LOW-FREQUENCY DISPERSION AND ITS INFLUENCE ON THE INTERMODULATION PERFORMANCE OF AlGaAs/GaAs HBTs

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Abstract

The relationship between low-frequency dispersion and the intermodulation performance of AlGaAs/GaAs HBTs has been demonstrated for the first time. The theoretical analysis and experimental results indicate that IM_3 will depend strongly on the frequency spacing ($\Delta f = f_2 - f_1$) in the two-tone measurement.

I. Introduction

In this paper, we demonstrate for the first time that the IM_3 value may not fully represent the linearity of an HBT amplifier if the HBT has the low frequency dispersion with the dispersion transition frequency f_{TH} higher than the frequency spacing between two signal components in a communication system. AlGaAs/GaAs HBTs have been widely used to fabricate microwave power amplifiers for mobile communication systems [1,2,3]. In these systems, the linearity performance is extremely important since the channel spacing can be as narrow as 25 kHz and the space between the signal frequency components from different channels can be much less [4]. A common figure of merit used to estimate the linearity of a system is the value of IM_3 from a two-tone measurement. The widely accepted frequency spacing Δf ($\Delta f = f_2 - f_1$) between two tones is 2-20 MHz [3,8]. It is proposed in this paper that the frequency spacing in a two-tone measurement must be carefully chosen to include the influence from the low-frequency dispersion.

The low-frequency dispersion in AlGaAs/GaAs HBTs is mainly caused by the self-heating effect. For example, the collector current characteristics of the HBT with a constant base current value often have a negative slope which implies $\frac{dI_C}{dV_{CE}} < 0$. The small-signal output resistance will have a negative value when the frequency is close to DC. The output resistance will increase smoothly with frequency and finally reaches a positive constant value at a frequency which is much greater than f_{TH}. Other small-signal parameters also have a similar frequency dependence. These phenomena can be used to characterise the dynamic part of the HBT thermal equivalent circuit and have been included in the existing large-signal HBT model using a simple RC section [6]. The influence of low-frequency dispersion on IM_3 is explained in the following section.

TH 2B

II. Theoretical Analysis

In Fig.1, an HBT and its thermal equivalent network is shown in a four-port fashion. Port 1 and Port 2 are the input and output ports for the electrical signals (they are base-emitter and collector-emitter for common-emitter operation). Port 3 and Port 4 are the thermal ports of the HBT. Port 3 is a current source where the current from the port represents the instantaneous power dissipation, P_D. The P_D spectrum is altered by a thermal low-pass network, with transfer function $H(\omega)$ in the frequency-domain [7]. The output spectrum from the thermal network represents the spectrum of junction temperature. This junction temperature, $T_J(t)$ is fed back to Port 4 which is a control port and its voltage will influence instantaneously the electrical behaviour of the HBT at Port 1 and Port 2. f_{TH} is used here to represent the transition frequency of this low-pass RC thermal equivalent circuit $H(\omega)$. For a signal frequency $f_s \ll f_{TH}$, the AC signal is located in the pass-band of the thermal network and its

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power will change the junction temperature instantaneously and alter the HBT's nonlinear behaviour. For $f_s \gg f_{TH}$, the AC signal is located in the stop-band, its power will be filtered by the RC thermal low-pass network and cannot influence the junction temperature. f_{TH} is normally less than 1 MHz for a normal HBT [5]. The spectrum of a two-tone measurement is also shown in Fig.1. When the two equal-amplitude signal components f_1 and f_2 are added to Port 1, a series of frequency components are generated due to the nonlinearity of the HBT. These components include $(f_2 - f_1)$, $(2f_1 - f_2)$, f_1, f_2, $(2f_2 - f_1)$, $2f_1$ and $2f_2$. $\Delta f = f_2 - f_1$ is the lowest frequency component in this spectrum. If $\Delta f \gg f_{TH}$, this frequency component does not influence the HBT behaviour and the junction temperature maintains a constant value and can be calculated using the DC bias condition. If $\Delta f \ll f_{TH}$, the instantaneous junction temperature of the HBT varies with time and the junction temperature can be considered as a DC component plus an AC component ($T_J = T_{J_DC} + \Delta T_{J_{AC}} \cdot \sin(\Delta\omega \cdot t)$). Since the electrical behaviour of the HBT is a strong function of the junction temperature, this temperature variation will instantaneously modulate the nonlinear behaviour of the HBT and modify the spectrum of the output signal. The whole interaction process is extremely complex and the only way to describe it is to use a large-signal HBT model with a dynamic thermal equivalent circuit [6]. The large-signal model has been used to simulate the two-tone behaviour at 2 GHz for the power HBT used in [6]. Fig.2 demonstrates simulated junction temperature for the IM_3 with $\Delta f \ll f_{TH}$ and $\Delta f \gg f_{TH}$. For the $\Delta f \gg f_{TH}$ case, the junction temperature is nearly constant and can be calculated from the DC bias condition. For $\Delta f \ll f_{TH}$, the junction temperature varies with the frequency Δf. Fig.3 shows the simulated two-tone results for the same power HBT. The results clearly indicate that the $\Delta f < f_{TH}$ case has IM_3 values several dB higher than the $\Delta f > f_{TH}$ case. For a fixed input power level, the IM_3 variation with Δf was simulated and the results are shown in Fig.4. The model uses one RC section with $f_{TH} = 3$ kHz. Fig.4 shows that the value of IM_3 increases sharply when Δf is close to the transition frequency, IM_3 becomes independent of Δf when $\Delta f \gg f_{TH}$.

