Analysis and Design of Active Antenna Arrays

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***Abstract* — In this paper, the FDTD method is extended successfully to analyze active antennas using Z-transform method for small signal model and by a stable scheme for large signal model. The two approaches are validated by comparison with analytical impedance expression in frequency domain. Through these approaches, we analyzed active antennas and antenna arrays containing tunnel diodes. Effects of various device parameters are investigated in order to find desired oscillations. Single and array active antennas are designed and tested. Experimental and simulated results are given and compared.**

I. INTRODUCTION

The Finite-Difference Time–Domain (FDTD) Method has been widely used to simulate various electromagnetic problems because of its flexibility and versatility. It applies second order, central differences to the space and time derivatives of Maxwell's time-dependent equations. The algorithm has been used in different areas involving electromagnetic scattering, antenna design, and electromagnetic interaction with biological tissues, electromagnetic hypothermia, design of digital components and microwave circuits and devices [1-3].

FDTD has been used for passive antenna simulation to predict input impedance and radiation pattern of an antenna. An impulsive excitation in the time domain gives input impedance over a broad frequency spectrum in a single run via a concurrently Fourier Transform run. The availability of both time-domain and frequency-domain data allows much physical insight into the problem.

For simulation of microwave structure with active devices, lumped elements could be incorporated with FDTD through several methods. One method is the use of deducted formulas for a simple circuit consisting of resistors, capacitors, inductors, or parallel combinations of them [4]. Another method is the use of SPICE in conjunction with FDTD to determine the relationship of device voltages and currents [5]. B. Toland, et al. [6] derived an update scheme for large signal model of resonant tunneling diode (RTD), combined with conventional FDTD method, to simulate a distributed cavity. In another approach, the device voltage is evaluated from the state equation of the circuit, and subsequently the voltage is used to update the electromagnetic field [7].

In this paper, we discuss the analysis and design of active antennas using FDTD technique. In section II, general model for analyzing active antennas is outlined. Small and large signal model schemes are described and justified in section III. A tunnel diode circuit model, extracted from measurement, is used to represent the active device. Simulated and experimental results are then discussed in section IV.

II. FDTD MODEL WITH ACTIVE DEVICE

In a pioneering paper of FDTD simulation by Yee [1], the computational domain is subdivided by using an orthogonal mesh in the Cartesian coordinate system. The electric fields are located along the edges of these cells, while the magnetic fields are positioned at the centers of these cells.

In general, the field update equation including a lumped circuit can be expressed according to the FDTD formula as

$$E_{i,j,k}^{n+1} = E_{i,j,k}^{n} + \frac{\Delta t}{\varepsilon} \nabla \times H_{i,j,k}^{n+1/2} - \frac{\Delta t}{\varepsilon \Delta s} I_{i,j,k}^{n+1/2} \qquad (1)$$

where $E_{i,j,k}^{n}$ is the electric-field component at the point (i, j, k) at time step n; $H_{i,j,k}^{n+1/2}$ is the magnetic quantity relative to $E_{i,j,k}^{n}$; $I_{i,j,k}^{n+1/2}$ is the current at the point (i, j, k) at time step (n+1/2); and Δs is the area that current $I_{i,j,k}^{n+1/2}$ passes through. It is assumed that each terminal occupies one FDTD cell. If more than one cell is involved, distributed model is applied.

III. ACTIVE DEVICE MODEL

A. Small Signal Model

In this section we describe the application of FDTD technique in the analysis of a negative resistance device such as a tunnel diode. In many practical applications these devices are biased in its negative resistance regime. The real part of the diode impedance must be negative at the desired frequency of interest. Fig. 1(a) and 1(b) show the large signal model and small signal model of a tunnel diodes. In the small signal model, the ideal tunnel diode is represented by a parallel combination of a junction capacitor and a negative resistor. The parasitic elements due to lead inductor and ohmic contact resistor, are also shown in Fig. 1(b). Based on these equivalent circuit models, we can build up the update relationship using Z-transform (Appendix) as follows,

