Extending Spice-Like Analog Simulator with A Time-Domain Full-Wave Field Solver

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Abstract **In this paper analog circuit simulator is integrated with a versatile full-wave finite-difference time-domain (FDTD) electromagnetic (EM) solution module. The circuit-field co-simulation method is introduced to connect a Spice-like circuit simulator with FDTD solver for simulating hybrid high-speed system. The interface that links both simulators is derived directly from the Maxwell's equations and is simple to implement. Results from example circuits show that the proposed technique is highly accurate and stable and is suitable for integrating with any existing analog simulators, enhancing their capabilities in high-frequency circuit and packaging analysis where field effects cannot be ignored.**

I. INTRODUCTION

As electronic circuits operating at higher and higher speed with ever shrinking dimensions, traditional analog or mixed-signal simulators meet more challenges in term of signal integrity and reliability of the system design. The artificial boundary separating analog/RF and microwave circuits is diminishing as the switching speed of electronic circuits increases rapidly. In many of the modern designs, system can be considered as a hybrid system, a system with both lumped and distributed circuits. Field effects in high-speed circuits, caused by high-frequency signal propagation and dispersion, are growing concerns for integrated circuit (IC) designers.

SPICE-like analog circuit simulators have been around for many years and are still the dominant simulation tools for daily analog design assignments. Extensive resources in device model development have been invested in such simulators to assure agreement between simulation and measurement. When designing system at higher frequency range where field effects cannot be ignored, the lack of a co-simulating tool for hybrid system makes accurate analysis and design of such circuit much more time consuming and expensive.

FDTD method [1,2] is a very powerful and versatile numerical technique for simulating EM system in time domain, which is especially suitable for handling nonlinear high-speed circuit. Approaches for integrating lumped circuit into FDTD method have been reported [3-8] and applied to many system analysis and design applications [9-11] in recent years. Until recently, most of the reports [3-6] were focused on various aspects of FDTD formulations for adding lumped subcircuit into FDTD grid, they could not be easily used in the reverse way, i.e., including field effects in the circuit simulation. Recently, [7] proposed a new generalized approach that bridges the gap between circuit (lumped) and field (distributive) simulation through a simple and stable bi-directional circuit-field model**.** This approach is applied to bridge a non-uniform FDTD field solver and an analogue circuit engine that solves the lumped circuit connecting across the distributed system. Applying the co-simulation model in simulating hybrid systems, it has shown that the formulation has good numerical accuracy and application flexibility.

Based upon the circuit-field co-simulation model in [7], time-domain circuit and field simulation engines can be integrated for simulating hybrid circuit with physical equivalencies. From circuit simulation point of view, the distributed system is modeled as an equivalent subcircuit in the lumped circuit; from field simulation point of view, lumped circuit is treated as an additional current in the general current integration of the Maxwell's equations. By synchronizing the two simulation engines in forward time stepping, a seamless circuit simulation that includes distributed system and their field effects can be accomplished. In this paper, we present the scheme for simulating hybrid circuit and explore the potential application for including field solver inside a standard Spice-like analog simulator. The developed algorithm and some application examples show that it is feasible to accurately co-simulate both lumped circuit and distributed system.

II. METHOD

By including an additional current term in Ampere's Law of Maxwell's equations, a hybrid system, made of a distributive system and a sub-system that contributes current flow to the surface integral, can be modeled numerically in combination with necessary equations relating current to the physical phenomena of the alien system. Therefore, to model a lumped circuit interacting with an EM system, Maxwell's equations are modified to include additional current caused by the lumped circuit

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$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{l} = I_{lumped} + \int_S \boldsymbol{J} \cdot d\boldsymbol{S} + \int_S e \frac{\P \boldsymbol{E}}{\P t} \cdot d\boldsymbol{S} \qquad (1)$$

where I_{lumped} represents current flow due to the lumped circuit sub-system.

Equation (1) can be solved by FDTD technique and in connection with nodal formulation of lumped circuit (to calculate lumped current, I_{lumped}), i.e. a lumped sub-system can be included in the simulation of a distributive system. Likewise, a lumped circuit simulation can be performed with the interaction from a full-wave solution of an EM sub-system described by Maxwell's equations.

