Identification of a Strongly Nonlinear Device Compact Model Based on Vectorial Large Signal Measurements

M. Camprini, A. Cidronali, C. Accillaro, I. Magrini, G. Loglio, G. Collodi, J. Jargon[1], G. Manes

Dept. Electronics and Telecommunications, University of Florence, V.S. Marta 3, Firenze,
Italy 50139, Phone +390554796369, Fax +39055494569, e-mail acidronali@ing.unifi.it
[1]National Institute of Standards and Technology, Boulder, CO 80305 USA

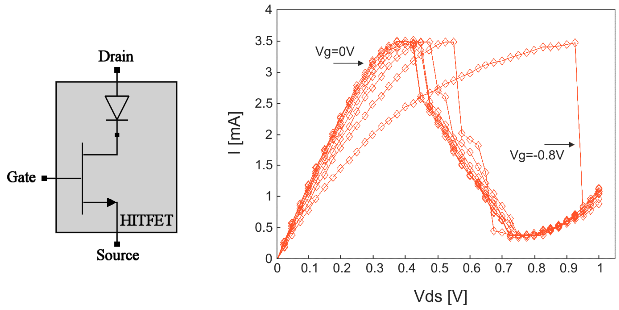
***Abstract* - This paper deals with the identification of equivalent circuit models for strongly nonlinear devices by taking advantage of the so-called "Vectorial Large-Signal Measurements". A very specific device, the Heterojunction Interband Tunneling FET (HITFET), has been selected as case of study for its peculiar nonlinear behavior. A comprehensive description of the identification is given along with a number of experimental results. In particular, the comparison between simulated and measured data for different power levels and frequencies from the set adopted during the identification confirms the extrapolation capability of the approach.**

I. INTRODUCTION

Modeling of microwave devices and circuits has seen a continuous effort aimed to follow the huge technological development. Among the various solutions available in literature, behavioral modeling and compact modeling are the most developed approaches due to their characteristics of effectiveness and easiness of implementation in a conventional CAD environment. In a behavioral model the description is generally provided in terms of state functions, which are commonly determined processing small-signal and DC measurements. Recently new techniques based on Vectorial Large Signal (VLS) measurements have been proposed to identify and validate such class of models [1],[2]. These models, in order to provide a meaningful interpolative capability, must be identified in a broad range of possible device functional states and usually their predictive capability is matter of concerns. Compact model approaches are based on the definition of an equivalent circuit. They represent a valid solution when the device physics is sufficiently simple or sufficiently understood to allow its translation in terms of controlled charge and current sources. In this case the identification process does not follow an established protocol, anyway, once the compact model parameters are successfully extracted, the model validity range can be extended to a wide range of functional states. This paper is aimed to demonstrate how the additional information deriving from VLS measurements can be used in the field of equivalent circuit model identification for strongly nonlinear devices. A device able to exhibit a very peculiar characteristic, the Resonant Interband Tunneling Diode, has been chosen as a case of study. The identification procedure is presented along with several experimental results in order to provide the potentialities of the technique.

II. THE QUANTUM MICROWAVE MONOLITHIC INTEGRATED CIRCUIT TECHNOLOGY

The device technology adopted in this paper has been developed for low-power microwave applications [3]-[5], whose description is beyond the aim of this paper. The Heterojunction Interband Tunneling FET (HITFET) is a three terminal device obtained by integrating a Heterojunction Interband Tunneling Diode (HITD) on the drain of a conventional P-HEMT as shown in Figure 1.a.



(a) (b)

Fig.1: HITFET schematic (a) HITFET's I\V characteristic for V_g spanning from 0 to -0.8V in 100 mV steps (b).

The embedded P-HEMT acts as a series load controlled by the DC voltage applied to the Gate Terminal. The Current–Voltage, characteristics of a HITFET in a common Source configuration for a Gate Bias spanning from 0 V to –0.8V is shown in Figure 1b. The right shift in the static IV curve is due to the increasing HEMT's channel resistance for a decreasing Bias applied to the Gate (see [4] for more details).