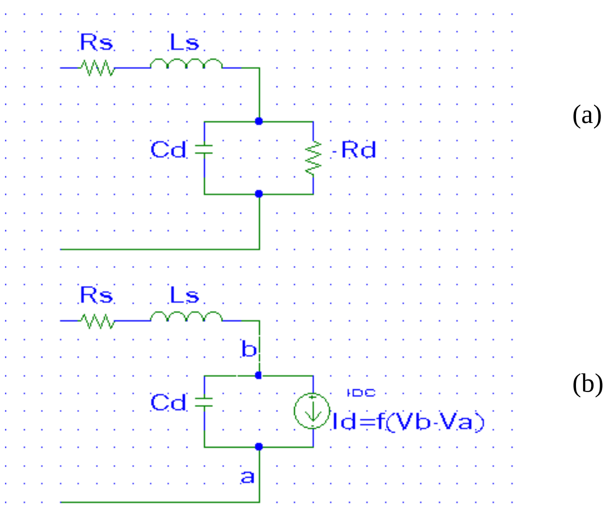


Fig.1. Small signal (a) and large signal model (b) for tunnel diodes

$$V_c^n = p_1 \cdot V_c^{n-1} - p_2 \cdot V_c^{n-2} + \Delta t \cdot \gamma \cdot p_3 \cdot V^{n-1} \qquad (2)$$

where $V_c(t)$ is voltage response cross the capacitor, and $V(t)$ is voltage drop in the entire diode.

B. Large Signal Model

For large signal model, we adopted the method described in [6] and the update scheme is,

$$V_c^{n+1} = V_c^n A_1 - A_2 F(V_c^n) - 2A_3 \Delta y V^{n+1/2} \qquad (3)$$

In above formula, we only consider the component in y direction since the diode is implemented in y direction.

The formula (2) and (3) used for active devices are justified in terms of input impedance looking into the devices. The large signal model (3) doesn't consider the effect of inductance L of the tunnel diode. In order to compare the results predicted from the large signal model with that of the small signal model, a reactance due to the inductor was added to the result obtained from large signal model. In Fig. 2, the impedance simulated from Z-Transform method for small signal model, and from large signal model are compared. In very wide frequency span from 100.0 MHz to 20.0 GHz, the Z-Transform method provided very accurate results. The difference between the two methods is less than 3.0 Ω (Fig. 2 (b)).

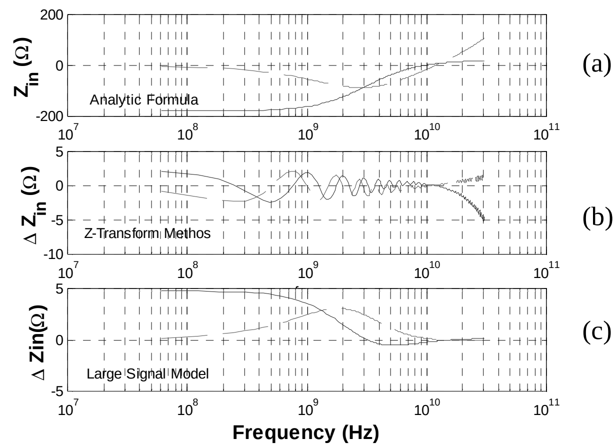
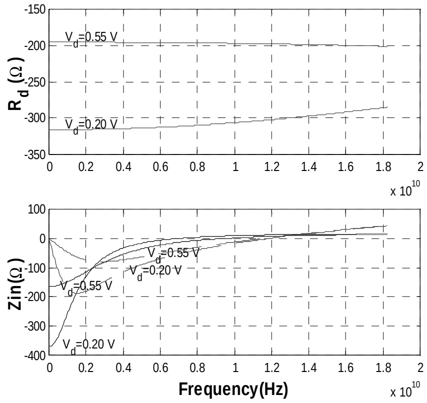


Fig. 2. Comparison of diode impedance between Z-Transform method and scheme from [6]. (a) Analytic expression. (b) Small signal model impedance error. (c) Large signal model impedance error. Device parameters C_d=0.25 pF, R_S=10.0 Ω, L=0.665 nH, R_d=-200.0 Ω. For large signal model, input signal level is less than 0.15 V, and bias point V_d is 0.55 V. Solid line is for real part, and dashed line is for imaginary part.

The bias point of the diode was set in the large signal model to obtain the same negative resistance of –200 Ω as used in small signal model. Fig. 2(c) shows the impedance error of large signal model thus calculated. In the frequencies of interest from 60.0 MHz to 20.0 GHz, the difference to the analytical expression is less than 5.0 Ω. It must be mentioned that the analysis of large signal model is more complicated. The negative resistance R_d in large signal model is not constant even at a fixed bias point. The Fig. 3(a) shows that at bias point V_d=0.20 V, the negative resistance varies from –320.0 Ω to -280.0 Ω in whole frequency span. However, at bias point 0.55 V, the large signal model can equivalently replaced by small signal model since the negative resistance R_d is almost constant.



