Time Domain Analysis of GaAS MESFET Transistors Excited by an Incident Electromagnetic Field

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Abstract **─** A numerical method for the fully distributed modeling of Field Effect Transistor (FET) excited by an incident electromagnetic field using a Finite-Difference Time-Domain (FDTD) method is described. The transistor is modeled using the fully distributed model which consists of a configuration of the conventional equivalent circuit of the transistor and three coupled lines as each distributed element. The distributed source terms represent the coupling with an electromagnetic field in the equation which can be used in the Electromagnetic Interference (EMI) analysis. As a numerical example, the method is applied to a GaAs MESFET and the time domain results are presented.

Index Terms **─** Coupled active transmission lines, Electromagnetic Interference (EMI), Field Effect Transistor (FET), Finite-Difference Time-Domain (FDTD), incident wave, transistor distributed modeling.

I. INTRODUCTION

Modeling and prediction of undesired Electromagnetic Interference (EMI), such as crosstalk and external incident field, is very important to increasing the frequency and high-density packaging of microwave circuits [1]-[3]. Perfect analysis of the microwave transistors is one of major steps in the analysis of a microwave active circuit. In the very high (micro/mm-wave) frequencies, the dimension of the electrodes of a transistor becomes comparable to the wave length. Therefore, the device modeling must include the effect of wave propagation. This effect is considered in the global modeling of mm-wave circuits, but a huge CPU time is necessary for this very slow full wave analysis [4]-[5]. Recently, a time domain fully-distributed model for transistors was presented to reduce the simulation time with a good degree of accuracy in 1-40 GHz [6]-[7]. The fully distributed model considers three coupled lines while the number of slices has been increased to the infinity [6]. This model can be easily implemented with a fast FDTD simulation while describing the transistor behavior accurately. On the other hand, the FDTD solution of some coupled transmission lines has the ability to consider an external incident field in its equations [8]. This electromagnetic fields may be caused by reflections of our circuit in a box [9], by other circuits [10]-[11], or by the lightning strike [12]-[13]. This paper presents a time domain fully-distributed model for a transistor excited by an incident electromagnetic field by considering the propagation along the electrodes. First, the differential equations are derived for a MESFET using the transmission line theory. Then, the FDTD approach is applied to solve the equations in the time domain. Finally, the simulation results for an example transistor are presented. The method can be extended to other active devices with transmission line model [14].

Although the model has some approximates, such as using a one dimensional model and ignoring the secondary scattering, to the best of authors' knowledge, this is the first publication that the excitation effects on a transistor have been considered and simulated in a very small simulation time. However, more accurate results can be obtained by modifying the model in two or three dimensions and considering multiple

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scattering effects of the structure.

II. FULLY DISTRIBUTED MODEL

A typical millimeter-wave FET excited by an incident electromagnetic field has been shown in Fig. 1. The fully distributed model of a millimeter-wave field effect transistor is one of the accurate models applied to consider the distributed and wave propagation effects on device behaviour. The following part shows that this model can also be used in the EMI simulations of active devices.

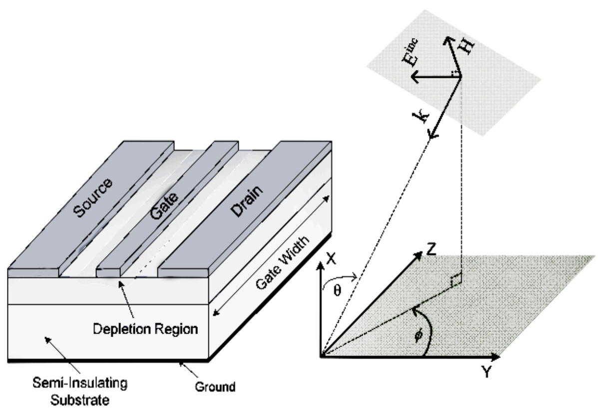

Fig. 1. The structure of a typical millimeter-wave FET excited by a plane wave.