III. HITFET VECTORIAL LARGE SIGNAL CHARACTERIZATION

In order to show the HITFET large-signal properties, the device has been characterized using a Non Linear Network Analyzer (NVNA). The NVNA consists of a 4-channel data acquisition system and provides magnitude and phase values of the incident and reflected waves at both ports of the device on a user-defined grid [6]. The measurement setup is represented in Figure 2; a large signal is applied to the DUT using only the port 2 of the NVNA, being port 1 properly termed. An appropriate amplitude and phase calibration procedure allows the correction of the "raw" quantities. The NVNA is able to measure the voltage and current waveforms of the HITFET as a function of the frequency and power level injected by the source 'SYNTH' shown in Fig.2. In the following these two quantities will be respectively termed as V_M and I_M. The fundamental assumption at the basis of the feasibility of the characterization is that the HITFET is stable once connected to the NVNA port and biased in the NDR region. This may not be always true but with a proper selection of the HITFET characteristic this constriction can be achieved [4].

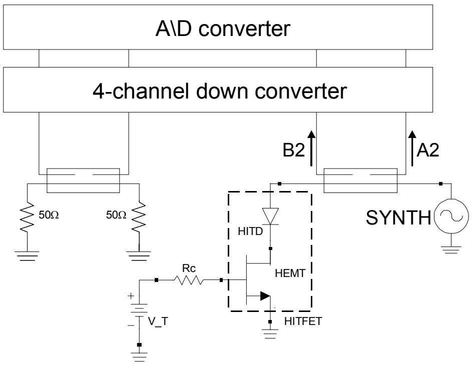


Fig.2: Set up adopted for the HITFET characterization based on NVNA (the bias part of the set is not shown).

The selected HITFET has been biased at Vd=650mV with a Vg=0V with a corresponding drain bias current of 1.02mA. Large signal characterization has been carried out by applying a signal at 1GHz and 2GHz with a power level ranging from –25dBm to 0dBm.

IV. HITFET NON LINEAR MODEL: EXTRACTION OF EQUIVALENT CIRCUIT PARAMETERS

If the Gate to Source bias voltage V_{GS} applied to the HITFET spans in a range between +0.2V and –0.6 V, by comparing the DC characteristics of the HEMT and the HITFET it can be easily demonstrated that the HEMT works in the VVR region for any value of V_{DS} applied to the Drain of the HITFET. This happens because the HEMT saturation current (~20 mA for V_{GS}=0V) is about one order of magnitude higher than the HITD peak current (~3.5 mA). This assumption is no longer valid if the HITFET is biased at lower V_{GS} voltages, since in this case the saturation current is comparable to the diode peak current. Within the range of V_{GS} values that forces the HEMT in the VVR region, the HEMT itself can be considered as a linear passive load; in these Gate bias conditions the non-linearity of the device is associated only to the diode and the HITFET's equivalent non-linear circuit is the one shown in Fig. 3.

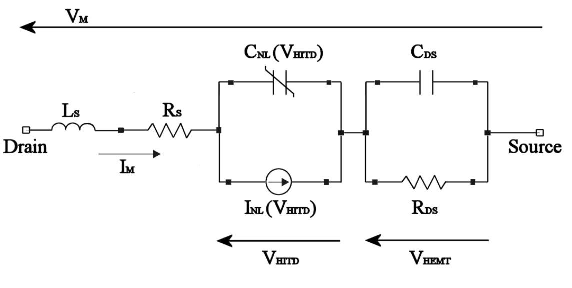


Fig.3: HITFET's non linear equivalent circuit.

The series inductance L_S is related to the reactive behavior of metallizations, while R_S takes into account the series resistance produced by the interconnections and the ohmic contacts of the two devices. The equivalent admittance of the HEMT's channel is reproduced by R_{DS} and C_{DS}, whose value is set by the Gate bias voltage V_{GS}. In the time domain the behavior of the circuit is described by the following system of differential equations:

$$\begin{aligned} V_M &= R_s \cdot I_M + L_S \cdot \frac{d}{dt} I_M + V_{HITD} + V_{HEMT} \\ I_M &= \frac{1}{R_{DS}} V_{HEMT} + C_{DS} \cdot \frac{d}{dt} V_{HEMT} \qquad (1) \\ I_M &= I_{NL}\left(V_{HITD}\right) + \frac{d}{dt}\left[Q_{NL}\left(V_{HITD}\right)\right] \end{aligned}$$

where:

$$\frac{d}{dt} Q_{NL} = \frac{d}{dV_{HITD}} Q_{NL} \cdot \frac{d}{dt} V_{HITD} = C_{NL} \cdot \frac{d}{dt} V_{HITD} \qquad (2)$$

