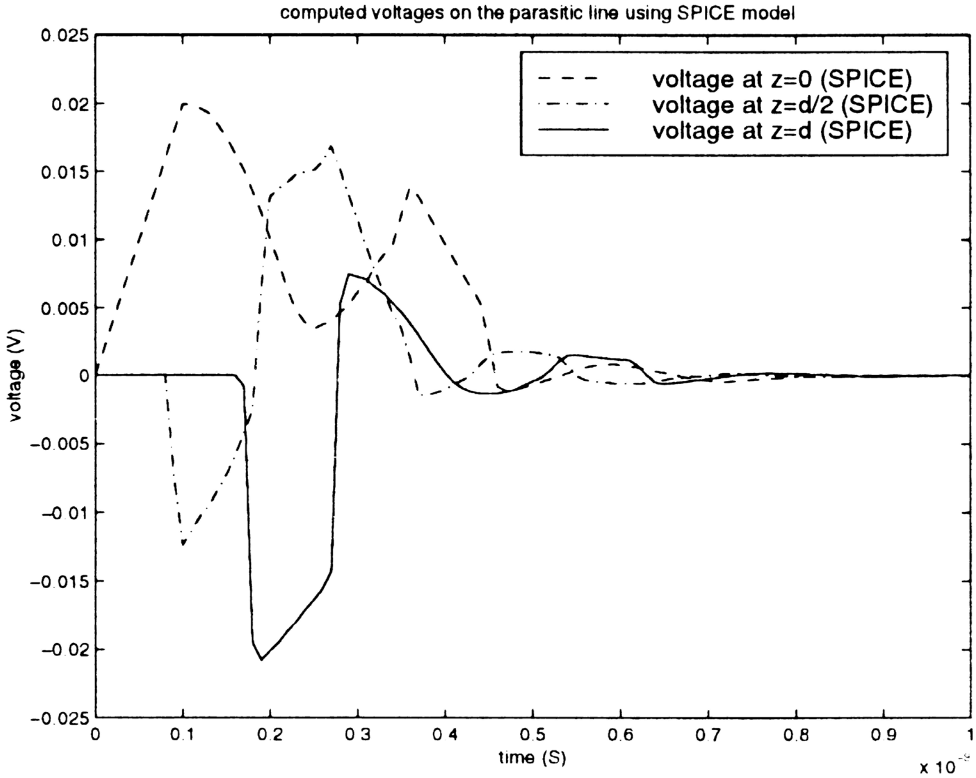

Figure 8. Voltages for the various points of the parasitic line (Compare the voltage at z = 0 and $z = d$ with Figure 9).

