AN EXTRACTION PROCEDURE FOR MESFET'S AND HEMT'S NON-LINEAR MODEL DETERMINATION

A. Di Martino, S. Pisa, P. Tommasino, A. Trifiletti

Dipartimento di Ingegneria Elettronica, Università "La Sapienza", Via Eudossiana 18, I-00184, Roma, ITALY
e-mail: trifilo@csgb-hp2.ing.uniroma1.it

ABSTRACT

A complete procedure for the extraction of non-linear empirical models for MESFET's and HEMT's has been developed. The procedure requires DC and small signal S-parameters measurements to find model elements, and no cold measurements are needed for extrinsic parameters determination. The proposed procedure is able to deal with non-linear models characterised by low-frequency dispersion. The optimisation step aimed to determine the linear circuit model uses a multi-bias extraction. A software tool has been developed to check the algorithms and average errors of 4.8% for DC drain current and 8.4% for S-parameters have been obtained up to 50GHz for a P-HEMT from PHILIPS PML-D02AH monolithic process.

INTRODUCTION

The design of microwave monolithic integrated circuits requires device models which have to fit measured data in different working regions and accurately describe circuit behaviour. Non-linear empirical models for MESFET were found and implemented in commercial time domain and HB simulators by Curtice and Ettemberg (1), Materka and Kacprzak (2), and Statz et al (3). In recent years, several empirical large-signal models for MESFET's and HEMT's have been developed in order to allow circuit design within CAD tools, by Angelov et al (4)-(5), Shirakawa et al (6), Tanimoto (7). The previous extraction techniques of MESFET's and HEMT's large-signal models, require a preliminary linear model extraction. Corbella et al (8) presented a formal approach to obtain a non-linear model from small signal measurements, by considering compatibility between the large-signal model and the linear model. Usually, additional measurements are required to determine the extrinsic elements (i.e. not bias-dependent) of the linear model by using the "cold-FET" method. Recently a new technique has been proposed by Shirakawa et al (9) in order to develop a single-bias point linear equivalent circuit. This technique allows to obtain frequency independent intrinsic parameters, without the use of further measurements to determine extrinsic elements.
In this paper a complete extraction procedure of an empirical non-linear model for HEMT's and MESFET's is presented, which makes use of a new multi-bias model extraction procedure. The non-linear model is obtained following this approach: firstly, a complete set of linear models characterised by the same extrinsic parameters, is found by using the measured S-matrices set. The fitting of the DC part of the model to the DC measurements is obtained, then the parameters of the RF part of the model are optimised by taking into account of the DC part of the model.
The extraction procedure presented in (9) is discussed in order to use it in the extraction process of a multi-bias linear model. The multi-bias linear model has to be composed by an extrinsic not bias-dependent part, and an intrinsic bias-dependent section. Moreover, all the components have to fit measurements in the whole frequency range of validity, but have to be not frequency-dependent. Criteria of multi-bias model validity are stated, and an improvement is proposed which allows to obtain the extraction of extrinsic circuit parameters by involving measured S-parameters at several bias points chosen in different device working regions.
The measured DC and S-parameters up to 50GHz of a P-HEMT from PHILIPS PML-D02AH monolithic process have been used to drive the optimiser and check the overall model extraction process.

EXTRACTION PROCEDURE

The non-linear model presented in Fig. 1 has been chosen to represent DC and RF behaviours, because of its compatibility, as it was stated in (8), with the commonly used linear models for HEMT's and MESFET's. Some elements in the model (Cgs, Cgd, Cds, Ids_{DC}, Ids_{RF}, and Ri) are considered to be bias-dependent, all the others are linear. Ids_{DC} is the DC drain-source current source and Ids_{RF} is a high-frequency correction of the DC source Ids_{DC}: two Ids current sources have been used to take into account of the low-frequency dispersion of transconductance and output conductance, which significantly affects device characteristics. The capacitors Cgs, Cgd, and Cds model the non-linear gate-source and gate-drain charge accumulations. The effects of forward biasing of gate-source and gate-drain junctions have not been taken into account.
An extraction algorithm has been developed in order to determine each of the model elements, starting from the measured total DC drain current and the S-parameters at several bias points. No additional measurements (i.e. cold measurements) are needed.

