The Assessment of Output Digital Spectra in Quasi Enhancement-mode pHEMTs by A Modified Large-signal Model

Shih-Cheng Yang, Chih-Wei Wang, Cheng-Kuo Lin, Hsien-Chin Chiu,and Yi-Jen Chan
Department of Electrical Engineering, National Central University, Chungli, Taiwan 32054, R.O.C
Phone: 886-3-4273593 Fax: 886-3-4255830
e-mail: yjchan@ee.ncu.edu.tw

Abstract — **A modified quasi enhancement-mode pHEMTs RF large-signal model is presented which achieves a good agreement with the device performance. This model is based on the Curtice model, by modifing the formula to have a detailed description about non-linear microwave behaviors. The output digital spectra of quasi enhancement-mode pHEMTs can be well predicted by this model, including the ACPR and non-linear spectra regrowth characteristics.**

I. INTRODUCTION

Power amplifiers (PAs) are the critical components, which determine the important system parameters such as talk time, standby time, overall cost, and size in today's communication systems. A handset requires the RF PA to offer a high power-added-efficiency (PAE) for achieving a longer operation. In addition, a single low voltage power supplied PA fabricated by pHEMTs is also necessary to eliminate the need for a negative power supply. For these reasons, an enhancement-mode pHEMT (E-pHEMT) offers an attractive solution for the handset PA applications [1]-[3]. However, due to the inherent device characteristics of E-pHEMTs, i.e. the low threshold voltage and its small gate turn-on voltage, result in a small operating dynamic range. It is easy for devices to be driven into the non-linear region away from the bias point. Therefore, it is necessary to propose a suitable device large-signal model to completely and accurately predict the device microwave non-linear behaviors.

Although there are many existing device models, such as Curtice model, Statz model or EE-HEMT model, have been developed for the large-signal simulation of GaAs FET circuit design [4]-[5]. All of them are either too complicated or can't well describe the device non-linear behaviors. Hence, in this paper we propose a modified large signal model for E-pHEMTs, which is based on the conventional Curtice model. In this study, we particularly focus on the model predictions of device non-linear characteristics under the digitally modulated scheme, which is important for the modern communication system.

II. THE DETAILS OF MODIFIED LARGE-SIGNAL MODEL

The modified large-signal model is based on the structure of Curtice model [4]. In order to take the device non-linear behaviors into consideration, instead of using its fixed junction capacitances (C_{gs}, C_{gd}), channel resistance (R_i), and output resistance (R_{ds}), we propose the following equations to describe these elements, which are the functions of V_{gs} and V_{ds} [6]. The measured data were extracted from the small-signal equivalent circuit model under the various biased measurements. These equations representing C_{gs}, C_{gd}, R_i and R_{ds} for quasi E-pHEMTs are expressed here:

$$C_{gs}=C_{gs0}(1+\tanh(A_0+A_1V_{gs}+A_2V_{gs}^2))(1+\tanh(A_3V_{ds})) \quad (1)$$

$$C_{gd}=C_{gd0}(1+\tanh(B_0+B_1V_{gs}+B_2V_{gs}^2))(1-\tanh(1+B_4V_{ds}+B_5V_{ds}^2)) \quad (2)$$

$$R_i=C_0+C_1V_{gs}+C_2V_{gs}^2+C_3V_{gs}^3+C_4V_{gs}^4 \quad (3)$$

$$R_{ds}=D_0+D_1\exp(D_2V_{gs}) \quad (4)$$

The fitting parameters in these equations are extracted from the multi-bias equivalent circuit model elements. As to the drain current equation, we used the same provided by the Curtice model shown in the following [4]:

$$I_{ds}=(A_0+A_1V_x+A_2V_x^2+A_3V_x^3)\tanh(\gamma V_{dsi}) \quad (5)$$

where

$$V_x=V_{gsi}(1+\beta(V_{ds}-V_{dsi})) \quad (6)$$

0.8 μm gate-length quasi E-pHEMTs with a gate-width of 200 μm were fabricated and characterized to build up this modified large-signal model. The simulated platform was carried out in the HP Advanced Designed System (ADS) simulator. The measured threshold voltage (V_{th}), peak transconductance (g_m), f_T and f_{max} are -0.1 V,

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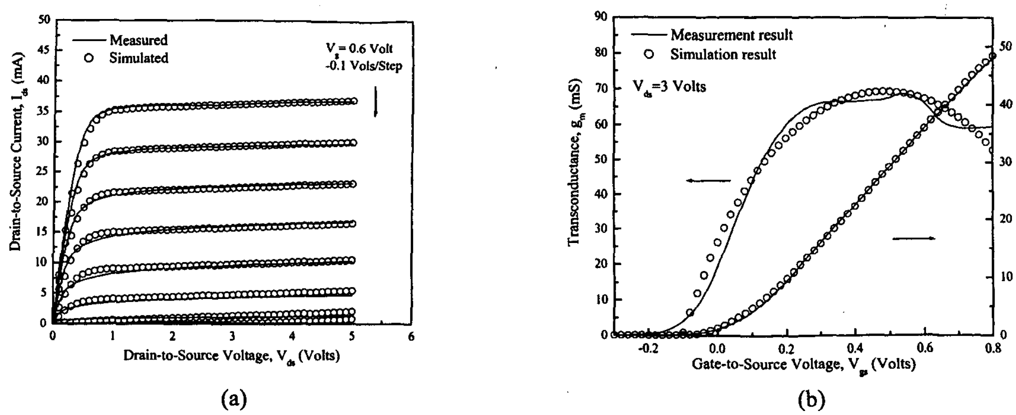


