NONLINEAR MODELING for MMIC's

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ABSTRACT

Nonlinear microwave CAD as applied to GaAs MMIC's is still in its infancy. A brief review is given of some of the work on modeling the nonlinear or "large-signal" behavior of the GaAs FET and nonlinear microwave circuit simulation. This is an important topic to the future success of GaAs MMIC's. Several important issues are raised with respect to nonlinear CAD for GaAs MMIC's.

INTRODUCTION

Many GaAs MMICs are designed today using "linear" CAD tools and "small-signal" device models. However, all MMICs exhibit nonlinear behavior. For example, the designer of a "small-signal amplifier" typically wants to know at what level the amplifier saturates (i.e., gain compression), and what the harmonic distortion looks like as a function of input drive. Of course, many circuits depend on nonlinearity to operate such as oscillators, mixers, and detectors. In the world of digital circuits, FETs are used as switches -- "large-signal" models are required for circuit simulation. This paper briefly reviews the present state of nonlinear circuit simulation tools and FET models available for GaAs MMIC design. In addition, many of the major issues facing MMIC designers are brought out in the discussion.

THE DRIVING FORCE BEHIND NONLINEAR SIMULATION OF GaAs MMIC's

Ultimately the success of GaAs MMIC's comes down to cost. R. A. Pucel [1] has described the need for a "cost-driven", as opposed to a "performance-driven", design methodology. In other words, the MMIC designer needs the tools and methodology to design GaAs IC's right the first time with high yields during manufacturing. Pucel pointed out the need for better CAD software, a parameter data base to call upon (after all, models can be no better than the data available), the inclusion of layout in the design cycle, and the necessity for design optimization with tolerances [1].

Obviously the MMIC designer must have accurate models for all components used in MMIC's, fast simulation engines capable of handling nonlinear distributed networks, and post processing of the data for ease of interpretation. Successful MMIC design requires simulation of all of the important parameters, including nonlinear or large-signal behavior, at the initial design stage with confidence.

FET MODELS FOR CIRCUIT SIMULATION

The GaAs MESFET (or MODFET) is a highly nonlinear active device. The GaAs FET is the most important nonlinear component used in GaAs MIC and MMIC design. Many workers have tackled the problem of modeling the MESFET (and MODFET). Some of this work (which is best known to this author) is referenced below.

The initial modeling work of Shockley [2] did not include velocity saturation. Of course, velocity saturation is a dominant feature in short channel GaAs FETs. Velocity saturation is generally included by either a two-region partitioning or with an analytic v-E relation. The effect of velocity saturation was first included by Turner & Wilson [3]; Hower & Bechtel [4] extended this work to a "small-signal" model. Other important modeling work following this general framework is Grebene & Ghandhi [5], and Lehovec & Zuleeg [6]. A three-region model was developed by Shur & Eastman [7] which modeled for the static dipole under the gate. One of the most widely referenced models is that of Pucel, Haus, & Statz [8] which has greatly influenced much of the modeling work since 1975. The above models are primarily analytical models.

Another class of models is that of the numerical two-dimensional device simulators using the semiconductor transport equations coupled to Poisson's equation (or Monte Carlo and hydrodynamic calculations). These include the work of Kennedy & O'Brien [9], Reiser [10], Barnes, et al. [11], Himsworth [12], and Grubin [13], to cite only some of the early work. While

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this modeling work has been very important in understanding the physics of the short channel FET, these models are not practical for circuit simulation because of their long computation times.

Two-dimensional numerical simulation by Yamaguchi & Kodera [14] was coupled to an analytical expression for the electron density in the channel. This allowed for a much simplified model which still retained some of the features from the full 2D analysis (e.g., velocity rotation in the channel accounted for the output conductance). Shur & Eastman [7] used results from Yamaguchi & Kodera in developing their model. Madjar & Rosenbaum [15] started with the work of Yamaguchi & Kodera and extended it into a fully analytic model.