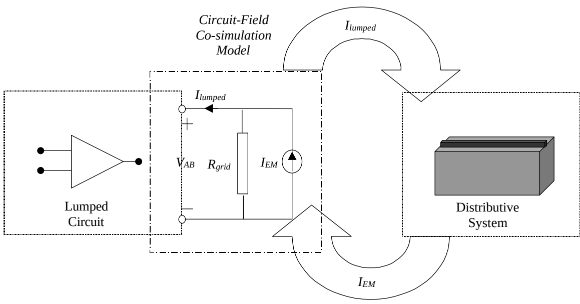

Figure 1. Illustration of the circuit-field co-simulation model. Distributed system is treated inside the lumped circuit as an equivalent sub-circuit made of a resistor and a current source. The lumped current, in return, is fed back to the field iteration.

Figure 1 shows the connection between the lumped circuit and the three-dimensional grid of the distributive system, where I_{lumped} and V_{AB} are the port current and voltage at the two nodes that connect the distributed system. Port voltage, V_{AB}, can be calculated from the electric field path integral

$$V_{AB}^{n} = \int_A^B \boldsymbol{E^n} \cdot d\boldsymbol{l} = \sum_{i=1}^{i_e - 1} E_i^n dx_i \qquad (2)$$

In above and the following equations, the lumped element is assumed to be connected along x-axis direction, so dx_i is the cell size in the direction of electric field integration.

With the aids of relations between electric filed and voltage, magnetic field and current, (1) can be deduced, in finite difference format, to a constitutive equation that relates port voltage and current at current instance of time:

$$I_{EM}^{n+1/2} = \frac{V_{AB}^{n+1}}{R_{grid}} + I_{lumped}^{n+1}) \qquad (3)$$

and once the lumped current I_{lumped} is known from the circuit simulator, the electric field components within the voltage integral path can be updated with the following equation

$$E_{xijk}^{n+1} = -I_{lumped}^{n+1} \cdot \Gamma_{ijk} + \mathrm{K}_{ijk}^{n+1/2} \qquad (4)$$

$$I_{EM}^{n+1/2} = (\sum_{i=i_s}^{i_e - 1} dx_i K_{ijk}^{n+1/2}) / (\sum_{i=i_s}^{i_e - 1} dx_i \Gamma_{ijk}) \qquad (5)$$

$$R_{grid} = \sum_{i=i_s}^{i_e - 1} dx_i \Gamma_{ijk} \qquad (6)$$

where R_{grid} is an equivalent resistance determined by the FDTD grid, I_{EM} is a known current from the FDTD iteration in previous time step.

$$A = (\sum_{p=j-1}^{j} \sum_{q=k-1}^{k} e_{ipq} dy_p dz_q) / (4dt) \qquad (7)$$

$$B = (\sum_{p=j-1}^{j} \sum_{q=k-1}^{k} s_{ipq} dy_p dz_q) / 8 \qquad (8)$$

$$\Gamma_{ijk} = \frac{1}{A+B} \qquad (9)$$

$$? _{ijk}^{n+1/2} = \frac{1}{A+B}[(H_{yijk-1}^{n+1/2} - H_{yijk}^{n+1/2}) \cdot \frac{dy_{j-1} + dy_j}{2} \qquad (10)$$
$$+ (H_{zijk}^{n+1/2} - H_{zij-1k}^{n+1/2}) \cdot \frac{dz_{k-1} + dz_k}{2}] + \frac{A-B}{A+B} E_{xijk}^{n}$$

The above equations are written for the case when the lumped circuit is connected along the x-direction only. When the lumped current is flowing in an arbitrary direction, all the electric field components in the integration path have to be updated by equations similar to (4). More details about the mathematical derivation and explanation of the formulation can be found in [7].

Equation (3) can be interpolated as a circuit branch consisted of a resistor in parallel with a controlled current source, as illustrated in Figure 1. Its implicit form guarantees the electrical field (therefore voltage V_{AB}) and current (I_{lumped}) are evaluated at the same time, that is one of the important factors contributing to the high stability of this co-simulation algorithm. The I-V relation in (3), which represents the effects of distributive system to the lumped system, can be easily be incorporated into modified nodal formulation of a circuit simulator.

