Fast EM/Circuit Transient Simulation Using Laguerre Equivalent Circuit (SLeEC)

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***Abstract*—Transient electromagnetic (EM)/circuit simulation using Laguerre polynomials is an unconditionally stable scheme. Prior work done on this topic, called Laguerre finite-difference time domain (FDTD), has the limitation of being able to simulate only for a certain time duration. An equivalent circuit model of the FDTD grid allows easier implementation of the algorithm, avoiding long cumbersome equations, and enabling the use of modified nodal analysis for transient EM simulation using Laguerre polynomials. The enhanced method has been called SLeEC, and stands for simulation using Laguerre equivalent circuit. In this paper, a memory and time-efficient solution has been proposed to overcome this limitation, so that transient simulation can be done for all time duration. SLeEC has been applied to solve linear transient circuit simulation problems. Equivalent companion models for inductors, mutual inductance, and capacitors have been derived.**

***Index Terms*—Finite-difference time domain (FDTD), Laguerre polynomials, modified nodal analysis.**

I. Introduction

TRANSIENT simulation methods, such as the finite-difference time-domain (FDTD) method [1] and the latency insertion method (LIM) [2], are one of the most widely used techniques for transient analysis. Finite-difference schemes for circuit simulation are differentiated from finite-difference schemes for electromagnetic (EM) simulation by the terms circuit-FDTD and FDTD, respectively. In the Circuit-FDTD method, time-domain differential equations are discretized, and nodal voltages and branch currents are updated in alternate time steps. Similarly, in FDTD, electric and magnetic fields are updated in alternate time steps. FDTD and circuit-FDTD are examples of marching-on-time (MOT)-based schemes, where transient simulation is done in the time domain.

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Methods such as the conventional FDTD scheme and LIM are limited by the Courant condition, which makes the time step prohibitively small for problems where a fine mesh would be required.

An unconditionally stable FDTD method using Laguerre polynomials has been proposed in [3]. It has been shown in [3] that MOT-based approaches can be made atleast $80\times$ faster, by using a marching-on-degree (MOD) method. In the MOD scheme, time-domain waveforms are represented by a sum of basis functions, scaled by basis coefficients. The basis coefficients that represent the output transient waveform are solved, and then converted to a time-domain waveform.

Laguerre polynomials applied to solve the problem of late time instability when solving time domain-EFIE are given in [4]. Transient simulation using Laguerre polynomials integrated with frequency domain is given in [5]. The limitation in prior work [3] is the limited time duration for which simulation can be performed, and therefore, cannot be directly applied to problems that oscillate for a long period of time, which often arises in packaging. One of the contributions of this paper is to extend the method, such that simulation can be done for all time.

A circuit model of the FDTD grid has been developed in [6]. The advantages of using the circuit model are: 1) equations can be set up in a systematic fashion by using the stamp rule of modified nodal analysis [7]; 2) the number of unknowns to be solved can be reduced to half without the use of long, cumbersome equations, making the implementation simpler; and 3) Spice modified nodal admittance (MNA) engine can be used to do transient simulation using Laguerre polynomials.

Simulation using Laguerre equivalent circuit (SLeEC) has also been applied to linear transient circuit simulation problems. Companion models of inductors, capacitors, and mutual inductance have been developed. By using these companion models, SLeEC can be integrated into the Spice simulator seamlessly.

The remaining paper is organized as follows. SLeEC transient simulation methodology is presented in Section II, Laguerre-domain representation of time-domain waveforms is described in Section III, improvements over prior work is given in Section IV, companion model for inductors, capacitors, and mutual inductance is given in Section V; memory efficiency is addressed in Section VI, which is followed by simulation results from test cases in Section VII, and finally, conclusions are presented in Section VIII.

