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Global modeling of microwave three terminal active devices using the FDTD method

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Abstract: This paper presents a new approach for the global electromagnetic analysis of the three-Terminal active linear and nonlinear microwave circuits using the Finite-Difference Time Domain (FDTD) Method. Here, we have updated the both electric field components on the three - terminal active device by correlating the voltage and current with its impedance. This approach is applied to the analysis of a linear amplifier which includes a three-terminal active MESFET device. Simulations results are in good agreement with those of the commercial tool.

Keywords: Active devices, amplifier, FDTD method, global modeling, MESFET

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The finite difference time domain method*, Norwood, MA, Artech house, 2000.

[2] W. Sui, D. A. Christensen, and C. H. Durney, "Extending the two dimensional FDTD method to hybrid electromagnetic systems with active and passive lumped elements," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 724–730, April 1992.

[3] M. Piket-May A. Taflove, and J. Baron, "FDTD-modeling of digital signal propagation in 3-D circuits with active and passive loads," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1514–1523, Aug. 1994.

[4] J. Xu, A. P. Zhao, and A. V. Raisanen, "A stable algorithm for modeling circuit source across multiple FDTD cell," *IEEE Trans. Microwave Guided Wave Lett.*, vol. 40, pp. 308–310, April 1997.

[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 analysis," *IEEE Trans. Microwave Guided Wave Lett.*, vol. 7, pp. 141–143, May 1994.

[6] C. N. Kuo, B. Houshamand, and T. Itoh, "Modeling of microwave active devices using the FDTD analysis based on the voltage-source approach,"

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IEEE Trans. Microwave Guided Wave Lett., vol. 6, pp. 199–201, May 1996.

[7] G. Emili, F. Alimenti, P. Mezanotte, L. Roselli, and R. Sorrentino, "Rigorous modeling of packaged schottky diodes by the nonlinear lumped network (NL2N)-FDTD-Approach," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2277–2282, Dec. 2000.

[8] O. El Mrabet and M. Essaaidi, "An Efficient Algorithm for the Global Modeling of RF and Microwave Circuits Using a Reduced Nonlinear lumped Network (NL2N)-FDTD-Approach," *IEEE Microwave Wireless Comp. Lett.*, vol. 14, pp. 86–88, Feb. 2004.

[9] T. K. Ishii, *Practical Microwave Electron Devices*, New York, Academic, Ch., 2., 1990.

1 Introduction

The design of today modern high frequency electronic systems requires the inclusion of electromagnetic coupling effects. This can be achieved by using a full wave approach, which can include the interaction between the active devices and their surrounding EM field.

The finite-difference time domain (FDTD) method [1] is one of the best candidates to be used in high frequency system simulation model to handle the field effect in the system. Several research works have been reported concerning the extension of the FDTD method to incorporate lumped microwave devices into 3-D full wave analysis. Among these, an extended FDTD method [2, 3] has been proposed to include simple lumped elements. However, this approach may become quite cumbersome in the modeling of three-terminal active devices with complicated equivalent circuit models and seems impractical when a multi-port lumped circuit is involved. Moreover, the actual device size cannot be easily taken into account, and tedious distributing procedures may be required [4]. In an effort to alleviate these problems, Thomas et al. [5] established the links between the FDTD method and the SPICE simulator. Although this approach is efficient in the sense that it exploits the already available codes, programming the link between FDTD and SPICE can be time consuming. Later on, C. N. Kuo et al. proposed in [6] another approach where the device-wave interaction is modeled through equivalent voltage-sources and state equations. In performing the calculation of state equations, however, the difference equations were not created at the same FDTD time step. Another approach has been proposed in [7, 8] incorporating a general two-terminals devices in a single FDTD cell. To the best of our knowledge, this approach has not been extended yet to three-terminal active devices. Thus, it is desirable that a more straightforward and simpler method is developed to include three-terminal active devices into FDTD algorithm.

