Short Papers

Improved HEMT Model for Low Phase-Noise InP-Based MMIC Oscillators

D. Schreurs, H. van Meer, K. van der Zanden, W. De Raedt, B. Nauwelaers, and A. Van de Capelle

***Abstract*— This paper focuses on two modeling aspects to improve the accuracy of low phase-noise monolithic-microwave integrated-circuit (MMIC) oscillator design. Up until now, the modeling of InP-based high electron mobility transistors (HEMT's) has mainly been limited to the representation of small-signal and thermal noise behavior. In this paper, we present a scaleable nonlinear and bias-dependent low-frequency (LF) noise model.**

***Index Terms*— MMIC oscillators, MODFET's, nonlinearities, phase noise.**

I. Introduction

InP-based high electron mobility transistors (HEMT's) are the optimum choice for high-performance low-noise microwave and, especially, millimeter-wave monolithic microwave integrated circuits (MMIC's). Regarding the stringent small-size requirement of future telecommunication systems, it is mandatory to extend this functionality to nonlinear circuits. The existing nonlinear HEMT models [1], [2] are elaborated for HEMT's in general and do not explicitly address the specific properties appropriate to InP-based HEMT's. Furthermore, the low-frequency (LF) noise studies on InAlAs/InGaAs HEMT's have been mainly limited to characterization in the linear region [3], [4]. They have not yet resulted in an accurate empirical LF noise model, which is valid over the total bias range and can be implemented in microwave circuit simulators, as has already been done for MESFET's [5].

In Section II, we summarize the problem areas inherent to the nonlinear modeling of InP-based HEMT's and propose solutions to overcome them. Secondly, we present a measurement-based bias-dependent LF noise model in Section III. As verification of this model, we discuss the results of a fabricated coplanar waveguide MMIC oscillator in Section IV.

II. Nonlinear InP HEMT Model

We have elaborated a procedure to generate a nonlinear HEMT model, which is dedicated for low-power nonlinear applications [6]. The model is shown in Fig. 1. The gate–source charge source Q_{gs} incorporates both the effect of the small-signal gate–source and gate–drain capacitances, whereas the drain–source charge source Q_{ds} includes the contributions of both the small-signal drain–source and gate–drain capacitances. The major differences with original MESFET-based and power-application-oriented model extractors [1] are an improved procedure for the extrinsic element extraction [7] and an optimized grid of intrinsic bias conditions at which S-parameter measurements are performed [8].

From the point-of-view of nonlinear modeling, the major difference between InP- and GaAs-based HEMT's is the more pronounced dispersion effect. We distinguish two types of dispersion. The first type is the LF dispersion, which corresponds to the frequency-dependent behavior of g_m and g_{ds} in the kilohertz and megahertz frequency range. We measured the dispersion degree as a function of bias for both GaAs- and InP-based HEMT's. The degree of dispersion is dependent on the layer structure and on the bias conditions. The largest g_{ds} dispersion is noticed in the knee region at the V_{gs}, corresponding to the maximum of the transconductance g_m $(V_{g\,\max})$. The g_{ds} variations are 6% and 30% for pseudomorphic GaAs HEMT's and lattice-matched (LM) InP HEMT's, respectively. The g_m variations at maximum g_m are 2% and 6%, respectively. These measurement results indicate that the LF dispersion is more significant for InP-based HEMT's than for GaAs-based HEMT's. In the nonlinear model description, the LF dispersion is modeled by a first-order transfer function [1].

The second dispersion type occurs in the gigahertz range and is related to the so-called kink effect, which is caused by impact ionization [9]. Impact ionization occurs in InP-based HEMT's at lower drain–source voltages V_{ds} compared to GaAs-based HEMT's due to the lower bandgap of the InGaAs channel layer. Hence, this effect is noticeable at typical operating conditions of nonlinear applications. Therefore, the high-frequency (HF) dispersion needs to be included in the nonlinear InP HEMT model. This phenomenon is more complex since it is accompanied by both a resistive (output conductance g_{ds}) and a reactive dispersion (output capacitance C_{ds}). Reuter *et al.* [10] have proposed to extend the intrinsic small-signal equivalent scheme at the drain side by a parallel branch consisting of a resistance R_{im} in series with the parallel connection of a transconductance g_{im}, controlled by the intrinsic drain–gate voltage V_{dg}, and a capacitance C_{im}. Based on this extended small-signal equivalent scheme, we can add the following implicit equation to the nonlinear model description to incorporate the HF dispersion:

$$g_{\mathrm{im}} V_{\mathrm{dg}} + C_{\mathrm{im}} \frac{dV_d}{dt} + \frac{V_d - V_{\mathrm{ds}}}{R_{\mathrm{im}}} = 0 \tag{1}$$

with V_d the voltage across C_{im}.