II. Transient Simulation Methodology

As mentioned earlier, the limitation of Laguerre-FDTD method proposed in [3] is that simulation can be performed

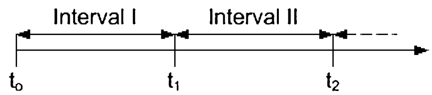

Fig. 1. Total simulation time of Laguerre-FDTD is divided into different time intervals.

only for a certain time duration. A discussion of the reasons for this limitation is deferred until Section IV. The solution to overcome this limitation is to divide the total simulation time into different intervals. Let Interval I span from time $t = t_0$ to $t = t_1$, Interval *II* span from time $t = t_1$ to $t = t_2$, and so on, as shown in Fig. 1. The length of each interval is chosen such that simulation can be accurately performed in that time duration. The final values at the end of Interval I are used as initial conditions to simulate in interval *II*. This process is repeated until the time duration for which the simulation needs to be done is completed.

SLeEC can be applied to linear transient circuit simulation or EM simulation. The SLeEC methodology in Fig. 2 is applied in each of the intervals shown in Fig. 1. The first step is to represent the source waveforms in time domain into equivalent representations in the Laguerre domain. The time-domain waveforms are represented as a sum of Laguerre polynomials that are scaled by Laguerre basis coefficients. The mathematical representation is explained in Section III. The second step is to replace: 1) the FDTD grid, or, in the case of circuit simulation, 2) capacitors, inductors, and mutual inductance with their equivalent Laguerre-domain companion models. The companion models for the linear circuit components are given in Section V. The transient sources are replaced with dc sources. For each of the values in the Laguerre domain that represents the time-domain source waveform, a dc analysis is performed once. The solution at the end of each dc analysis is used to update the companion models, before the next dc analysis is performed. After updating the companion models, a dc analysis is carried out using the next value in the Laguerre domain that represents the source waveform. These series of steps are given by steps 2 and 3 in Fig. 2. The final step (step 4) is to construct the time-domain waveform from the dc solution of the output of interest.

III. Laguerre-Domain Representation of Source Waveforms

The first step is to represent the time-domain source waveforms into equivalent Laguerre-domain representations. A transient source waveform $W(t)$ can be represented as a sum of N Laguerre basis functions $\varphi_p(\bar{t})$, scaled by Laguerre basis coefficients W_p as [3]

$$W(t) = \sum_{p=0}^{p=N-1} W_p \varphi_p(\bar{t}) \tag{1}$$

$$\bar{t} = st. \tag{2}$$

In (2), $\bar{t}$ is the real-time t multiplied by a scaling factor s. The actual time scale at which the simulation is run is very small, typically picoseconds, when rise/fall times are in the order of

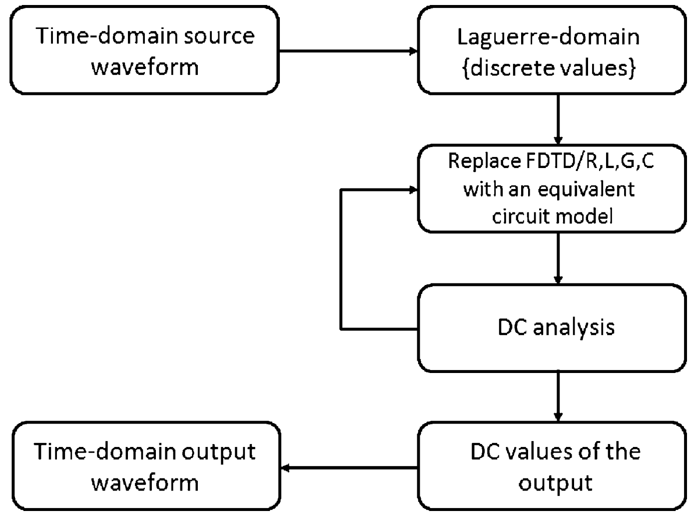

Fig. 2. Flowchart for transient simulation using Laguerre polynomials.

picoseconds. To make the basis function work, the real time is multiplied by s to scale the magnitude in the order of seconds. The basis functions span a time in the order of seconds; hence, the need for the scale factor.

