An Accurate Photonic Capacitance Model for GaAs MESFETs

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***Abstract*—A new set of pseudoempirical equations is presented in order to simulate the optical and bias dependencies of GaAs MESFET junction capacitances, which is valid for the whole *I–V* plane. The variations induced in the small-signal equivalent circuit by the optical illumination are extracted from on-wafer scattering-parameter measurements. New linear and quasi-logarithmic variations versus the incident optical power are shown for gate–drain and gate–source (Cgd and Cgs) capacitances. Furthermore, experimental results are in very good agreement with the simulated values for a wide range of optical power and bias conditions. Large-signal MESFET models show a better fit with measured S-parameters than those previously published, leading to a greater degree of confidence in the design of photonic monolithic microwave integrated circuits.**

***Index Terms*—Incident optical power, junction capacitances, laser, modeling, photonic MMIC.**

I. Introduction

AT PRESENT, optical fiber communication plays an important role in cable communication technology for wide-band, multimedia, and high-speed applications. In order to be able to manufacture wireless terminals for optical fiber links at reasonable cost, good agreement must be achieved between the photo-detector and the millimeter-wave circuit, as well as small size and low weight [1], [2]. Integration of microwave transistors with conventional photodiodes [p-i-n, metal–semiconductor–metal (MSM)] requires additional processing steps. GaAs MESFET devices can be used as photodetectors, embedded in the monolithic chip and acting as an optical port, an idea that has been widely investigated recently [2], [3].

It is very important, in order to work with efficient computer-aided design (CAD) tools, to have good modeling approaches, capable of predicting the small- and large-signal behavior of GaAs devices. A comprehensive knowledge of these technologies and related applications in communications, as well as the control of microwave systems, requires an accurate understanding of the optical properties of microwave transistors. According to the previous considerations, a careful characterization is required, as well as the development of an accurate model for an optically controlled microwave device, in order to be able to perform efficient simulations and accurate predictions of photonic microwave integrated system behavior.

When a GaAs MESFET device is optically illuminated, absorption phenomena take place at the gate–drain and gate–source regions, which induce both photoconductive and photovoltaic effects [4]. Several authors have developed models to describe some of these optical effects [5]–[7]. Our group has investigated the large-signal dynamic properties of GaAs FET devices under optical illumination and has developed the first accurate electrooptical model for the drain–source current ($I_{\rm ds}$), which includes the effects of optical illumination on the bias-dependent dynamic behavior [8], [9].

From a large-signal point-of-view, the simulation of nonlinear microwave circuits using GaAs MESFET devices under laser illumination reveals that simulation accuracy is quite sensitive to the precision used to model the gate–source and gate–drain capacitances as functions of bias voltage [9]. A limited amount of research have covered this aspect and, perhaps, the most innovative was presented by Kawasaki *et al.* [7]. It includes the optical parameters in the modified Statz [10] capacitance model, which takes into account optical effects by using first-degree polynomial ratios.

From the multibias capacitance results we have obtained, it is observed that the variations of $C_{\rm gd}$ and $C_{\rm gs}$ with optical power are more complex than those given by Kawasaki, following a quasi-linear form for $C_{\rm gd}$ and quasi-logarithmic for $C_{\rm gs}$. Our approach leads to more accurate fitting with experimental measurements for both $C_{\rm gd}$ and $C_{\rm gs}$. Furthermore, the Statz approach was considered unsuitable because of its complexity since, for circuits with a large number of devices, it consumes excessive computational time. In many cases, a compromise between dc and ac accuracies is required, as can be observed, for example, in the output conductance found by Kawasaki. The electrooptical model presented in this paper for GaAs MESFET devices is based on the Scheinberg model [10] using a classical FET model and provides higher accuracy and flexibility than previous models, both in the linear and saturation regions, as a function of $V_{\rm gs}$, $V_{\rm gd}$, and the incident optical power (PL). The capacitor fitting parameters are not involved in the simulation of any of the devices' nonlinearities, therefore, allowing for independent simulation of static and dynamic behavior, as well as high execution speed in a standard PC. This allows the new expressions to be used easily in designs, which include electrooptical devices, such as optical switches, optically tuned oscillators, etc. [12], with a higher degree of confidence.