A certain number of fitting process steps, as described in the flow-diagram shown in Fig. 2, are required in order to determine model elements:

-i) A multi-bias linear circuit extraction is performed. Firstly, the extrinsic part composed by bias independent circuit elements, is derived by using S-parameters measurements at different bias points. Then, a complete multi-bias linear circuit composed by a set of vectors is determined, each vector containing the values of a circuit element calculated at all bias points.

-ii) DC Ids_{DC} current source parameters are determined by fitting Angelov empirical function reported in (5) (eqs. 1-2) to static measured data.

-iii) The non-linear RF-compatible model is composed by using a set of empirical functions, one for each of the bias-dependent model elements. Parameters of each function are extracted one by one by means of a further optimisation step.

A single procedure has been developed which allows the implementation of each of the previous optimisation steps. The basic optimisation step consists of two cascaded blocks: the Simulated Annealing (SA) technique described by Rutenbar (10) and used by Vai et al (11), and by Bilbro et al (12) for microwave devices modelling, and a further gradient-based optimisation step have been used to produce the final solution.

A software tool has been developed to achieve the desired output (i.e. single-bias linear circuit, multi-bias linear circuit, non-linear circuit), starting from DC and multi-bias S-parameters measurements. The algorithms and the extraction procedure have been checked by evaluating errors obtained on measured DC Ids current and S-parameters up to 50GHz, for a P-HEMT from PHILIPS PML-D02AH monolithic process.

LINEAR MODEL EXTRACTION

The small-signal equivalent circuit used in the extraction procedure is presented in Fig. 3. It is fully compatible with the non-linear equivalent circuit presented in the previous section and is simply deduced by the non-linear circuit, for frequencies much greater than $F_{tr}=(2\pi R_{tr}C_{tr})^{-1}$, by considering gm and gds as given by the sum of DC and RF contributions:

$$gm(Vgsi, Vdsi) = \partial\, Ids_{DC} / \partial Vgsi + \partial\, Ids_{RF} / \partial Vgsi; \quad (1)$$

$$gds(Vgsi, Vdsi) = \partial\, Ids_{DC} / \partial Vdsi + \partial\, Ids_{RF} / \partial Vdsi; \quad (2)$$

where Vgsi, Vdsi refer to intrinsic parameters as shown in Fig. 1.

The algorithm presented in (9) is used to determine element values of linear equivalent circuit, with modifications in order to adapt it to the development of a linear model oriented to a multi-bias extraction. This algorithm performs both intrinsic and extrinsic circuit determination for a single bias point. Analytical expressions are used in order to perform intrinsic parameters calculation, as functions of extrinsic parameters and frequency, starting from measured S-parameters.

We have checked this extraction procedure to obtain a multi-bias linear model, with measured S-parameters from 1GHz up to 50GHz of a multi-finger P-HEMT from PHILIPS PML-D02AH monolithic process. Three validation criteria have been taken into account for multi-bias model checking: firstly, the extrinsic parameters set has to be independent from the bias point; then, the elements of intrinsic model have to show small frequency dispersion at each bias point; finally, the multi-bias linear model extracted by using the extrinsic model, have to exhibit low S-parameters errors.

A certain number of sets of extrinsic parameters at different bias points in all HEMT's working regions have been extracted; then, for each of the extrinsic parameter sets, the intrinsic parameters of the multi-bias linear circuit have been calculated. As a first result, we have found that the extrinsic parameters showed strong dependency from the bias point. In Tab. 1 the values of extrinsic parameters extracted for three different bias points are reported. Moreover, high errors have been found for S-parameters in the HEMT's working regions far from the bias point used for the extrinsic parameters extraction. No significant difference has been found in intrinsic parameters frequency dispersion.

Therefore we have modified the basic algorithm in (9) in order to improve the multi-bias equivalent circuit performance. In the modified procedure, the extraction of extrinsic parameters is performed inserting in the error function reported in eq. 16 of (9), the data related to several different bias points. A single set of extrinsic parameters is used in the cost function, and so the first validation criterion is satisfied.

In Tab. 2 the mean percentage error of S-parameters calculated on 270 bias points and in the bandwidth 1-50GHz, is reported for the multi-bias linear circuit obtained using three bias points, and only each of them. A mean percentage error for S-parameters slightly lower and much more uniform in the whole saturation working region is obtained. This result has been obtained starting from three bias points chosen respectively in the deep saturation region, in the linear region, and in the "knee" region of Ids-Vds characteristics.