Output of step 1 is a set of Laguerre basis coefficients $\{W_p\}$ for each of the transient source waveforms. Detailed procedure for step 1 to compute the set of the Laguerre basis coefficients is described in [6].

IV. Improvements Over Prior Work

The drawback of the methodology in [3] is that the transient simulation can be performed only for a certain time duration, and cannot be done for all time. There are two reasons for this limitation: the first reason is due to the nature of the Laguerre basis functions and the second reason is due to the finite precision of the computer, which makes it impossible to represent very large numbers or very small numbers.

The first reason for the limitation is due to the nature of the basis functions. All of the basis functions approach 0, as t tends to ∞. Therefore, any time-domain waveform that is spanned by these set of basis functions also goes to 0 as t tends to ∞. Structures that are lossless or have a low loss cannot be simulated accurately, because the fields can be nonzero for a long period of time.

The second reason for the limitation is due to the finite precision of the computer. The Laguerre basis function is an exponentially decaying function multiplied by Laguerre polynomial. The exponential function quickly decays to 0, and beyond a certain time point, the exponential function is treated exactly as 0. Laguerre polynomials become very large with increasing time. Beyond a certain time, the numbers become very large to be represented with the limitation of finite precision, and is represented as Inf in the IEEE 754 floating-point standard. Consequently, beyond a certain time point, the basis function is represented as $0 \times$ Inf or NaN, and not by a number.

Consider the lossless resonant cavity shown in Fig. 3. The E_y field at the location marked *probe* is plotted in Fig. 4. Theoreti-

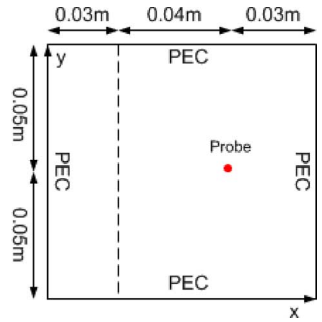

Fig. 3. Example to illustrate breakdown in the simulation.

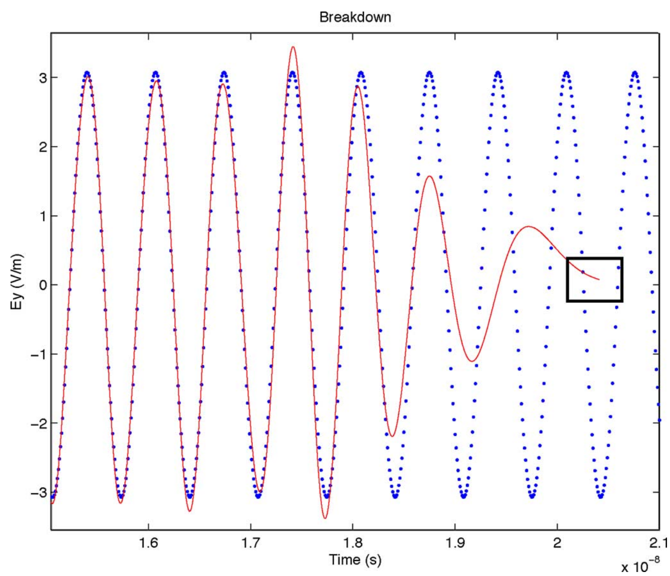

Fig. 4. Limitation of prior work. (Red, solid line) Laguerre-FDTD. (Blue, dots) FDTD.

cally, since the cavity is lossless, the fields must never decay to 0. The red solid waveform is formed by using Laguerre-FDTD and the blue dots by conventional FDTD scheme. Since the basis functions go to 0, as t tends to ∞, the red waveform starts to decay to 0, as shown in the figure. The abrupt termination of the red waveform (indicated by the box) occurs due to the finite-precision problem described earlier.

A solution to fix the problem is to divide total simulation time into different intervals; the final values at the end of an interval are used as initial condition in the next time interval. The differential equations have initial conditions explicitly included to enable restarting the simulation. Using the proposed solution, simulation can done for all time duration.

