A Distributed Approach for the Characterisation of Parasitic Networks in Electron Device Modelling

A.Cidronali, G.Collodi, C.Toccafondi, R.Cignani[*], A.Santarelli **, G.Vannini [*], F.Filicori**

Dept. Electronics and Telecommunications, University of Florence, V. S. Marta 3, Firenze, Italy 50139, Phone +390554796766, Fax +390554494569, e-mail acidronali@ing.unifi.it
* Department of Engineering, University of Ferrara, Via Saragat 1, 44100 Ferrara, Italy
** Department of Electronics, University of Bologna, V.le Risorgimento 2, 40136 Bologna, Italy

A new modeling approach for electron devices up to millimeter-wave frequencies is proposed. It exploits a previously proposed distributed approach with the aim of deriving a more computationally efficient model still preserving good accuracy. In particular, a new electron device model based on a "single active device" and a "distributed description of the parasitic structure" is derived, which can easily be identified through conventional scattering parameter measurements and electromagnetic simulations. Preliminary validation results are provided in the paper.

INTRODUCTION

Increasing operating frequencies and demanding bandwidth requirements in many applications of the communication area require accurate CAD tools for micro- and millimeter-wave MMIC design also in order to satisfy first-success design and low-cost constraints, Abidi (1). In this context, accurate electron device models up to millimeter-wave frequencies play a key role; however, conventional modelling approaches based on lumped equivalent circuits become inappropriate at very high frequencies where complex distributed and coupling effects strongly affect the transistor performance, Cidronali et al. (2,3).

Over the last years, different research groups have been involved in the development of comprehensive and effective analysis/design tools, often classified under the term "global modelling approaches", Cidronali et al. (2,3), Steer et al. (4), Imitaz and El – Ghazaly (5), capable of simultaneously considering several interacting circuit elements, e.g., the active and passive devices, the radiation elements and the packaging influence. Among these approaches, the small-signal electron device model presented in (2) by the authors, adopts a distributed description both for the active device area and the extrinsic structure. More precisely, it is based on a proper partitioning of the "active part" of the device in a convenient number of "internal elementary devices" (or "active slices") fed by a "passive distributed structure". The latter is characterised in terms of scattering parameters by means of an accurate electromagnetic simulation of the device layout. This kind of analysis enables the actual device geometry and material stratification, as well as losses in the dielectrics and electrodes, to be taken into account for any given device structure and size by means of a multi-port S-matrix distributed description. The model has been extensively validated for MESFET and PHEMT devices, taking also into account its scaling (2) and frequency extrapolation (3) capabilities, up to very high frequencies (110GHz).

The distributed model proposed in (2,3), although very accurate, may result computationally heavy especially when a large number of electron devices, possibly composed by many gate fingers, is included in the MMIC structure. The problem becomes even more relevant if a similar approach is applied for non-linear device modelling. In such a case, in fact, a possibly large number of "non-linear active slices" jointly with the iterative analyses required by the Harmonic Balance algorithms (involving the repeated computation of the non-linear component responses) may lead to a huge CPU effort.

In this paper, in order to overcome the above mentioned problems, a new modelling approach based on a "distributed description of the passive structure" of the device, but involving a "single active slice/device" is proposed with the main aim of obtaining a more computationally efficient model yet preserving good accuracy. The potentiality of this approach can also be justified by considering that, from a different point of view, the proposed model can be seen as a conventional equivalent circuit model where the description of parasitic effects is made in terms of a distributed network instead of lumped components, reasonably leading to higher prediction accuracy. Moreover, model scaling and frequency extrapolation can be carried out according to the procedures proposed in (1,2). Simulation and experimental results seem to confirm that the single active device distributed approach should provide good accuracy in the prediction of the device behaviour up to millimetre-wave frequencies.

THE EQUIVALENT DISTRIBUTED PARASSITIC NETWORK

Let us consider a FET, whose active area is suitably partitioned in a proper number of active slices, as shown in Fig.1a. According to the distributed modelling approach presented in (2,3), the metal passive structure interconnecting the active slices is described in terms of a multi-port scattering matrix $\underline{\mathbf{S}}$, computed by means of an accurate electromagnetic simulation on the basis of layout geometry and material parameters usually provided by the manufacturing foundry, OMMIC (6). Moreover, the same three-port scattering matrix $\underline{\boldsymbol{\beta}}_{AS}$ is assumed for all the active slices; this matrix can be identified following the procedures described in (2,3).