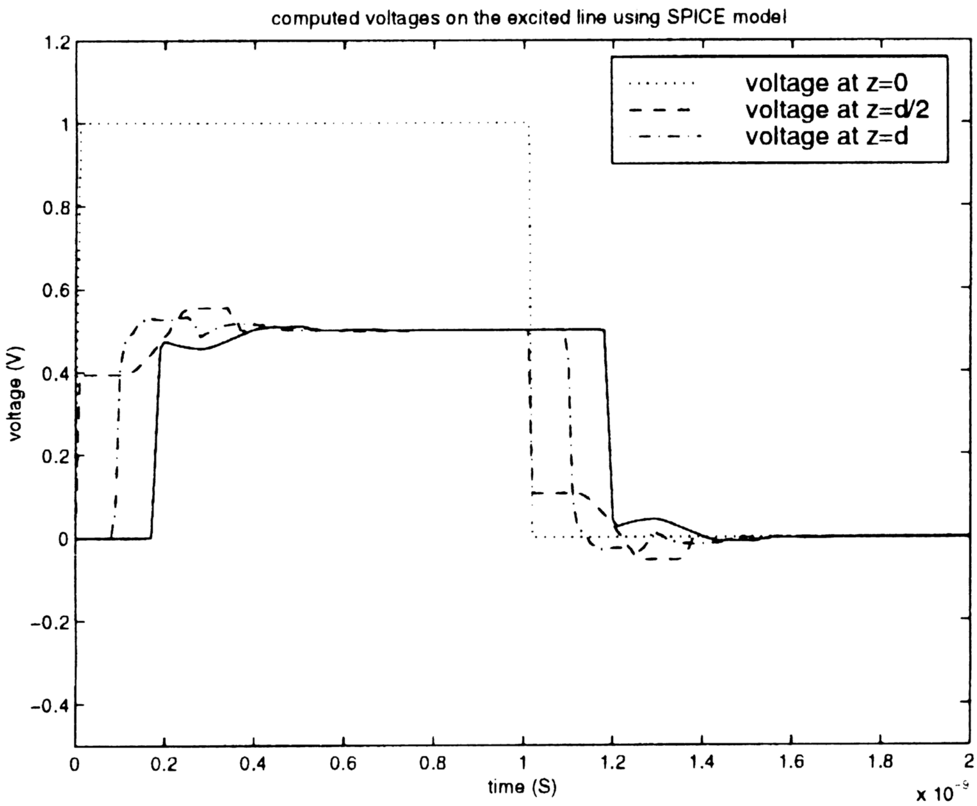

Figure 9. Input voltage waveform and voltages for the various points of the excited line.

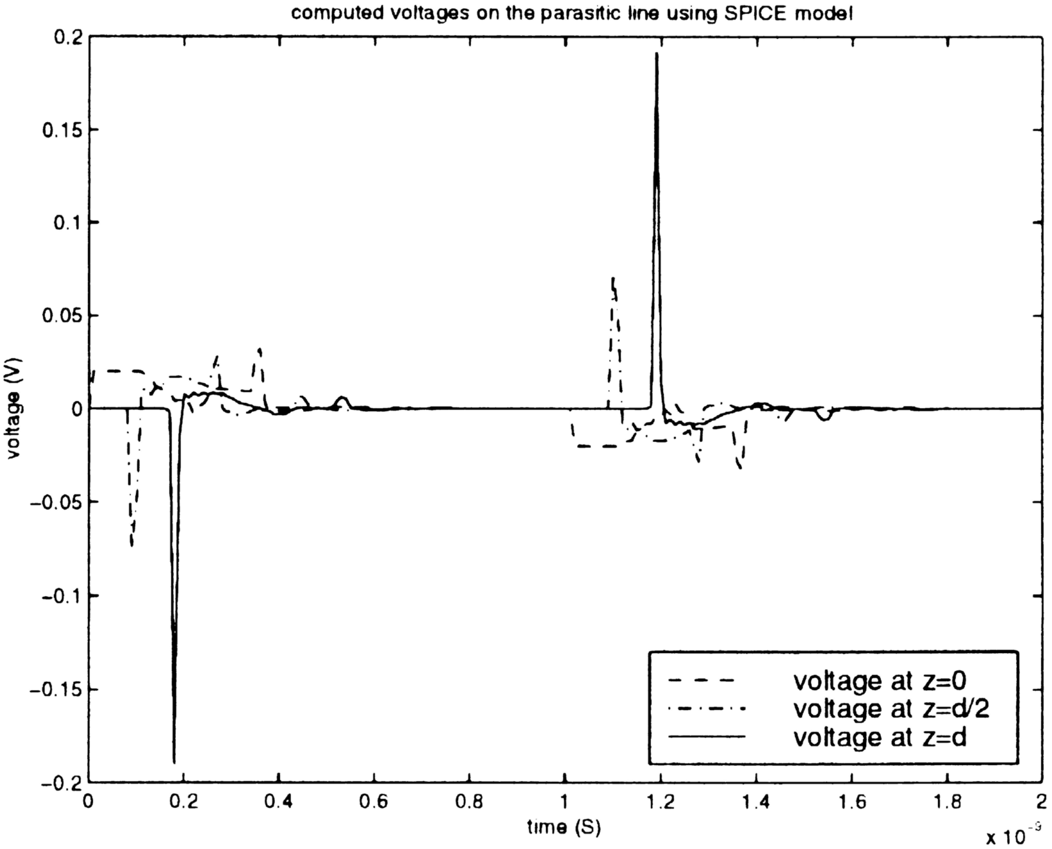

Figure 10. Voltages for the various points of the parasitic line.

