Requirements of a large-signal HEMT model with regard to non-linear MMIC design

D. Schreurs, B. Nauwelaers, W. De Raedt* and M. Van Rossum*
K.U.Leuven, Div. ESAT-TELEMIC, Kard. Mercierlaan 94, B-3001 Leuven, Belgium
* IMEC, Div. ASP/CSP, Kapeldreef 75, B-3001 Leuven, Belgium

Abstract

The most important requirement on large-signal HEMT models, for use in non-linear MMIC design, is a high accuracy of the I_{ds}-curve and this at least up to the third order derivative near pinch-off. The existing large-signal HEMT models can't model this accurately. Therefore, we will propose a modified Angelov model.

I. Introduction

Today, HEMTs have proven to be the optimum devices for low-noise, millimetre wave applications. The use of these devices in non-linear applications, presently less developed, is an issue of importance, due to the increasing demand of MMIC-integration of non-linear millimetre wave applications. For these applications MESFETs are not applicable because of their limited frequency range. However, while the characterisation of the non-linear behaviour of these devices is well established, the characterization of HEMTs is still in its infancy.

Therefore, we will start this paper by stating the requirements of a large-signal HEMT model to be used in non-linear MMIC design. In relation to these requirements, different existing large-signal HEMT models will be compared. The investigated devices are pseudomorfic AlGaAs/InGaAs HEMTs. To conclude, we will briefly outline the modelling of the large-signal behaviour of InP based HEMTs.

II. Requirements of large-signal models with regard to non-linear circuit design

The operation of the non-linear MMICs is based on the generation of harmonics, e.g. mixers and frequency doublers. We will not pay attention to power applications. The most important requirements for large-signal HEMT models are:

1. possibility of implementation in commercial non-linear circuit simulators;
2. accurate prediction of harmonics;
3. modelling of intermodulation distortion: higher order derivatives have to be included.

A first requirement is the possibility to implement the large-signal model in commercial non-linear circuit simulators. Therefore all mathematical expressions should only contain simple functions with a short evaluation time. This is important because the most appropriate analysis tool to design non-linear MMICs is harmonic balance analysis, which requires a lot of iterations. For this reason, physical models and database-models will not be considered.

In our opinion, the most important requirement to model this kind of circuits is the accurate prediction of the harmonics. For most applications, these are generated by biasing the HEMT near pinch-off. This implies a high accurary in this bias region, not only of the I_{ds} versus V_{gs} and the g_m versus V_{gs} curves, but also of the higher order derivatives. Maas [1,2] has shown that there exists a direct relationship between the order of the derivative and the coefficients of the Volterra series expansion. This implies that in order to model the intermodulation distortion, at least up to the third derivative has to be taken into account [3].

Fig. 1 shows the measured intrinsic I_{ds}-curve and its higher order derivatives of a 0.2 μm pseudomorphic AlGaAs/InGaAs HEMT, scaled to 1 mm width.

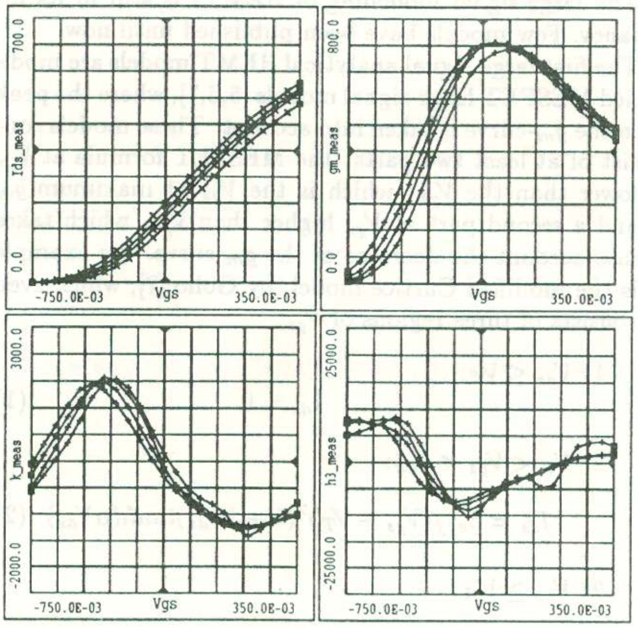

Fig. 1: Measurements of the intrinsic I_{ds} [mA/mm] and its first (g_m [mS/mm]), second (k) and third ($h3$) order derivatives of a 0.2 μm GaAs PHEMT at different external V_{ds} biaspoints (0.5 V, 1 V, 1.5 V and 2 V).

