FDTD Analysis of an Active Antenna

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***Abstract*— Coupled FDTD-SPICE simulations are performed for an active antenna problem. The results are comparable to previously published results using FDTD in conjunction with special integration techniques for the nonlinear elements. Some differences occur, and better agreement with experiment is observed for our newer approach. The main advantages are that all of the SPICE device models are directly available for FDTD modeling and the efficient SPICE integration schemes can be used directly. No user intervention is required for either the device models or the integration schemes.**

I. Introduction

The FDTD solution of Maxwell's equations is a powerful, general method that can be applied to a wide variety of electromagnetic boundary value problems [1]. Until recently, the FDTD method has been used mainly to simulate electromagnetic fields in linear and passive media. However, many complicated microwave circuits are embedded with media that are both active and nonlinear (e.g. semiconductor devices), and future electromagnetic field simulators will be required to model these circuits. The FDTD algorithm is well-suited for this task, and in recent years in some general applications of the FDTD method to this class of problem have been published. For instance, in [2] a method was proposed that treats a few circuit elements as subgrid models on the FDTD grid, and a three-dimensional implementation with improvements was presented in [3]. The method was further modified and applied to a circuit embedded with nonlinear and active components in [4].

A disadvantage of the method used in [4] is that it relies on a special integration scheme that must be modified for each type of active and nonlinear component. A more general approach based on a coupling of FDTD and SPICE was presented in [5]. This approach has the advantage that any circuit model in SPICE can be readily incorporated into the FDTD algorithm without modifying the differencing scheme. In this paper, we use this approach to simulate the active antenna problem from [4] and compare the results. The simulation techniques show much agreement, but some differences exist.

II. Model

The system under consideration is shown in Fig. 1. Two

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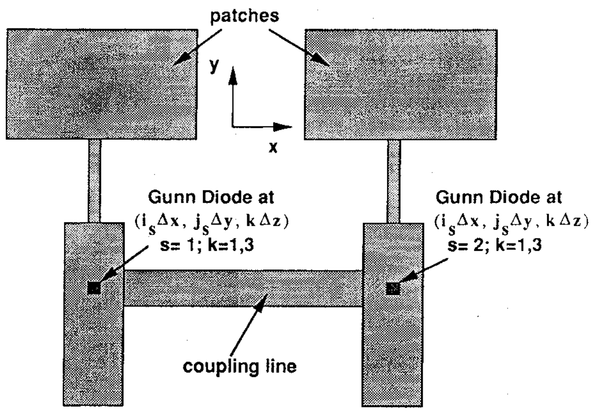

Fig. 1. Schematic of the two-element patch array (identical to Fig. 1 in [4]).

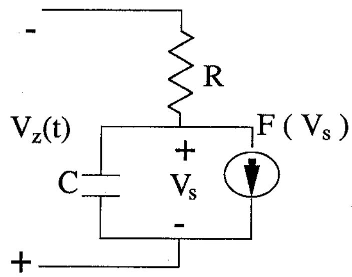

Fig. 2. Equivalent circuit for the Gunn diodes (identical to Fig. 2 in [4]).

patch antennas are coupled with a coupling line. The coupling line may be entirely metal or there may be a small chip resistor in the center. At the positions indicated in the figure there are two Gunn diodes. These are modeled using the equivalent circuit shown in Fig. 2. The functional form for $F(V_s)$ is given by

$$F(V_s) = -G_1 V_s + G_3 V_s^3 \tag{1}$$

The parameters were estimated from the measured Gunn diode response in a narrow frequency range and are $R = 1.0\,\Omega$, $C = 0.2$ pF, $G_1 = 0.0252\,\Omega^{-1}$, and $G_3 = 0.0265\,\Omega^{-1}\mathrm{V}^{-2}$. The FDTD calculations were performed with constant but different dx, dy, and dz. First-order Mur wave-transmitting boundary conditions were used. The FDTD calculations were coupled to SPICE using the approach described in [5]. The user has only to write a standard SPICE input deck containing the Gunn diode model. More general Gunn diode models could be tried merely by substituting a different SPICE file into the calculation.

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III. RESULTS

When the coupling line is entirely metal, the simulations indicate the same dominant mode as the experiment and the previous calculation [4]. That is, the Gunn diodes are operating in an anti-phase ("difference") mode. The frequency predicted by the simulation is 11.7 GHz, which compares well with the observed frequency of 11.8 GHz. The previous simulation yielded a frequency of 12.4 GHz [4] and the predicted value from the nonlinear circuit analyses yielded 12.2 GHz [6], [7].

