CAD-oriented modeling of the optically-controlled GaAs MESFET

Enrico F. Calandra, member, IEEE, and Guglielmo Sirna, student

Dipartimento di Ingegneria Elettrica, Universita' di Palermo
Viale delle Scienze, 90128 PALERMO (Italy)

Abstract

A CAD-oriented circuit model for the optically-controlled GaAs MESFET was developed on the basis of a dedicated characterization method. By exploiting separation of direct and indirect photo-induced effects, a simple but accurate modeling of both the static and microwave characteristics of the illuminated transistor was achieved. As demonstrated by the test circuits implemented, good agreement between measured and simulated performances can thus be obtained with limited device parameter identification effort.

Introduction

Recently, optical control of GaAs FETs has gained much attention in view of the development of non-conventional microwave circuits incorporating lightwave and fiber-optic techniques (see [1-2] and cited references). To take full advantage of this new approach to the design of microwave systems, by exploiting the powerful CAD tools nowadays available, it is however necessary to have at one's disposal reliable models for the illuminated transistor.

In this regard, it has to be pointed out that while the physics of the photo-induced effects in GaAs FET's has been quite extensively investigated in the last decade [3-4], only few researchers focused their attention on circuit modeling issues [5-6]. The consequence is that there is still a lack of adequate CAD-oriented models for the optically controlled GaAs MESFET. In particular, no measurement-based identification procedure which is simultaneously simple, systematic, and accurate has been so far presented in the literature.

In this paper, an attack to above problem is proposed. It exploits, both in the characterization and in the modeling phase, the separation which can be made between direct and indirect (i.e., bias shift related) effects of illumination on the microwave performances of GaAs MESFETs. Such approach not only simplifies the structure of the equivalent model for given accuracy limits, but it also permits a first-approximation (DC+RF) model of the illuminated transistor to be obtained from the conventional dark one, with the help of a few additional DC measurements only.

Experimental results pertaining to the application and verification of the proposed modeling procedure to the case of a commercial GaAs MESFET, optically driven by a 633nm (CW) and a 850nm (AM) laser source are also reported.

Device characterization

It is well known that when the active region of a GaAs MESFET is illuminated by a photon beam with quantum energy greater of the semiconductor bandgap both the DC and the microwave characteristics of the transistor change, because of the combined influence of photo-voltaic and photo-conductive effects.

In order to perform a meaningful characterization and to achieve a good phenomenological insight, it is convenient to avoid unnecessary interactions to occur between different photo-induced effects. As a first step along this line, all the measurements should be performed with reference to the internal voltages E_{xy}, i.e., by removing the influence of access parasitics resistances R_g, R_s and R_d (see Fig. 1). This can can be conveniently done by measuring them beforehand, and then adopting a computer-controlled bias system with a software feedback loop. In this regard, it can be pointed out that, although in theory such resistances should be treated as light-intensity dependent and nonlinear, in practice they can be often considered constant and linear, their variation being of the order of a few percents under normal (electrical and optical) operating conditions.

The photo-generated excess electron-hole pairs and the modification of the potential barriers at the gate-to-channel and channel-to-substrate (or buffer-layer) interfaces cause variations both in the gate and in the drain currents, as illustrated by the shift in the relevant DC characteristics reported in Fig. 2. Such variations, occurring at fixed internal voltages (E_{gs},E_{ds} = const.), are a *direct* (DC) effect of illumination, and nomally interact through the parasitic resistor R_s. This means that the functional dependence of I_g and I_d on the external voltages (V_{gs},V_{ds}), usually considered in the DC characterization of an illuminated transitor, would be more difficult to model and to relate to the device physics. As an example of this fact, it can be analyzed the measured dependence of the gate and

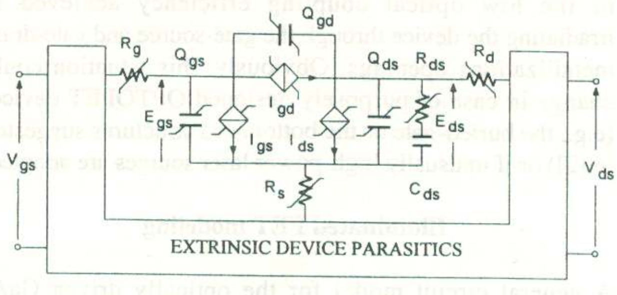

Fig. 1. General scheme of the optically-controlled MESFET.