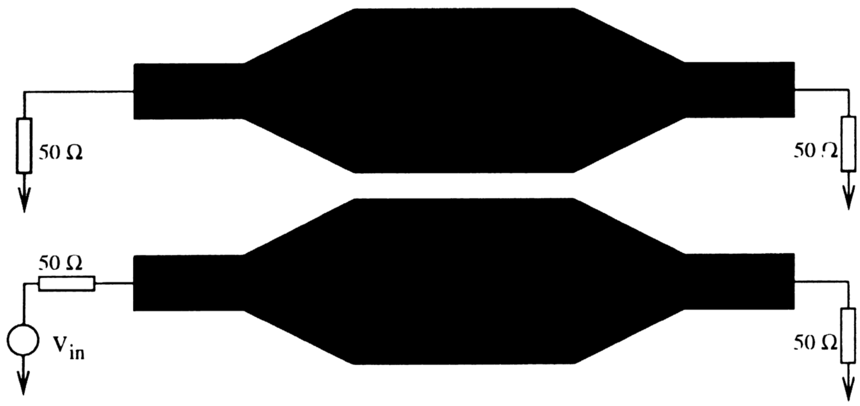

Figure 11. Nonuniform-coupled TL's system discussed in the third example.

points of the lines can be monitored, and the effect of external electromagnetic fields on the system can be considered by adding proper additional input sources at suitable points of the model.

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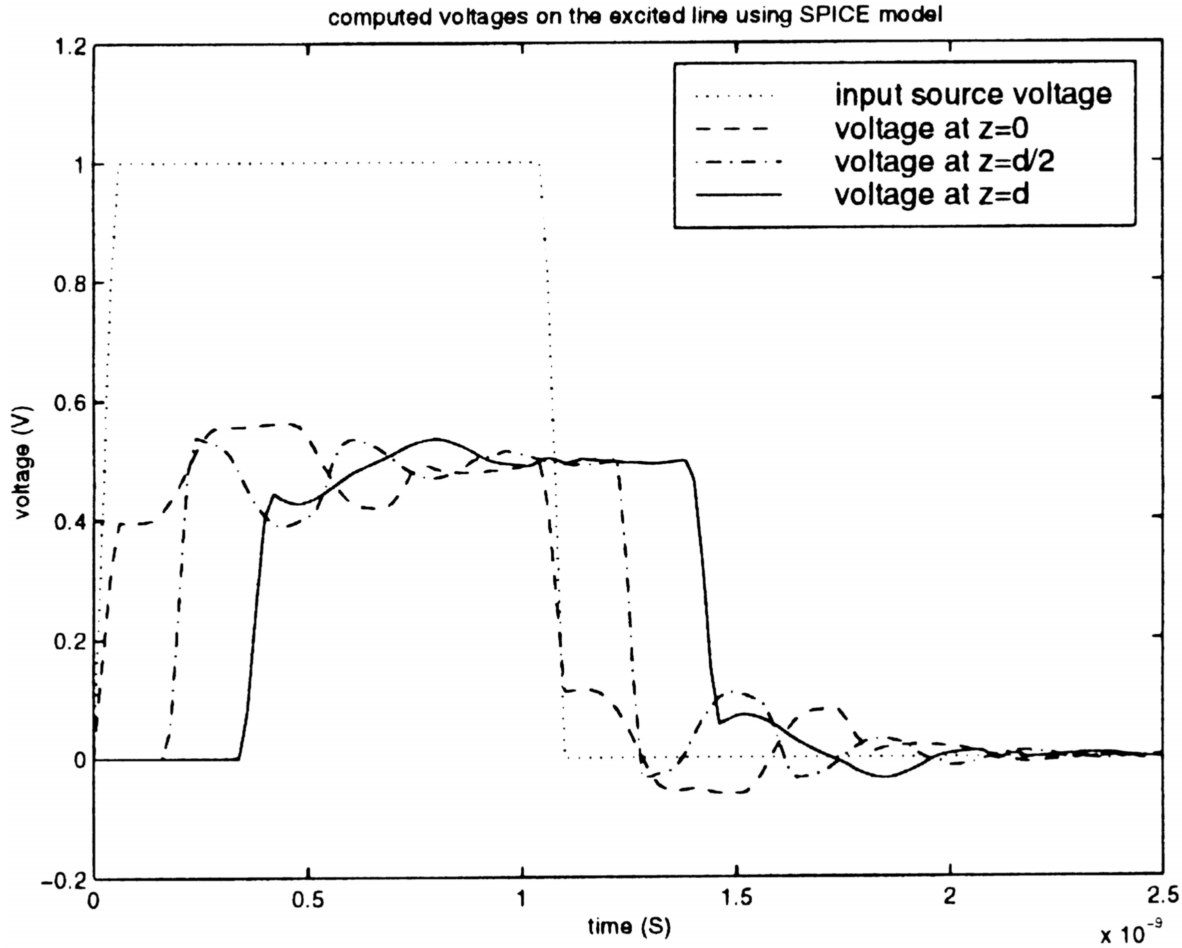

Figure 12. Input voltage waveform and voltages at sonic points of the excited line for input signal with short rise and fall times.