To obtain this intrinsic I_{ds}-curve, we extracted the small-signal equivalent scheme at different bias points. To circumvent the problem of charge conservation, we developed an adapted small-signal equivalent scheme [4]. By integrating the g_m with respect to V_{gs}, the intrinsic I_{ds}-

curve is calculated.

It is important to distinguish the intrinsic and external terminal voltage V_{ds}. The intrinsic V_{dsi} is calculated by taking into account the voltage drop over the parasitic resistances R_s and R_d. The external applied and intrinsic gate terminal voltage V_{gs} are equal due to the very low I_{gs}. Fig. 2 shows the intrinsic terminal voltage V_{dsi} versus V_{gs} at different external V_{ds}. As V_{gs} increases, I_{ds} increases and the difference between V_{ds} and V_{dsi} becomes greater. This implicates that the intrinsic I_{ds} versus the intrinsic V_{dsi} is not a straight vertical line, like I_{ds} versus V_{ds} is.

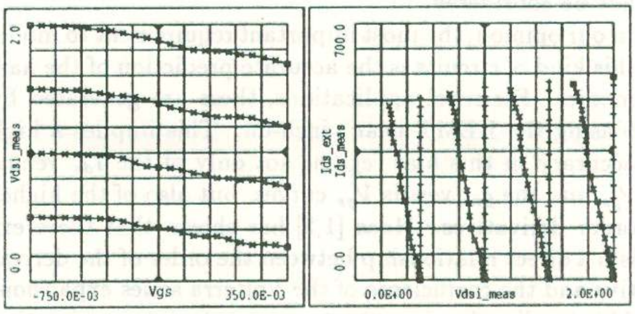

Fig. 2: left: intrinsic V_{dsi} vs V_{gs} at different V_{ds}, right: I_{ds} (x) vs the intrinsic V_{dsi} and I_{ds} (+) vs the extrinsic V_{ds}.

III. Comparison of large-signal HEMT models

The large-signal modelling of HEMTs is still in its infancy. Few models have been published until now.

The first large-signal analytical HEMT models are modified MESFET large-signal models [5,6,7], where the peak in the g_m-curve is taken into account. These models consist of at least two parts: the MESFET formula at V_{gs} lower than the V_{pk}, which is the V_{gs} at maximum g_m and a second part at V_{gs} higher than V_{pk}, which takes into account the decrease of the g_m-curve. An example is the modified Curtice model, by Golio [7], which even consists of three regions of V_{gs}:

1. $V_{gs} \leq V_T$:
$$I_{ds} = 0 \tag{1}$$
2. $V_T < V_{gs} < V_{pk}$:
$$I_{ds} = \beta_{eff}(V_{gs} - V_T)^2(1 + \lambda V_{ds})tanh(\alpha V_{ds}) \tag{2}$$
3. $V_{gs} \geq V_{pk}$:
$$I_{ds} = \beta_{eff}(V_{gs} - V_T)^2(1 + \lambda V_{ds})tanh(\alpha V_{ds}) - \frac{\xi}{(\Psi + 1)}(V_{gs} - V_{pk})^{\Psi+1}(1 + \lambda V_{gs} V_{ds})tanh(\alpha V_{ds}) \tag{3}$$

These models fail on the first requirement stated above, because at least two distinct regions in the V_{gs} range have to be considered. In our opinion, it is better to use one analytical formula, which has continual higher order derivatives, over the whole V_{gs} range.

