Temperature Dependent Linear HEMT Model Extracted with Multi-Temperature Optimization

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Abstract — Temperature dependent model is conventionally developed with 1) individual linear model extraction at each temperature and 2) temperature dependence extraction for each model parameter. A novel approach based on a multi-temperature optimization is proposed in this study. The new approach is faster and more accurate since the linear models at different temperatures are extracted simultaneously and interrelatedly. It has been found, based on the model extracted, that there is a specific gate-source voltage of $V_{gs0}$, where the transconductance ($G_m$) keeps constant versus temperature. $G_m$ increases (decreases) with temperature for $V_{gs}<V_{gs0}$ ($V_{gs}>V_{gs0}$). With increasing temperature, a substantial decrease in extrinsic inductance is also observed. Our findings are believed to be useful for designing HEMT amplifiers with less temperature dependence.

Index Terms — Amplifiers, circuit simulation, HEMTs, parameter extraction, semiconductor device model, temperature dependence.

I. INTRODUCTION

A temperature dependence linear GaAs HEMT model is needed to predict circuit performance over wide operating temperature range. A temperature dependent model is conventionally developed with 1) extracting linear model for each given temperature, and 2) establishing temperature dependence for each model parameter [1]-[3]. For example, the temperature dependence of the transconductance ($G_m$) can be established by fitting the extracted $G_m$ with a linear function. Since each $G_m$ is extracted independently, the residual error of the linear fitting could sometime be substantial.

In this paper, a novel approach is proposed for developing a temperature dependent linear HEMT model. A multi-temperature optimization is used instead of multiple single temperature optimizations. Two optimal variables, the nominal value and the temperature coefficient, are assigned to each model parameter, the same model parameters at different temperature are thus correlated during the optimization. This correlation among the model parameters can be regarded as constraints to the optimization, which effectively reduces the number of local minima and initial value dependence. Our approach improves on the conventional one in much faster extraction and more accurate temperature dependent linear model.

This paper is organized as follows. Experimental details are given in section II. The proposed approach and the extracted temperature dependent model are described in section III and IV, respectively, and the paper is then concluded in section V.

II. EXPERIMENT

Enhancement-mode pseudomorphic AlGaAs/InGaAs/GaAs HEMTs with signal-ground-signal test pad were fabricated on GaAs substrate. The pinch-off voltage of the device is around 0.3V. DC and S-parameter measurements were conducted via probe station at the six different temperatures of -10, 0, 25, 50, 80, and 105°C, respectively. S-parameters were measured in the frequency range of 0.2 to 20.2GHz.

III. MULTI-TEMPERATURE OPTIMIZATION

The equivalent circuit model with fifteen model parameters is shown in Fig 1; $R_{gs}$ is added to account for the Schottky diode under forward bias. At first, six linear models, corresponding to the temperature of -10, 0, 25, 50, 80, and 105°C, were obtained by performing optimization for each temperature individually. Then a linear fitting was performed to obtain the temperature dependence for each model parameter. The extracted $G_m$ , for example, are shown in Fig. 2. As can be seen that it is sometime difficult to establish an accurate temperature dependence because of the scattered data.

A multi-temperature optimization is then used to replace the six single temperature optimizations and the fifteen linear fitting. Before doing optimization, a temperature dependence is assigned to each model parameter as
Fig. 1. Equivalent circuit of E-PHEMT used in this study.

Fig. 2. Temperature dependence of $G_m$ extracted with single temperature and multi-temperature approaches.

$$X = A[1 + B(T - 25)],$$  \hspace{1cm} (1)

where $A$ and $B$ are the nominal value and temperature coefficient of the model parameter $X$. Model parameters at different temperature are thus correlated with (1) during the optimization. Instead of model parameter itself, $A$ and $B$ are used as optimal variables. The optimization residual error is now the sum of the residual error at each temperature.