V. Companion Models

The second step is to replace the FDTD grid, or the inductors and capacitors in the case of circuit simulation, by its respective companion model, as shown in Fig. 2. Companion model of an inductor is derived in Section V-A and the companion model of a capacitor is given in Section V-B. The companion models

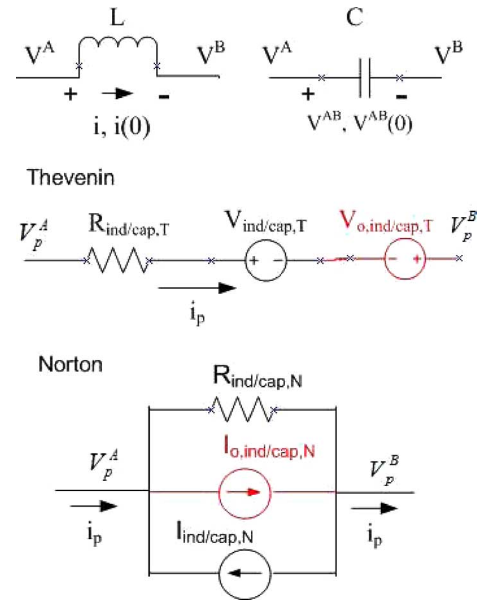

Fig. 5. Thevenin/Norton form of the companion model for an inductor/capacitor.

for mutual inductance and FDTD grid are given in [8] and [6], respectively.

The *structure* of the companion models in the Laguerre domain of an inductor and a capacitor are the same as the time-domain companion models used by the Spice simulator [7]. The models presented here can be seamlessly integrated into the Spice simulation engine.

A. Companion Model of an Inductor

The Thevenin/Norton forms of the companion model for an inductor of value L is shown in Fig. 5. The current through the inductor at time t is i, the initial current through the inductor is $i(0)$, and the direction of the current flow is marked by the arrow shown in the figure. The voltages at node A and node B are V^{A} and V^{B}, respectively. V_p^{A} and V_p^{B} represent the pth basis coefficient of voltages $V^{\mathrm{A}}(t)$ and $V^{\mathrm{B}}(t)$, respectively. The pth basis coefficient of the branch current i is marked as i_p. In the Thevenin form, an inductor is replaced by a resistor in series with two voltage sources. The value of the series resistor is

$$R_{\mathrm{ind},T} = 0.5Ls \tag{3}$$

where s is the time-scale factor and subscript T stands for Thevenin. The value of the first voltage source is a function of the previous dc results of the branch currents. The value of the first voltage source is

$$V_{\mathrm{ind},T} = Ls \sum_{k=0,p\geq 1}^{p-1} i_k. \tag{4}$$

For the first dc analysis that is performed $(p = 0)$, $V_{\mathrm{ind},T}$ is set to 0. The value of the second voltage source (marked in red) is

$$V_{o,\mathrm{ind},T} = Lsi(0). \tag{5}$$

The rest of the section presents the mathematical derivation of the companion model.

The voltage across the inductor is given by

$$V^{\mathrm{A}} - V^{\mathrm{B}} = L\frac{di}{dt} - Li(0)\delta(t). \tag{6}$$

The current and voltages, i, V^{A}, and V^{B} can be written as a sum of Laguerre basis functions as

$$i = \sum_{q=0}^{\infty} i_q \varphi_q(\bar{t}) \tag{7}$$

$$V^{\mathrm{A}} = \sum_{q=0}^{\infty} V_q^{\mathrm{A}} \varphi_q(\bar{t}) \tag{8}$$

$$V^{\mathrm{B}} = \sum_{q=0}^{\infty} V_q^{\mathrm{B}} \varphi_q(\bar{t}). \tag{9}$$