In this paper, a new approach is presented without using state equations which must be solved at each time step. Therefore, it provides important savings in computational cost over [6]. Furthermore, the three-terminal active

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device can be easily extended over multiple FDTD cells without a significant modification to the method and without an increase in computational cost.

2 Theory

In order to include the equivalent circuit model of the MESFET Fig. 1 into the FDTD mesh, the active device can be inserted as shown in Fig. 2 (a), where V_1 and V_2 are aligned to the FDTD grid edges beneath and perpendicular to the microstrip line with each ends connected to the microstrip line or a grounded via. Those vias are modeled as perfect conductors and provide a voltage reference to V_1 and V_2.

Assume that the V_1 and V_2 are connected at the nodes $r_{E_{z_1}}$ and $r_{E_{z_2}}$ respectively along the z-direction; the update equations for $E_z^{n+1}(r_{E_{z_1}})$ and $E_z^{n+1}(r_{E_{z_2}})$ at the two ports of a MESFET can be found as:

$$E_z^{n+1}(r_{E_{z_1}}) = E_z^n(r_{E_{z_1}}) + \frac{\Delta t}{\varepsilon}\,[\nabla \times H]_z^{n+1/2}(r_{E_{z_1}})$$

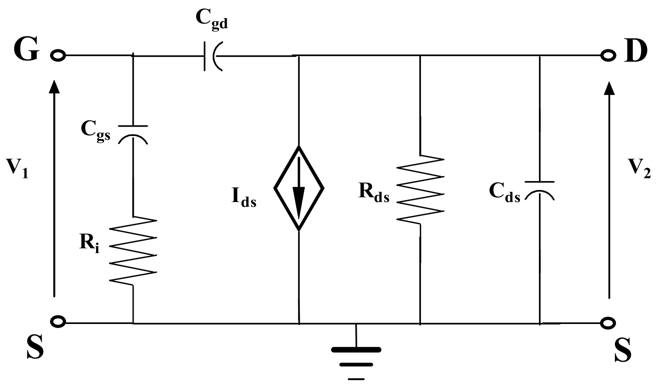

Fig. 1. Equivalent circuit for the JS8851-AS MESFET without parasitic elements (after [9]. C_{gd} = 0.06 pF, C_{ds} = 0.26 pF, C_{gs} = 0.69 pF, R_i = 1.42′Ω, g_m = 65 mS, gds = Rds = 197′Ω.

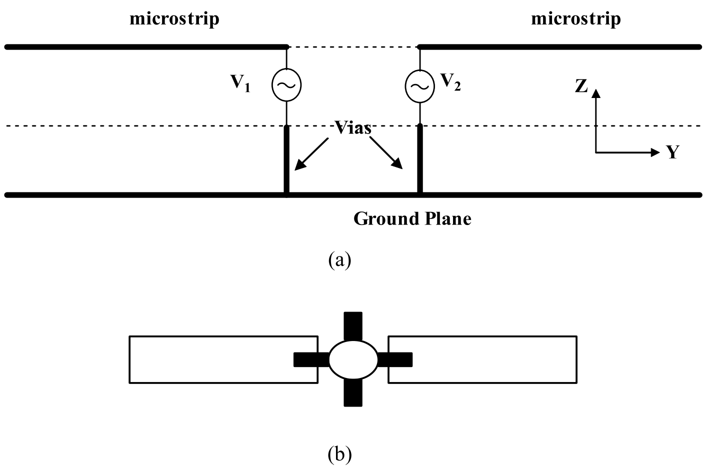

Fig. 2. (a) Implementation of the three–terminal active device. (b) structure of an amplifier without matching network