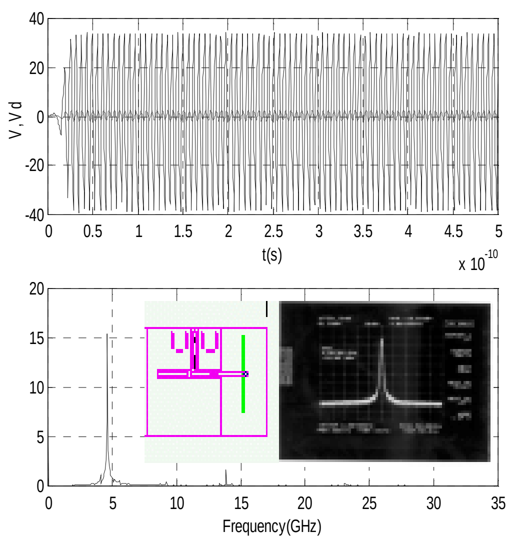
(a)

(b)

Fig. 3. Large signal model impedance of diode with parameters C_d=0.25 pF, R_S=20.0 Ω, and L_s=0.665 nH. (a) Negative resistance of diode itself. (b) Input impedance of diode with external elements. The input signal amplitude level is less than 0.15 V. Solid line is for real part, and dashed line is for imaginary part.

IV. ACTIVE ANTENNAS

A slot active antenna is simulated using the large signal model. The FDTD computational domain consists of 31x91x111 cells. A rectangular mesh, with dx=0.389 mm,

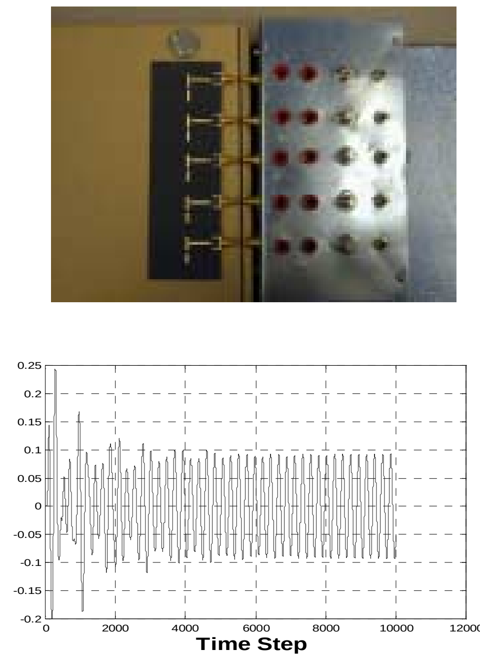


(a)

(b)

Fig. 4. Oscillation of single active antenna. (a) Waveform of diode voltage. (b) Spectrum of simulated and measured oscillation. Large signal model is extracted as C_d=0.25 pF and Rs=10.0 Ω. The simulated oscillation is 4.90 GHz, while the measured one is 4.8070 GHz.

dy=0.265 mm and dz=0.40 mm, is used. Perfect Matching Layer (PML) absorbing boundary condition with 6 layers, is applied to the six surfaces in the computational domain. In Fig. 4, we show the layout of the active antenna (insert of Fig. 4(b)), the steady state voltage across the diode, and the spectrum of the voltage. The simulated oscillation frequency of 4.90 GHz is in good agreement with measured result 4.8070 GHz. The non-linearity of the diode causes some harmonics. In the simulation, a fifth-order polynomial based on measured data, is fitted to represent the DC I-V nonlinear characteristics [8-9].



(a)

(b)

Fig. 5. (a) Fabricated slot antenna array and DC bias supply box. The slots are on the other side of the board. (b) The time development of the electric field E_y (V/cm) at an observation point for active antenna array. The desired oscillation frequency obtained from Discrete Fourier Transform (DFT) of time domain data, is 6.80 GHz. The device circuit parameters are R_d=-200.0 Ω, R_S=10.0 Ω, C_d=0.25 pF and L_S=0.665 nH.

Array antenna was designed and fabricated as shown in Fig. 5. The separation of element is 0.8 λg. The oscillation frequency of individual antenna in the array varies slightly from each other around 6.50 GHz, due to the variation of diode parameters. By careful tuning of the bias points, we found a synchronized oscillation at frequency 6.436 GHz, while the simulated one is 6.80 GHz. The simulated results from small signal model are depicted in Fig. 5. The array oscillation is strongly dependent upon the series inductance of the diodes. By tuning the inductance, a desired oscillation can be achieved where each inductance has value of 0.665 nH.

V. CONCLUSION

A FDTD algorithm simulating active slot antenna/array has been described. Z-Transform method was first used in the device equation update scheme. The validation of Z-Transform and large signal model schemes was justified. The simulation was used to design active antennas. Simulated results are in good agreement with experimental ones. In terms of oscillation frequencies, the large signal model scheme yields more stable solution for single active antenna, while Z-Transform scheme provides faster solution for active antenna array. Furthermore, the Z-Transform scheme is capable of taking into account the effect of series inductance.