Fig.1 The measured and simulated dc performances of 0.8x200 μm^2 gate-dimension of quasi E-pHEMTs. I_{ds}-V_{ds} curves (a), and g_m-I_{ds}-V_{gs} (b)

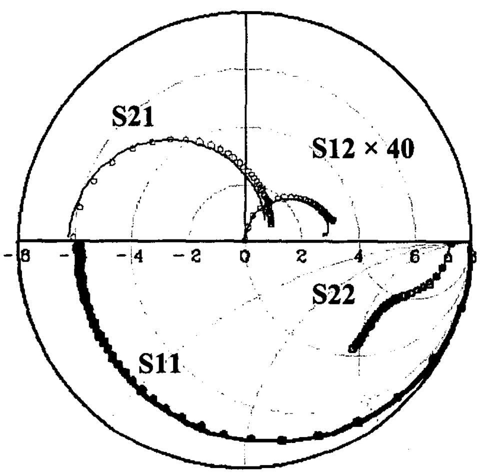


Fig.2 The measured (solid lines) and simulated (open circle points) results of S-parameters under the bias of V_{gs}=0.3 V and V_{ds}=3 V from 50 MHz to 20

325 mS/mm, 18 GHz and 45 GHz, respectively, under the gate and drain biases of 0.3 V and 3 V for this AlGaAs/InGaAs quasi E-pHEMT device.

Fig.1 shows the device dc I-V and g_m characteristics for quasi E-pHEMTs. The model simulating results are also included in these figures, where a good agreement with the experimental ones can be reached. Fig.2 shows the device microwave S-parameters of the frequency range from 50 MHz to 20 GHz (V_{gs}=0.3 V and V_{ds}=3 V.) It is obvious that the excellent agreement is also obtained by using this modified quasi E-pHEMT model.

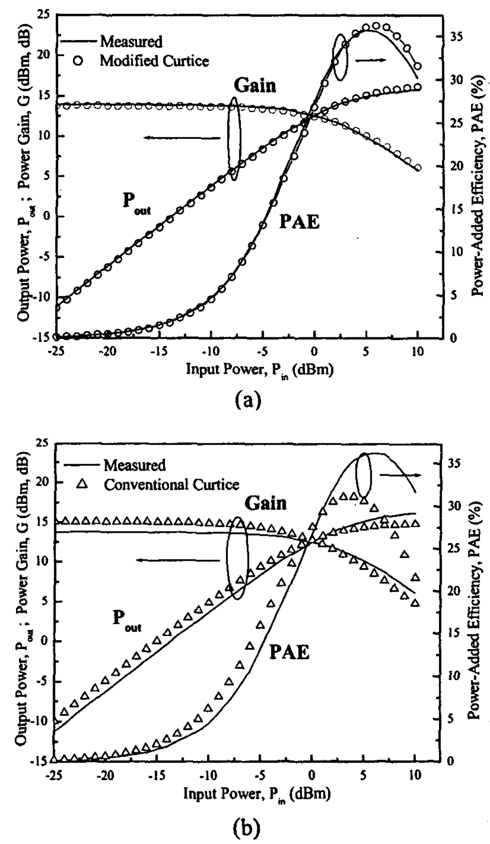


Fig.3 The measured (solid lines) and simulated (open points) output power performance at 2.4 GHz under the bias of V_{gs}=0.3 V and V_{ds}=3 V. Modified Curtice model (a), and conventional Curtice model (b)

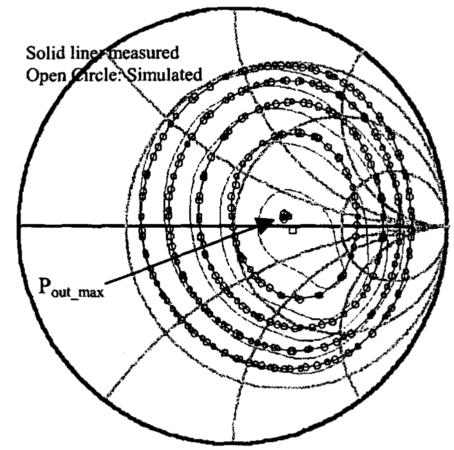
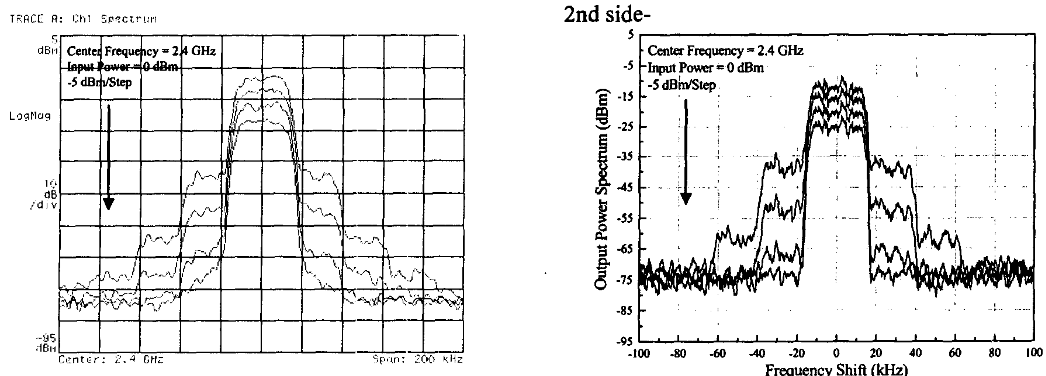