In order to maintain the accurate description level of the distributed approach proposed in (2,3) and at the same time to reduce the computational cost, a transformation from the actually distributed model to an equivalent compact version is derived in the paper. The transformation is based on the idea that the distribution of signals feeding the active slices can be approximated, without relevant loss of accuracy, with a mean, weighted value which depends mainly on the distributed nature of the entire metal and dielectric passive structure of the FET. This assumption, which is justified both by electromagnetic simulations and preliminary validation results, leads to the definition of an equivalent model where the passive structure multi-port description $\underline{\mathbf{S}}$ is replaced, as shown in Fig.1b, by an *equivalent* five-port scattering matrix $\underline{\boldsymbol{\chi}}$, which besides preserving the distributed description of the parasitic device network, is computationally much more efficient, since it allows for the connection of a *single equivalent active device* as normally happens in conventional modeling approaches.

By taking into account the symmetry of the device layout structure[1], a new scattering matrix $\underline{\tilde{\mathbf{S}}}$ can be defined on the basis of $\underline{\mathbf{S}}$ in such a way that:

$$\begin{bmatrix} b^G & b^D & \mathbf{b}^1 & \cdots & \mathbf{b}^N \end{bmatrix}^T = \underline{\tilde{\mathbf{S}}} \cdot \begin{bmatrix} a^G & a^D & \mathbf{a}^1 & \cdots & \mathbf{a}^N \end{bmatrix}^T \quad (1)$$

where $\mathbf{a}^i$ and $\mathbf{b}^i$ are the arrays of incident and reflected waves defined at the three ports of the *i-th* active slice and N is the number of active slices in one half of the device.

An important simplification of the distributed approach can be achieved by assuming that every active slice is equally fed by the same[2] incident wave: $\mathbf{a} = \mathbf{a}^1 = \mathbf{a}^2 = \cdots = \mathbf{a}^N$. This hypothesis is partially justified by the results presented in Fig.2, where magnitude and phase of the voltage phasors at the interconnecting sections between the active slices and the multi-port passive structure are shown for a 6x30µm GaAs PHEMT. Since a single active slice per finger has been considered here, three complex voltage phasors are shown in the figure corresponding to the sections present in one half of the symmetrical device. As can be seen, not important differences are observable either in magnitude or phase due to distributed phenomena, confirming the validity of the proposed assumption.

In this case, since all the active slices are described by the same three-port scattering matrix $\underline{\boldsymbol{\beta}}_{AS}$, the reflected waves must satisfy the condition: $\mathbf{b} = \mathbf{b}^1 = \mathbf{b}^2 = \cdots = \mathbf{b}^N$. Thus, after simple algebraic manipulation, it can be shown that equation (1) can be simplified as:

$$\begin{bmatrix} b^G & b^D & \mathbf{b} \end{bmatrix}^T = \underline{\boldsymbol{\chi}} \cdot \begin{bmatrix} a^G & a^D & \mathbf{a} \end{bmatrix}^T \quad (2)$$

where $\underline{\boldsymbol{\chi}}$ is a five-port scattering matrix defined by:

$$\begin{aligned}
&\underline{\boldsymbol{\chi}}_{i,j} = \underline{\tilde{\mathbf{S}}}_{i,j} && i,j = 1,2 \\
&\underline{\boldsymbol{\chi}}_{i,j} = \sum_{h=1}^{N} \underline{\tilde{\mathbf{S}}}_{i,3h+j-3} && i = 1,2;\ j = 3,4,5 \\
&\underline{\boldsymbol{\chi}}_{i,j} = \frac{1}{N} \cdot \sum_{h=1}^{N} \underline{\tilde{\mathbf{S}}}_{3h+i-3,j} && i = 3,4,5;\ j = 1,2 \\
&\underline{\boldsymbol{\chi}}_{i,j} = \frac{1}{N} \cdot \sum_{l=1}^{N} \sum_{m=1}^{N} \underline{\tilde{\mathbf{S}}}_{3l+i-3,3m+j-3} && i = 3,4,5;\ j = 3,4,5
\end{aligned} \quad (3)$$

The corresponding three-port matrix $\underline{\boldsymbol{\beta}}_{AS}$ of the *single equivalent active slice* (the intrinsic device) can now be obtained from the measured device S-parameters after

1 A symmetric structure is very common in most devices for high-frequency applications. However, the proposed approach can also be applied to non symmetrical devices.

2 In a more general case, suitable delays between the incident waves a^1 .. a^N could be accounted for; good results were however obtained in this preliminary work by assuming $a = a^1 = a^2 = \ldots = a^N$.

de-embedding from the obtained distributed description $\underline{\chi}$ of the parasitic network[3].

