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Large-Signal Circuit-Based Time Domain Analysis of High Frequency Devices Including Distributed Effects

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Abstract — **A fully distributed equivalent circuit model for MESFET is presented in this paper. The distributed circuit model incorporates sufficient number of segments to account for accurately wave propagation effects along device width. For the first time, distributed model having several segments is analyzed in time domain, which has the capability to evaluate large signal behavior. For a given MESFET, passive equivalent circuit elements are extracted from full wave simulation of the passive part as coplanar-coupled transmission lines using finite difference time domain technique. Active equivalent circuit elements are obtained from full hydrodynamic simulation with Curtice large signal model. The two equivalent circuits are combined together to form the basic unit segment. Several high frequency and high power characteristics of transistors are investigated and compared with previously published results.**

I. INTRODUCTION

At high frequency when device dimension becomes comparable to wavelength, the wave propagation effect needs to be considered in device modeling. Full wave global modeling approach can be used to describe wave device interaction [1]. But full wave technique is time consuming and needs extensive computer memory. On the other hand distributed equivalent circuit model [2]-[4] can well accounts the wave propagation effect and it is very suitable for CAD applications.

In our work for distributed equivalent circuit model, the device is divided in two parts- passive and active. The three electrodes (source, drain and gate) form the co-planar coupled transmission line which describes the passive part. From full wave analysis of the passive structure by FDTD all the self and mutual inductances and capacitances of the transmission line are determined. The full wave analysis is done by Gaussian pulse excitation, which in turn gives the transmission line circuit elements in a wide frequency range. The active part is the intrinsic part of the device, a full hydrodynamic simulation is done to get the active parameters for different bias conditions. Proper Curve fitting technique is used to derive Curtice large signal model [5] parameters from the current voltage characteristic obtained from full hydrodynamic simulation of the device. Thus obtaining all the equivalent circuit parameters for per unit width, scaling rule [5] is used to develop the complete equivalent circuit of several unit segments as shown in Fig. 3. To simulate the multi segments distributed circuit model time domain solving technique is developed which incorporates explicit iterative scheme for non linear circuit elements such as transconductance (Gm), junction capacitances (Cgs,Cds) and output conductance (Gds).

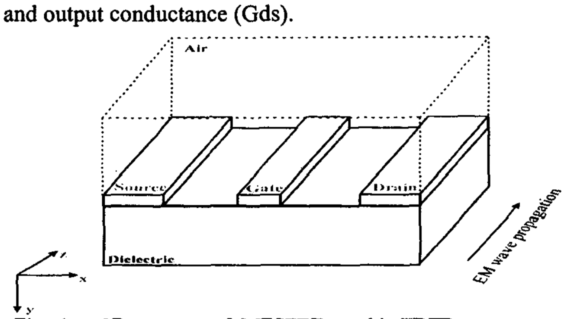

Fig. 1. 3D structure of MESFET used in FDTD

II. THE MODEL AND ITS ELEMENTS

A. Determination of Passive Circuit Parameters

To consider the EM wave propagation along the electrodes of the MESFET, three electrode lines are viewed as co-planar coupled transmission lines (Fig. 1) and are represented by the distributed circuit elements as shown in Fig. 3. In order to evaluate all these distributed elements the MESFET passive structure is excited in even and odd modes and for both modes EM wave propagation characteristics are completely solved by FDTD technique. Gaussian pulse is used as excitation to obtain a broadband frequency response. Line resistances are calculated considering the skin effect for high frequency [6].

B. Determination of Active Circuit Parameters

The equivalent circuit of the intrinsic device used in our model is shown in fig. 3. Full hydrodynamic 2D simulation is performed for the sample MESFET to generate current voltage characteristic curves as shown in fig. 2. for different bias conditions , which is then fitted with Curtice large signal model [5]. Fitted model parameters are shown in the Table I.

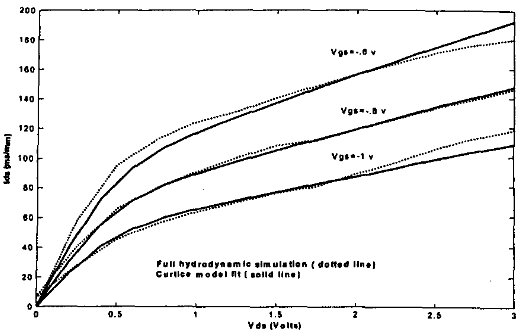

Fig. 2. I-V characteristics of the MESFET obtained from physical simulation with Curtice model fitted lines.