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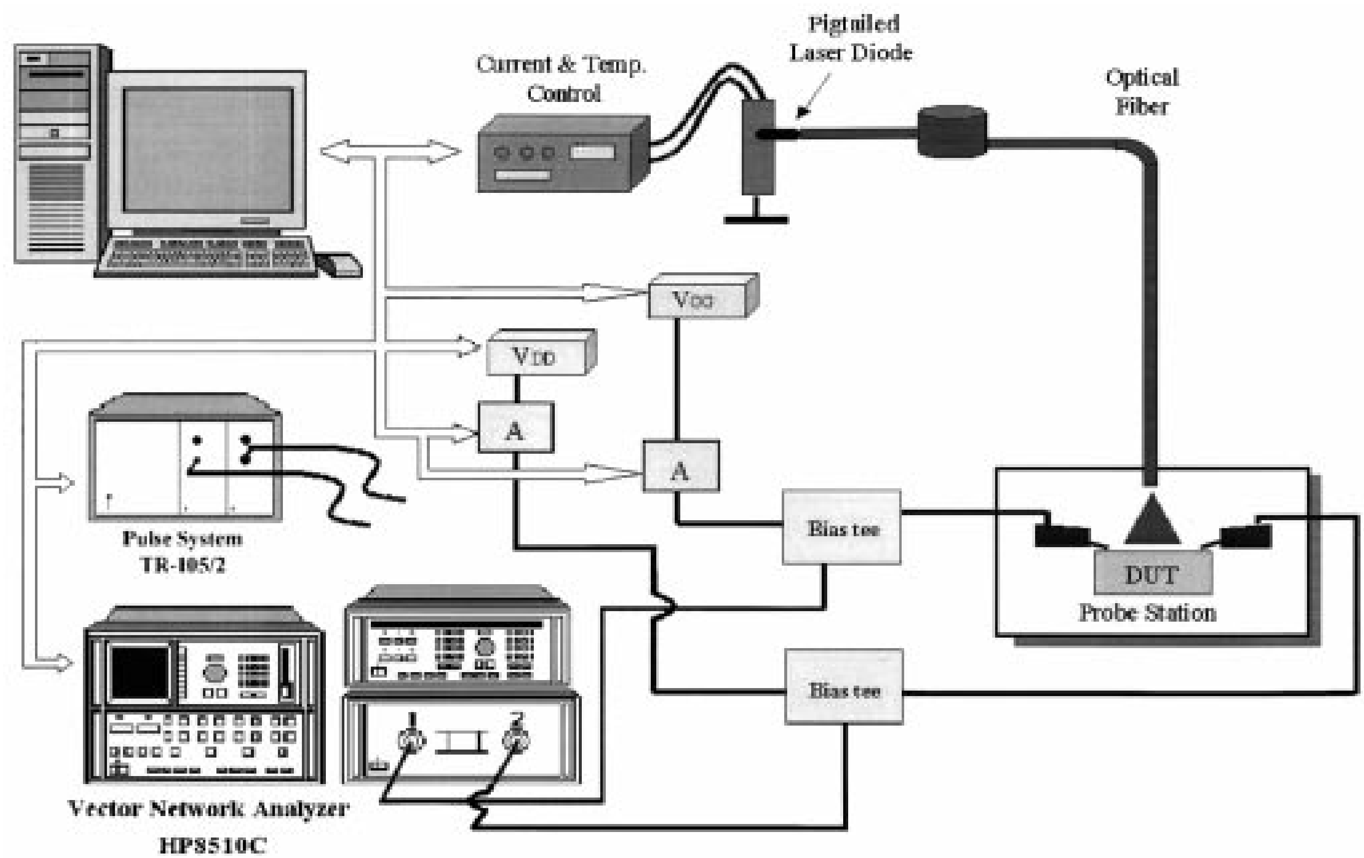

Fig. 1. Experimental setup.

II. Experimental Procedure

To establish an accurate FET model that includes optical parameters, experiments were performed at dc and pulsed *I–V* characteristics, along with S-parameter measurements for various optical powers, using a set of F20 GEC-Marconi GaAs MESFET devices with different gate lengths. Even when these devices were not designed for optical applications, they had enough optical coupling efficiency to allow the observation and measurement of this type of interaction.

Direct optical illumination was provided by a pigtailed laser diode SDL5301-G1 with $\lambda = 0.83$ nm and maximum optical power of 12.5 mW. The output of the laser diode was guided to the illumination point on the MESFET by a single-mode fiber (5/125), whose end was positioned using a micropositioner to illuminate the active area (fingers) of the GaAs MESFET. The experimental setup is shown in the block diagram of Fig. 1. It must be noted that an external gate resistance was not included in the gate bias circuit. The conditions for the far-field Gaussian profile were obtained from the optical fiber parameters. The Gaussian beam diameter at the fiber's end was $W_0 = 3.1$ mm and the diffraction angle $\phi = 0.085$ rad. The dc, pulsed *I–V* characteristics, and small-signal S-parameters were measured on wafer for various optical powers, with a Cascade SUMMIT 9000 microprobe test station, our in-house developed pulsed measurement system [12] and an HP8510 vector network analyzer.