Variables i_q, V_q^A, and V_q^B are qth basis coefficients for the current and voltages, φ_q is the qth Laguerre basis function, and $\bar{t}$ is the scaled time defined in (2). Time derivative of U, written in terms of Laguerre basis coefficients, is given as [3]

$$\frac{dU}{dt} = \frac{d}{dt}\left(\sum_{q=0}^{\infty} U_q \varphi_q(\bar{t})\right) = s\sum_{q=0}^{\infty}\left(0.5U_q + \sum_{k=0,q\geq 1}^{q-1} U_k\right)\varphi_q(\bar{t}). \tag{10}$$

Substituting (7)–(9) in (6) and using the time-derivative relationship in (10), (11) can be obtained as

$$\sum_{q=0}^{\infty} V_q^{\mathrm{A}}\varphi_q(\bar{t}) - \sum_{q=0}^{\infty} V_q^{\mathrm{B}}\varphi_q(\bar{t}) = Ls\sum_{q=0}^{\infty}\left(0.5i_q + \sum_{k=0,q\geq 1}^{q-1} i_k\right)\varphi_q(\bar{t}) - Li(0)\delta(t). \tag{11}$$

Multiplying (11) by $\varphi_p(\bar{t})$, integrating from $[0,\ \infty]$, and using the orthonormal property of basis functions, (12) can be obtained as

$$V_p^{\mathrm{A}} - V_p^{\mathrm{B}} = Ls\left(0.5i_p + \sum_{k=0,p\geq 1}^{p-1} i_k\right) - Lsi(0). \tag{12}$$

In deriving (12), (13) is used when integrating the delta function term as

$$\int_0^{\infty} \delta(t)\varphi_p(\bar{t})d\bar{t} = s\varphi_p(0) = s. \tag{13}$$

Equation (12) can be represented as a Thevenin form in terms of circuit components by a resistor in series with two voltage sources with values given in (3)–(5). Equation (12) can be rearranged in order to obtain a Norton representation. Solving for i_p in (12), (14) can be obtained as

$$i_p = 2i(0) + \frac{1}{0.5Ls}(V_p^{\mathrm{A}} - V_p^{\mathrm{B}}) - 2\sum_{k=0,p\geq 1}^{p-1} i_k. \tag{14}$$

The Norton representation of the companion model for an inductor is a resistor and two current sources, all in parallel configuration. The Norton representation is shown in Fig. 5. The value of the resistor term is

$$R_{\mathrm{ind},N} = 0.5Ls. \tag{15}$$

The value of the current source that represents the initial condition is

$$I_{o,\mathrm{ind},N} = 2i(0). \tag{16}$$

The value of the second current source in parallel with the rest of the components is

$$I_{\mathrm{ind},N} = 2\sum_{k=0,p\geq 1}^{p-1} i_k. \tag{17}$$

B. Companion Model of a Capacitor

The companion model of a capacitor is shown in Fig. 5. The voltage across the capacitor at time t is given by V^{AB}; the initial voltage across the capacitor of value C is $V^{\mathrm{AB}}(0)$ and the polarity of the voltage is shown in the figure. V_p^{A} and V_p^{B} represent the pth basis coefficient of voltages $V^{\mathrm{A}}(t)$ and $V^{\mathrm{B}}(t)$, respectively. The pth basis coefficient of the branch current i is marked as i_p. The Norton form of the companion model for a capacitor is two current sources and a resistor, all in parallel configuration, as shown in Fig. 5. The value of the parallel resistor is

$$R_{\mathrm{cap},N} = \frac{1}{0.5sC} \tag{18}$$

where s is the time-scale factor. The value of the current source is a function of the previous dc nodal voltages across the capacitor. The value of the current source is

$$I_{\mathrm{cap},N} = -sC\left(\sum_{k=0,p\geq 1}^{p-1} V_k^A - \sum_{k=0,p\geq 1}^{p-1} V_k^B\right). \tag{19}$$