In Curtice model [5] the drain current Ids is related with gate voltage Vgs and drain voltage Vds by the following equation. Where β, λ, α and Vt are the model parameters.

$$Ids = \beta(Vgs - Vt)^2 (1 + \lambda Vds) \tanh(\alpha Vds) \quad (1)$$

The transconductance Gm and output conductance Gds are defined as:

$$Gm = \frac{\partial Ids}{\partial Vgs} = Ids[2/(Vgs - Vt)] \quad (2)$$

$$Gds = \frac{\partial Ids}{\partial Vds} = \beta(Vgs - Vt)^2 (1 + \lambda Vds)\{\alpha/[\cosh^2(\alpha Vds)]\} + \beta(Vgs - Vt)^2 \lambda \tanh(\alpha Vds) \quad (3)$$

The expressions used for gate to source capacitance Cgs and drain to source capacitance Cds are given by:

$$Cgs = Cgso\left(1 - \frac{Vgs}{Vbi}\right)^{-1/2} \quad (4)$$

$$Cgd = Cgdo\left(1 - \frac{Vgd}{Vbi}\right)^{-1/2} \quad (5)$$

where Vbi is the built in potential of the Schottky gate and Cgso, Cgdo are zero bias gate-source and gate-drain capacitances. Other active circuit elements Rgs and Cds are taken as constant for a specific bias condition in our analysis .

III. Distributed Circuit Model

The complete distributed model consists of several unit segments as shown in Fig. 3. Each unit segment is formed with active part embedded in passive elements. To make the unit cell symmetrical half of the passive elements are included at input side and other half at the output side. The passive equivalent circuit of the transmission line contains self and mutual inductances and capacitances and line resistance to include conductor loss. Fig. 3 shows the complete multi segmented distributed equivalent circuit model with gate and drain termination.

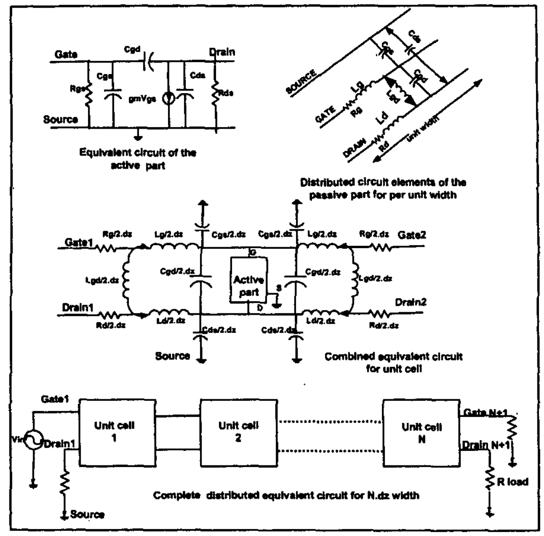

Fig. 3. The active and passive equivalent circuit elements, unit segment and complete distributed circuit model of multiple segments.

IV. Time Domain Analysis

The complete distributed circuit model is analyzed in time domain. For a unit cell input-output currents and voltages are related by four simultaneous discretized differential equations in time domain. Output-input relationship for fist stage and 2^{nd} stages in time domain can be expressed in matrix form as (6).

$$\begin{bmatrix} Ig2 \\ Vg2 \\ Id2 \\ Vd2 \end{bmatrix} = inv[A]\cdot[B/C(1)]\cdot\begin{bmatrix} Ig1 \\ Vg1 \\ Id1 \\ Vd1 \end{bmatrix}, \begin{bmatrix} Ig3 \\ Vg3 \\ Id3 \\ Vd3 \end{bmatrix} = inv[A]\cdot[B/C(2)]\cdot\begin{bmatrix} Ig2 \\ Vg2 \\ Id2 \\ Vd2 \end{bmatrix} \quad (6)$$

