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Modeling and analysis of a nonlinear fully distributed FET using FDTD technique

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Abstract

In this paper, a new method for the time-domain analysis of a PHEMT transistor operating in the nonlinear region based on the fully distributed model is presented. Considering a nonlinear lumped equivalent circuit as an active part and applying the finite-difference time-domain (FDTD) technique to solve the equations extracted from this model, the voltages at each point of the electrodes are calculated.

The procedure has been applied to a $0.2 \times 1600\,\mu\text{m}$ PHEMT with 16 gate fingers operating at 28 GHz and the results achieved from MATLAB are compared with semi-distributed model which is simulated by ADS simulator. By using this new method, more accurate results are obtained. This approach can be applied to the transistors used in nonlinear regions at microwave and millimeter-wave frequencies.

Keywords: Distributed model; Nonlinear; Finite-difference time-domain; Cubic–Curtice model; Differential equation

1. Introduction

Accurate and perfect analysis of a transistor is the main step in complete analysis of the active microwave circuits. Recent developments in millimeter-wave applications of FETs demand more attention on modeling problems [1–5]; furthermore, increasing the frequency up to millimeter wave requires models which can consider the wave propagation along the electrodes [6]. As a result, in this frequency range the electrodes are assumed to be transmission lines in the width direction and therefore a transistor can be referred as a set of three active coupled transmission lines.

In semi-distributed modeling (sliced modeling) [1], the electrodes are divided into finite segments in propagation direction. It has to be noted that the model is derived from Quasi Transverse Electromagnetic Mode (Q-TEM) assumption; thus, the wave travels just in one dimension. Each cell is uniquely made up of passive and active sections. The semi-distributed model with both linear and nonlinear lumped elements for active part has been probed in different papers [7–10]. In this modeling, the final result can be achieved by cascading the cells. Abdipour et al. [1] applied the slicing model to the FET structure and compared the results with data obtained from measurement. Moreover, Ongareau et al. [10] considered a nonlinear and semi-distributed model for analyzing an FET so that they could obtain the time-domain signals in each slice.

Reaching more accurate results in high frequency and assuming the harmonic generation effects leads us to develop the nonlinear semi-distributed model. The modified model is introduced as the fully distributed model. In this method, the number of segments along electrodes must be goes to infinite. Like semi-distributed model, each unit in distributed model is made up of passive and active sections. As

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a result,the differential equations can be easily obtained by applying the KVL and KCL to the equivalent circuit. So, a set of nonlinear differential equations are created. Analysis of the fully distributed model consisting of nonlinear active part considers the high-frequency effects [11].

Harmonics are generated by various nonlinearities of FET and are subsequently amplified by traveling-wave (TW) interaction. The gate–source capacitance (C_{gs}) and drain–current (I_{ds}) are the most important nonlinearities in the intrinsic model. Selecting the lumped model for intrinsic part of the distributed model and its nonlinear elements is known as the critical point in consideration of harmonic generation. In other words, the harmonic generation plays an important role in design of circuits such as oscillator and mixer. Also, effects of diverse phenomena can be investigated in large signal excitation.

Tiwari et al. [11] were the first group that studied on the nonlinear differential equations of a distributed model in frequency domain. For obtaining the complete analytical solution from the nonlinear differential equations, they assumed many assumptions that many of them were limiting parameters. Finally, they could find the final response of V_d as a Weierstrass elliptical function. Extracting the analytical solution for a system of coupled nonlinear differential equations is very difficult even if one of the equations does not consist of nonlinear term such as approximation that Tiwari et al. [11] assumed. Two fundamental assumptions were in their work: firstly, they converted the time-domain equations to the phasor equations by very simple assumption of transforming $v^2(t), v^3(t), \ldots$ to $V^2, V^3, \ldots$ in frequency domain. Secondly, they presumed that signal attenuation along the gate electrode is a step function and also they assumed that the perturbation in the drain electrode voltage due to gate voltage was kept constant.

In the present work, the fully distributed model is used for modeling a typical millimeter-wave FET transistor. The model consists of the nonlinear lumped equivalent circuit (Cubic–Curtice model) as an intrinsic part. Then, the equations describing the model are derived in time domain. It should be noted that finding the equations for the model in time aspect has been done for the first time. Choosing the finite-difference time-domain (FDTD) technique to solve the obtained nonlinear system is the main characteristic in our trend [12].

This paper is organized as follows: first, the nonlinear differential equations system explaining the distributed model are derived; then, the discritized equations are achieved by applying the FDTD method to the system extracted from previous step. Consequently, the voltage at each point of electrodes using the Newton–Raphson approach will be accessible in time region. Finally, the procedure is applied to a $0.2 \times 1600\,\mu$m PHEMT with 16 gate fingers working at 28 GHz and the results obtained from MATLAB are compared with those simulated by ADS.

2. The distributed model and its elements

A typical layout of millimeter-wave FET is shown in Fig. 1a. The proposed device consists of three coupled electrodes fabricated on a thin layer of GaAs, supported by a semi insulating GaAs substrate. By using the distributed model, the millimeter-wave FET structure is divided into spatial discritization, Δz. Each segment is made up of an active part combined with linear section which is known as passive section. In this model a regular three-dimensional problem can be reduced to a one-dimensional one by applying the TEM waves in the z-direction. Both active and passive parts have elements per unit length. Now, the device can be presented by the model shown in Fig. 1b.

Any differential subsections ($\Delta z \to 0$) of the model can be considered as three active coupled transmission lines in which the scaled lumped model of transistor is used. The active part which acts just similar to a usual FET can be modeled by either linear or nonlinear circuit. The harmonic generation in the components which operate at high power and at the high frequency can be known as one of the most important reasons to choose proper model for intrinsic (active) part. The passive section indicates to behavior of the physical structure and consists of elements describing losses and mutual effects between the electrodes. By choosing the Cubic–Curtice model for the active part, the final schematic of the fully distributed model is shown in Fig. 2.

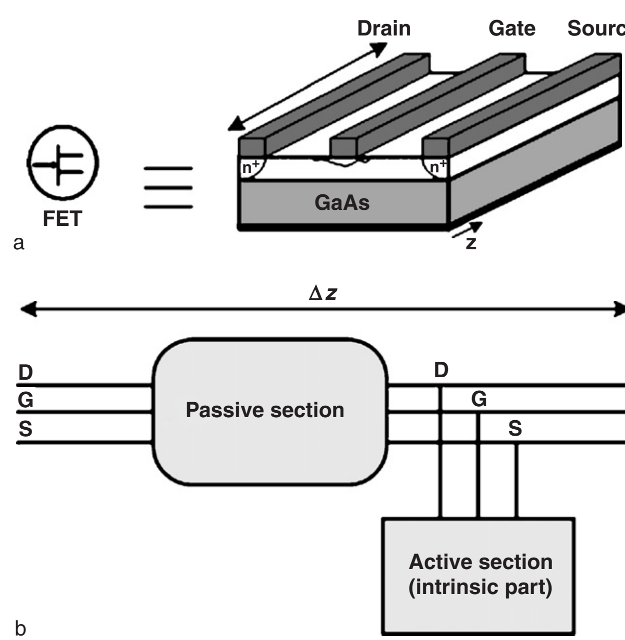

Fig. 1. (a) 3D structure of FET used in millimeter-wave frequency. (b) a segment of distributed model along the wave propagation direction.