Once these two components are included and updated in the analog simulation iteration, the transient solution of the lumped circuit would include the field effects due to the connected distributed sub-system and interactions between the lumped and the distributive systems, therefore achieving hybrid circuit co-simulation. Looking from the circuit simulator side, the distributed system is modeled by an equivalent resistor (R_{grid}) and a controlled current source (I_{EM}).

Those two equivalent lumped elements, in general, are time varying and their values should be updated every time iteration. The equivalent sub-circuit described by (3) is for every connection from the distributed system to the lumped circuit, so in general there could be more than one equivalent sub-circuit branch.

III. MODEL VERIFICATION

Two three-dimensional hybrid circuits are analyzed to illustrate the accuracy and application of the circuit-field co-simulation model presented in this paper. The circuit solver used in these examples is a simple self-built circuit simulator with limited number of lumped components and their combinations. The FDTD simulator can implement nonuniform mesh grid with an improved perfect matching layer (PML) absorbing boundary condition that can be applied in nonuniform multilayer structures [12].

The first example is a 3D microstrip line power divider, as shown in Figure 2. The hybrid circuit is consisted of a lumped resistive voltage source driving a microstrip line power divider, which is loaded with a pair of diodes at each of its two output ports. A resistor is connected between the last two sections of the striplines for balancing. The FDTD grid is made of 120×90×20 1mm cubic cells and the timestep for FDTD is 1.667ps. For comparison purpose, a similar microstrip line structure is constructed in Agilent Advanced Design System (ADS) simulator, with only the last section of the parallel lines modeled as coupled microstrip lines.

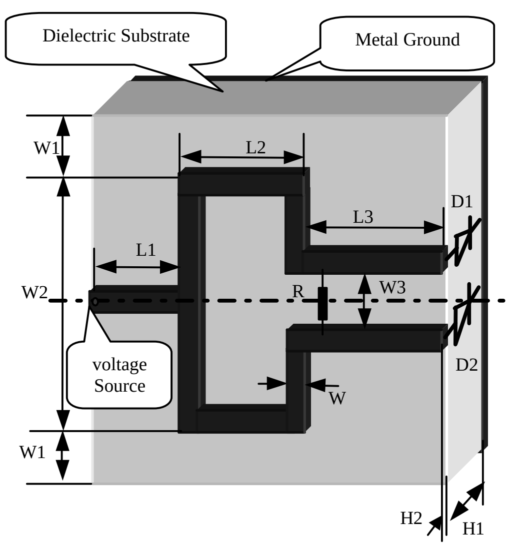

Figure 2. Configuration of the microstrip line power divider. The dimensions are (unit: mm): $W=1$, $W1=10$, $W2=48$, $W3=12$, $L1=20$, $L2=28$, $L3=32$, $H1=1$, $H2=5$. The substrate permittivity is 9.07 and metal conductivity is 10^7mho/m. Sinusoidal voltage source is 900MHz and $R_s=R=50\Omega$.

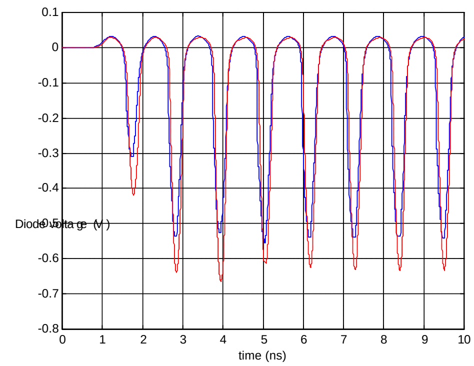

Figure 3. Comparison of load diode currents from both the circuit-field co-simulation and ADS simulation.

Figure 3 shows the current responses at the load diode in time domain with a 900MHz sinusoidal excitation at the input port. Since the divider has a balanced configuration, currents in both load diodes are identical. The simulated current flowing through the load diode is compared with simulation result from ADS transient simulation. As can be seen in Figure 3, both curves are very close to each other for the most parts of the responses, except the negative magnitudes of the currents.