Comparing with a single temperature optimization, there are only two times as many optimal variables, and, however, six times as many equations for a six temperature optimization. In other words, there are more constraints for a multi-temperature optimization, which leads to less local minima and less initial value dependence.

Six linear models and the temperature dependence for each model parameter have been obtained simultaneously with the multi-temperature optimization. Good S-parameter fittings are achieved for all them. The new approach is faster and more reliable. The extracted temperature dependence of $G_m$, as an example, is also shown in Fig. 2. A much better linear fitting can be achieved since the model parameters at different temperature are interrelatedly extracted. A better linear fitting for each model parameter leads to a more accurate temperature dependent linear model.

IV. HEMT LINEAR PERFORMANCE OVER TEMPERATURE

The linear temperature dependence shown in (1) is good enough to predict the HEMT thermal behavior in the temperature range of -10 to 105°C. With increasing temperature, decrease in $R_{gs}$ and increases in $R_g$, $R_d$, $R_s$, $C_{gs}$, $C_{gd}$, and $C_{ds}$ are observed. The temperature dependences of $C_{pg}$ and $C_{pd}$ are found to be negligible.

A. Temperature Dependence of $G_m$ and $R_{ds}$

With increasing temperature, a decrease in $G_m$ and an increase in $R_{ds}$ have been reported. However, it has been found, in this study, that both an increase and a decrease in $G_m$ and $R_{ds}$ can be expected depending on the bias point. The temperature dependences of the extracted small signal $G_m$ are shown in Fig. 3. $G_m$ increases (decreases) with temperature for $V_g=0.5V$ (0.7V), and keeps constant for $V_g=0.575V$.

The $G_m$ extracted from the DC transfer curve is shown Fig. 4. The DC $G_m$ is consistent with the small signal $G_m$. In the lower $V_g$ region, the $G_m$ increases with temperature due to the shift in pinch-off voltage; in the higher $V_g$ region, the $G_m$ decreases with temperature due to the decrease in the electron saturation velocity. The two effects cancel each other at a specific $V_g$, where a constant $G_m$ can be expected. The temperature dependence of $R_{ds}$ ($G_{ds}$) is shown in Fig. 5, which can be explained in the same way.

B. Temperature Dependence of Extrinsic Inductances
The temperature dependences of the extrinsic inductances extracted with multi-temperature optimization are shown in Fig. 6. While the source inductance ($L_s$) keeps almost constant, both drain and gate inductances ($L_d, L_g$) decrease substantially with temperature. Since it is not clear yet how to attribute physical meaning to the decrease in the inductances, efforts were made to achieve good S parameter fitting for every temperature with constant inductances. After many tries, our conclusion is, however, that a good fitting can only be achieved with temperature dependent inductances as long as the equivalent circuit shown in Fig.1 is used.

In addition to optimization, the extrinsic inductances can also be extracted directly from cold-FET measurements. For example, $L_d$ can calculated as 

$$L_d = \frac{\text{imag}(Z_{22} - Z_{12})}{a}, \quad (2)$$

where the Z parameters are converted from the S parameters measured at $V_d=0$ and $V_g=1$V over temperature. The directly extracted $L_d$, as shown in Fig. 7, is pretty stable versus frequency. The decrease in $L_d$ with temperature can be clearly observed. Substantial decreases have been observed for both $L_d$ and $L_g$, and the decrease in $L_s$ is minor. The directly extracted inductances are consistent with those obtained from optimization.

V. CONCLUSION

Multi-temperature optimization has been used for extracting temperature dependent linear HEMT model, which simplifies the extraction procedure and yields a more accurate temperature dependent model. It has been found, based on the model extracted, that both increase and decrease in $G_m$ can be expected by increasing temperature, which is believed to be useful for designing amplifier with less temperature dependence. The decrease in extrinsic inductances with temperature has also been observed, which needs to be taken into account for achieving an accurate temperature dependent linear HEMT model.

REFERENCES

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