The value of the current source that represents the initial condition is given by

$$I_{o,\mathrm{cap},N} = -sCV^{\mathrm{AB}}(0). \tag{20}$$

The derivation of the companion model of a capacitor is similar to an inductor. The current through a capacitor is given by

$$i = C\frac{dV^{\mathrm{AB}}}{dt} - CV^{\mathrm{AB}}(0)\delta(t). \tag{21}$$

The time-domain current and voltages can be written in terms of Laguerre basis functions, as given by (7)–(9). Substituting these into (21), using the time-derivative relation in (10), multiplying both sides by $\varphi_p(\bar{t})$, integrating from $[0,\infty]$, and using the orthonormal property of Laguerre basis functions, (22) can be obtained as

$$i_p = 0.5sC(V_p^{\mathrm{A}} - V_p^{\mathrm{B}}) + sC\left(\sum_{k=0,p\geq 1}^{p-1} V_k^{\mathrm{A}} - \sum_{k=0,p\geq 1}^{p-1} V_k^{\mathrm{B}}\right) - sCV^{\mathrm{AB}}(0). \tag{22}$$

In deriving (22), (13) is used when integrating the delta function term. Equation (22) can be represented in a Norton form by a resistor and two current sources, all in parallel, as shown in Fig. 5. Equation (22) can be rearranged in order to obtain a Thevenin representation. Solving for $V_p^{\mathrm{A}} - V_p^{\mathrm{B}}$ in (22), (23) can be obtained as

$$V_p^{\mathrm{A}} - V_p^{\mathrm{B}} = \frac{1}{0.5sC} i_p + 2V^{\mathrm{AB}}(0) - 2\left(\sum_{k=0,p\geq 1}^{p-1} V_k^{\mathrm{A}} - \sum_{k=0,p\geq 1}^{p-1} V_k^{\mathrm{B}} \right). \quad (23)$$

The Thevenin represention for the companion model of a capacitor is a resistor in series with two voltage sources. The value of the resistor is given by

$$R_{\mathrm{cap},T} = \frac{1}{0.5sC}. \quad (24)$$

The value of the voltage source that represents the initial condition is given by

$$V_{o,\mathrm{cap},T} = -2V^{\mathrm{AB}}(0). \quad (25)$$

The value of the second voltage source is given by

$$V_{\mathrm{cap},T} = -2\left(\sum_{k=0,p\geq 1}^{p-1} V_k^{A} - \sum_{k=0,p\geq 1}^{p-1} V_k^{B} \right). \quad (26)$$

VI. Memory Requirements

It must be noted that SLeEC does not require storing all nodal voltages and all branch currents from the series of dc analysis that has been performed. At the end of each dc analysis, once the companion models have been updated, there is no need for saving the solution. The only solution that needs to be stored at the end of each dc analysis is the solution of the output for which the transient waveform is to be observed, which is a constant amount of memory.

The final values at the end of an interval, e.g., interval Q, must be computed in order to use these values as the initial conditions in the next time interval, interval $(Q+1)$. Not all the coefficients, i.e., the dc solution, for the voltage across a capacitor and the current through an inductor need to be saved, in order to compute the final value at the end of a time interval. At the end of each dc analysis, the contribution of pth Laguerre basis coefficient (W_p) to the final value of the transient waveform at the end of a time interval (t_f) can be computed by using

$$\mathrm{value}(t_f) = \mathrm{value}(t_f) + W_p \varphi_p(st_f). \quad (27)$$

value(t_f) is first initialized to 0, before using (27). By using (27), the coefficients of the dc solution need not be saved in order to compute the final value of a quantity at the end of a time interval.