NON-LINEAR MODEL EXTRACTION AND VERIFICATION

A set of empirical functions has been chosen to perform fitting of the static Ids_{DC} current source to DC measurements, and of the six non-linear RF circuit elements Cgs, Cgd, Cds, $gds_{RF} = \partial\, Ids_{RF} / \partial Vdsi$, $gm_{RF} = \partial\, Ids_{RF} / \partial Vgsi$, and Ri to corresponding vectors of the multi-bias circuit.
Three different analytical functions presented in the literature (4)-(7), have been checked in order to choose the expression for Ids_{DC} fitting, and finally Angelov expression has been used and a medium percentage error of 4.8% has been obtained.
Fitting of gm_{RF} and gds_{RF} functions has been performed by using partial derivatives (with respect to Vgsi for gm_{RF} and to Vdsi for gds_{RF}) of Angelov function. Two distinct optimisation steps have been performed for gm_{RF} and gds_{RF} fitting, with two independent fitting parameters sets.
Shirakawa charge function Q(Vgs,Vds), reported in eqs. 1-2 of (6), has been modified to obtain a better fitting in Cgs, Cgd, Cds functions. Charge function and fitting capacitance expressions, used in the present work, are the following:

$$Q(Vgs,Vds)= Q_o\, ((1{,}5 + \tan^{-1}(Vj))\, Vj - 0{,}5 \ln(1 + Vj^2))/(|Kd| + \exp(\delta\, Vds)) \quad (3)$$

$$Vj= \gamma_o + \gamma\, (Vg + \alpha\, (1+Vg^2)^{1/2} - Vds\, K1 + \beta\, (Vds^2 + |K2|)^{1/2}) \quad (4)$$

$$Vg = Vgs - Val \quad (5)$$

$$Cgd = \partial Q(Vgs,Vds) / \partial Vgd \quad Cgs =\partial Q(Vgs,Vds) / \partial Vgs \quad Cds = \partial Q(Vgs,Vds) / \partial Vds \quad (6)$$

where three distinct optimisation steps have been performed for capacitors fitting, with three independent fitting parameters sets. Finally, a power series expression has been used for the fitting of non-linear resistor R_i.
The non-linear model has been checked by using measured S-parameters from 1GHz up to 50GHz of the multi-finger P-HEMT PH4x15 from PHILIPS PML-D02AH monolithic process. A linearised RF circuit has been extracted from non-linear model at 270 different bias points and S-parameters have been calculated and compared to measurements for each linear circuit. An average error of 8.4% has been obtained for the fitting of measured S-parameters from 1GHz up to 50GHz. In Fig. 4 the S-parameters measured and calculated from the non-linear model, linearised in some bias points are reported for the device PH4x15.

CONCLUSION

An empirical non-linear model for MESFET's and HEMT's and an extraction procedure based on a multi-step optimisation algorithm, have been presented. A single-bias point linear equivalent circuit extraction technique has been extended to multi-bias circuit fitting. A software tool has been developed and checked on measured data of a multi-finger P-HEMT PH4x15 from PHILIPS PML-D02AH monolithic process up to 50GHz, and average errors of 4.8% for DC drain current and 8.4% for S-parameters have been obtained.

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Bias point	Rg(Ω)	Rs(Ω)	Rd(Ω)	Lg(H)	Ls(H)	Ld(H)	Cpg(F)	Cpd(F)	Cdc(F)
Vgs=-0.5, Vds=2.8	5.5E-4	4.4E-3	4.1E-2	3.2E-11	3.6E-14	3.5E-11	4.9E-17	3.1E-18	4.2E-18
Vgs=0.1, Vds=1.2	1.5E-4	1.6E-4	3.5	3.1E-11	6.2E-15	3.0E-11	7.8E-18	5.2E-19	4.2E-18
Vgs=0.3, Vds=0.8	2.5	7.9E-4	1.15	2.1E-11	1.9 E-14	2.8E-11	5.4E-17	1.4E-17	4.6E-17

Tab. 1 Extrinsic parameters extracted for three different bias points.

