The Effect of Temperature on the Nonlinearity of pHEMTs

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Abstract— An understanding of the nonlinearity caused by a change in temperature is important in the design of microwave circuits, most of which are designed using pseudomorphic high electron mobility transistors (pHEMTs). The approach used here is to extract the Taylor series coefficients of the nonlinear drain current and then calculate the values of these coefficients at different temperatures. The calculated coefficient values are then used to obtain and analyse the output powers.

Index Terms— Intermodulation distortion, temperature characterization, semiconductor device modelling.

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1 INTRODUCTION

GaAs-based pHEMTs are gaining wide applications for high-efficiency power amplification as well as applications requiring low noise figures and high gain, particularly at millimeter-wave frequencies[5]. As such, an understanding of the nonlinearity caused by a change in temperature is important in the design of microwave circuits.

In this study, the pHEMT presented is a (0.5×200μm²) AlGaAs/InGaAs/GaAs double channel pHEMT. An analysis of the pHEMT output power is presented and data regarding the temperature effects on the Taylor series coefficients is provided.

We use the Curtice quadratic drain current model[2] to model the drain current, I_{ds} of the pHEMT, given as:

$$I_{dsFET} = \beta(V_{gs} - V_{TO})^2 \tanh(\alpha V_{ds})(1 + \lambda V_{ds}) \quad \text{for } V_{gs} \le V_{pf}$$

$$I_{ds} = I_{dsFET}\left[1 - \frac{\left(\frac{\varepsilon}{\psi+1}\right)(V_{gs} - V_{pf})^{\psi+1}}{\beta(V_{gs} - V_{TO})^2}\right] \quad \text{for } V_{gs} > V_{pf} \qquad (1)$$

where V_{pf} denotes the point on the transfer characteristic where the transconductance begins to degrade, α represents the fitting parameter between the linear and the saturated region, β is the transconductance parameter, λ is the output conductance parameter and it models the slope of the curve in the saturation region, ψ is the exponent of the empirical transconductance degradation parameter, ε is the empirical transconductance degradation parameter, V_{TO} is the pinch-off voltage [4][9]. Other parameters have their usual meanings.

The small signal incremental drain current can be represented by[9]:

$$i_{ds} = g_m v_{gs} + G_{ds} v_{ds} + \tfrac{1}{2}(g_m^I v_{gs}^2 + G_{ds}^I v_{ds}^2 + 2m_{11} v_{gs} v_{ds}) + \tfrac{1}{6}(g_m^{II} v_{gs}^3 + G_{ds}^{II} v_{ds}^3 + 3m_{12} v_{gs} v_{ds}^2 + 3m_{21} v_{gs}^2 v_{ds}) \qquad (2)$$

where the g_m terms g_m, g_m^I, and g_m^{II} are respectively, the transconductance, the second and third order derivatives with respect to V_{gs}. The G_{ds} terms G_{ds}, G_{ds}^I and G_{ds}^{II} are respectively, the output conductance, the second and third order derivatives with respect to V_{ds}. The coefficients $m_{11} = \partial g_m/\partial v_{ds} = \partial G_{ds}/\partial v_{gs}$, $m_{12} = \partial^2 g_m/\partial v_{ds}^2 = \partial G_{ds}^I/\partial v_{gs}$ and $m_{21} = \partial g_m^I/\partial v_{ds} = \partial^2 G_{ds}/\partial v_{gs}^2$ are the cross-terms.

Also, the expression for the fundamental output power and IMD products of a pHEMT amplifier which is based on (2) is given by[7]:

$$P_{lin} = \frac{1}{2}(g_m + G_{ds}A_v)^2 V_s^2 R_L \qquad (3)$$

$$P_{IMD2} = \frac{1}{8}(g_m^I + G_{ds}^I A_v^2 + 2m_{11}A_v)^2 V_s^4 R_L \qquad (4)$$

$$P_{IMD3} = \frac{1}{128}(g_m^{II} + G_{ds}^{II} A_v^3 + 3m_{12}A_v^2 + 3m_{21}A_v))^2 V_s^6 R_L \qquad (5)$$

2 MEASUREMENTS AND MODEL ANALYSIS

We use the d.c measurement data obtained from the Research Group at the School of Electrical and Electronic Engineering, University of Manchester. The modelled drain current values are calculated from (1). The optimum parameter values are obtained by minimizing the sum of the squared errors between the measured values and the calculated/modelled values. However, the beta and alpha for the output characteristic is 0.058 and 0.008 respectively. The optimized parameter values for the model are in Table 1.