VII. Simulation Results

1) Test Case 1: The first test case is a power plane structure, where two solid metal planes are sandwiched between dielectric material, as shown in Fig. 6. The dimension of the power plane is 100 mm × 50 mm. The mesh is 1 mm × 1 mm, except at the center, where a fine mesh of 1 mm × 10 μm is used. The source waveform J_z is a Gaussian pulse, place at the center of the cells, 19.5 mm away from the left edge of the plane. Simulation results from 0 to 5 ns are shown in Fig. 7. At the end of 5 ns, the final values are used as initial conditions for simulation from 5 to 10 ns. Simulation results from 5 to 10 ns are shown in Fig. 8. The (solid line) red waveform represents results from SLeEC and the (dotted) blue waveform is formed by using conventional FDTD scheme. The value of the time-scale factor used is $s = 8.1 \times 10^{10}$. The number of basis functions used in SLeEC is 308. Using one-tenth of the Courant time step, conventional FDTD requires a million iterations to complete the simulation. However, SLeEC requires only 308 iterations to generate the time-domain waveform. The run time comparison between FDTD and SLeEC for test case 1 in terms of the number of iterations is summarized in Table I.

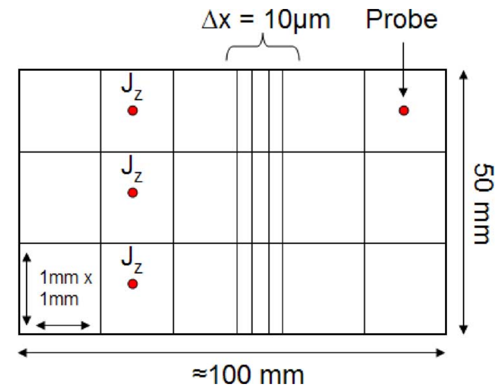

Fig. 6. Test case 1. Solid power plane structure with a nonuniform mesh.

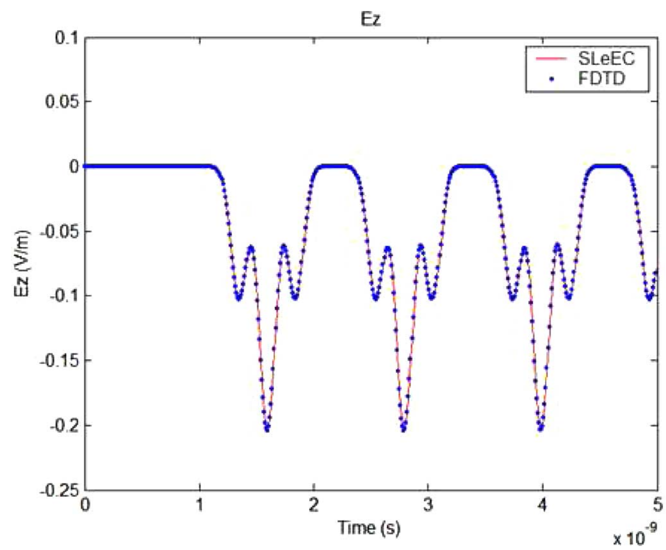

Fig. 7. Simulation results from 0 to 5 ns for test case 1. (Red, solid line) SLeEC. (Blue, dotted) FDTD.

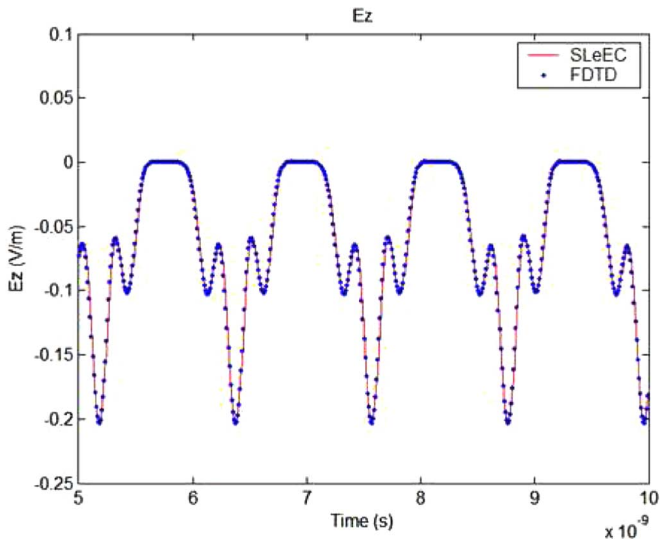

Fig. 8. Simulation results from 5 to 10 ns for test case 1. (Red, solid line) SLeEC. (Blue, dotted) FDTD.

