Analysis of Intermodulation Distortion in GaAs/AlGaAs HBT's

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Abstract

The purpose of this work is to help explain the third-order intermodulation distortion properties of the heterojunction bipolar transistor at millimeter wave frequencies. By using both measured data and an analytical computer model that includes transit time effects, we have investigated the frequency and bias dependence of the IMD3 intercept point. A computer controlled mechanical tuner system has been used to measure the IMD3 performance of several HBT's from 8 to 16 GHz. A separate active load pull system has been built to characterize the HBT's from 26.5 to 35 GHz. Comparison between theoretical and experimental results is given. [1]

I. Introduction

Over the past decade, vast improvements in fabrication technology have made high frequency power HBTs realizable. Output powers as high as 5 Watts have been obtained for a 6 cell monolithic HBT amplifier [1] and intermodulation intercept points as high as 35 dBm have been reported [2]. In many applications, device linearity, as well as power, is a significant design consideration. It is therefore necessary to accurately characterize the device nonlinearity using intermodulation distortion measurements.

In this paper, we present the measured and modeled third-order IMD intercept point from 8 to 35 GHz for a typical HBT operating in class A mode. The first part of the paper discusses our measurement systems. At low frequencies, a conventional passive tuner system was used. However, beyond 27 GHz, an active load pull approach was implemented. Subtle differences between active and passive tuning techniques are discussed, with particular attention being given to errors in the measurement technique and ways to reduce it. To help understand the measurements, a harmonic balance based computer model has been developed. We briefly describe this model. The remainder of the paper discusses our results.

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II. Measurement Systems

Third-order intercept measurements were performed by using two signal generators at frequency f_1 and f_2. The signals were kept equal in amplitude and were separated in frequency by a small amount, typically 1 MHz. Intermodulation distortion (IMD3) was measured using a spectrum analyzer to detect the power level of a signal at a frequency $2f_1 - f_2$. Two different measurement systems have been used to characterize the IMD3 intercept of several HBTs.

A. 8-16 GHz Measurements

At lower frequencies (8 to 16 GHz), a commercial computer controlled tuner system was used to vary the load impedance [3]. The source impedance was nominally 50 ohms. Before measuring any devices, the IMD of the system was checked to be sure it was well below detectible limits. Since the devices we were testing often had gains in excess of 12 dB at 8 GHz, we made sure that the worst case system IMD was 22 dB below the noise floor of the spectrum analyzer (12 dB to account for the gain of the device and an extra 10 dB safety margin). This guaranteed that any IMD we measured came from the device and not from the measurement system.

B. 27-35 GHz Measurements

Because of the insertion loss in the bias tees and test fixture available to us, passive tuning was not practical at millimeter wave frequencies. Instead, we had to use an active load pull approach. The system was originally constructed to measure power saturation characteristics from 27 to 35 GHz. Preliminary results from the system at 27 GHz were given in [4]. Details of the error correction techniques along with overall system improvements were presented in [5]. At 27 GHz, the system is capable of reflection coefficient magnitude accuracy better than 0.007, phase error less than 4 degrees, and gain uncertainty less than 0.15 dB. An additional source and a spectrum analyzer have been added to the setup in order to measure intermodulation distortion. Figure 1 shows the system configuration.

There is subtle difference between the active and passive load pull approach which becomes important when doing IMD measurements. When two tones are present, the load impedance at the IMD frequencies ($2f_1 - f_2$ and $2f_2 - f_1$) may not be the same as the impedance at the fundamental frequencies (f_1 and f_2). For the active approach, the

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load impedance is controlled by varying the reflected signal power with respect to the signal power out of the HBT. Unfortunately, the reflected signal only has components at f_1 and f_2. This means we can only actively control the load at the fundamental frequencies. At the IMD frequencies, $2f_1 - f_2$ and $2f_2 - f_1$, the load remains fixed at the system source impedance, nominally 50 ohms. [2]

This difference between fundamental and IMD load impedance can, if uncorrected, cause 3 to 4 dB error in measured intercept point. However, if one assumes that all IMD products are generated by the two fundamental tones (a reasonable assumption since the third-order products are 30 to 40 dB below the fundamental), then the output of the transistor at the IMD frequencies can be modeled as a generator with impedance Z_{out}, the output impedance of the device. Given the IMD load impedance and power, the amount of IMD power delivered to a load equal to the fundamental load impedance can be calculated using the principles found in [6]. Doing this yields:

$$P_L^{imd,corr} = P_L^{imd,meas} \cdot \frac{|1 - \Gamma_L^{imd}\Gamma_{out}^{TR}|^2}{|1 - \Gamma_L^{fund}\Gamma_{out}^{TR}|^2} \cdot (1 - |\Gamma_L^{fund}|^2) \quad (1)$$