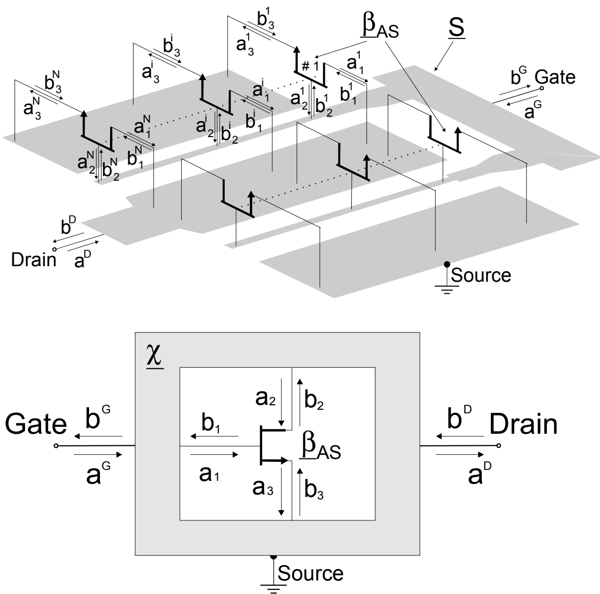


Fig.1: a) Active device partitioning in accordance with the distributed model presented in [2-3]b) equivalent "compact" model

MODEL VALIDATION

Preliminary validation of the proposed approach has been carried out by considering an OMMIC foundry 6x30um GaAs PHEMT. Accurate electromagnetic simulations of the device layout were carried out in order to characterize the passive structure of the device. One active slice per finger, for a total of six active slices, was considered in this phase. According to the procedure described above the scattering matrixes $\underline{\chi}$ and $\underline{\beta}_{AS}$ respectively for the parasitic network and the equivalent active part of the device (see Fig.1b) have been identified in the range 2-110GHz. Clearly, since the matrix $\underline{\beta}_{AS}$ is obtained through a simple de-embedding procedure from S-parameter measurements, the model composed by the matrixes $\underline{\chi}$ and $\underline{\beta}_{AS}$ exactly reproduces the original measurements. For this reason, as a preliminary validation test, the active slice description $\underline{\beta}_{AS}$ derived for the equivalent single active slice model has been used in conjunction with the distributed network including six active slices, originally characterized through electromagnetic simulations, to predict the S-parameter behavior up to 110GHz. Figure 3 shows the comparison between measured and predicted scattering parameters for four different bias conditions (Vgs=0,-0.5V, Vds=3,1.5V).

The good agreement of the data in Fig.3, together with the results in Fig.2, preliminary suggests that the model identification procedure considering a single equivalent active slice, instead of a completely distributed approach, leads to results which are practically comparable and represents a good starting point for developing a computationally efficient nonlinear distributed model.

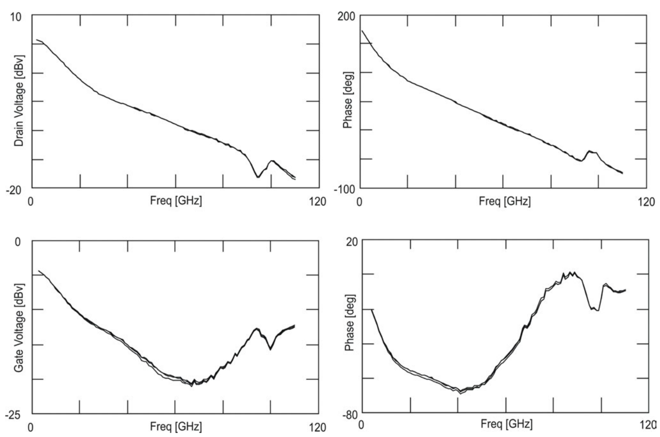
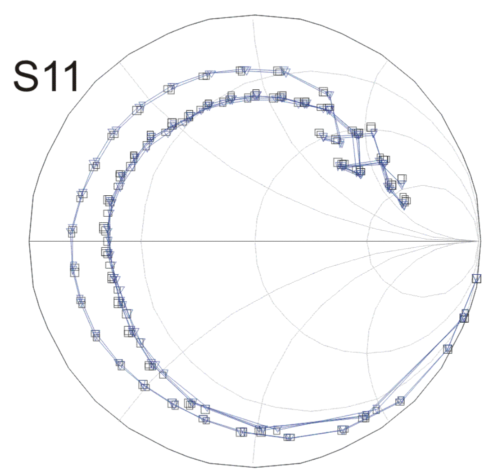
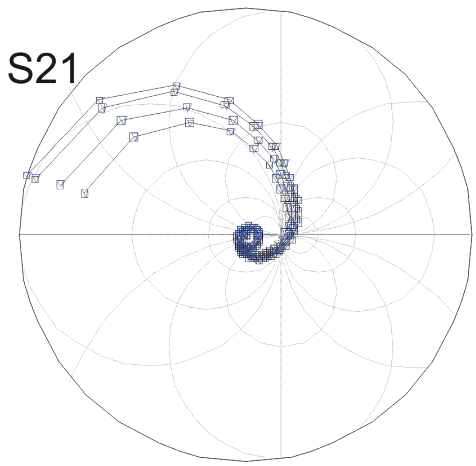