In order to define the HITD non-linear current source $I_{NL}(V_{HITD})$ and the HITD non-linear capacitance $C_{NL}(V_{HITD})$, the linear part of the circuit has to be de-embedded from the measured data (V_M and I_M). In other words, the non linear part of the circuit can be characterized only once the relation between I_M and V_{HITD} has been found. Considering that, due to the different dimensions of the two devices [4], the only layout difference between the HITFET and the HEMT is the presence of the HITD on the Drain microstrip line, the easiest way to characterize the linear part of the circuit is to extract L_S, R_{DS} and C_{DS} from the high-frequency behavior of the HEMT's scattering parameters and then calculate the value of R_S from the HITFET's small signal measures.

After the linear part of the circuit has been dimensioned, the non linear current source I_{NL} can be evaluated from the measured static I/V characteristic of the device. Since in DC there is no contribution from reactive elements (L_S, C_{NL} and C_{DS}), the measured current is due only to the non-linear current source and parasitic resistor. The relation between I_{NL} and V_{HITD} is therefore easily determined by de-embedding from the measured static voltage the contribution added by R_S and R_{DS}. Once the non linear current source $I_{NL}(V_{HITD})$ is known, the non linear capacitance $C_{NL}(V_{HITD})$ can be extracted from large-signal measures considering that:

$$\frac{d}{dt} Q_{NL}\left(V_{HITD}\right) = C_{NL}\left(V_{HITD}\right) \cdot \frac{d}{dt} V_{HITD} = I_M - I_{NL} \qquad (3)$$

which then leads to the following equation:

$$C_{NL}\left(V_{HITD}\right) = \left(I_M - I_{NL}\right) \Big/ \frac{d}{dt} V_{HITD} \qquad (4)$$

Since at this point I_{NL} and V_{HITD} have already been extracted, $C_{NL}(V_{HITD})$ can be calculated evaluating (4) over a time interval corresponding to half a period and starting from a peak of $V_{HITD}(t)$. This step is required in order to avoid incurring in an undefined condition due to a null first order derivative of $V_{HITD}(t)$. The result of this procedure is shown in Figure 4.

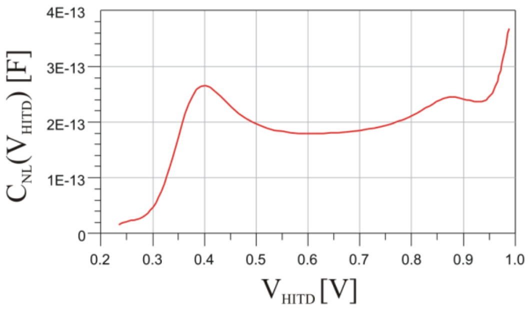


Fig.4: HITD's non linear Capacitance.

V. MODEL VALIDATION

The procedure described above has been carried out on the measured data obtained by applying a 1GHz - 0dBm signal to the Drain of the device. The model is then validated comparing simulated and measured data when a signal with a different frequency or power level is applied. The comparison is shown in Figures 5 and 6 by plotting in the I_M,V_M plane the curves obtained injecting respectively a 1GHz signal and a 2GHz signal with two different power levels.

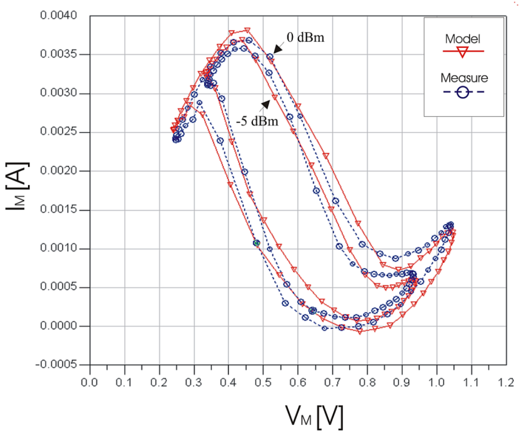


Fig.5: I\V voltage plane at the HITFET's drain, pumped by a 1GHz signal. Bias voltage Vd=0.65V; Vg=0V.