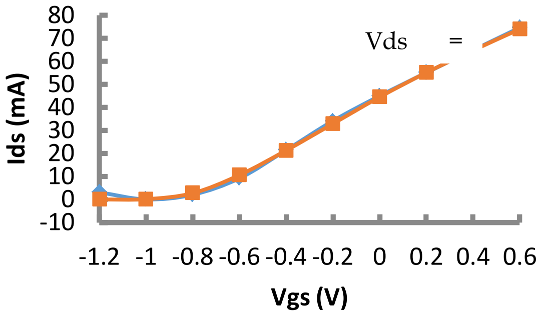
Fig. 1 shows good agreement between the measured and modelled drain currents. The analysis that follows depends on the I_{ds} data at V_{gs} values from -1V to +0.6V. This is to prevent the error at V_{gs}= -1.2V in Fig. 1a from propagating to other values during differentiation. The trans-conductance is obtained by differentiating the drain current with respect to the gate to source voltage at constant V_{ds}, in this case, V_{ds} = 3V and in saturation. The output conductance is obtained by differentiating the drain current with respect to the drain voltage. The cross-terms are calculated by first differentiating with respect to V_{ds} and at constant V_{ds}, differentiated with respect to V_{gs} [7].

Table 1

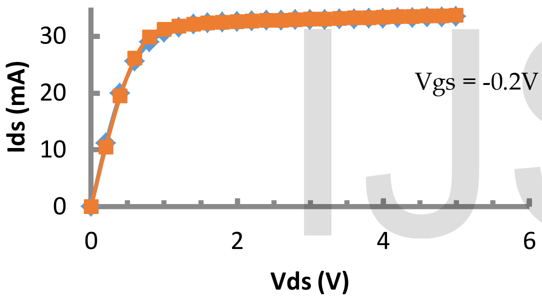
The fitting parameter values for the nonlinear drain current.

Parameter	Values(Transfer Characteristic)
ψ	0.8
ξ	0.105
β (A/V²)	0.044

α	1.8
λ	0.15
P_{in} (dBm)	-10 to 10 with a step of 5
V_{gs} (V)	-1.2 – 0.6 with a step of 0.2 V
V_{TO} (V)	0.98
V_{pf} (V)	-0.4



(a) The transfer characteristic of the 0.5 × 200µm² GaAs DCh pHEMT



(b) The output characteristic of the 0.5 × 200µm² GaAs DCh pHEMT

Fig. 1. The transfer characteristic (a) and the output characteristic (b) of the 0.5 × 200µm² GaAs DCh pHEMT, showing a close match between the measured and simulated results. Simulated ─◆─ , Measured ─■─

3 TEMPERATURE DEPENDENCE MODELLING

In the temperature range, -25ºC to 125ºC, all equivalent circuit parameters and indeed the physical parameters show a linear temperature dependent relationship expressed as [1][8]:

$$P(T) = P(T_o)[1 + \beta(T - T_o)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where β is the temperature coefficient in units per degree, T_o is the reference temperature in ºC, and $P(T_o)$ is the value of the parameter at the reference temperature. The temperature coefficients of g_m and R_{ds} are -1.44×10^{-3} and 0.39×10^{-3} respectively[8]. From R_{ds}, the temperature coefficient of G_{ds} is calculated as -0.36×10^{-3}. These temperature coefficients are used to determine the values of the Taylor series coefficients at different temperatures. It is important to note that the cross terms were also found to vary with temperature in the same way as G_{ds}. The temperature coefficients for m_{11}, m_{12} and m_{21} are -0.359×10^{-3}, -0.36×10^{-3} and -0.37×10^{-3}, respectively. The cross terms are obtained by first differentiating the drain current with respect to the drain voltage before differentiating with respect to the gate voltage. This accounts for the similarity of their temperature coefficients with G_{ds}.

4 OUTPUT POWER

Equations for the linear output power and intermodulation products (IMD) in (4) – (6) are used to calculate the output powers.