The empirical approach by Willing, Rauscher, and de Santis [16] used S-parameters at representative bias points to determine the element values of their model as a function of the terminal voltages. Time domain analysis was used in [16]. Peterson, Pavio & Kim [17] extended this work to include gate forward conduction and gate-to-drain breakdown; they used both S-parameters and pulsed I-V measurements for parameter determination. Another noteworthy model based on DC characteristics was reported by Tajima, Wrona & Mishima [18].

Many of the above mentioned models are not especially suited for standard generic circuit simulation programs (e.g., ASTAP and SPICE). The challenge is to model the FET's nonlinear behavior with a "simple" model suitable for computer simulation of relatively complex circuits in a reasonable time frame. The remainder of this section will discuss modeling work aimed at conventional IC circuit simulators.

The first GaAs IC large-signal MESFET model targeted for circuit simulation (ASTAP initally, and later SPICE) was developed by Rory Van Tuyl [19-20] in 1973. Unfortunately, this analytical model has never been published in full (its development was a continuing effort which continues to this day). It is a four node topology where a bulk node effectively partitions the channel into two regions. This model formed the foundation for later work by H. Yeager [21] on a MODFET (or HEMT) model used in SPICE. In addition, D. Root [22] has extended the Van Tuyl MESFET model to include the formalism set forth by Ward [23] for charge-based, multi-terminal, voltage-dependent capacitance inclusion (4x4 non-reciprocal capacitance matrix). This guarantees conservation of charge and linearization of the I-V equation.

Most JFET and MESFET models intended for SPICE are analytical models of the three node topology (intrinsic portion of the MESFET). This is illustrated in Figure 1. Early work attempted to make use of the Shichman & Hodges model [24] in SPICE (which is of this topology). A model presented by Curtice [25] in 1980 is a major improvement over Shichman-Hodges and has been used quite extensively, especially for digital GaAs IC simulation. A number of other models have followed the work of Curtice: for example, White & Namordi [26], Brown [27] and Sussman-Fort et al. [28].

Following this same progression, an even more recent analytical model is that of Statz et al. [29]. It has an improved drain current characteristic and much better representation of the (multiterminal) voltage-dependent capacitance than the conventional SPICE JFET model. Capacitance modeling [30-31] in MESFET's has been one of the problem areas for a long time. This model is being implemented in SPICE3 and HARMONICA at the University of California, Berkeley.

Some recent modeling effort has focused on special features. For example, Peltan, Long & Butner [32] have developed a model for improved accuracy in the linear region of operation. Larson [33] has included the frequency dependence of the output conductance in a MESFET model using external components.

Only a fraction of the GaAs FET modeling effort has been included here. Next, nonlinear circuit simulation is discussed.

CIRCUIT SIMULATION PROGRAMS

Several groups have developed unified strategies for the design and analysis of nonlinear networks. Lipparini et al., Rizzoli & Lipparini, and Rizzoli et al. [34-36] have reported a frequency-domain harmonic balance approach [37-38] including optimization by searching both the network parameters and voltage harmonics. Other approaches to this problem have been presented by Chua & Ushida [39], Sobhy et al.

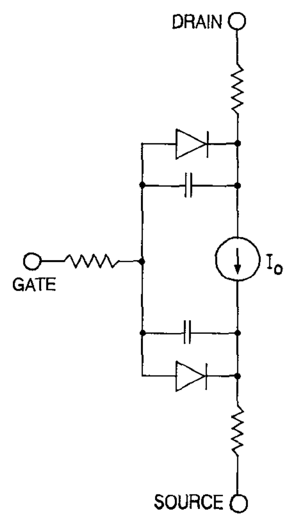

Figure 1.

[40] (using ANAMIC), Hente & Jansen [41] (frequency domain continuation method), and Rhyne & Steer [42] (generalized power series). None of these are available as products (although ANAMIC [48] may eventually be).