Since for a circuit designer the device width has to be a degree of freedom in order to achieve optimal performance, we have investigated the scaling properties of 0.2-μm InAlAs/InGaAs HEMT's. We found that the scaling rules of the extrinsic elements agree with the physical expectations. Since it is our aim to set up a scaleable nonlinear model, we directly investigate the gatewidth dependency of the intrinsic constitutive relations (I_{gs}, Q_{gs}, I_{ds}, and Q_{ds}) and not that of the small-signal intrinsic elements. The scaling behavior of I_{ds} is presented in Fig. 2. From the relation between the constitutive relations and the physical behavior of the device, we know that the constitutive relations are proportional to the device width W and, hence, ideally become zero at zero device width. However, in practice, we found that there might be a small bias-dependent W-independent term. This nonzero part is primarily due to the slightly different device characteristics because of a slight

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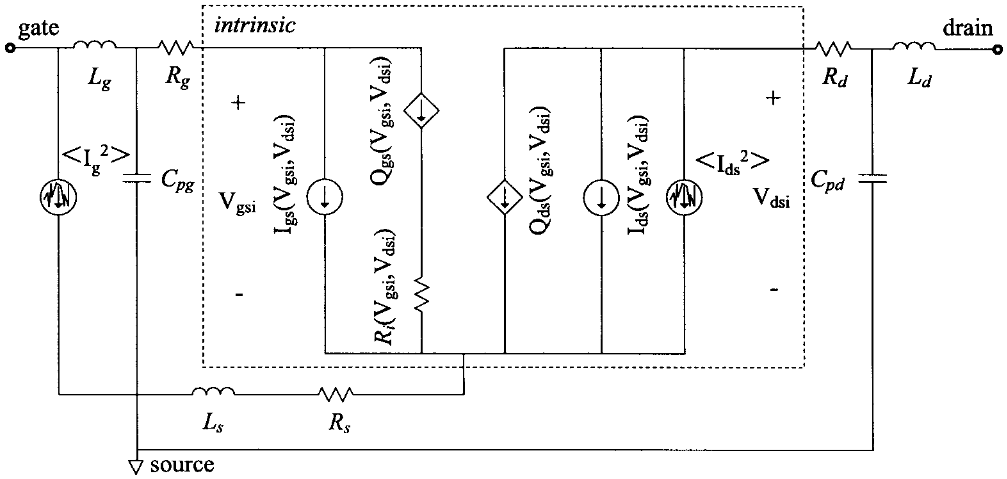

Fig. 1. Nonlinear and LF noise model for InP-based HEMT's.

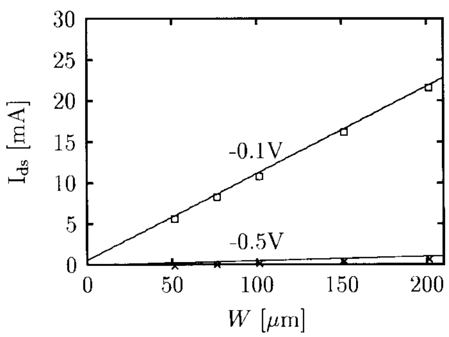

Fig. 2. I_{ds} of InP LM HEMT's versus W at $V_{ds} = 1$ V and $V_{gs} = -0.5$ V ($\approx V_T$) and -0.1 V ($\approx V_{g\max}$).

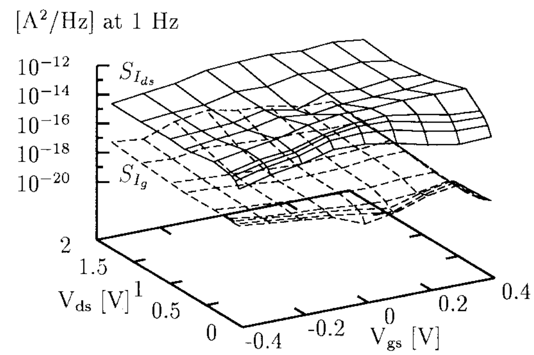

Fig. 3. $1/f$ noise in the gate current $S_{I_g}(f)$ and in the drain current $S_{I_{ds}}(f)$ at $f = 1$ Hz versus V_{gs} and V_{ds}.

nonuniformity across the wafer. Therefore, it is more accurate to take the least squares fit of the constitutive relations of several devices with gatewidths within the width range of interest than to rely on the nonlinear model of only one representative device, as in [1]. The scaleable nonlinear InP HEMT model is implemented straightforwardly in the HP Microwave Design System (HP MDS).

