The Thermal Gain Effect in GaAs-Based HBT's

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Abstract — **The existence of increased, low frequency gain in GaAs HBT amplifiers is shown to be due to temperature modulation by the input signal. Device data is presented and the effect is reproduced using an electro-thermal HBT model. The effect may be important in many broadband, bipolar device applications.**

I. Introduction

In the development of multiple-stage, broadband InGaP/GaAs HBT amplifiers to recover received signals for telecommunication applications, a significant gain increase was observed at low frequencies. The increased gain has been found to result from operation at a frequency where the device's temperature can be modulated by the input signal. The effect is inherent to bipolar devices and therefore may be of great importance in many applications. In addition, the effect may influence the noise spectra of a device. Bruce et al. [1] have shown that this effect also occurs in Si/SiGe HBTs and may be used to measure the thermal time constant.

Telecommunication receiver post-amplification and modulator driver applications may require amplifiers operating from 10 KHz to 2.5, 10 or even 40 GHz. The increased gain effect, here called thermal gain, can occur for 10 KHz to several MHz. The increased gain can result in severe distortion of the signal waveforms.

In this paper, we will present an analytical derivation of the effect, evaluate its importance in real devices and show that an electro-thermal bipolar model can simulate the effect.

II. Typical Device Data

Fig. 1 shows S21 gain data for a typical InGaP/GaAs HBT device of 2x2 um^2 emitter area. Notice that the gain increases significantly below 5 MHz. The device is operated at constant base current of 10 μA and has a fixed collector voltage bias of 1.5 V. The gain at 30 KHz is about 0.5 dB larger than the gain in the larger MHz range. In a multiple-stage circuit design, the low-frequency gain was found to be 26 dB, whereas the higher frequency gain was 20 dB. This resulted in an unacceptable level of signal distortion.

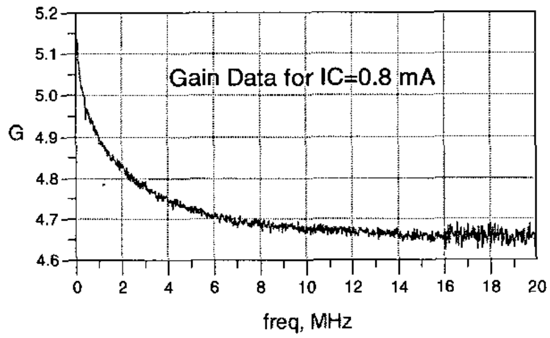

Figure 1. S21 gain in dB vs. frequency for a typical GaAs HBT.

III. Derivation of the Thermal Gain Effect

The collector current of a bipolar device is

$$I_c = I_s e^{\frac{V_{be}}{v_{th}}} , \quad (1)$$

where

$$v_{th} = N \frac{kT}{q} . \quad (2)$$

The gain of the device is proportional to the transconductance , g_{mo}, which is

$$g_{mo} = \frac{d I_c}{d V_{be}} . \quad (3)$$

For constant temperature, this is simply equal to

$$g_{mo} = \frac{I_c}{v_{th}} . \quad (4)$$

However, if the device temperature is modulated by the input signal, then both I_s and v_{th} are functions of V_{be} and their derivatives must be included to evaluate g_{mo}. It is

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shown in the Appendix that these additional derivatives generate the following expression

$$g_{mo} = (1.0 - D1 \times D2)\frac{I_c}{v_{th}} , \quad (5)$$

where

$D1$ = the dynamic derivative of the device temperature with input voltage, V_{be}, change,

and

$D2$ = the static derivative of V_{be} with temperature to maintain I_c constant.

D2 can be easily measured by biasing the device at constant current and operating at various values of heat sink temperature. *D1* will be determined by the circuit and input frequency. For high frequencies whose period is much smaller the thermal time constants, *D1* will be very small, since very little change of temperature will occur during the RF cycle. But, for low frequencies, *D1* will be important. Since *D1* is usually positive and *D2* typically is negative, equation (5) predicts larger gain when *D1* is not negligible.

IV. SIMULATION RESULTS

Using a model that includes self-heating effects [2], harmonic-balance simulations were made for a device with Gummel-Poon model parameters extracted in the usual manner. The circuit uses the same biasing conditions as for the data of Fig. 1 and has 50 ohm input and output impedances.

Fig. 2 shows the waveforms for the circuit with input power of –60 dBm at 10 KHz. Notice that all waveforms are in phase with the input signal at this frequency. Thus, device temperature clearly is a function of the instantaneous base-emitter voltage. The relationship of the I_c and V_{ce} waveform (not shown here) is that of negative resistance.

Fig. 3 shows the gain increase at low frequencies as a function of the value of *D2* as evaluated from simulations. The value of *D2* could be adjusted by varying the bandgap parameter of the model. Fig. 3 is in good agreement with the simple analysis, i. e. Eq. (5). However, the curve of Fig. 3 does not go through zero when *D2* is zero because base current is held constant in the simulation, as in the actual test. Eq. (5) assumes constant collector current.