TABLE I
COMPARISON OF THE NUMBER OF ITERATIONS BETWEEN FDTD AND SLEEC FOR TEST CASE 1

Solver	Comparison
FDTD	1 000 000 iterations
SLeEC	308 coefficients

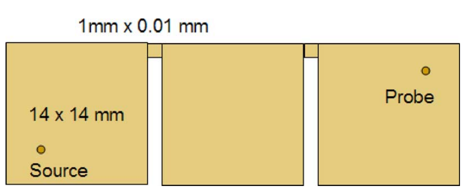

Fig. 9. Test case 2: an EBG structure.

2) Test Case 2: The second test case is an EM bandgap (EBG) structure, which is a power plane structure as before, with metallization that have been removed in certain regions, as shown in Fig. 9. The patch size is 14 mm $\times$ 14 mm, with three patches connected in series. The patches are connected by a branch that is 1 mm $\times$ 0.01 mm, with 0.01-mm-wide narrow slots. Simulation results from 0 to 10 ns are shown in Fig. 10. The source and the time-scale factor used are the same as test case 1. The source waveform J_z is placed 5 mm away from the edges of the lower-left corner, and the E_z is calculated 5 mm away from the edges of the top-right corner in Fig. 9. The (solid line) red waveform represents results from SLeEC and the blue (dotted) represents conventional FDTD scheme. To generate the time-domain waveform, 309 basis functions were used in SLeEC. The number of iterations required by FDTD, using one-tenth of the Courant time-step is a million. As described before, SLeEC requires a lot fewer iterations compared to conventional FDTD scheme,due to which the speed up can be obtained. The run time comparison between FDTD and SLeEC for test case 2 in terms of the number of iterations are summarized in Table II.

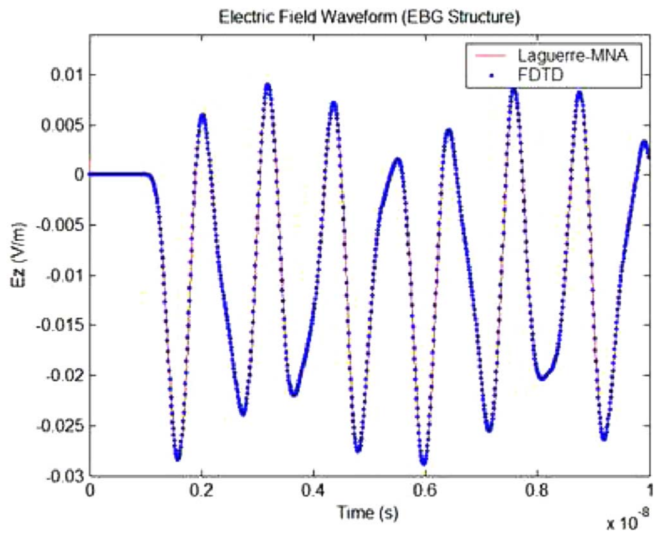

Fig. 10. Simulation results from 0 to 10 ns for test case 2. (Red, solid line) SLeEC. (Blue, dotted) FDTD.

TABLE II
COMPARISON OF THE NUMBER OF ITERATIONS BETWEEN FDTD AND SLEEC FOR TEST CASE 2

Solver	Comparison
FDTD	1 000 000 iterations
SLeEC	309 coefficients

VIII. CONCLUSION

SLeEC transient simulation methodology, which can be used to simulate for all time and for all structures, has been proposed. A companion model for inductors, capacitors, and mutual inductance has been derived, which enables transient simulation using the Spice MNA engine. Simulation results from test cases showing excellent correlation between SLeEC and conventional FDTD method were presented.

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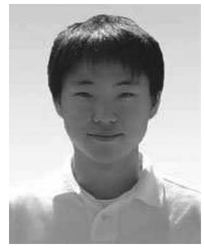

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