A model, fulfilling this condition is the model of Angelov [8], which is in fact a series expansion at maximum g_m. The formula for I_{ds} is:

$$I_{ds} = I_{pk}(1 + tanh(\Psi))(1 + \lambda V_{ds})tanh(\alpha V_{ds}) \tag{4}$$

with

$$\psi = P_1(V_{gs} - V_{pk}) + P_2(V_{gs} - V_{pk})^2 + P_3(V_{gs} - V_{pk})^3 + \ldots \tag{5}$$

This formula doesn't explicitly take into account the dependence of the intrinsic V_{dsi}. Fig. 3 shows that a closer fit of I_{ds} is obtained at higher V_{gs}, when the V_{dsi} dependence is taken into account.

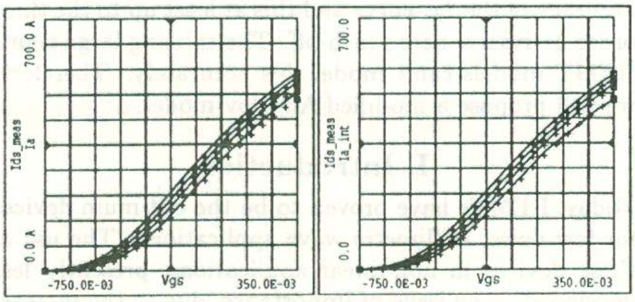

Fig. 3: Comparison of I_{ds} vs V_{gs} at different V_{ds}. +: measurements, left: Angelov model, right: Angelov model, taking into account V_{dsi} dependence.

A disadvantage of this model is that a low accuracy is obtained near pinch-off, even with a lot of terms in the series expansion. A good fit can only be obtained by giving in on the accuracy of the model near V_{pk}. Fig. 4 shows the g_m-curve versus V_{gs} at different V_{ds} using a five term series approximation for Ψ. Optimizing the absolute error (Fig. 4: left) a rather poor fit is obtained near pinch-off. Optimizing the procentual error (Fig. 4: right) a good fit is obtained near pinch-off, but the accuracy near V_{pk} is deteriorated.

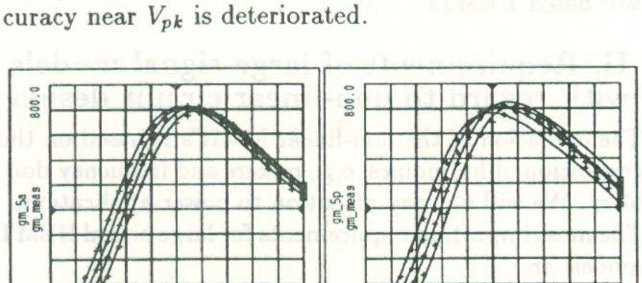

Fig. 4: g_m [mS/mm] vs V_{gs} at different V_{ds}, using a five order term approximation of Ψ. +: measurements, left: optimized absolute error, right: optimized procentual error.

We propose a modified Ψ formula:

$$\psi = P_1(V_{gs} - Vpk) + P_2(V_{gs} - V_{pk})^2 + P_3(V_{gs} - V_{pk})^3 + \ldots - \frac{D_1}{V_{dsi}}\exp(-D_2(V_{gs} - V_T)) \tag{6}$$