Fig.4 The measured (solid lines) and simulated (open points) power contours with a constant input power of 0 dBm at 2.4 GHz. (-1 dBm/step)

III. MICROWAVE POWER PERFORMANCE OF QUASI E-pHEMTs

Besides the fundamental requirements of the well-matched dc and small signal characteristics provided by the model, a strict and accurate estimation of microwave power performance for quasi E-pHEMTs is also demanded. To fully evaluate the device microwave non-linear behaviors, the device power performance either under a continuous wave or a digitally modulated scheme should be characterized first. Microwave load-pull power performance was evaluated for quasi E-pHEMTs at 2.4 GHz sinusoidal signals under a bias of V_{gs}=0.3 V and V_{ds}=3 V with a 50 Ohm input and output load. Fig.3 (a) represents the output power (P_{out}), power gain (Gain) and power-added efficiency (PAE) as a function of the input power (P_{in}) for the measured and model predicted results. It is observed that an excellent consistence between both is obtained under a wide input power range (-25 dBm~10 dBm). The power gain is 13.9 dB, and the maximum output power density is 190 mW/mm with a maximum PAE of 35.8% for a 200 μm wide E-pHEMT. Furthermore, we also compared them with the predictions from the conventional Curtice model, as shown in Fig.3(b), and it evidences again the accuracy provided by our modified large-signal model. In addition, we also simulated device output power contours, and compared them with the measured ones. In order to obtain the maximum output power, the source impedance of 22.03+j83.1 ohm was fixed. As shown in Fig.4, with a 0 dBm input power, the load-impedance locations for the maximum output power is 15.3 dBm at Γ_L= 0.28 ∠ -3.66° from the load-pull measurement, and is 15.8 dBm at Γ_L=0.24∠9.2° from the model simulation, respectively. A well agreement from both sides can be reached in this power contour evaluation.

Finally, since the signals are digitally modulated in modern communication systems, this is important to assess the device performance by the model under this modulation scheme. In order to evaluate the device non-linear digital behaviors, we applied a π/4 DQPSK modulated NADC signal into this quasi E-pHEMTs to examine the adjacent channel power ratio (ACPR) and output power spectra, and compared them with the simulated results. Fig.5 shows the output spectra versus different input power levels, including the model predicted results, where the pHEMT gate-width is 200 μm. The first side-lobe appears at the input power level larger than –10 dBm, and after input power reaching –5 dBm 2nd side-



(a) (b)

Fig.5 The device output nonlinear behavior, spectral regrowth, at a 2.4 GHz by applying a π/4 DQPSK modulated NADC input signal. Measured spectra (a), and the model prediction spectra (b)

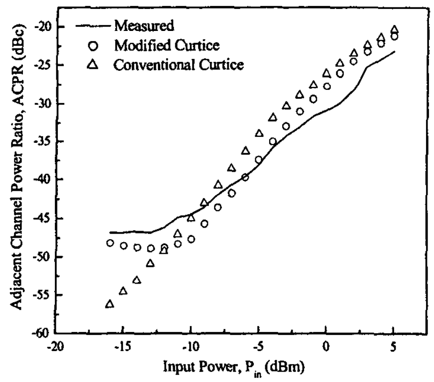


Fig.6 The measured (solid lines) and simulated (open points) ACPR at 2.4 GHz by applying a $\pi/4$ DQPSK modulated NADC input signal.

lobe starts to show up, which indicates that microwave non-linear behaviors become significant at input power of −10 dBm. Suprisingly, our modified model can predict exactly the same output digital spectra as shown in Fig. 5(b). As to the ACPR values extracted from the Fig.5, ACPR increases dramatically at the input power reaching −10 dBm, where the non-linear behaviors start to take off, as shown in Fig.6. However, the conventional Curtice model can't precisely handle the microwave non-linear behaviors of quasi AlGaAs/InGaAs E-pHEMTs.

IV. CONCLUSIONS

In this study, we proposed a modified large-signal model for quasi E-pHEMTs. This model has successfully evidenced to a well prediction of the dc I-V, S-parameters and RF power performance. The device ACPR and spectra regrowth can also be characterized under a digital modulation scheme.

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