The mode where the Gunn diodes are in phase can be achieved by placing a chip resistor in the center of the stripline connecting the two patch antennas. This then introduces a current null at this location, which eliminates anti-phase oscillations. For this case, our simulations predict a frequency of approximately 11.4 GHz, as shown in Fig. 4. The experimental value is 11.04 GHz and a frequency of slightly less than 12.2 GHz was obtained using the other simulation method [8].

One problem in the simulations is the fact that the parameters used in the lumped element were obtained at a single frequency appropriate for the out of phase mode. This is one explanation for the observed difference between simulation and experiment. Another problem was that the chip resistor in the simulations has a value of 100 Ω, whereas in the experiment the chip resistor has a value of 10 Ω. For the 10 Ω case, the simulation did not converge to the in-phase mode of operation within the tens of thousands of time steps required for the in-phase mode to converge when the resistance is 100 Ω, although the mode switching has noticeably begun. This difference in the resistance might also be a factor in the discrepancy between the simulations and the experiments.

Both this simulation and the simulation presented in [4] are capable of predicting the correct steady state mode of the circuit under various loading conditions, which confirms the validity of the FDTD analyses. However, the simulation method presented here has better agreement with experiment than does the method used in [4]. One explanation might be in the integration scheme for the lumped element. In [4], a problem specific approach was used. In this paper, the SPICE program was used to integrate the lumped element. Since the SPICE program has been under continuous and extensive development for a number of years, the integration package is probably able to handle a nonlinear circuit update with more fidelity than schemes with significantly less development time.

One manifestation of the difference in the simulation is the amplitude of the oscillations. The oscillations in [4] have an amplitude of about 0.95 V, whereas the oscillations in the FDTD-SPICE simulations have an amplitude of 1.13 V, or about 20 percent larger as that seen in Fig. 3. This larger amplitude results in a waveform that is more distorted in appearance, due to the nonlinear nature of the device. This extra nonlinearity in the response of the lumped element could be responsible for the frequency differences of about 5% that occur between this work and [4] for both the in-phase and the out-of-phase mode.

One may imagine many types of modifications to the form of the lumped element model used in this paper to resolve some of the minor discrepancies between simulation and experiment. The beauty of the combined FDTD-SPICE approach is that they can all be tried by modifying only the SPICE file for the lumped element, since real SPICE models are used and not just user-developed, SPICE-like models. No user intervention or modification is required and one can make use of the tremendous investment of time that has already been put into SPICE. Other circuit simulation programs can also be used in the same manner, since the link in the FDTD calculation and lumped element calculation is through independently executing programs.

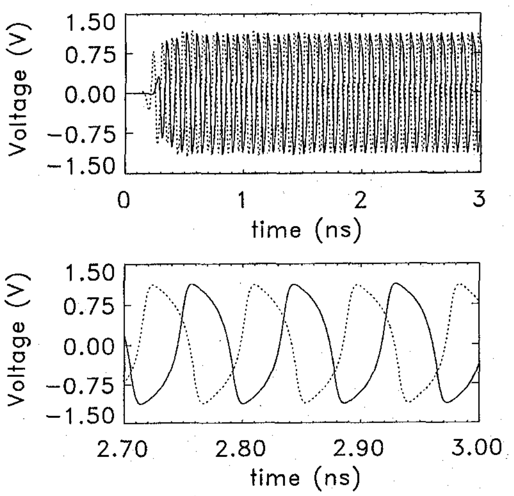

Fig. 3. Gunn diode voltages as a function of time for the out-of-phase mode.

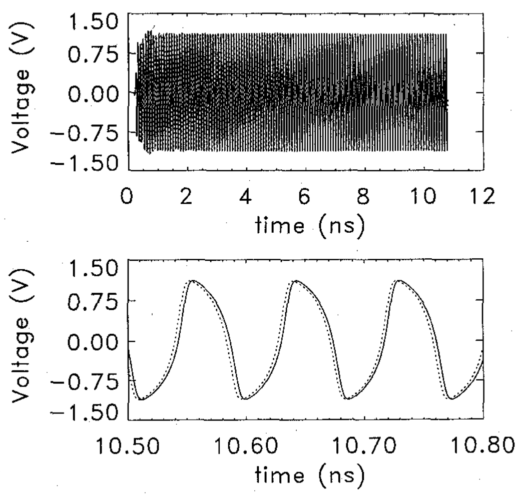

Fig. 4. Gunn diode voltages as a function of time for the in-phase mode.

IV. CONCLUSION

A simple and effective approach has been developed for coupling SPICE lumped elements into FDTD calculations. Calculations of an active antenna show general agreement with experiments and previous FDTD calculations [4]. Generalizations to different lumped element models involve changing only the SPICE file describing the model. Therefore, this approach is capable of modeling electromagnetic fields in a wide variety of microwave and millimeter wave circuits.

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