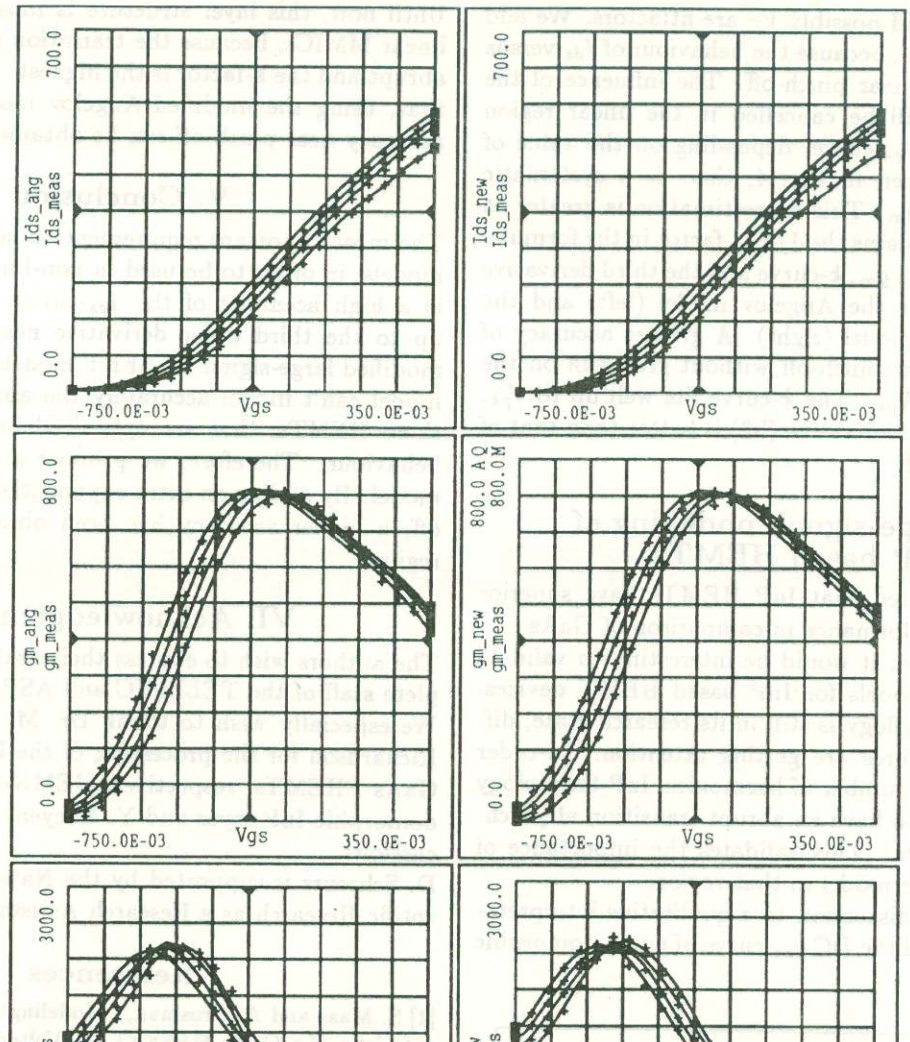

Fig. 5: I_{ds} [mA/mm], g_m-curve [mS/mm], k-curve and the third derivative (h3) vs V_{gs} at different V_{ds} of a 0.2 μm pseudomorphic GaAs HEMT. +: measurements, left: Angelov model, right: new proposed model.

whereby D_1, D_2 and possibly V_T are fitfactors. We add an exponential term, because the behaviour of I_{ds} versus V_{gs} is exponential near pinch-off. The influence of the additional term will be cancelled in the linear region of the I_{ds} versus V_{gs}-curve, depending on the value of D_2. As can be seen in Fig. 4, there is a systematic overestimation of g_m. This overestimation is greater at lower V_{ds}. This explains the $1/V_{dsi}$ factor in the formula. Fig. 5 shows the I_{ds}, g_m, k-curve and the third derivative (h3) versus V_{gs} for the Angelov model (left) and the modified Angelov model (right). A greater accuracy of g_m is obtained near pinch-off without giving in on the performance near V_{pk}. The k-curve fits well up to V_{pk}. The fit of the third derivative (h3) is better than that of the Angelov model.

IV. Large-signal modelling of InP based HEMTs

Recently, it is stated that InP HEMTs have superior noise and gain performance in comparison of GaAs HEMTs. Therefore, it would be interesting to validate the large-signal models for InP based HEMT devices. Because this technology is still in its research state, different layer structures are getting attention. In order to get the highest number of harmonics, InP technology can be optimized to have an abrupt transition at pinch-off in the g_m-curve. This validates the importance of having an accurate model in that region.
We will limit our discussion to a qualitative interpretation of the shape of the DC g_m-curve of a pseudomorphic InP layer (Fig. 6). Until now, this layer structure is most suited for non-linear MMICs, because the transition at V_T is the most abrupt and the k-factor is the highest. This figure shows that, using the modified Angelov model, a very good accuracy near pinch-off can be obtained.