From Figure 2, the value of *D1* for this circuit is approximately 0.055 deg/mV. The measured value of *D2* for the biasing conditions of Fig. 1 is –1.04 mV/deg. From Fig. 3, the simulated gain increase is about 0.45 dB, in good agreement with the data of Fig. 1.

V. DISCUSSION

The increased gain at low frequencies has resulted from the variation of the device temperature by the input voltage. It is often assumed that the thermal time constant is slow enough that these effects should be very small. However, the transient thermal behavior is not well represented by a single time constant. At least two quite different values are required [3,4]. Physically, this means that there is a local time constant and a remote time constant. The latter is most likely associated with the heat sink. The local time constant is the fastest and is responsible for the behavior seen here. The data of Fig. 1 indicates a fast time constant of about 0.05 us. The remote time constant is believed to be about 2 us.

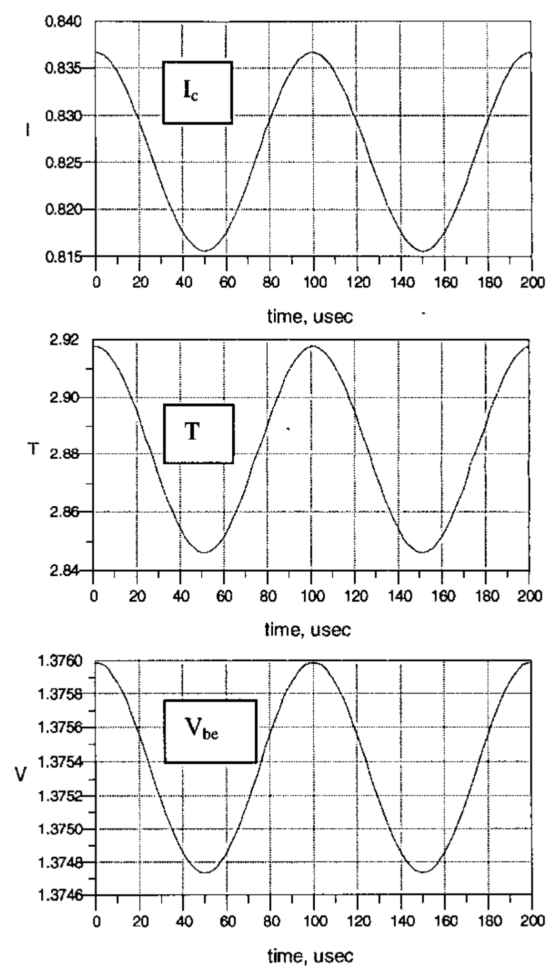

Figure 2 I_c in mA, Temperature rise in Deg. C., and V_{be} in Volts as a function of time.

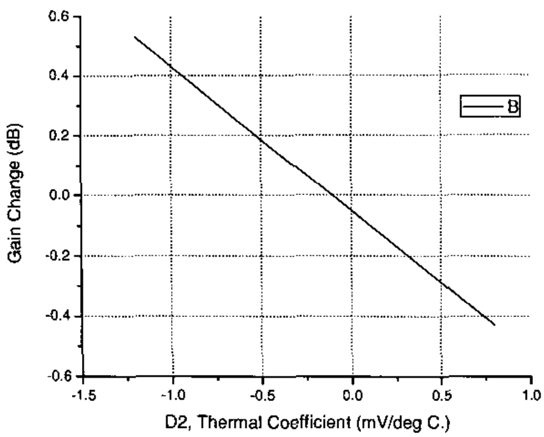

Figure 3. Calculated Gain Change as a function of the Value of D2 for the 50-ohm circuit.

It was found that the value of *D1* depends strongly on the resistive load. In fact, Cherepko and Hwang[5] have shown that *D1* can be made zero by choosing a load line that produces constant temperature as V_{be} is varied. For the HBT device shown here, such a load would be much larger than desired for proper circuit design.

VI. Conclusion

Increased gain at low frequencies has been shown to be due to temperature modulation of the device by the input signal. We call this additional gain, thermal gain and it occurs even though the power dissipation is negligible. It should be observable in all bipolar devices, not just the GaAs-based HBT, as shown here.

Appendix

The derivative of collector current with respect to base emitter-voltage, Eq. (3), is

$$g_{mo} = I_c \left\{ \frac{1}{v_{th}} + \frac{dT}{dV_{be}} \left(\frac{dI_s}{dT}\frac{1}{I_s} - \frac{V_{be}/T}{v_{th}} \right) \right\}.$$

If collector bias current is held constant as the temperature changes, $dI_c/dT = 0$. But,

$$\frac{dI_c}{dT} = \left\{ \frac{dI_s}{dT} + \frac{I_s}{v_{th}}\frac{dV_{be}}{dT} + I_s\left(\frac{-V_{be}}{T} \middle/ v_{th} \right) \right\} e^{\frac{V_{be}}{v_{th}}}.$$

Combining these three equations gives Eq. (5), with

$$D1 = \frac{dT}{dV_{be}}$$

and

$$D2 = \left. \frac{dV_{be}}{dT} \right|_{I_c = const.}.$$

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