ACKNOWLEDGEMENT

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REFERENCES

[1] K. S. Yee, " Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equation in Isotropic Media," *IEEE Transactions on Antennas and Propagation*, AP-14, pp. 302-307, May 1966.

[2] T. Itoh (ed), *Time-domain Methods for Microwave Structures*, NJ, IEEE Press, 1998.

[3] A. Taflove (ed), *Advances in Computational Electro-magnetics: The Finite-Difference Time-Domain Method*, Boston, MA, Artech House, 1998.

[4] W. Sui, D. A. Christensen, and C. H. Durney, " Extending the two-dimensional FDTD method to hybrid electromagnetic system with active and passive lumped element," *IEEE Trans. Microwave Theory Tech*. vol. 40, pp. 724-730, Apr. 1992.

[5] V. A. Thomas, M. E. Jones, M. Piket-May, A. Taflove, and E. Harrigan," The use of SPICE lumped circuits as sub-grid models for FDTD high-speed electronic circuit design," *IEEE Microwave and Guided Wave Lett*., vol. 4, no. 5, pp. 141-143, May 1994.

[6] B. Toland, B. Houshmand, and T. Itoh, "Modeling of Nonlinear Active Regions with the FDTD Method, " *IEEE Microwave and Guided Wave Letters*, vol. 3, no. 9, pp. 333-335, Sept. 1993.

[7] Vincent A. Thomas, Kuok-Mee Ling, Michael E. Jones, Brent Toland, Jenshan Lin, and Tatsuo Itoh, "FDTD Analysis of an Active Antenna," *IEEE Microwave and Guided Wave Letters*, vol. 4, no. 9, pp. 296-298, Sept. 1994.

[8] K. Liu, S. M. El-Ghazaly, V. Nair, N. El-Zein, and H. Goronkin, "Active integrated antennas using resonant tunneling diodes," *29th European Microwave Conference Dig.* , vol. , pp. , Oct. 1999.

[9] Mandar R. Deshpande, Kai Liu, et al., "Tunnel Diode Non-Linear Model for Microwave Circuits and Active Antennas", submitted to *IMS 2001*, Phoenix, USA, May 20-25, 2001.

APPENDIX

The impedance of the junction capacitor C_d paralleled with R_d, as shown in Fig. 1, is given by

$$Z_d = \frac{1}{j\omega C_d} \| R_d = \frac{R_d}{1 + j\omega R_d C_d} \tag{1}$$

The transformation function $H(\omega)$ is given by

$$H(\omega) = \frac{y(\omega)}{x(\omega)} = \frac{Z_d}{Z_d + j\omega L + R_s} = \frac{\gamma\beta}{(\alpha^2 + \beta^2) + 2j\alpha\omega - \omega^2} \tag{2}$$

where,

$$\alpha = \frac{R_s R_d C_d + L}{2R_d L C_d}, \quad \beta = \sqrt{\frac{R_s + R_d}{R_d L C_d} - \alpha^2}, \quad \gamma = \frac{\frac{1}{LC_d}}{\beta} \tag{3}$$

From Z-transform pair,

$$\frac{\gamma\beta}{(\alpha^2 + \beta^2) + 2j\alpha\omega - \omega^2} \Leftrightarrow \frac{e^{-\alpha\Delta t}\sin(\beta\Delta t)z^{-1}}{1 - 2e^{-\alpha\Delta t}\cos(\beta\Delta t)z^{-1} + e^{-2\alpha\Delta t}z^{-2}} = \gamma\frac{p_3 z^{-1}}{1 - p_1 z^{-1} + p_2 z^{-2}} \tag{4}$$

where,

$$p_1 = 2e^{-\alpha\Delta t}\cos(\beta\Delta t), \quad p_2 = e^{-2\alpha\Delta t}, \quad p_3 = e^{-\alpha\Delta t}\sin(\beta\Delta t) \tag{5}$$

and convolution theory,

$$Y(z) = \Delta t \cdot X(z) \cdot H(z) \tag{6}$$

we have,

$$Y(z) = \Delta t \cdot X(z) \cdot \gamma\frac{p_3 z^{-1}}{1 - p_1 z^{-1} + p_2 z^{-2}} \tag{7}$$

After being manipulated, it turns out that

$$Y(z) = p_1 Y(z) z^{-1} - p_2 Y(z) z^{-2} + \Delta t \cdot X(z) \cdot \gamma p_3 z^{-1} \tag{8}$$

Finally, we have time domain update equation for small signal model as follows

$$Y(t) = p_1 \cdot Y(t-1) - p_2 \cdot Y(t-2) + \Delta t \cdot \gamma \cdot p_3 \cdot X(t-1) \tag{9}$$