SCALEABILITY OF DC/AC NON-LINEAR DISPERSION MODELS FOR MICROWAVE FETs

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ABSTRACT

This paper addresses the issue of scaleability in circuit based models for FETs, emphasising for the first time the particularly difficult problems associated with the scaleability of DC/AC dispersion phenomena. Results of a study carried out on both MESFET and PHEMT foundry processes, show that while the differential DC/AC transconductance obeys straightforward scaling rules, the output conductance does not. An equivalent circuit based solution that incorporates a differential DC/AC dispersion modelling methodology is presented. The solution is compact, obeys the required conservation constraints and can account for the scaling inconsistencies observed in the output conductance.

INTRODUCTION

Despite intense studies in recent years into the problem of non-linear microwave FET modelling, the subject continues to cause great concern to microwave and RF design engineers, as it remains one of the major sources of errors in MMIC design. Very significant progress has been achieved in many areas of the field, but there are still some important aspects that have been traditionally sidelined, such as scaleability and yield analysis. These issues are of paramount importance, particularly to design engineers working in MMIC foundries, who have to deal with circuits of increasing complexity, and need to have the flexibility and confidence to use a wide range of device sizes in their designs. Consequently, for them, the availability of very accurate device models without correspondingly good scaling qualities, makes little practical sense.

In this contribution, we present some results from a recent study, carried out on two FET foundry processes, one MESFET and one PHEMT, from different manufacturers, regarding, among other aspects, the scaleability of a general-purpose model for microwave FETs. Scaleability, in general, presents particular difficulties in equivalent circuit based and black-box modelling approaches, since geometrical dimensions do not appear explicitly in the model structure. In the case of equivalent circuit based models, our study showed that up to medium size devices, most of the important equivalent circuit elements can be scaled using straightforward linear rules. It has to be stressed however, that this is strictly true only when a correct and reliable parameter extraction methodology is used to extract all extrinsic and intrinsic elements of the circuit model [7][8]. But even when such a methodology has been used, we have found that there are some second-order phenomena, i.e. the DC/AC dispersion of the output conductance, that do not obey these simple scaling rules. This is likely to generate even more difficulties in finding a solution to the scaleability problem, within most of the modelling approaches currently in use.

We propose a relatively straightforward, empirical equivalent circuit solution (Fig. 1) and an associated modelling methodology, which obeys the required conservation laws and at the same time can deal with the observed scaling inconsistencies of the differential DC/AC output conductance, via an additional non-linear conductance in the output circuit. Experimental results are shown, representing the observed scaling behaviour of the differential DC/AC transconductance and output conductance. Finally, the improvement achieved by implementing the new equivalent circuit and scaling solutions into a general-purpose, scaleable model (*COBRA*), are proved in a simple small-signal test, for the case of two PHEMT devices of different sizes.

SCALEABILITY OF DISPERSION EFFECTS

We have determined the differences between the DC and the small-signal transconductances and output conductances, for a number of PHEMT devices with the total gate width varying between 60 and 1200 μm. As a general rule, it has been observed that the differential DC/AC transconductances follow a straightforward

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scaling pattern, as shown in a typical example in Fig.2.a,b. However, in the case of the output conductances, the scaling pattern is found to be quite significantly different. To better represent this phenomenon, we have calculated the relative errors in estimating the differential DC/AC conductances, when straightforward scaling rules are employed, as follows:

$$g_{m,\,diff\_err} = \frac{g_{m,\,diff} - g_{m,\,diff\_sc}}{g_m} \cdot 100 \quad [\%]$$
$$g_{ds,\,diff\_err} = \frac{g_{ds,\,diff} - g_{ds,\,diff\_sc}}{g_{ds}} \cdot 100 \quad [\%] \tag{1}$$

where $g_{m,diff}$ and $g_{ds,diff}$ are the differential DC/AC conductances, while $g_{m,diff\_sc}$ and $g_{ds,diff\_sc}$ are the differential DC/AC conductances as scaled from a device of a different size. The two relative errors are compared in Fig.3. a,b for the case of an 120μm and a 300μm devices. It is seen that the relative error in the case of the differential transconductance remains generally below 3% whereas in the case of the output conductance, this error is about 6-7 times higher. Results compare in similar fashion for the other device sizes tested.