Bias point	**Err_{S11}(%)**	**Err_{S12}(%)**	**Err_{S21}(%)**	**Err_{S22}(%)**	**Err_{TOT}(%)**
Vgs=-0.5, Vds=2.8	2.9	5.0	8.9	11	6.9
Vgs=0.1, Vds=1.2	2.7	5.1	9.0	9.3	6.5
Vgs=0.3, Vds=0.8	2.0	5.9	11.8	11.6	7.8
Three bias points	3.6	4.9	6.5	7.9	5.7

Tab. 2 Mean percentage error of S-parameters calculated on 270 bias points for the multi-bias linear circuit obtained with three bias points, compared with the one obtained from a single bias point.

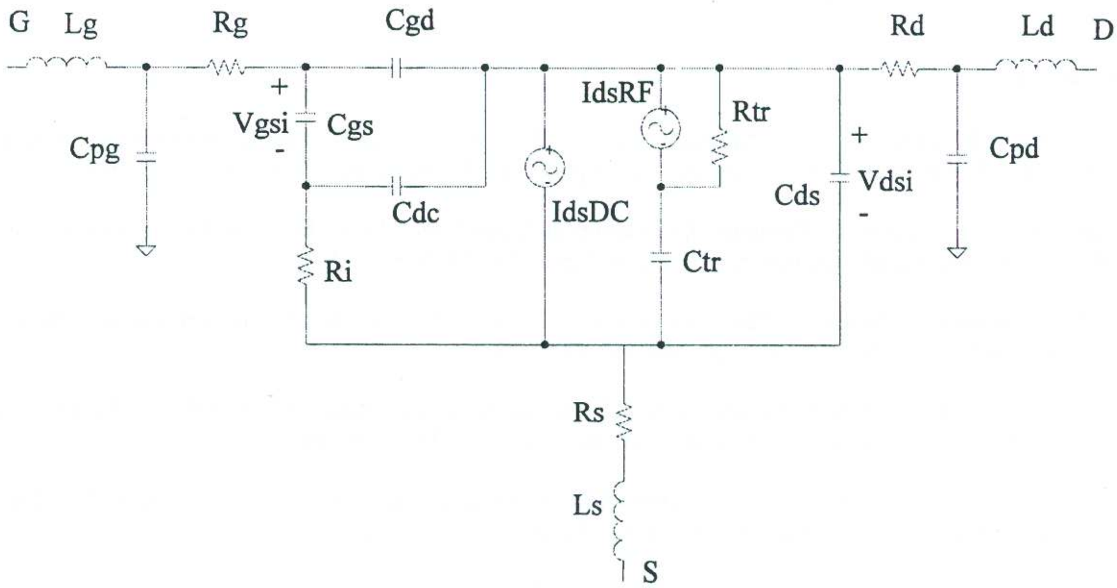

Fig. 1 Non-linear equivalent circuit of MESFET's and HEMT's.