III. Bias-Dependent LF-Noise InP HEMT Model

This nonlinear model has been extended with an accurate bias-dependent LF noise model to enable phase-noise simulations. We have measured the spectral current noise power densities of 0.2×50 μm^2 InP-based HEMT's in the ohmic as well as in the saturation regime for various values of gate–source voltages V_{gs} and for frequencies from 1 Hz to 100 kHz. The principle of the LF noise measurement setup has been described in [11]. All gate and drain current noise measurements produced merely $1/f$-like spectra, which implies that the generation–recombination and thermal noise sources are not dominant below 100 kHz. Fig. 3 shows the measured $1/f$ noise in the gate and drain current $S_I(f)$ at $f = 1$ Hz versus V_{gs} and V_{ds}. According to the literature, the LF noise in the drain current is proportional to V_{ds}^2 for low values of V_{ds} [3], i.e., in the linear regime, which is in agreement with our measurement results. The relative $1/f$ noise in the drain current of an InAlAs/InGaAs HEMT is about three decades smaller than the reported value for GaAs-based HEMT's [12]. The noise in the gate current is strongly dependent on the operating point and is proportional to I_g^2 [13]. From our gate current noise measurements, it can be concluded that this dependence is only valid for values of V_{ds} near 0 V.

We also measured the coherence $\Gamma_{I_g,I_d}(f)$ between the gate and drain noise sources at several gate–source bias points in the ohmic and saturation regions. The maximum value is approximately 0.15, which implies that in a first approximation, the gate noise source can be treated separately from the drain noise source. This facilitates the LF noise modeling considerably.

The LF noise can be represented in the nonlinear model by a spectral gate current noise source between the gate and source contacts and by a spectral drain current noise source parallel to the intrinsic drain current source (see Fig. 1). The bias-dependent behavior of these noise sources is characterized by the spectral power densities S_{I_g} and $S_{I_{ds}}$ at 1 Hz and the coefficient γ in $S_I(f) = S_I(f = 1)/f^\gamma$ as variables which are dependent on V_{ds} and V_{gs}. These results can also be applied on devices with other gatewidths if the current noise sources are scaled by using, for example, Hooge's relation [14]. In this way, we obtain a scaleable bias-dependent LF noise model.

IV. InP HEMT Model Verification

Based on this developed scaleable nonlinear and bias-dependent LF noise InAlAs/InGaAs HEMT model, a 22.8-GHz coplanar waveguide (CPW) MMIC oscillator (see Fig. 4) has been designed and fabricated with the in-house developed MMIC technology [15]. The oscillator consists of a 0.2×150 μm^2 InAlAs/InGaAs HEMT, which is destabilized by a metal–insulator–metal (MIM) capacitor in the source. As this circuit is meant as a simple demonstrator, it has an on-chip resonator, which is formed by the combination of the

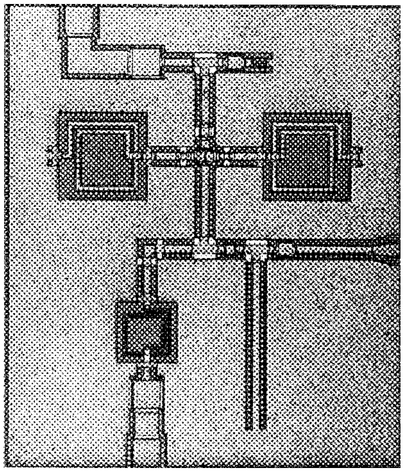

Fig. 4. Picture of the InP LM HEMT-based CPW MMIC 22.8-GHz oscillator (1.4×1.7 mm^2).

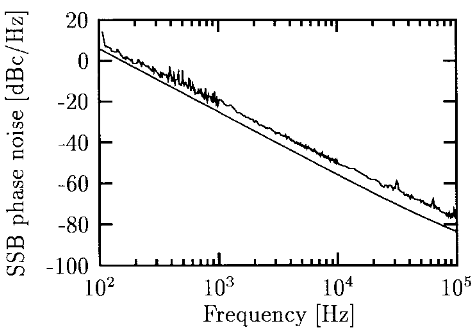

Fig. 5. Comparison of the measured and simulated phase noise.

gate bias network and a CPW transmission line. Fig. 5 compares the measured [16] and simulated phase noise, calculated with the phase-noise analysis tool of HP MDS. The measured phase noise is -77 dBc/Hz at 100 kHz from the carrier. This agrees well with the simulated value of -83 dBc/Hz. The phase-noise performance of this 22.8-GHz oscillator is comparable to reported values of HBT-based oscillators in the same frequency range [17], which underlines the important potential of InP-based HEMT's in nonlinear applications.

V. Conclusions

InP-based HEMT's are suitable candidates for microwave and millimeter-wave MMIC oscillators. We have developed a scaleable nonlinear and bias-dependent LF noise model for these devices. It has been highlighted that the LF and HF dispersion have to be included to correctly represent the specific physical characteristics. The model accuracy has been successfully demonstrated by phase-noise measurements on a CPW MMIC oscillator.

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