Fig. 2: Gate and drain voltage phasors (magnitude and phase) for a OMMIC foundry 6x30μm GaAs PHEMT at the interconnecting sections between the active slices and the multi-port distributed passive network (one active slice per finger). As expected, almost negligible differences are observable at the different sections.

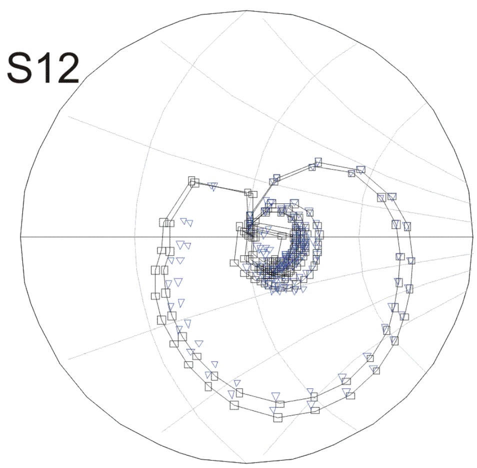


(a)

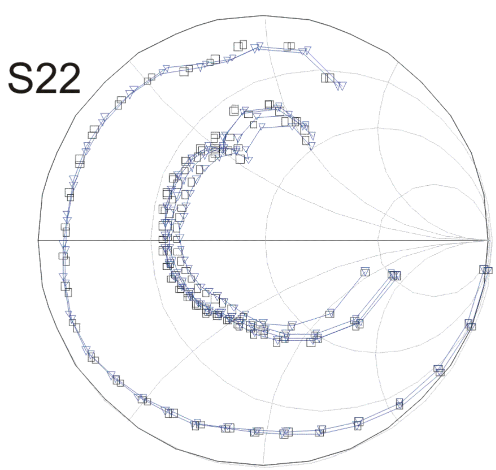
3 The existence of possibly residual parasitic effects in the equivalent active slice should be carefully evaluated for the accurate non linear modeling of the intrinsic device.



(b)



(c)



(d)

Fig.3: S-parameters of a 0,2µm gate-length, PML 6x30µm GaAs PHEMT (V_{GS}, V_{DS} biases: -0.5V,1.5V; -0.5V,3V; 0V,1.5V; 0V,3V). Measurements (symbols) vs. predictions obtained by means of the three-port scattering matrix of the "equivalent" intrinsic device connected to the multi-port distributed description of the device passive structure (lines).

REFERENCES

(1) A. Abidi, G. Pottie, W. J. Kaiser, "Power-conscious design of wireless circuits and systems", Proceeding of the IEEE, Vol.88, no. 10, Oct. 2000, pp. 1528-1545.

(2) A.Cidronali, G.Collodi, G.Vannini, A.Santarelli, G.Manes "A new approach to FET model scaling and MMIC design based on electromagnetic analysis," *IEEE Transaction. on MTT,* Vol. 47, no. 6, June 1999.

(3) A.Cidronali, G.Collodi, G.Vannini, A.Santarelli, G. Manes,' Millimeter-wave FET modeling using on-wafer measurements and EM simulation,' *IEEE Transaction on Microwave Theory and Techniques*, vol. 50, pp. 425-432, no. 2, Feb. 2002.

(4) M. B. Steer, *et al.,* "Global Modeling of Spatially Distributed Microwave and Millimeter-Wave Systems" *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 830-839, June 1999.

(5) S. M. S. Imitaz, S. M. El-Ghazaly, "Global modeling of millimeter-wave circuits: Electromagnetic simulation of amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol.45, pp. 2208-2216, Dec. 1997.

(6) OMMIC, Foundry Process ED02AH V 1.1 Design.