DIFFERENTIAL DC/AC DISPERSION MODELLING METHODOLOGY

Various ways have been proposed to deal with modelling the transconductance and output conductance dispersion in FETs, ranging from a simple R-C network [1], or an extra AC current source in the drain circuit [2], within the traditional equivalent circuit models, to the introduction of a correction term in the formulation of the total drain current as a line integral over the differences between DC and small-signal conductances, within the most recent look-up table-based models[3][4]. In a similar fashion, the total drain current has been defined within so-called conservative FET models [5]. Whatever the modelling approach, for a model to be physically sound, the following conservation (or integrability) condition needs to be satisfied, as previously shown in [4],[6]:

$$\frac{\partial\left(g_m(V_{gs},V_{ds}) - g_{m,\,DC}(V_{gs},V_{ds})\right)}{\partial V_{ds}} = \frac{\partial\left(g_{ds}(V_{gs},V_{ds}) - g_{ds,\,DC}(V_{gs},V_{ds})\right)}{\partial V_{gs}} \tag{2}$$

The two circuit model solutions mentioned above, although giving reasonable results in many situations, do not identically satisfy condition (2). A way to correct this, is by employing a circuit model as seen in Fig. 1, where the elements in the drain circuit are determined following a sequence of steps as described bellow:

(i) $I_{ds,DC}$ is simply determined by fitting the DC model function on the DC data;

(ii) the differences are found between the small-signal and DC transconductances;

(iii) $I_{ds,gm}$ is described by a similar non-linear function as $I_{ds,DC}$, but its parameters are determined by fitting a non-linear function of the form:

$$g_{m,\,AC}(V_{gs},V_{ds}) = \frac{\partial}{\partial V_{gs}} I_{ds,\,DC}(V_{gs},V_{ds}) \tag{3}$$

to the data calculated in step (ii);

(iv) differences are calculated between the small-signal output conductance and the output conductance determined by $I_{ds,DC}$ and $I_{ds,gm}$ combined;

(v) the non-linear conductance $g_{ds,corr}$ is determined by fitting the data determined in step (iv) to an appropriate empirical non-linear function.

(vi) the capacitor C_d, can be implemented as a non-linear element and its value can be determined from pulsed DC measurements. However, our experience shows that for the large majority of applications of practical interest, allocating a constant value to C_d is very satisfactory.

This equivalent circuit modelling solution and methodology have been implemented as part of the scaleable, general-purpose *COBRA* model for FET devices. From the modelling technique described above, it is quite clear that the scaling inconsistencies seen in the differential DC/AC output conductance, can be incorporated in our model via the additional non-linear conductance $g_{ds,corr}$, by an appropriate selection of the empirical function that describes it. As an example, we compare in Fig. 4. a,b,c, simulated (*COBRA*) and experimental small-signal parameters (*S21* and *S22*). Fig. 4. a), represents the simulation with the *COBRA* model for a 120μm PHEMT, while Fig. 4. b) and c) shows the simulations with the same model for a 300μm PHEMT, using simple scaling rules for $g_{ds,corr}$ (b), and using a separate scaling rule for $g_{ds,corr}$ (c), respectively. The improvement introduced in the latter case, particularly in *S22*, is quite obvious. In Fig. 5, model scaleability is also proved in a large-signal test, for the same two devices.

CONCLUSIONS

In this study, we have shown that accounting for the scaleability of dispersive phenomena in the modelling of microwave FETs is not trivial. Up to medium sized devices, simple scaling rules apply to most of the equivalent circuit parameters, providing that a correct and reliable parameter extraction technique is employed. However, in the case of dispersive phenomena, it appears that: a) differential DC/AC transconductance obeys, with good approximation, straightforward scaling rules; b) for differential DC/AC output conductance, such rules are no longer applicable. Such behaviour, is likely to create difficulties in most of the modelling approaches currently in use, if they are to be completed with adequate and accurate scaling features. We have presented an empirical differential DC/AC dispersion modelling methodology, which is compact, complies with the required conservation constraints, and has the flexibility to accommodate for the scaling behaviour described above.

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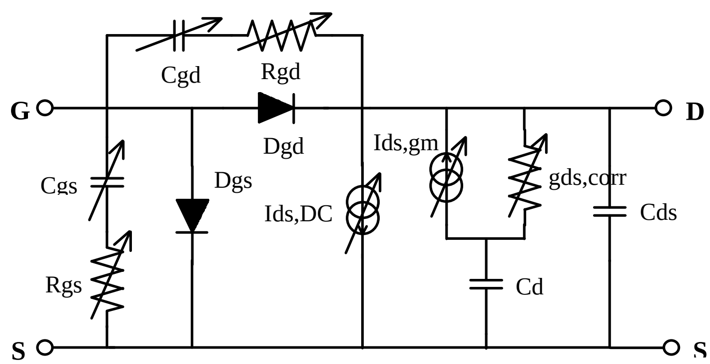
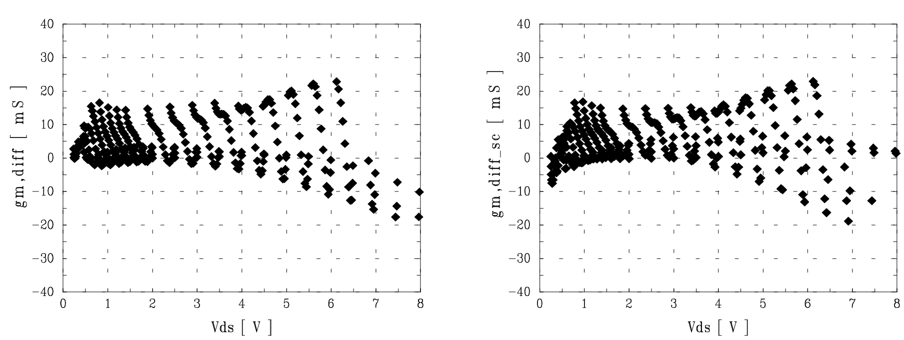
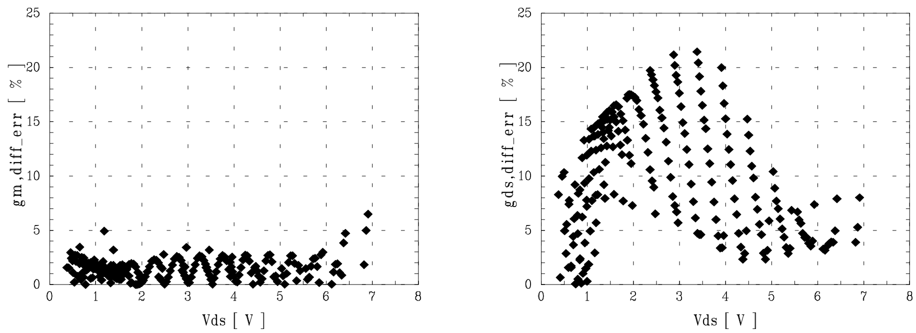