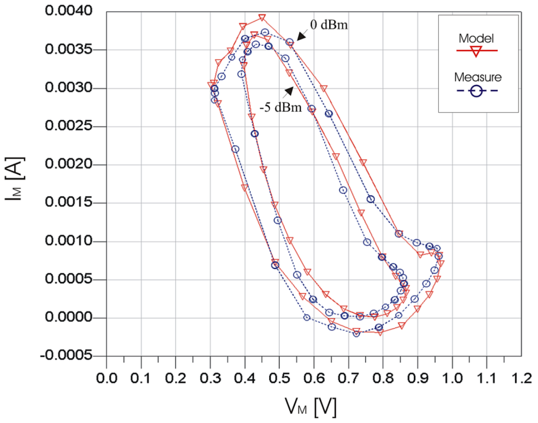


Fig.6: I\V voltage plane at the HITFET's drain, pumped by a 2GHz signal. Bias voltage Vd=0.65V; Vg=0V.

The hysteresis-like behavior that can be observed is due to the reactive component associated to the device and the increase of the trajectory width is related to the capacitance non linearity and the harmonics growth. Finally, the amplitude of the trajectory is associated both to the dissipated power and to the HITFET's I\V characteristic.

CONCLUSION

In this paper a procedure for extracting the equivalent circuit of a strongly non-linear device from NVNA measurements has been introduced. It is worth to point out that, to the best of our knowledge, as far as today no physical-based analytical description of the non-linear HITD capacitance has been proposed. Considering that, the method proposed in this paper also provides a meaningful insight on the device physics. The comparison between measured and simulated trajectories, in particular the ones shown in Fig. 6, confirms the extrapolation capability of the approach.

Acknowledgments

The authors want to acknowledge the technical support of the Motorola Physical Sciences Lab, Tempe (AZ), in the realization and development of the devices presented in this paper. Research reported here was performed in the context of the network TARGET – "Top Amplifier Research Groups in a European Team" and supported by the information Society Technologies Programme of the EU under contract IST-1-507893-NOE, www.target-org.net.

REFERENCES

[1] D. M. Schreurs, J. Verspecht, S. Vandenberghe and E. Vandamme, "Straightforward and Accurate Nonlinear Device Model Parameter-Estimation Method Based on Vectorial Large-Signal Mesurements", *IEEE Trans. On Microwave Theory and Tech.*, vol. 50, no. 10, pp 2315-2319, Oct. 2002.

[2] D. Root, S. Fan and J. Meyer, "Technology Indipendent Large Signal non Quasistatic FET Models by Direct Construction from Automatically Characterized Device Data", *1991 European Microwave Week Conference Proceedings*, pp. 927-932.

[3] A. Cidronali, G. Collodi, M. Camprini, V. Nair, G. Manes, J. Lewis and H. Goronkin, "Ultra Low-Power VCO Based On InP-Hemt And Heterojunction Interband Tunnel Diode For Wireless Applications", *IEEE Trans. on Microwave Theory and Tech.*, vol. 50, no. 12, pp. 2938-2946, Dec. 2002

[4] A. Cidronali, V. Nair, G. Collodi, J. Lewis, M. Camprini, G. Manes and H. Goronkin, "MMIC Applications of Heterstructure Interband Tunnel Devices", *IEEE Trans. On Microwave Theory and Tech.*, vol. 51, no. 4, pp. 1351-1367, Apr. 2003.

[5] M. Camprini, I. Magrini, G. Collodi, A. Cidronali, V. Nair, G. Manes, A Hybrid Self-Oscillating Mixer Based on InP Heterojunction Interband Tunnel HEMT for Wireless Applications, *2003 European Microwave Week Conference Proceedings*, pp. 205-208.

[6] E J. Verspecht and P. Van Esch, "Accurately characterizating of hard nonlinear behaviour of microwave components by the Nonlinear Network Measurement System: introducing the nonlinear scattering function", Proc. Int. Workshop on *Integrated Nonlinear Microwave and Millimiterwave Circuits*, (Duisburg, Germany), 10-11 October,1996 , pp. 17-26.