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$$- \frac{\Delta t}{2\varepsilon}\left[J_{lz}^{n+1}(r_{E_{z_1}}) + J_{lz}^{n}(r_{E_{z_1}})\right] \tag{1}$$

$$E_z^{n+1}(r_{E_{z_2}}) = E_z^{n}(r_{E_{z_2}}) + \frac{\Delta t}{\varepsilon}\left[\nabla \times H\right]_z^{n+1/2}(r_{E_{z_2}}) - \frac{\Delta t}{2\varepsilon}\left[J_{lz}^{n+1}(r_{E_{z_2}}) + J_{lz}^{n}(r_{E_{z_2}})\right] \tag{2}$$

The admittance matrix of a MESFET in frequency domain, written as,

$$[Y] = \frac{1}{D(\omega)}\begin{bmatrix} j\omega A_1 - \omega^2 A_2 & j\omega A_3 + \omega^2 A_2 \\ A_4 + j\omega A_5 + \omega^2 A_2 & A_6 + j\omega A_7 - \omega^2 A_8 \end{bmatrix}$$

$$\begin{aligned} &A_1 = C_{gs} + C_{gd},\ A_2 = R_i C_{gs} C_{gd},\ A_3 = -C_{gd},\ A_4 = g_m \\ &A_5 = g_m R_i C_{gs} - C_{gd},\ A_6 = g_{ds},\ A_7 = C_{ds} + C_{gd} + g_{ds} R_i C_{gs} \\ &A_8 = R_i C_{gs}(C_{ds} + C_{gd}),\ D(s) = 1 + j\omega R_i C_{gs} \end{aligned} \tag{3}$$

The resulting admittance matrix representation in the this domain is given by

$$I_1(\omega) = \sum_{q=1}^{2} Y_{1q}(\omega) V_q(\omega) \tag{4}$$

$$I_2(\omega) - I_{ds} = \sum_{q=1}^{2} Y_{2q}(\omega) V_q(\omega) \tag{5}$$

Where q $= 1, 2$ is the port indexe. The coefficients C_r^{pq} and d_r are obtained as in [8].

By replacing $j\omega$ with $\frac{\partial}{\partial t}$ and $-\omega^2$ with $\frac{\partial^2}{\partial t^2}$, the finite difference form of Eq. (4) is easily obtained as follow:

$$d_0 I_1^{n+1} = \sum_{r=0}^{2} C_r^{11} V_1^{n-r+1} + \sum_{r=0}^{2} C_r^{12} V_2^{n-r+1} - d_1 I_1^n \tag{6}$$

$$d_0 I_2^{n+1} = \sum_{r=0}^{2} C_r^{21} V_1^{n-r+1} + \sum_{r=0}^{2} C_r^{22} V_2^{n-r+1} + \sum_{r=0}^{1} d_r I_{ds}^{n-r} - d_1 I_2^n \tag{7}$$

Using the following relationships:

$$\begin{aligned} V_1^n &= -E_z^n(r_{E_{z_1}})\Delta z \\ V_2^n &= -E_z^n(r_{E_{z_2}})\Delta z \\ I_1^n &= -J_{lz}^n(r_{E_{z_1}})\Delta x \Delta y \\ I_2^n &= -J_{lz}^n(r_{E_{z_2}})\Delta x \Delta y \end{aligned} \tag{8}$$

Eq. (6) and Eq. (7) become

$$d_0 J_{lz}^{n+1}(r_{E_{z_1}})\Delta x \Delta y = C_0^{11}\Delta z E_z^{n+1}(r_{E_{z_1}}) + C_0^{12}\Delta z E_z^{n+1}(r_{E_{z_2}}) - \alpha_z^n \tag{9}$$

$$d_0 J_{lz}^{n+1}(r_{E_{z2}})\Delta x \Delta y = C_0^{21}\Delta z E_z^{n+1}(r_{E_{z_1}}) + C_0^{22}\Delta z E_z^{n+1}(r_{E_{z_2}}) - \beta_z^n \tag{10}$$