Fig. 1. Large-signal equivalent circuit model for microwave FETs including dispersion phenomena



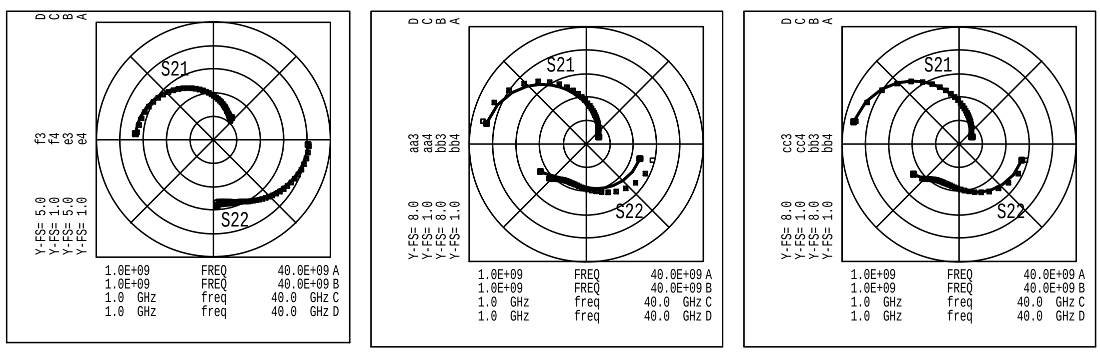
a) b)

Fig. 2. The differences between DC and small-signal transconductances for a 300μm PHEMT: **a)** as extracted directly; **b)** as scaled from a 120μm device



a) b)

Fig. 3. The relative error computed for the two differential DC/AC conductances in the case of a 300µm PHEMT, between the values determined directly and scaled from a 120µm device:
a) differential transconductance error; **b)** differential output conductance error



a) b) c)

Fig. 4. Comparison between measured and simulated S21 and S22 using *COBRA* model
a) for a 120µm PHEMT; **b)** scaled to a 300µm PHEMT (using simple scaling rules);
c) scaled to a 300µm PHEMT (using separate scaling for $g_{ds,corr}$)

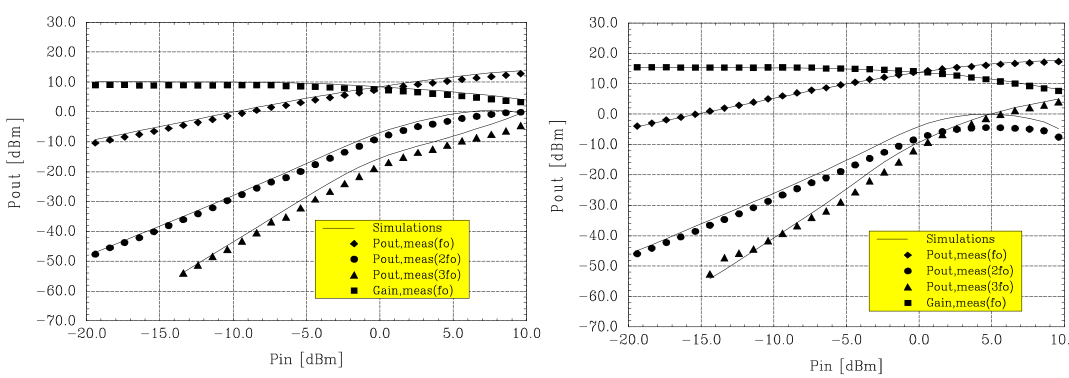


Fig. 5. Large-signal, single-tone tests using the scaleable *COBRA* model (Vgs = - 0.9V, Vds = + 6.0V)
a) for a 0.2x(4x30)µm PHEMT; **b)** scaled to a 0.2x(6x50)µm PHEMT.