The variations of some figures-of-merit are an important issue to take into account in the design of optically controlled circuits. With this in mind, common-source current gain cutoff frequency (f_T) and maximum stable gain (MSG) were employed and both were computed with and without illumination. At $V_{\mathrm{gs}} = -1.5$ V and $V_{\mathrm{ds}} = 1.5$ V, maximum f_T without illumination was 9.5 and 17.75 GHz with an optical power of 10 mW. The maximum value of f_T was, therefore, increased by 80%, while the MSG was improved by 2.5 dB (Fig. 2). Bearing in mind the aforementioned experimental observations; we believe that the development of an accurate optical capacitance model to describe the photonic microwave characteristics of GaAs MESFETs is very important. The S_{21}- and S_{22}-parameter variations for a six-finger 50-mm/finger GEC-Marconi MESFET induced by different optical illumination powers, at one bias point, are shown in Fig. 3.

III. Capacitance Model

A complete set of multibias S-parameter measurements was performed in the range of 0.5–26.5 GHz for various different optical powers. The typical FET small-signal equivalent circuit was also computed using the classical technique described in [13].

It must be emphasized that no extra elements were included in the model in order to characterize optical effects. In our study, we paid special attention to variations of C_{gs} and C_{gd} when the

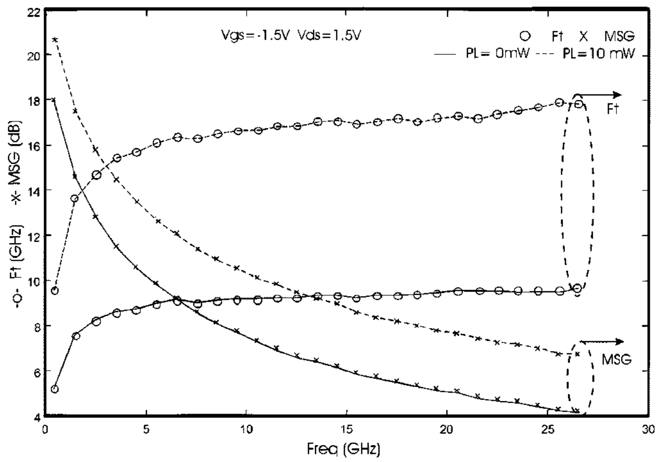

Fig. 2. f_T and MSG with and without optical illumination.

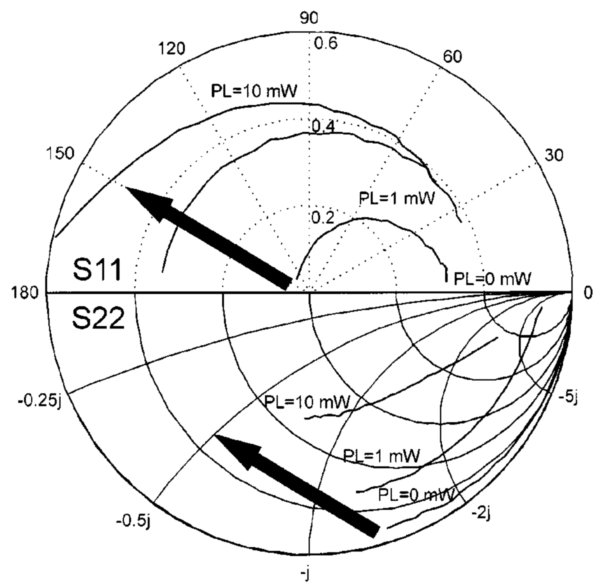

Fig. 3. S-parameter variations with optical illumination at $V\mathrm{gs} = -1.5$ V and $V\mathrm{ds} = 1.5$ V (optical powers $= 0, 1, 10$ mW).

device is subjected to optical illumination. To be able to develop an accurate expression for such variations, taking into account the optical effects, the empirical capacitance model developed by Scheinberg and Chisholm [10] has been modified to include a new parameter for the incident optical power (PL). Since $C\mathrm{gd}$ shows an approximately linear dependence on optical power, the new equation, including this parameter, can be stated as follows:

$$C_{\mathrm{gd}} = C_{\mathrm{gdo}}\left\{1+C_f\cdot\tanh\left(S_g\cdot\left[V_{\mathrm{GD}}-D_C\cdot\tanh(D_k\cdot V_{\mathrm{GS}})\right]\right)\right\} + m\cdot PL \tag{1}$$

where C_{gdo}, C_f, S_g, D_c, and D_k are the parameters given by Scheinberg and Chisholm, and m is a new semiempirical constant introduced to include the optical power as a new variable.