Where α_Z^n and β_Z^nrepresent the memory of the circuit:

$$\alpha_z^n = \sum_{r=1}^{2} -C_r^{11}\Delta z E_1^{n-r+1}(r_{E_{z_1}}) - \sum_{r=1}^{2} C_r^{12}\Delta z E_2^{n-r+1}(r_{E_{z_2}}) - d_1 \Delta x \Delta y J_{lz}^n(r_{E_{z_1}})$$

$$\beta_z^n = \sum_{r=1}^{2} -C_r^{21}\Delta z E_1^{n-r+1}(r_{E_{z_1}}) - \sum_{r=1}^{2} C_r^{22}\Delta z E_2^{n-r+1}(r_{E_{z_2}}) + \sum_{r=0}^{1} d_r I_{ds}^{n-r} - d_1 \Delta x \Delta y J_{lz}^n(r_{E_{z_2}}) \tag{11}$$

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Substituting Eq. (9) into Eq. (1), Eq. (10) into Eq. (2) respectively and using the following definitions:

$$q_{z_1} = 1 + \frac{\Delta t C_0^{11} \Delta z}{2\varepsilon d_0 \Delta x \Delta y}, \quad \gamma_{z_1} = -\frac{\Delta t C_0^{12} \Delta z}{2\varepsilon d_0 \Delta x \Delta y q_{z_1}}$$

$$\delta_z^n(r_{E_{z_1}}) = \frac{1}{q_{z1}}\left(E_z^n(r_{E_{z_1}}) + \frac{\Delta t}{\varepsilon}\ [\nabla \times H]_z^{n+1/2}(r_{E_{z_1}}) - \frac{\Delta t}{2\varepsilon} J_{lz}^n(r_{E_{z_1}}) + \frac{\Delta t \alpha_z^n}{2\varepsilon d_0 \Delta x \Delta y}\right) \tag{12}$$

$$q_{z_2} = 1 + \frac{\Delta t C_0^{22} \Delta z}{2\varepsilon d_0 \Delta x \Delta y}, \quad \gamma_{z_2} = -\frac{\Delta t C_0^{21} \Delta z}{2\varepsilon d_0 \Delta x \Delta y q_{z_1}}$$

$$\delta_z^n(r_{E_{z_2}}) = \frac{1}{q_{z_2}}\left(E_z^n(r_{E_{z_2}}) + \frac{\Delta t}{\varepsilon}\ [\nabla \times H]_z^{n+1/2}(r_{E_{z_2}}) - \frac{\Delta t}{2\varepsilon} J_{lz}^n(r_{E_{z_2}}) + \frac{\Delta t \beta_z^n}{2\varepsilon d_0 \Delta x \Delta y}\right) \tag{13}$$

The discretized Ampére-Maxwell's Eq. (1) and Eq. (2) become

$$\begin{aligned} E_z^{n+1}(r_{E_{z_1}}) &= \gamma_{z_1} E_z^{n+1}(r_{E_{z_2}}) + \delta_z^n(r_{E_{z_1}}) \\ E_z^{n+1}(r_{E_{z_2}}) &= \gamma_{z_2} E_Z^{n+1}(r_{E_{z_1}}) + \delta_z^n(r_{E_{z_2}}) \end{aligned} \tag{14}$$

From (14), we obtain easily the update equations for $E_z^{n+1}(r_{E_{z_1}})$ and $E_z^{n+1}(r_{E_{z_2}})$

$$\begin{aligned} E_z^{n+1}(r_{E_{z_1}}) &= \frac{1}{1 - \gamma_{z_1}\gamma_{z_2}}(\delta_z^n(r_{E_{z_1}}) + \gamma_{z_1}\delta_z^n(r_{E_{z_2}})) \\ E_z^{n+1}(r_{E_{z_2}}) &= \frac{1}{1 - \gamma_{z_1}\gamma_{z_2}}(\delta_z^n(r_{E_{z_2}}) + \gamma_{z_2}\delta_z^n(r_{E_{z_1}})) \end{aligned} \tag{15}$$