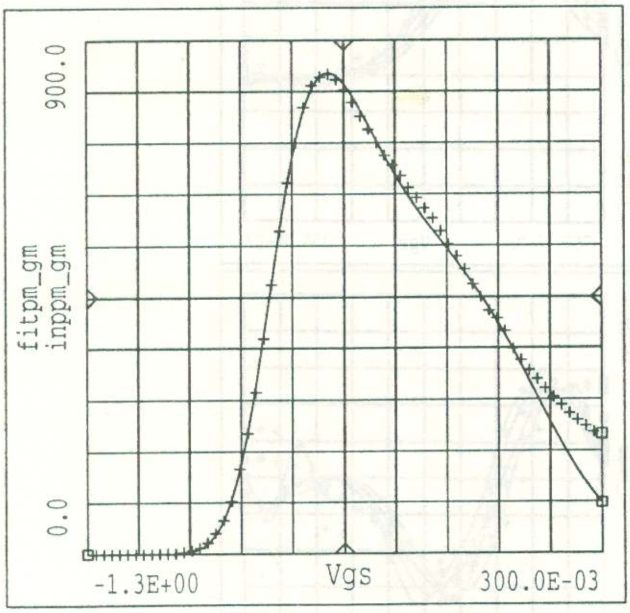

Fig. 6: g_m [mS/mm] vs V_{gs} at V_{ds}=1.5 V for a 0.2 μm pseudomorphic (pm) InP HEMT. +: measurements, solid line: fit using the modified Angelov model.

V. Conclusion

The most important requirement on large-signal HEMT models, in order to be used in non-linear MMIC design is a high accuracy of the I_{ds}-curve and this at least up to the third order derivative near pinch-off. The modified large-signal MESFET models and the Angelov model can't model accurately the abrupt transition in those HEMTs, that are optimized for their non-linear behaviour. Therefore, we propose a modified Angelov model. By adding an extra exponential term near pinch-off, a higher accuracy has been obtained in this V_{gs}-region.

VI. Acknowledgements

The authors wish to express their gratitude to the complete staff of the TELEMIC and ASP/CSP group.
We especially wish to thank Dr. M. Van Hove and P. Richardson for the processing of the InP PHEMTs and GaAs PHEMTs, respectively, IEMN-Lille for the pseudomorphic InP layer and Y. Baeyens for his useful discussions.
D. Schreurs is supported by the National Fund for Scientific Research as a Research Assistant.

References

[1] S. Maas and A. Crosmun, "Modeling the Gate I/V Characteristic of a GaAs MESFET for Volterra-Series Analysis", MTT Vol. 97, No. 7, 1989
[2] S. Maas and D. Neilson, "Modeling MESFET's for Intermodulation Analysis of Mixers and Amplifiers", MTT Vol. 38, No. 12, 1990
[3] S. Maas, "How to Model Intermodulation Distortion", MTT-S, 1991
[4] Ph. Jansen, D. Schreurs, W. De Raedt, B. Nauwelaers and M. Van Rossum, "Consistent Small-Signal and Large-Signal Extraction Techniques for Heterojunction FETs", in press in IEEE Trans. Microwave Theory and Tech.
[5] M. Golio, "Microwave MESFETs and HEMTs", Artech House, 1991 [6] M. Miller, M. Golio,B. Beckwith, E. Arnold, D. Halchin, S. Ageno, S. Dorn, "Choosing an Optimum Large Signal Model for GaAs MEFETs and HEMTs", IEEE MTT-S, 1990
[7] J. Staudinger, M. Miller, M. Golio, B. Beckwith and D. Halchin,"An accurate HEMT Large Signal Model Usable in SPICE Simulators", MTT-S, 1991.
[8] I. Angelov, H. Zirath and N. Rorsman, "A New Empirical Nonlinear Model for HEMT and MESFET Devices", IEEE Trans. on MTT, Vol. 40, 1992.