Replacing the 1^{st} stage expression in 2^{nd} stage, we get the relationship between 2^{nd} stage output in terms of first stage input as:

$$\begin{bmatrix} Ig3 \\ Vg3 \\ Id3 \\ Vd3 \end{bmatrix} = inv[A]\cdot[B/C(2)]\cdot Inv[A]\cdot[B/C(1)]\cdot\begin{bmatrix} Ig1 \\ Vg1 \\ Id1 \\ Vd1 \end{bmatrix} \quad (7)$$

In this way for N segments the final output can be expressed in terms of first segment input by a final matrix term (8) which is simply the multiplication of all the individual matrix of each state .As the output is terminated with load, there are two unknowns at output and two at input . Arranging all the four unknown at one side of the matrix we get expression (9), where elements of matrix M are all known at each time step. So input and output currents are evaluated as well as corresponding voltages.

$$\begin{bmatrix} Ig_{n+1} \\ Vg_{n+1} \\ Id_{n+1} \\ Vd_{n+1} \end{bmatrix} = [F] \cdot \begin{bmatrix} Ig1 \\ Vg1 \\ Id1 \\ Vd1 \end{bmatrix} \quad (8) \quad \& \quad \begin{bmatrix} Ig_1 \\ Id_1 \\ Ig_{n+1} \\ Id_{n+1} \end{bmatrix} = [M] \quad (9)$$

Thus solving voltage and current at first stage input and final stage output all the voltages and currents for each stage are evaluated in time domain.

V. VALIDATION OF TIME DOMAIN TECHNIQUE

The main advantage of the technique presented here is its ability to accurately analyze large signal behavior of semiconductor devices while taking wave-propagation effects into consideration. This approach incorporates the nonlinear characteristics and wave propagation effects in transistor without sacrificing the computational speed. To validate the presented approach we analyzed the same device presented in [7]. Fig. 4 shows the result we obtained for maximum available power gain at 6 Ghz operating frequency with variation of device width, to make the comparison all the conditions such as output load and other terminations are kept same as the reference device [7].

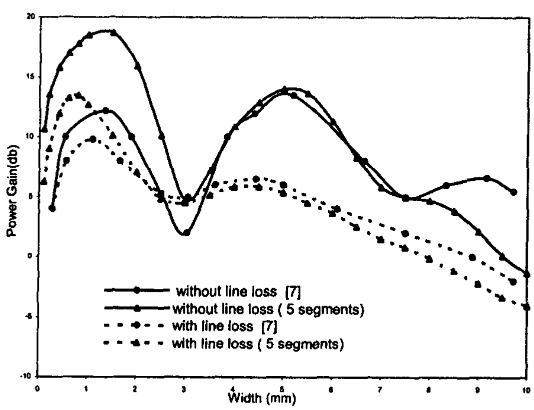

Fig. 4. Comparison of the results obtained by time domain technique with presented results [7] for maximum available gain versus device width.

In our time domain analysis to include the wave propagation effects accurately we employed five segments along the device width. The small signal simulations show good agreement with the results presented in Ref. [7]. The two approaches give almost identical results for the intermediate frequency range. The difference observed for high frequencies are due to the fact that we used five segments to model this transistor, which significantly improves the accuracy.

VI. LARGE SIGNAL RESULTS

To demonstrate the large signal capabilities of this approach, it was applied to study the MESFET transistor whose parameters are shown in Table 1. Fig. 5(a)-(b) show the time domain large signal responses of the transistor. The frequency components of the output clearly show the non-linearity of the output signal for a sinusoidal input signal of 1 Ghz frequency. The large signal behavior is more obvious by the distortion of the output signals when the device is partially driven to pinch off by a large input signal (Fig. 5(b)). The gain versus frequency characteristics (Fig. 6) show resonance at high frequency when line is loss-less. The occurrence of resonance at high frequency clearly demonstrates the wave propagation effect. When line loss is considered the resonance like response disappears (Fig. 6) due to the effect of lossy transmission line. We obtained the power relationship curve (Fig. 7) with large signal analysis taking only the fundamental frequency component's power. The saturation of the output power with the increase of input power is the typical large signal behavior of the transistor.