III. Measurement Set-up and Results

Since this is the first time that the influence of the dispersion on IM_3 is proposed theoretically for AlGaAs/GaAs HBTs, a carefully designed measurement procedure is required to verify the theory. The measurement system is shown in Fig. 5. Two spectrum-analysers are used to monitor the input and output ports of the HBT. It is very important to monitor the input port spectrum to avoid any possible IM_3 components from the driving amplifier. The two signal sources are isolated from each other and a 6 dB attenuator is used to isolate the amplifier output and the HBT input. Another 3 dB attenuator is also connected between the spectrum analyser and the HBT to isolate these two parts. Using this set-up, the possible influence from the measurement system on the measurement results is minimised. Two measurements have been performed on a power HBT which is mounted in a 50 Ω environment. Fig.6 shows the P_{out} vs. P_{in} and IM_3 vs. P_{in} results at 1.8 GHz with two different values of Δf. The IM_3 with small Δf ($\Delta f = 4.65kHz$) is at least 4 to 6 dB higher than the large Δf ($\Delta f = 5.03MHz$) for both low power and high power levels. Then the power levels of the two signals were kept constant (3 dBm), and Δf was varied. The variation in IM_3 with Δf in the range 4 kHz to 7 MHz was measured. In Fig.7, IM_3 is constant from 10 kHz to 10 MHz and rises sharply for $\Delta f < 10$ kHz. This sharp rise indicates that f_{TH} is located around a few kHz for this device. Comparing the simulated (Fig.3 and 4) and measured (Fig.6 and 7) results, there is no doubt that it is the low-frequency dispersion that causes these variations in the IM_3 values of an HBT. It should be pointed out that the simulated example and measured device represent HBTs from different sources, but they are both power HBTs biased in the same region. Since the objective is to prove the influence of low-frequency dispersion on IM_3, using different devices does not affect the conclusion. f_{TH} depends on the device size and finger layout and is normally in the range from a few kHz to

1 MHz [5].

IV. Conclusions

The influence of low-frequency dispersion of the AlGaAs/GaAs HBT on the values of IM_3 is reported for the first time in this paper. The frequency spacing between two-tone signals in a two-tone measurement can influence the IM_3 value strongly. The simulated and measured results indicates that the IM_3 value is dependent on Δf, if the HBT has the low-frequency dispersion effect caused by self-heating. The results presented here suggest that the IM_3 measurement with the conventional 2-20 MHz frequency spacing between two-tone signals may not fully represent the linearity performance of HBT amplifiers. The frequency spacing in a two-tone measurement should be carefully chosen to ensure that the measurement is a true reflection of the system performance. Other microwave devices, such as MESFETs and PIN diodes also exhibit low-frequency dispersion and may face a similar situation to the one discussed in this paper.

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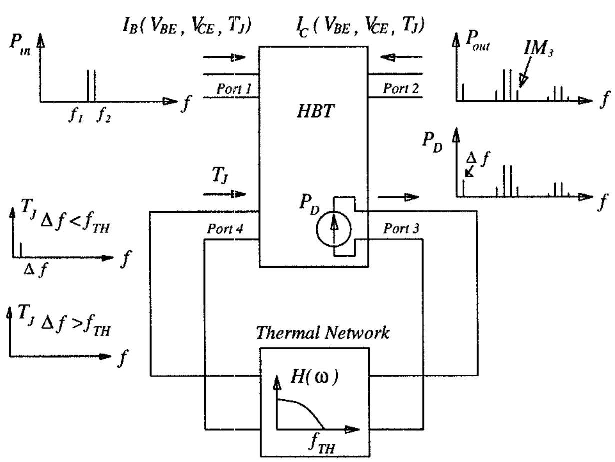

Figure 1: Electro-thermal Equivalent Circuit of an HBT.