The fully distributed model contains infinite cells cascaded together [6]. Each cell has two parts: the passive part which contains the coupled electrode transmission lines, resistance and internal inductance of electrodes, and the active part or an intrinsic GaAs FET equivalent circuit, whose elements are per unit length. We assume a linear circuit as equivalent circuit of a FET similar to [7], and add the incident wave to its equations (Fig. 2). For a transistor with electrodes in the z-direction excited with an incident wave, the time domain equations can be written as:

$$\frac{\partial}{\partial z}V\left(z,t\right)+L\frac{\partial}{\partial t}I\left(z,t\right)+RI\left(z,t\right) = \underbrace{-\frac{\partial}{\partial z}V_T\left(z,t\right)+E_L\left(z,t\right)}_{V_F(z,t)}, \quad (1)$$

$$\frac{\partial}{\partial z}I'\left(z,t\right)+C\frac{\partial}{\partial t}V'\left(z,t\right)+GV'\left(z,t\right) = \underbrace{-C\frac{\partial}{\partial t}V_T'\left(z,t\right)}_{I_F(z,t)}, \quad (2)$$

where $V_F(z,t)$ and $I_F(z,t)$ are 3×1 vectors containing the effects of the incident field;

$$V\left(z,t\right)=[V_d\,V_g\,V_s]^T\left(z,t\right), \quad (3)$$

$$I\left(z,t\right)=[I_d\,I_g\,I_s]^T\left(z,t\right), \quad (4)$$

$$V'\left(z,t\right)=[V_d\,V_g\,V_s\,V_g']^T\left(z,t\right), \quad (5)$$

$$I'\left(z,t\right)=[I_d\,I_g\,I_s\,0]^T\left(z,t\right), \quad (6)$$

$$V_T\left(z,t\right)=[V_{Td}\,V_{Tg}\,V_{Ts}]^T\left(z,t\right), \quad (7)$$

$$E_L\left(z,t\right)=[E_{Ld}\,E_{Lg}\,E_{Ls}]^T\left(z,t\right), \quad (8)$$

$$V_T'\left(z,t\right)=[V_{Td}\,V_{Tg}\,V_{Ts}\,0]^T\left(z,t\right), \quad (9)$$

are the functions of position z along the device and the passive parameters are defined as:

$$L=\begin{bmatrix} L_d & M_{gd} & M_{ds} \\ M_{gd} & L_g & M_{gs} \\ M_{ds} & M_{gs} & L_s \end{bmatrix}, \quad (10a)$$

$$C=\begin{bmatrix} C_{11} & -C_{12} & -C_{13} & 0 \\ -C_{12} & C_{22} & -C_{23} & C_{gs} \\ -C_{13} & -C_{23} & C_{33} & -C_{gs} \\ 0 & 0 & 0 & R_iC_{gs} \end{bmatrix}, \quad (10b)$$

$$R=\begin{bmatrix} R_d & 0 & 0 \\ 0 & R_g & 0 \\ 0 & 0 & R_s \end{bmatrix}, \quad (10c)$$

$$G=\begin{bmatrix} G_{ds} & 0 & -G_{ds} & G_m \\ 0 & 0 & 0 & 0 \\ -G_{ds} & 0 & G_{ds} & -G_m \\ 0 & -1 & 1 & 1 \end{bmatrix}, \quad (10d)$$

where $C_{11}=C_{dp}+C_{dsp}+C_{dg}+C_{dgp}$, $C_{22}=C_{gp}+C_{gsp}+C_{dg}+C_{dgp}$, $C_{33}=C_{sp}+C_{ds}+C_{dsp}+C_{gsp}$, $C_{12}=C_{dg}+C_{dgp}$, $C_{13}=C_{ds}+C_{dsp}$, and $C_{23}=C_{gsp}$. In the above equations, V_d, I_d, V_g, I_g, V_s, and I_s are the drain, gate and source voltages and currents, respectively. The values of V_T and E_L describe the incident field excitation.

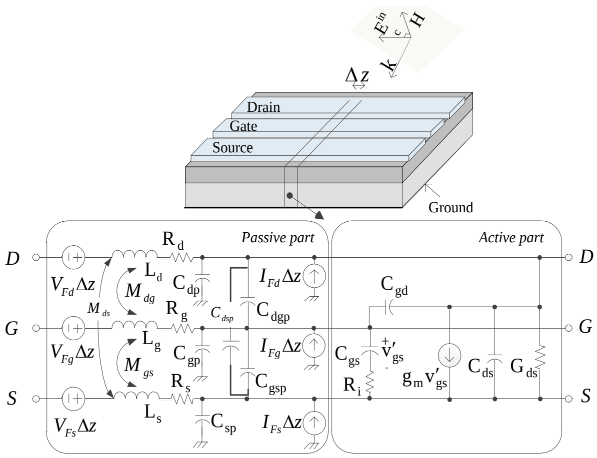

Fig. 2. The equivalent circuit of a differential slice in the fully distributed model with an incident field.