drain photocurrent on the beam intensity (Fig. 3). For the gate photocurrent, a nearly perfectly linear dependence from the injected optical power (W_o) is observed, independently of the bias point selected. This experimental result is in agreement with the theoretical expectations, and would have not been analogously evident from the measurements of $I_g(V_{gs}, V_{ds}, W_o)$, especially at highest current levels. As to the drain current dependence on W_o, it can be noticed that it is instead higly nonlinear, with a logaritmic-type shape. This result too is in good qualitative agreement with physics-based considerations, although the quantitative aspects of its functional dependence on DC bias are more complicated than calculable from simplified theories.

Passing to the microwave characterization, it can be noticed that, since a variation of the light intensity alter the bias point and therefore the AC response of the transistor, without appropriate methods to counterbalance this DC shift, what is obtained from a conventional VANA measuring system is a combination of the (*direct*) light-induced effects and of the (*indirect*) bias-shift related ones. Therefore, a smart (computer- assisted) biasing technique is required for the microwave characterization too. In particular, for this research, the same hardware and software used for the DC measurements have been integrated into a hp8510B network analyzer and its external controlling computer, respectively.

The S-parameters measurements executed by this approach (i.e., by fixing internal voltages, but letting gate and drain current to vary), exhibited some peculiar features. In particular, all the samples of the GaAs MESFET tested (the MGF1801 by Mitsubishi) have shown a rather limited variation of the small signal device parameters throughout the whole 20GHz frequency range investigated (see Fig. 4). Moreover, such variations - once related to an equivalent circuit model - are attibutable for the most part to changes in the resistive elements and not to the reactive ones. Both results are not in agreement with previous observations made by other authors. In this regard, it can be pointed out that a conventional biasing scheme would have provided different results for the same devices, exhibiting fictious variations of the device intrinsic capacitances. That might explain above mentioned discrepancy, as well as the difficulties encountered in correlating theoretical predictions and previous experimental results of the literature. Indeed, although a variation of intrinsic capacitances for the direct effect of illumination is within the theory, quantitatively high numbers are not expected to occur in practice, because of the low optical coupling efficiency achieved in irradiating the device through the gate-source and gate-drain metallizations openings. Obviously, this situation could change in case of purposely designed OPTOFET devices (e.g., the buried-gate or the bottom-fed structures suggested in [2]) or if unusually high-power laser sources are adopted.

Illuminated FET modeling

A general circuit model for the optically driven GaAs MESFET is shown in Fig. 1. The fourport embedding the intrinsic transistor represents the parasitic elements of the chip device (including bond wires and the package, if applicable) and is thus assumed to be linear and light-independent. Consequently, it can be identified by conventional techniques and will not be considered further. On the other hand, all the elements modeling of the intrinsic device are in theory both nonlinear and illumination-dependent. However, on the basis of the experimental results reported in the previous section, a number of simplifications can be done in order to derive a first-approximation, but phenomenologically valid model of the optically controlled transistor. In particular, the DC characterization results justify the following assumptions:

- to use linear and constant resistors for R_g, R_s and R_d;
- to adopt, for the controlled current generators I_{gs} and I_{gd}, a functional dependence of the form

  $$I_{gx}(E_{gs}, E_{ds}, W_o) = I_{gx}(E_{gs}, E_{ds}, 0) + K_{gxo} \bullet (E_{gxo} - E_{gx})\, W_o$$

  where $I_{gx}(\bullet,\bullet,0)$ is the nonlinear relationship modeling the gate-source or gate-drain current under dark operating conditions, K_{gxo} and E_{gxo} are parameters characterizing the gate photo-current, and W_o is the optical power.
- to employ, for the controlled generator I_{ds}, a functional dependence of the form

  $$I_{ds}(E_{gs}, E_{ds}, W_o) = I'_{ds}(E_{gs} + E_o(W_o, T_{ch}),\, E_{ds},\, 0)$$

  where $I'_{ds}(\bullet,\bullet,0)$ is the nonlinear relationship modeling the static characteristics of the unilluminated transistor, and $E_o(W_o, T_{ch})$ is an equivalent voltage which account for the drain photo-current. Its dependence on optical power and channel temperature can be approximated by

  $$E_o(W_o, T_{ch}) = E_{ggo} \bullet (1 - K_\theta T_{ch}) \bullet \ln(1 + K_{ggo} W_o)$$

  Notice that above formulas are explainable either on an experimental basis, e.g., by considering the similarity existing among the $\{I_d(\bullet,\bullet,W_o) - I_d(\bullet,\bullet,0)\}$ curves and the device transconductance, or by theoretical considerations on the barrier lowering effect caused by the illumination.