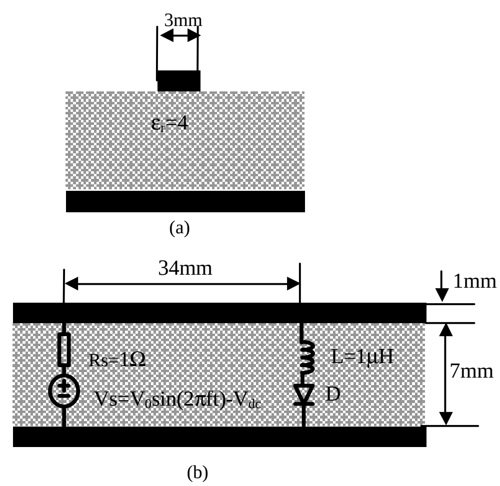

Figure 4. Three-dimensional structure of a narrow pulse generator. (a) cross-section view and (b) longitudinal view. V_0 $=80V$, $f=900$MHz and $V_{dc}=0.6$. Parameters of diode are $I=I_0e^{(V/h)}$, $I_0=0.5mA$, $h=0.026$.

Figure 4 illustrates another microstrip line hybrid circuit, which can generate very narrow pulse from a sinusoidal input signal. Again the three-dimensional structure is modeled in FDTD by a 120×90×20 grid with uniform cell size of 1mm. The microstrip line is considered as infinitely long in the longitudinal direction and this is realized by extending the substrate and conductor all the way to the absorbing boundary. The co-simulation results are compared with that from

ADS simulation, as pictured in Figure 5. Other than the differences in initial transient process, magnitude-wise both results have good agreement to each other. Apparently the most notable differences between the two set of curves are the timing difference at about 0.1ns, which worth some more discussions. FDTD method uses a time-step that satisfying the CFL stability condition and no estimate of any propagation parameter is necessary, so it predicts actual signal propagation time accurately. The frequency bandwidth of the analytical model in ADS is limited and circuit-dependent. Since the propagation speed is inverse proportional to the square root of the effective dielectric constant of the line, it is easy to show that an error of 10% in effective dielectric constant would cause 0.1ns in the delay. Varying different simulation parameters (like maximum frequency and sampling points) and circuit parameters (like dielectric constant, properties of the metal strip), it can be shown that simulation results from ADS are not as stable.

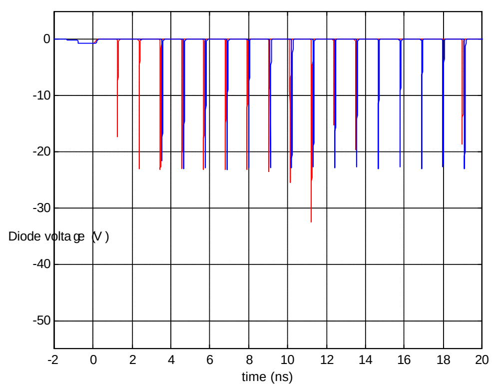

Figure 8. Comparison of circuit-field co-simulation result with ADS result for the narrow pulse generator.

In conclusion to the discussion about the pulse generator example, the above comparison and discussion show that the circuit-field co-simulation has better numerical accuracy and solution stability. It provides a true time-domain analysis for a highly nonlinear hybrid circuit under very large signal condition. Although the hybrid circuit examples in this paper are relatively simple, they demonstrate the accuracy of the method, application flexibility and promising potential of the proposed method.

IV. CONCLUSION

In this paper, a method for including a field solver inside an analog circuit simulator is proposed. This approach provides a capability to take advantages of both existing Spice-like circuit simulators along with their vast resources and a newly developed hybrid FDTD formulation. The combination of the two techniques enables the circuit-field co-simulation of any hybrid system, which may include complicated three-dimensional structure in open space. The equivalent model used in the method is simple to implement, yet provides good physical intuition and excellent numerical simulation accuracy. The usefulness of the technique is highlighted by a few of hybrid circuit examples that could not be handled easily by other simulators.

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