III. THE FDTD EQUATION

The solution of (1) can be determined by using an iterative finite difference procedure [6]. In this method, the transmission line is divided into small elements along the length of the line and similarly the time is divided into small steps. In order to insure stability in the FDTD solution of the equations, the discrete voltage and current solution points are not physically located at the same point, but they are staggered one-half cell apart. In addition, the discrete voltages and currents must be similarly staggered or "interlaced" in time with the time points for the voltages and one-half temporal cell apart spaced points for the currents. The boundary conditions must be applied at the first and last nodes. Hence, the currents I_0 and I_{Nz+1} are calculated by V_{in} and R_{in} at the beginning of gate, and R_L at the end of drain, respectively (Fig. 3). Approximation of derivatives in (1) by the finite differences gives the following equations:

$$V_1'^{\,n+1} = \left(\frac{C}{\Delta t}+\frac{G}{2}+\frac{1}{R_s'\Delta z}\right)^{-1} \left\{ \begin{array}{l} \left(\frac{C}{\Delta t}-\frac{G}{2}-\frac{1}{R_s'\Delta z}\right)V_1'^{\,n} \\ -\frac{2}{\Delta z}\left(I_1'^{\,n+\frac{1}{2}}-\frac{V_{in}'^{\,n}+V_{in}'^{\,n+1}}{2R_s'}\right) \\ -\frac{C}{\Delta t}\left(V_{T,1}'^{\,n+1}(z,t)-V_{T,1}'^{\,n}(z,t)\right) \end{array} \right\}, \tag{11}$$

$$V_k'^{\,n+1} = \left(\frac{C}{\Delta t}+\frac{G}{2}\right)^{-1} \left\{ \begin{array}{l} \left(\frac{C}{\Delta t}-\frac{G}{2}\right)V_k'^{\,n} \\ -\frac{2}{\Delta z}\left(I_k'^{\,n+\frac{1}{2}}+I_{k-1}'^{\,n+\frac{1}{2}}\right) \\ -\frac{C}{\Delta t}\left(V_{T,k}'^{\,n+1}(z,t)-V_{T,k}'^{\,n}(z,t)\right) \end{array} \right\}, \tag{12}$$

$$V_{N_z+1}'^{\,n+1} = \left(\frac{C}{\Delta t}+\frac{G}{2}\right)^{-1} \left\{ \begin{array}{l} \left(\frac{C}{\Delta t}-\frac{G}{2}\right)V_{N_z+1}'^{\,n}+\frac{2}{\Delta z}I_{N_z}'^{\,n+0.5} \\ -\frac{C}{\Delta t}\left(V_{T,N_z+1}^{\,n+1}(z,t)\right. \\ \left.-V_{T,N_z+1}^{\,n}(z,t)\right) \end{array} \right\}, \tag{13}$$

$$I_k^{\,n+1.5} = \left(\frac{L}{\Delta t}+\frac{R}{2}\right)^{-1} \left\{ \begin{array}{l} \left(\frac{L}{\Delta t}-\frac{R}{2}\right)I_k^{\,n+0.5}+\left(E_{L,k}^{\,n+1.5}(z,t)\right. \\ \left.+E_{L,k}^{\,n+0.5}(z,t)\right)-\frac{1}{\Delta z}\left(V_{k+1}^{\,n+1}-V_k^{\,n+1}\right. \\ \left.+V_{T,k+1}^{\,n+1}(z,t)-V_{T,k}^{\,n+1}(z,t)\right) \end{array} \right\}, \tag{14}$$

where

$$V_k^n = V\,[(k-1)\Delta z\,, n\Delta t\,], \tag{15}$$

$$I_k^n = I\,[(k-\frac{1}{2})\Delta z\,, n\Delta t\,], \tag{16}$$

$$\begin{aligned}\left[V_{T,k}^{\,n}\right]_i &= x_i E_x^{inc}(x_i, y_i, (k-1)\Delta z, n\Delta t)) \\ &\quad + y_i E_y^{inc}(x_i, y_i, (k-1)\Delta z, n\Delta t)),\end{aligned} \tag{17}$$

$$\begin{aligned}\left[E_{L,k}^{\,n}\right]_i &= E_z^{inc}(x_i, y_i, (k-0.5)\Delta z, n\Delta t)) \\ &\quad - E_z^{inc}(0,0,(k-0.5)\Delta z, n\Delta t)),\end{aligned} \tag{18}$$

where coordinates x_i and y_i describe the locations of the individual conductors. It should be noted that the excitation due to fields should be computed as the incident field, thus, all conductors should be removed when computing the $V_{T,K}$ and $E_{L,K}$ vectors.