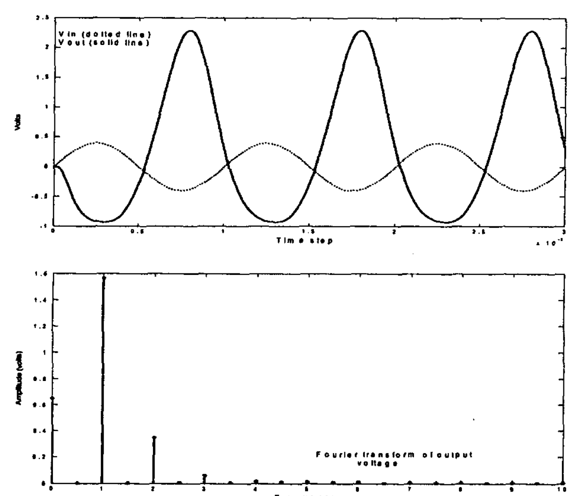

Fig. 5 (a). Large signal output voltage and its frequency components.

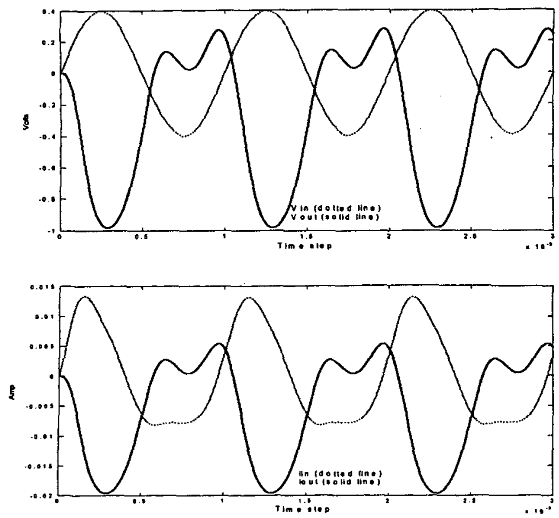

Fig. 5(b). Voltages and currents when device is driven to pinch off.

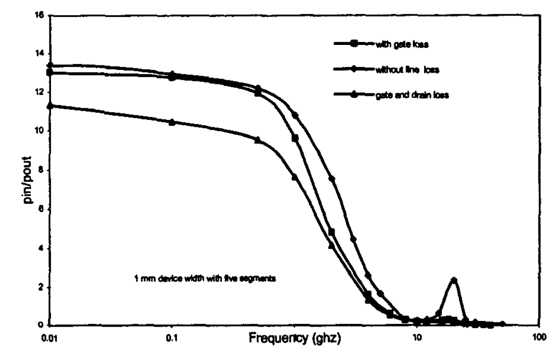

Fig. 6. Power gain versus frequency curve

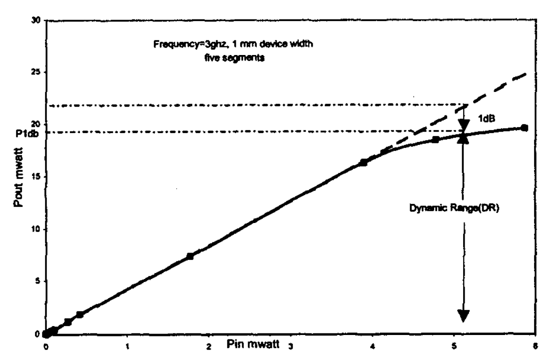

Fig. 7. Input -output non- linear power relationship curve

TABLE I

Sample Device specifications			
Material	GaAs	Gate length	0.3 um
Active layer doping	2e17/cm^3	Gate source separation	0.5 um
Substrate doping	1e14/ cm^3	Drain source separation	0.5 um
Active layer thickness	0.1um	Drain source contacts	0.5 um
Device thickness	0.5 um	Schottky barrier	0.8 volts
Curtice model parameter			
λ=0.45	α=2.45	β=0.032	Vt=2

CONCLUSION

A time domain approach for large signal high frequency device modeling is presented. First the distributed multi-segment equivalent circuit model for a MESFET is presented which contains both passive and active elements. The solution technique for the complete distributed circuit model in time domain is developed. The accuracy of this technique is validated by a comparison with published results, which gives good insight of the capabilities of this technique and its potential for optimizing device width for maximum output power and power gain of the device. Large signal characteristics are presented as well for a given MESFET.

ACKNOWLEDGEMENT

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