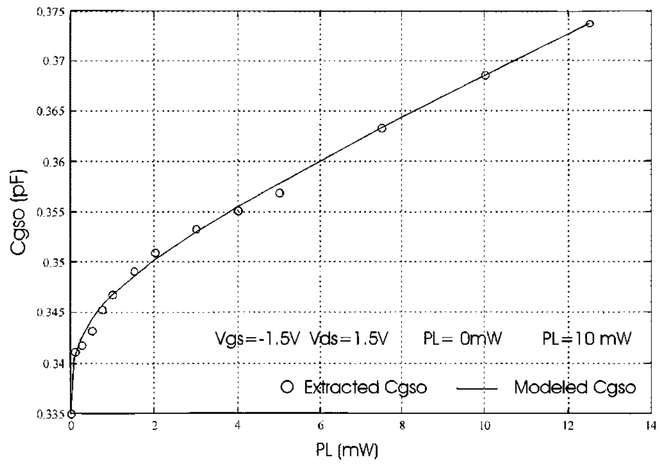

Fig. 4. Extracted and simulated C_{gso} parameter for different optical powers.

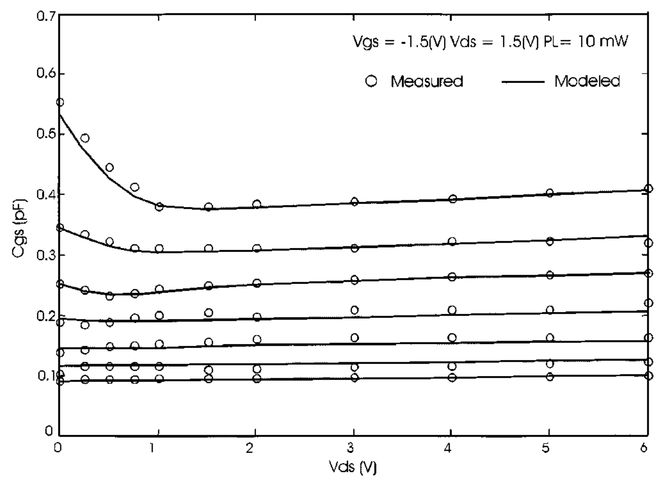

Fig. 5. Measured and simulated $C\mathrm{gs}$ capacitance for a 6 × 50 μm GaAs MESFET with an optical power of 10 mW.

The gate-to-source capacitance equation developed by Scheinberg and Chisholm is

$$C_{\mathrm{gs}} = C_{\mathrm{gso}}\left\{1+C_{f\mathrm{gs}} \cdot\tanh\left(S_g\cdot\left[V_{\mathrm{GS}}-D_{\mathrm{CGS}}\cdot\tanh\left(D_k\cdot V_{\mathrm{GD}}\right)\right]\right)\right\}. \tag{2}$$

The correct description of this capacitance when the MESFET is illuminated is more complicated and it is necessary to relate some of its parameters to the incident optical power as follows:

$$C_{\mathrm{gso}} = C_1 + \frac{C_2\cdot PL + C_3\cdot PL^2}{1+C_4\cdot PL^{C_5}} \tag{3}$$

$$C_{f\mathrm{gs}} = A + \frac{B\cdot PL}{1+C\cdot PL^D} \tag{4}$$

$$D_c = D_{C1} + \frac{D_{C2}\cdot PL + D_{C3}\cdot PL^2}{1+D_{C4}\cdot PL^{D_{C5}}} \tag{5}$$

where C_1, $C_2 C_3$, C_4, A, B, C, D, D_{C1}, D_{C2}, D_{C3}, D_{C4}, and D_{C5} are semiempirical constants.

Fig. 4 shows the measured (at $V_{\rm GS} = -1.5$ V) and simulated value of $C_{\rm gso}$ versus the optical power, using our approach. In this figure, the quasi-logarithmic dependence on optical illumination can be observed.

IV. Conclusions

Agreement between extracted and simulated values of $C_{\rm gso}$, as well as for the other two parameters (C_f and D_c) has been found to be quite good. The measured and simulated value of $C_{\rm gs}$ as a function of $V_{\rm ds}$ and $V_{\rm gs}$ when the device is illuminated with 10 mW of optical power has been shown in Fig. 5. We believe that this is the first model to provide this degree of accuracy as a function of bias and optical power. Moreover, since additional elements are not included in the small-signal equivalent circuit and the parameters introduced do not affect other aspects of the behavior of the model, no convergence problems were experienced and no special parameter optimization techniques need to be employed. This makes the model very suitable for incorporating in standard CAD tools in order to improve the accuracy of optical monolithic microwave integrated circuit (MMIC) designs.

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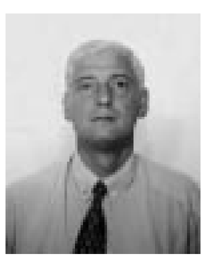

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