In general, the accuracy of the solution depends on having sufficiently small spatial and temporal cell sizes. It means that we have to consider the Courant condition, $\Delta t<(\Delta z/v_p)$, where v_p is the phase velocity of the medium. In the case of multi-conductor lines, more than one velocity exists on the lines [1]. In fact we can obtain the mode velocities by calculating the eigenvalues of the product matrix LC. Therefore, we consider the largest of the mode velocities to satisfy the Courant condition.

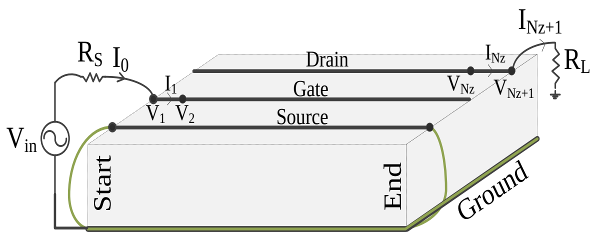

Fig. 3. The circuits used as boundary conditions.

IV. NUMERICAL RESULTS

In this part a GaAs MESFET (NE710) excited by an incident plane wave was modeled using the FDTD method for active transmission lines. The distance between the electrodes and ground plane, which is important in the calculation of the effects of incident field, has been considered as 140 μm and the width of gate is 240 μm. Using Δz=10 μm, we have 24 cells along the z-direction. Both input and output nodes were connected to the center of gate and drain electrodes. The source electrode is grounded at the beginning and the end. The element values used in the fully distributed model are shown in Table 1 [6]. The transistor is biased at V_{ds}=3 V and I_{ds}=10 mA, and the incident wave is considered as a sinusoidal pulse at the frequency of 40 GHz. The incidence direction is θ=90°, ϕ=90°, and η=90°. The amplitude of the incident wave is selected in such a way that produces a voltage of 1 mV at the start of the gate line. The numerical results of voltage and current at the start and end of the drain are shown in Figs. 4 and 5. It can be seen that the amplitude of output voltage at the drain line is equal to 2.03 mV. A comparison of the formulation of this paper with the results in the literature can be made when the amplitude of the incident wave is small with respect to the amplitude of the local oscillator, which is connected to the beginning of the gate. The transistor is excited by a local oscillator at the frequency of 25 GHz to make 100 mV at the beginning of the gate. Therefore, the incident wave is very small with respect to the excited signal and as shown in Fig. 6, the results of this work's formulation is very close to the results of [6]. The frequency response of transistor can be calculated using a Gaussian waveform as the excitation. The Gaussian pulse is considered by the expression $\exp[-\alpha(ndt-\beta dt)^2]$ where β=8 and $\alpha=(4/\beta/dt)^2$. The incidence direction is θ=90°, ϕ=90°, and η=90°. Simulation result of wide frequency band is shown in Fig. 7. The maximum output is appeared in 69 GHz. Moreover, the optimal gate width of transistor can be finding for the operation at a desired frequency. Figure 8 shows the voltage of drain's end with respect to the gate width, at 25 GHz, which has a maximum value at 390 μm.

Table 1: Per unit length values of distributed model for NE710 (at V_{ds}=3 V and I_{ds}=10 mA) [6]

Element	Value
C_{gs}	0.771 nF/m
C_{ds}, C_{gd}	0.0178 nF/m
g_m	146.42 S/m
R_i	0.002 Ω/m
L_d	780 nH/m
L_g	161 nH/m
L_m	360 nH/m
C_{gp}	29.6 pF/m
C_{dp}	148 pF/m
C_{gdp}	29 pF/m
R_d	900 Ω/m
R_g	34300 Ω/m
C_{gpk}	0.036 pF/m
C_{dpk}	0.0296 pF/m
L_{gpk}	0.766 nH/m
L_{dpk}	0.869 nH/m

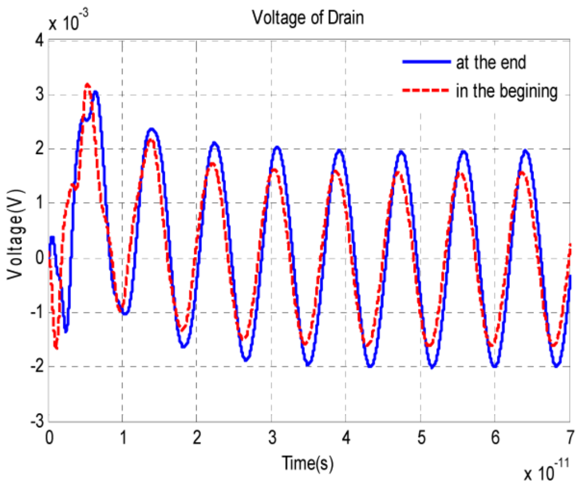

Fig. 4. Voltage of the drain line.