Since the observed variation of the device S-parameter with illumination is already accounted for by the change in the resistive nonlinear elements (and the consequent bias shift), no additional optical-drive related parameters are introduced for simulating the AC characteristics of the FET.

Summing up, according to the proposed method, only the above cited seven parameters are required for the modeling of all photo-induced effects. Such number can be further reduced in case of devices with structural simmetry or if thermal effects are disregarded. In any case, their computer-assisted identification is straightforward, and can be done on the basis of the sole DC characterization data acquired.

Experimental verifications

To test the validity of the proposed modeling approach, several experiments have been performed using a medium power GaAs MESFET by Mitsubishi (MGF1801). Since this device is a packaged one, its metallic top cover lids has been removed, and a hole was drilled in the transistor holding insert of test fixture (hp85041), to allow for the optical injection. In particular, unguided propagation of the (He-Ne) laser beam was employed for the characterization at

633nm, while a cleaved optic fiber was micro-positioned through the hole in the nearby of the chip surface, for the experiments using the (Laser Diode) source at 850nm.

For each sample device tested, the following modeling procedure has been applied. After aligning of the optical bench (using the gate photo-current as indicator), a full characterization of the DUT was first made under dark condition. The relevant DC and AC bias-dependent model was then derived using a custom extraction software (MES-FIT), which employes a combination of direct identification and optimization techniques for the fitting. This step generates the look-up tables for the bias-dependent dark model parameters. Thereafter, the characterization was repeated for seven different levels of illumination (optical attenuation values of 0, 1, 2, 3, 5, 7 and 10 dB). From the DC data, the additional parameters involved in the illuminated device model (five, exploiting the DUT structural simmetry) have been identified by least square criterion curve fitting.

On this basis, the S-parameter of the illuminated MESFET have been simulated, and compared to the measured ones. In general, quite satisfactory agreement was obtained, thus discouraging the idea of resorting to a "tuning" of the look-up tables of the incremental model parameters, which would have certainly improved the simulation accuracy, but would have also implied dealing with a more involved (both bias- and light--dependent) AC model, which was not the goal of this work.

To better evaluate the simulation capabilities of the extracted model, by testing it under operating conditions different from those of the initial characterization, and more similar to those occurring in a practical circuit, additional measurements have been performed.

First, a simple optically-controlled variable-gain amplifier was implemented, directly on the network analyzer. In particular, a fixed supply/resistor circuit was used for biasing gate (V_{gg}, R_{gg}=270kΩ) and drain (V_{dd}, R_{dd}=3Ω) of the device under test. At difference with previous measurement conditions, in this case there is a strong interaction between direct and indirect photo-effects (and therefore between DC and microwave response). Thus, it is a valid test of the global quality of the model under CW optical drive operation. The measured and predicted dependence of drain current on the optical beam intensity (for fixed V_{dd} and stepped V_{gg}) are compared in Fig. 5, while the frequency dependence of amplifier insertion gain (for fixed V_{gg} and V_{dd}, and three different optical drive levels) is reported Fig. 6. It can be seen that quite good agreement was achieved in either case.

As a final test, a GaAs MESFET photodetector circuit was realized, by 50Ω terminating its input and output, and by optically driving it with a low-frequency amplitude-modulated LD source (at 850nm). Although the model here presented is not intended for use under short-pulse or microwave-frequency AM optical drive (since dynamics of photo-effects was not characterized nor accounted for), it is expected that if the beam modulation period is much less than the involved optical time-constants, the model should maintain its validity. In fact, as demonstrated by Figs. 7-8, at 1kHz modulation the detector output is quite accurately simulated, over a more than 10dB of optical-signal dynamic range. Notice that the strongly nonlinear response shown by the two photos of Fig. 7, constitute also an independent validation of the logarithmic-type dependence of E_o on W_o identified under stationary DC operation. In this regard, it is authors' opinion that, by properly exploiting such type of measurements, it can be derived a frequency dispersive functional dependence for E_o, thus improving the model and extending its applicability to high-speed optical drive.