Consider commercially available or public domain simulators. Figure 2 gives one perspective where the four quadrants (domains) separate linear from nonlinear and lumped element from distributed element. Simulators such as SUPER-COMPACT and TOUCHSTONE clearly cover the linear-lumped and linear-distributed domains. SPICE [43] and ASTAP [44] do well in the linear-lumped and nonlinear-lumped domains, but are not well suited for the inclusion of distributed elements (although some versions of SPICE have a simple transmission line model). Some MMIC design work has used SPICE [45], but the results are varied. Time domain simulation is clearly of value, but it is quite restrictive because it is not suitable for a large class of microwave circuits. Convergence problems [46] have also been a problem in the time-domain simulation. At present conventional simulators, such as SPICE, do not handle the nonlinear-distributed domain with sufficient generality to be widely useful for MIC and MMIC design. Still, SPICE (or its equivalent) will probably be used for MMIC design in select cases for a long time despite its shortcomings.

Presently interest has been developing in the technique of harmonic balance. Harmonic balance works best on circuits in the steady-state at near sinusoidal condition. HARMONICA [47] is an such a program being developed at U.C., Berkeley; it will be in the public domain (perhaps in late 1987). It is aimed at handling a large class of nonlinear circuits of considerable complexity. Its run times are significantly faster than programs such as SPICE without a reduction in accuracy.

It is not clear at present which simulation approach will eventually be the most fruitful or gain the widest acceptance for nonlinear microwave CAD.

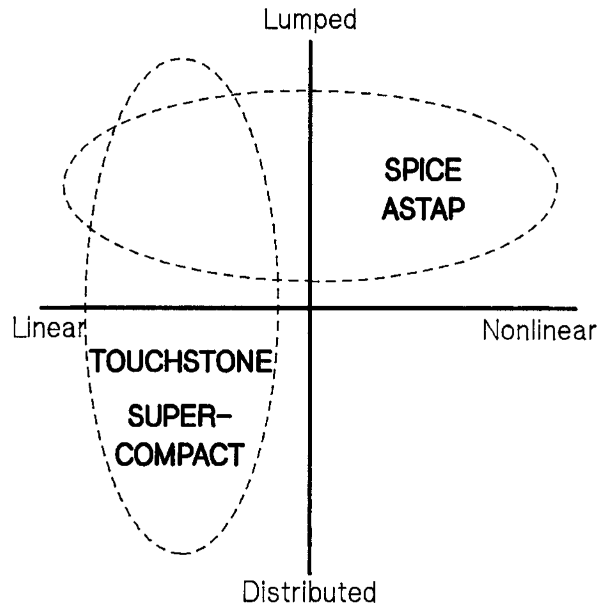

Figure 2.

CONCLUSIONS AND IMPORTANT ISSUES

Nonlinear CAD applied to GaAs MMIC's is still in its infancy. There are many problems to be addressed. Work on improved nonlinear active device models and nonlinear simulators will continue for years. It is doubtful if there will ever be "one best nonlinear FET model" which gives acceptable accuracy for all tasks.

Some of the important questions to be addressed include:

(1) Given a good nonlinear FET model, how does one chose the the parameters for the "nominal", the "best" and the "worst" devices for simulations?

(2) How can "optimization with tolerances" be implemented with respect to the nonlinear behavior of MMIC's?

(3) Is robust "optimization" going to be practical for nonlinear circuits with many active devices? Or even a few active devices?

(4) Will nonlinear simulators be general enough for meeting the needs of the broad range of MMIC circuit types? (For example, can the harmonic balance technique be extended to handle circuits such as oscillators (frequency to be determined) and mixers (two signal sources)?)

We are certain of one thing: increasing effort and resources will be channeled into nonlinear CAD for MMIC's because of its importance in the future success of GaAs MMIC's. It should be most interesting to watch this field develop in the coming years.

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