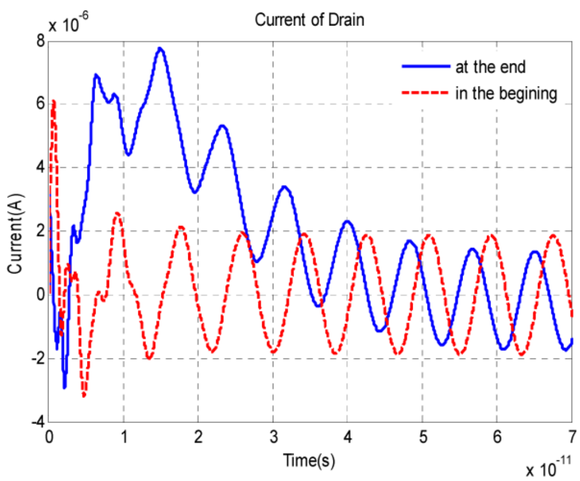

Fig. 5. Induced current on the drain line.

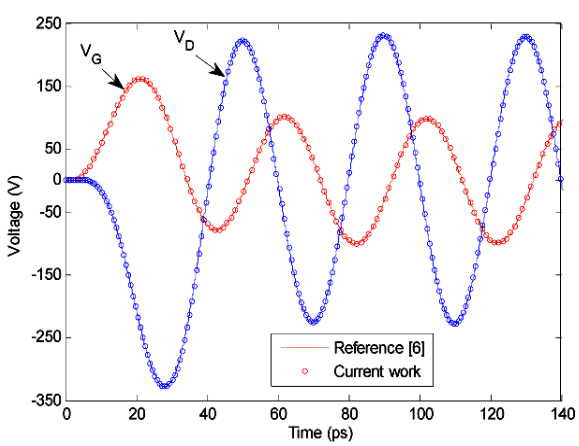

Fig. 6. Voltage in the beginning of gate (V_G) and end of drain (V_D).

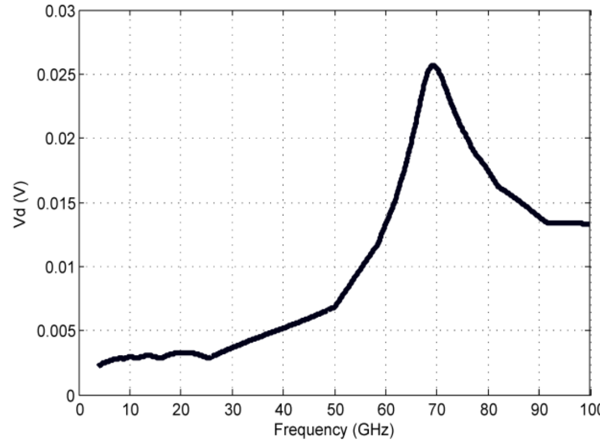

Fig. 7. Voltage at the end of rain with respect to the frequency.

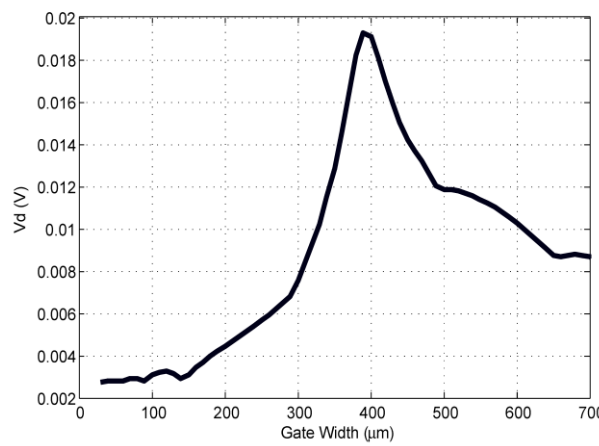

Fig. 8. Voltage at the end of drain with respect to the gate width.

IV. CONCLUSION

An accurate method for transient analysis of millimeter wave transistors excited by an external wave has been described using the FDTD. The method can be used in the EMI analysis of high frequency active circuits which has some transistors. Also, it is usable in the calibration steps of a micro/mm-wave measurement when the active device is tested in an environment with a strong EMI, which may be caused by radio transmitters. The effect of gate width can be studied with presented method, which is helpful in a transistor design.

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