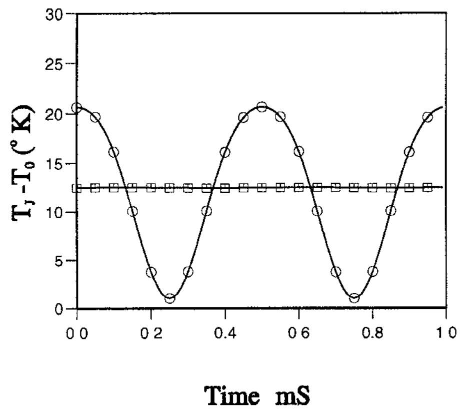

Figure 2 Simulated T_J, $f_{TH} = 3kHz$
Circles: $\Delta f = 2kHz$; Boxes: $\Delta f = 2MHz$

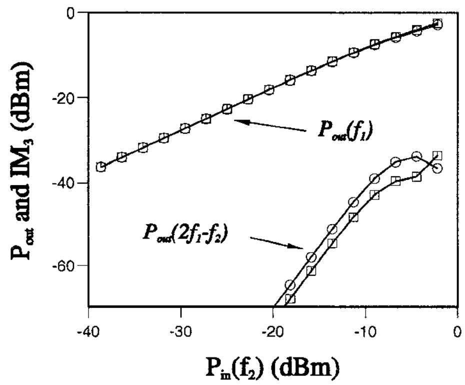

Figure 3 Simulated P_{out} and IM_3 vs. P_{in}
Circles: $\Delta f = 2kHz$; Boxes: $\Delta f = 2MHz$

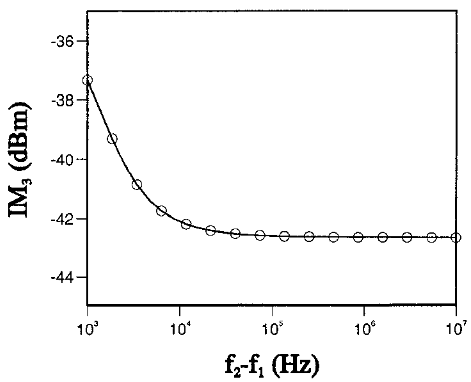

Figure 4 Simulated IM$_3$ vs. Δf ($f_{TH} = 3kHz$)

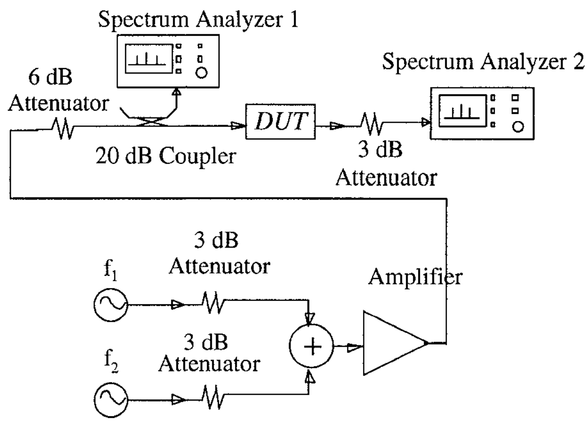

Figure 5 Two-tone Measurement Setup

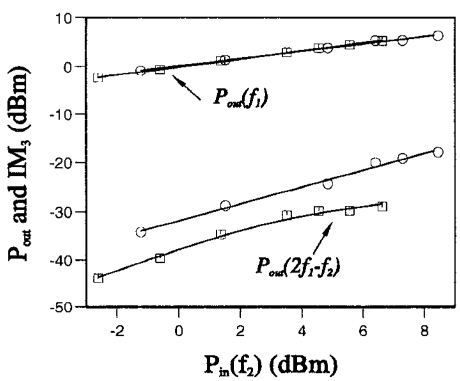

Figure 6 Measured P$_{out}$ and IM$_3$ vs. P$_{in}$ at $1.8GHz$
Circles: $\Delta f = 4.65kHz$; Boxes: $\Delta f = 5.03MHz$

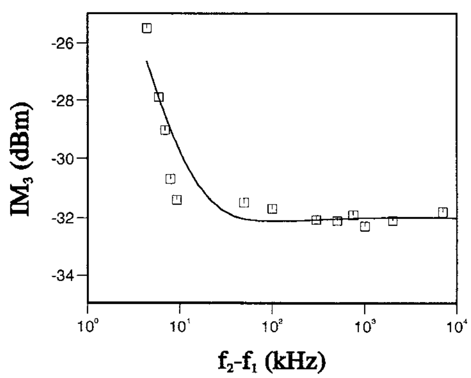

Figure 7 Measured IM$_3$ vs. Δf with
P$_{in}$(f$_1$) = 3dBm and $f_1 = 1.8GHz$