3 Numerical results

We have tested the validity of the new approach on the linear amplifier configuration shown in Fig. 2 (b), where $I_{ds} = g_m V_1$. We selected the JS8851-AS linear MESFET depicted in Fig. 1 (a). To get a 50 Ω characteristic impedance using a substrate material of a thickness of 0.795 mm and a relative dielectric permittivity of 2.2, the width of the microstrip line becomes 2.4 mm. The cell sizes are $\Delta x = \Delta y = 0.4\,mm, \Delta z = 0.265\,mm$ and $\Delta t = 0.4\,ps$. The unsplit-field PML ($\sigma_{\max} = 60, m = 4, d = 10$) is used to truncate the circuit. The active region occupies four cells in the y-direction. Using this set of parameters and a Gaussian pulse excitation with 15 GHz bandwidth, we performed the FDTD simulation.

Fig. 3 (a) and 3 (b) show the magnitudes of S11 and S21, respectively, simulated by our approach and the Hewlett-Packard's Advanced Microwave Design System (ADS). Very good agreement can be seen between the two sets of data proving the validity of our model. Because of the numerical dispersion of the FDTD simulation and also since the vias were modeled as perfect conductors, there is a small discrepancy between the two results.

4 Conclusion:

A novel approach is proposed to include three-terminal active devices into FDTD without the need to use the state equations approach. This allows

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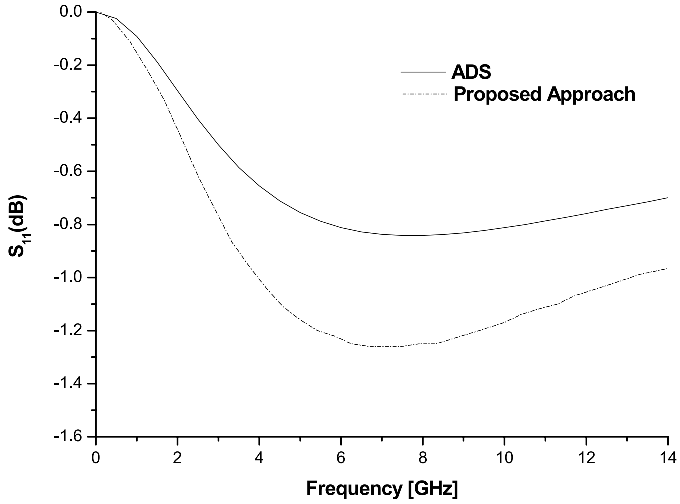
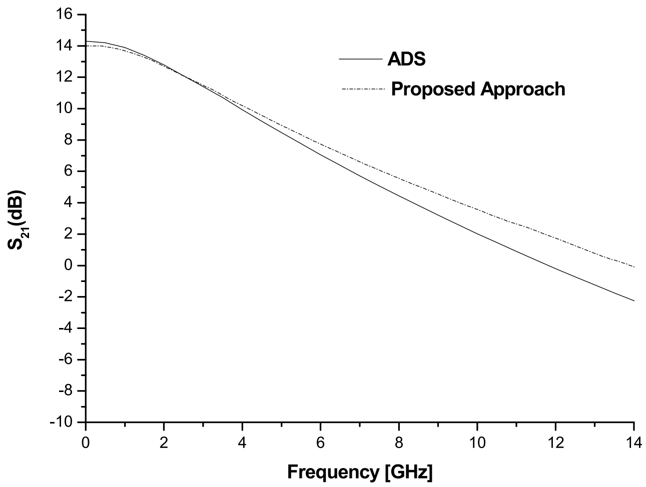


(a)



(b)

Fig. 3. The calculated results using the proposed approach and a commercial tool S-Parameters (a) $|S_{11}|$. (b) $|S_{21}|$.

considerable savings on computational efforts. Also, this approach allows the active device to be easily extended across multiple cells without a significant modification to the algorithm and without an increase in computational cost. Simulation results show very good agreement with ADS. Furthermore, this approach can be easily used for the modeling of nonlinear active devices.

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