Conclusions

Starting from an appropriate experimental characterization aimed at separating direct and indirect light-induced effects, a first-approximation CAD-oriented circuit model of the optically-controlled GaAs MESFET was derived. Once the (DC nonlinear, AC bias-dependent) unilluminated transistor model is obtained through conventional identification methods, the additional parameters characterizing the photo-effects can be extracted from a simple procedure based on DC measurements only. The selected model structure allows its straightforward integration into most commercial circuit simulators with custom or behavioural modeling capability. Notwithstanding its simplicity, the developed model inherits from its phenomenological basis accurate simulation capabilities, as demonstrated by the good agreement between measured and predicted performances of the verification circuits realized.

Acknowledgements

This work was supported by the Finalised Project "TEO" of the italian National Research Council (CNR). The experiments have been performed at the Center for the Research on Electronics in Sicily (CRES) of Monreale, Italy, that supplied instrumentation and technical support.

References

[1] R. Simons, *Optical Control of Microwave Devices*, Artech House, London, 1990.

[2] A. J. Seeds and A. A. De Salles, "Optical control of micro-wave semiconductor devices", IEEE Trans. Microwave Theory Tech., vol. 38, pp. 577-585, 1990.

[3] R. N. Simons and K. B. Bhasin, "Analysis of optically controlled microwave/millimiter-wave device structures", IEEE Trans. Microwave Theory Tech., vol. 34, pp. 1349--1355, 1986.

[4] S. H. Lo and C. P. Lee, "Numerical analysis of the photo-effects in GaAs MESFET's", IEEE Trans. Electron Devices, vol 39, pp. 1564-1569, 1992.

[5] J. L. Gautier, et al., "Optical effects on the static and dynamic characteristics of a GaAs MESFET", IEEE Trans. Microwave Theory Tech., vol. 33, pp. 819-822, 1985.

[6] A. Adibi, K. Eshraghian, "Generalised model for GaAs MESFET photodetectors", IEE Proc., Part G, vol. 136, pp. 337-343, 1989.

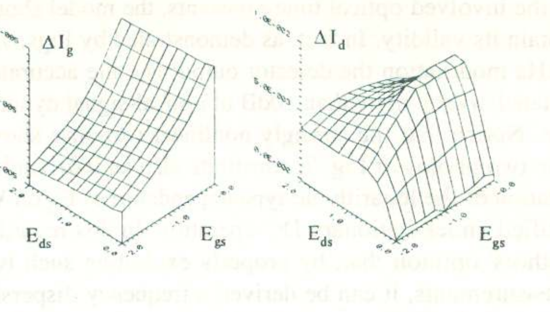

Fig. 2. Measured variation of gate (left) and drain (right) current for fixed Egs, Eds values ad full-to-zero optical power step.

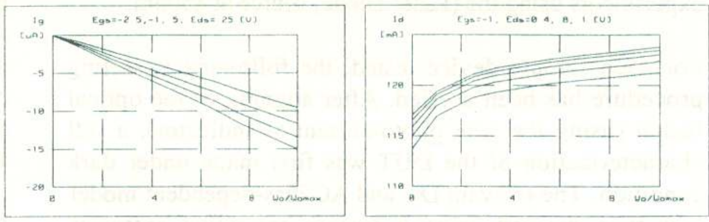

Fig. 3. Measured dependence of gate (left) and drain (right) current on optical power, for fixed Egs and Eds values.