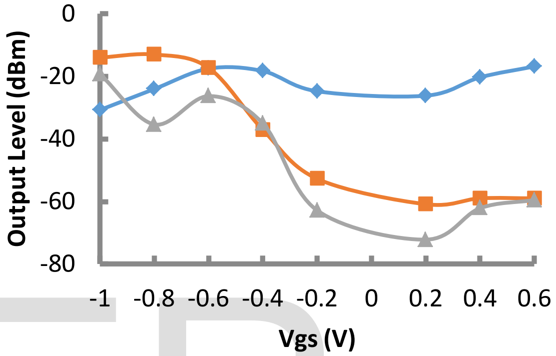
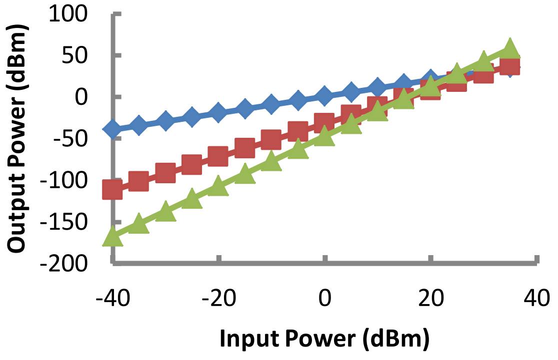


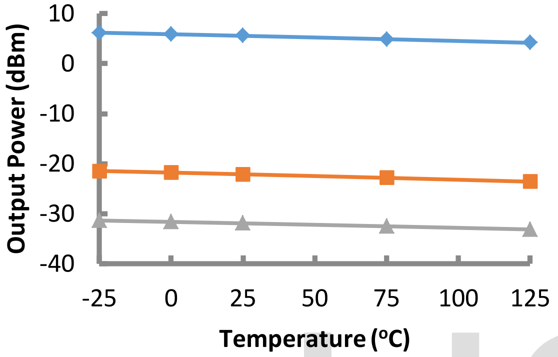
Figure 2 shows the linear output power, the second and third order IMD products. It appears Fig. 2 does not accurately model the IMD2 and IMD3. However, it is important to note that intermodulation products are both bias and load dependent[3][6]. It is suggested[3] that an increase in V_{ds} leads to a decrease in the IMD products due to G_{ds}. It is also observed that the cancellation points (dips) in the IMDs are delayed or postponed as V_{ds} is increased

Fig. 2. Fundamental(─◆─),second order(─■─) and third order (─▲─) IMD output levels of a (0.5×200µm²) AlGaAs/InGaAs/GaAs double channel pHEMT biased at V_{ds} = 3V.

There is also some nulling when V_{ds} is increased. These, in addition to measurement errors, may account for the reduction in IMD2 and IMD3 powers at V_{ds} = 3V, and also the delay in the cancellation effects of the second and third order G_{ds} and g_m terms.



(a) Output power at 25°C and P_{in} = -40dBm to 35 dBm



(b) Temperature = -25°C to 125°C, P_{in} = 5dBm,V_{gs} = -0.2 V

Fig. 3. Fundamental(—◆—),second order(—■—) and third order (—▲—) IMD output levels of a (0.5×200µm²) AlGaAs/InGaAs/GaAs double channel pHEMT biased at V_{ds} = 3V.

A regression analysis shows that the fundamental output power depends mostly on the trans-conductance and voltage gain (A_v), both are highly negatively correlated. The variation of IMD2, it was found, depends almost equally on g_m^I and G_{ds}^I while the IMD3 depends slightly more on G_{ds}^{II} than g_m^{II}. It is known that the contribution of the G_{ds} terms dominate at low input powers while the g_m terms dominate at high input powers [3]. The statistical results give some insight as to the extent to which these terms affect the variation of the total output powers.

With the exception of the IMD2, the output powers showed very little difference when the cross terms were removed. Fig. 3 shows calculated output powers at P_{in} = 5dBm for different temperatures using Taylor series coefficient values at those temperatures. It is easy to see in the Figure that the linear output power and the intermodulation products decline steadily as temperature increases. The converse is also true. This is due mainly to the negative temperature coefficients of the terms that contribute to these output powers.

5 CONCLUSION

The use of temperature coefficients of the extracted Taylor series coefficients of the nonlinear drain current in analysing the effect of temperature on the nonlinearity of pHEMTs has been demonstrated. The factors and interactions that lead to a reduction in the pHEMTs' output power have also been analysed. The analysis presented in this paper is important as the data provided can be used in the design optimization of pHEMT devices for future high performance power amplifiers.

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