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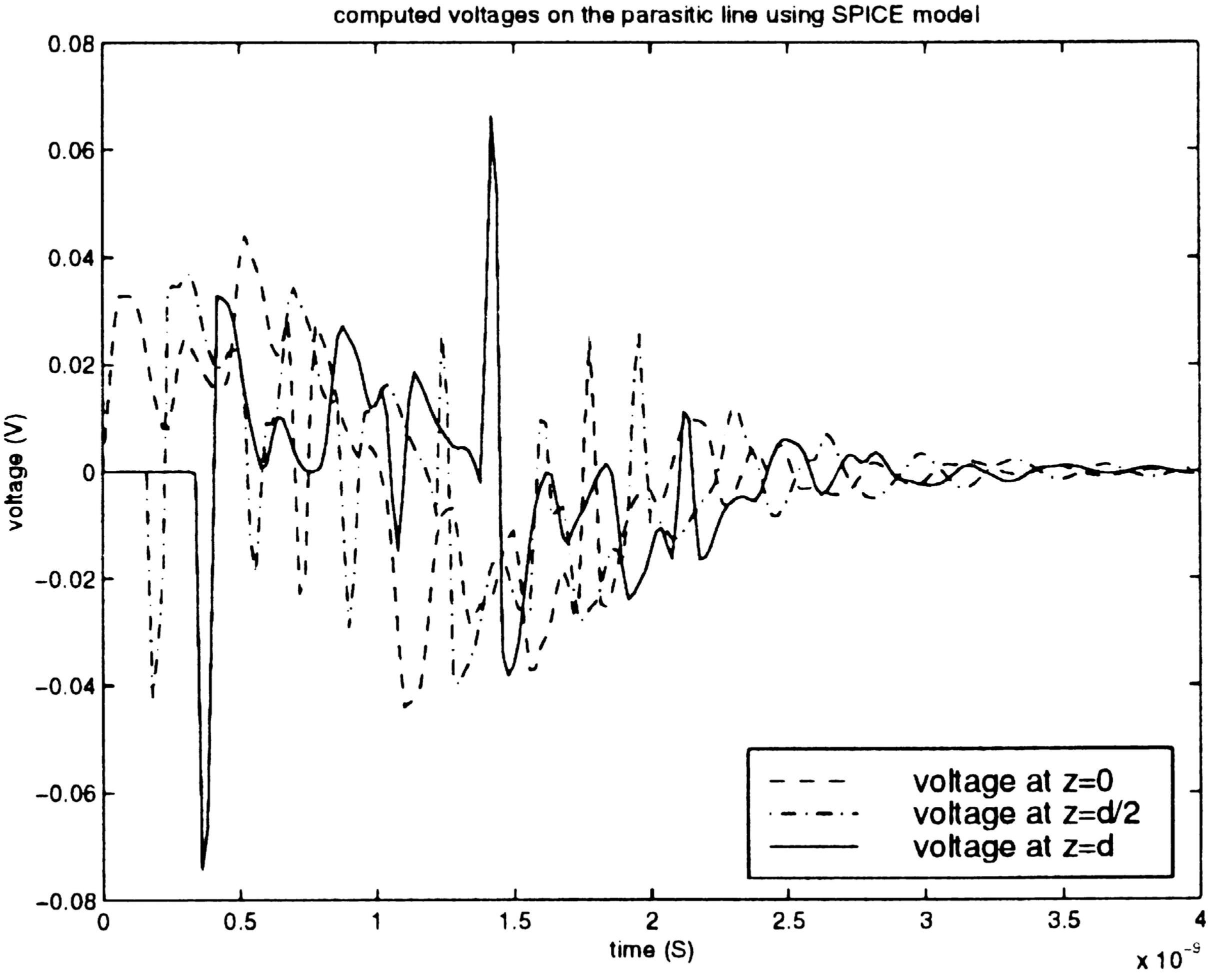

Figure 13. Voltages at some points of the parasitic line for input signal with short rise and fall times.

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