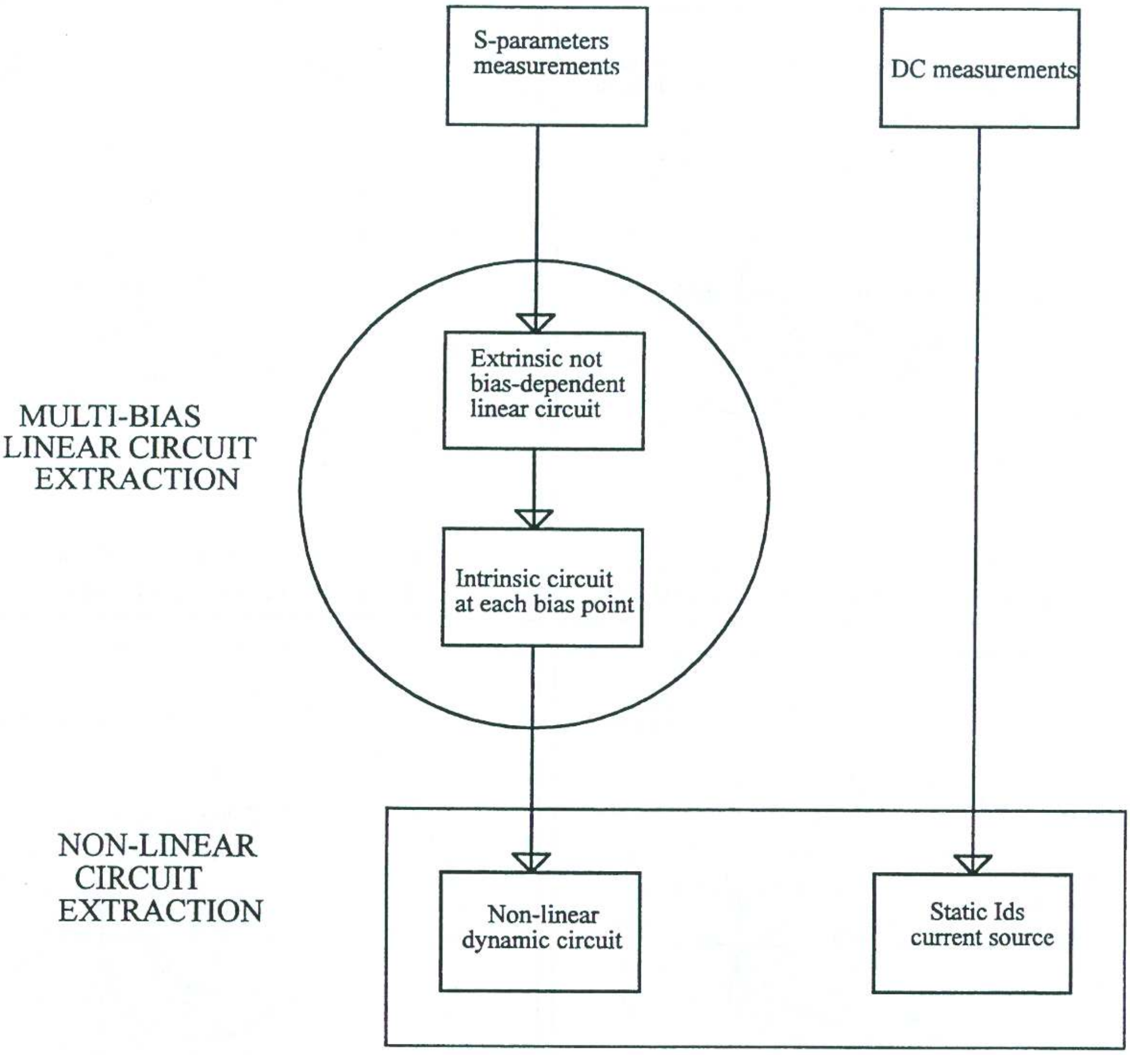

Fig. 2 Flow-diagram of non-linear circuit extraction procedure.

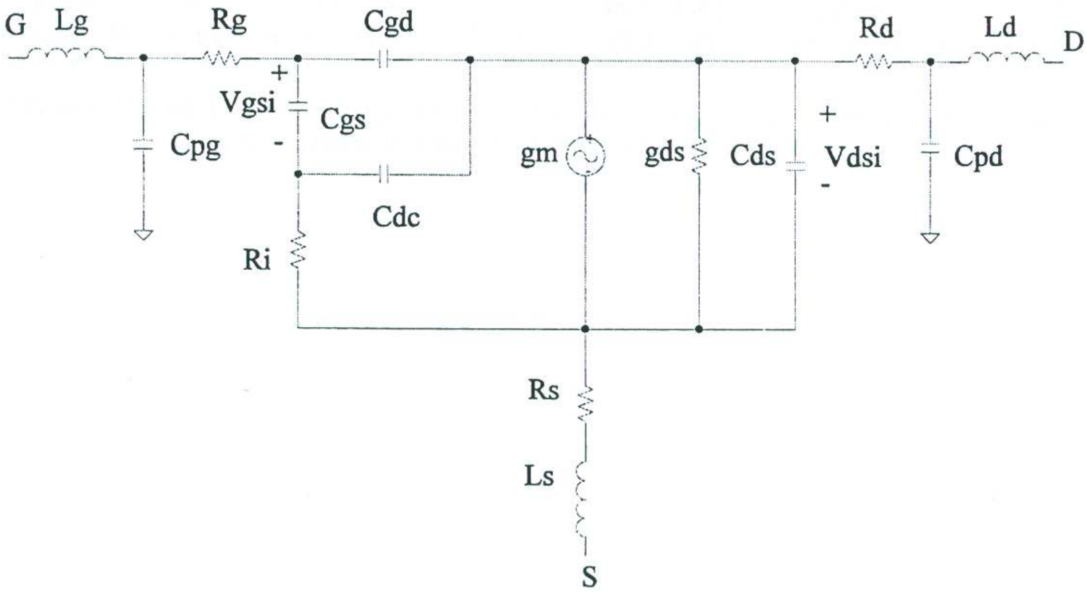

Fig. 3 Small signal model used to fit MESFET's and HEMT's measurements.