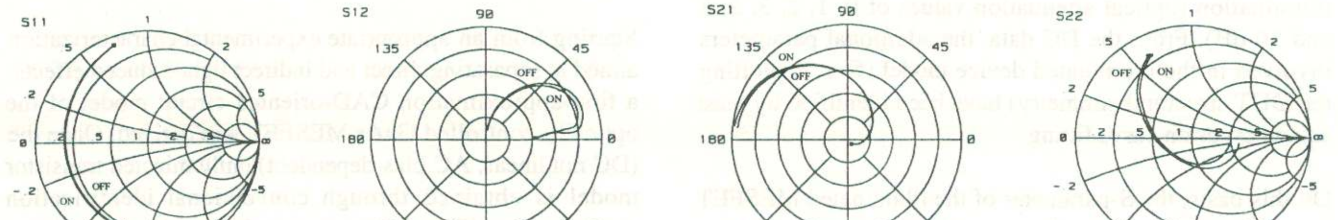

Fig.4 .Measured variation of S-parameters for Egs=-2, Eds=1 and full-to-zero optical power step.

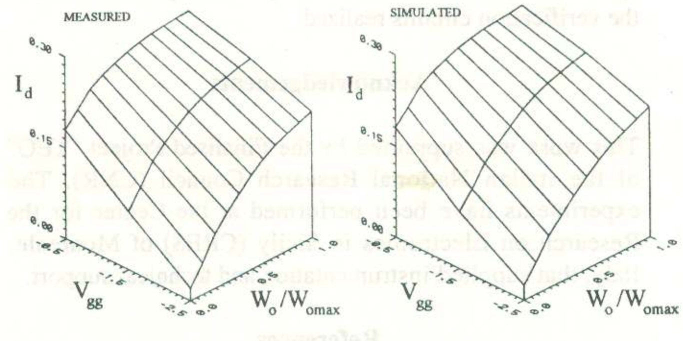

Fig. 5. Measured (left) and simulated (right) drain current of the optically-controlled test amplifier versus Wo/Womax and Vgg, for Vdd=1V.

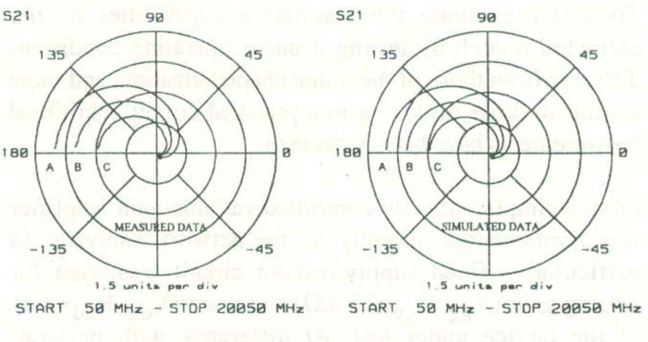

Fig. 6. Measured (left) and simulated (right) insertion gain of the optically-controlled test amplifier for Vgg=-2.5, Vdd=1V, Wo/Womax=0 (A), .5 (B), 1 (C)

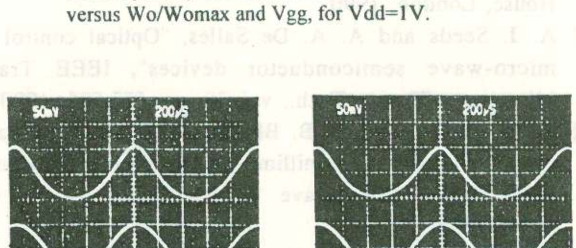

Fig. 7. Measured response (top trace) of the photodetector circuit, for a scaled optical power Wo/Womax =1 (left) and 0.1 (right) and 1 Vpp modulation signal (bottom trace).

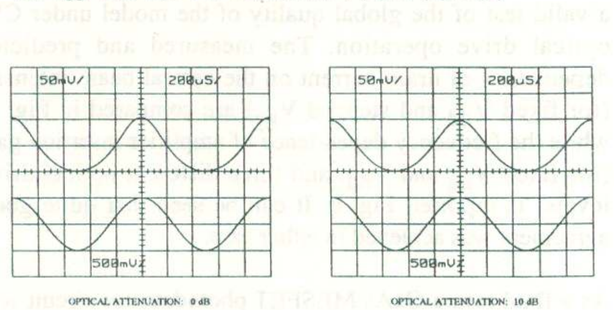

Fig. 8. Simulated response (top trace) of the photodetector circuit, for a scaled optical power Wo/Womax =1 (left) and 0.1 (right) and 1 Vpp modulation signal (bottom trace).