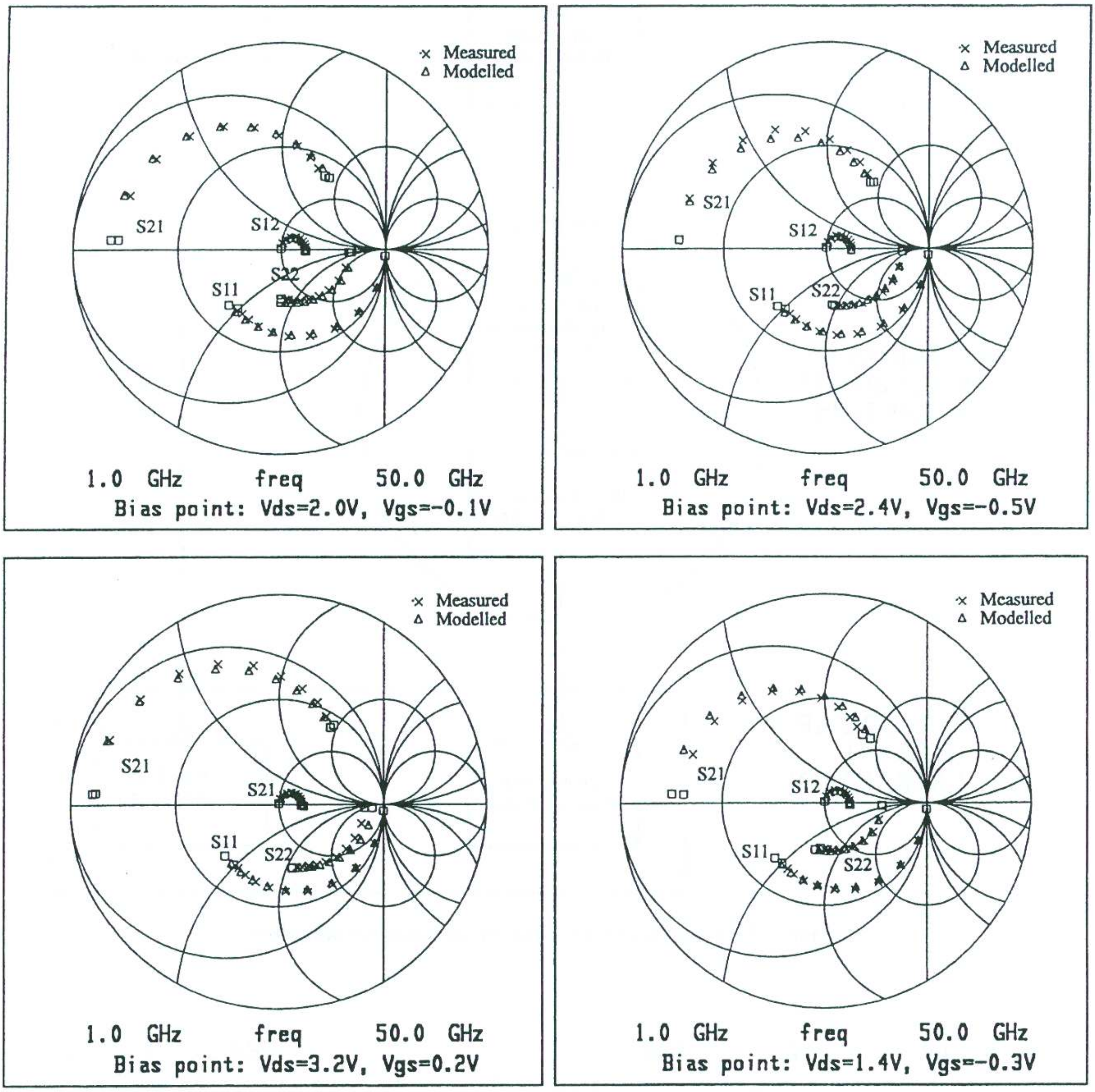

Fig. 4 S-parameters measured and calculated from the non-linear model for the P-HEMT PH4x15 from PHILIPS PML-D02AH monolithic process, linearised at different bias points.