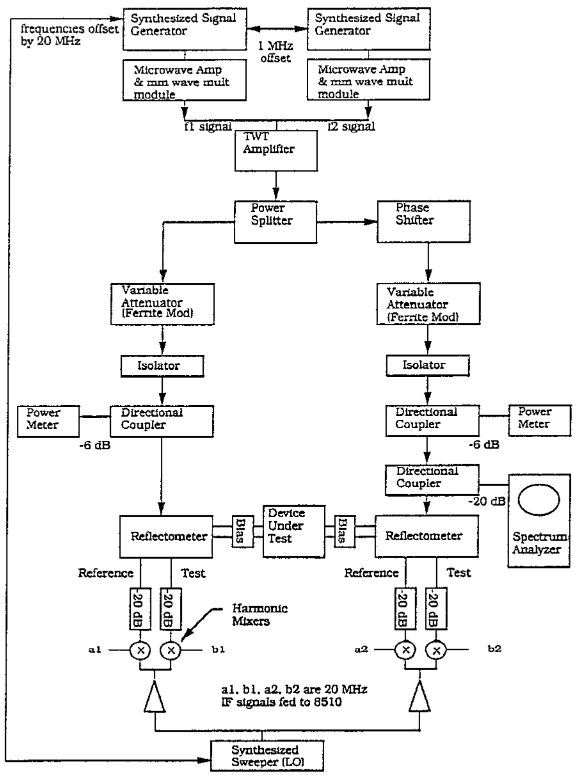

Figure 1: Active load pull system used for 27-35 GHz intermodulation measurements.

[2]Nonidealities in our bias tees, test fixture, and transitions will cause this impedance to be slightly different.

where $P_L^{imd,corr}$ is the corrected IMD power that would be delivered to an IMD load equal to the fundamental load, $P_L^{imd,meas}$ is the IMD power measured on the spectrum analyzer, Γ_{out}^{TR} is the output reflection coefficient of the transistor, Γ_L^{fund} is the measured load reflection coefficient at the fundamental frequency, and Γ_L^{imd} is the measured load reflection coefficient at the IMD frequency.

We verified the correction procedure outlined above using our simple model with the Libra harmonic balance software (see section III.). Active tuning at 32 GHz was simulated by varying the IMD load ($2f_1 - f_2$ and $2f_2 - f_1$) while keeping the fundamental load (f_1 and f_2) fixed. For a nominal system reflection coefficient of 0.3 or less, the uncorrected error in intercept point was between 2.5 and 4.4 dB. However, after applying our correction procedure, the error was reduced to a maximum of 0.5 dB.

Utilizing the analysis above to estimate measurement uncertainty, we have successfully used our active load pull system to measure the intercept point of several HBT's from 27 to 35 GHz. To our knowledge, this is the first demonstration of active load pull being used for intermodulation measurements at millimeter wave frequencies.

III. Modeling

To help understand the measured results, we have developed a modified Ebers Moll model which includes transit time effects. A detailed numerical simulator which includes velocity overshoot and energy relaxation effects was used to help arrive at the simplified model. Excellent agreement between measured and simulated 1 dB compression power at millimeter wave frequencies has already been obtained [7]. Figures 2 and 3 depict the parasitic and active device circuit models used. The corresponding model parameters and device structure are given in tables I,II, and III. In this work, we use the model to predict the frequency and bias dependence of the IMD3 intercept point from 8 to 35 GHz.

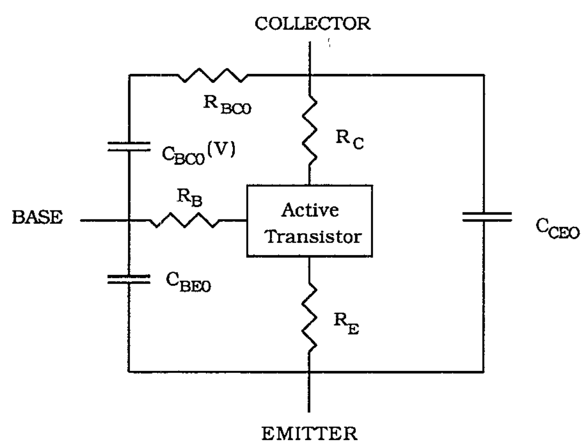

Figure 2: Circuit used to include parasitic elements in our improved Ebers Moll model.

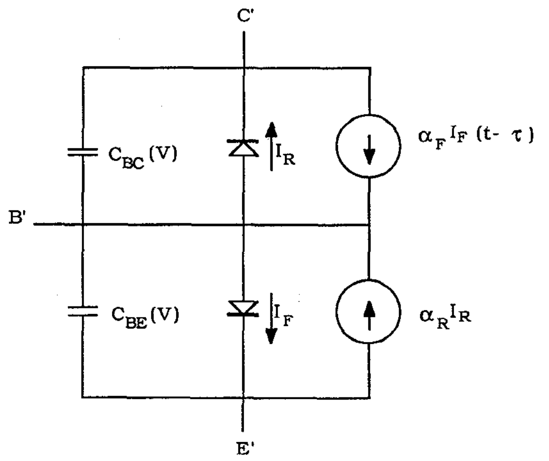

Figure 3: Active portion of the improved Ebers Moll device model.

Table I: Parasitics (I_c = 18 mA, V_{ce} = 2 V) [3]

component	value	component	value
C_{bco}	50 fF	C_{beo}	45 fF
R_{bco}	2.1 Ω	C_{ceo}	71 fF
L_{via}	14.5 pH	R_b	15.6 Ω
R_c	6.8 Ω	R_e	2.1 Ω

Table II: Model Parameters

parameter	value	description
α_F	0.94	CB current gain (forward)
α_R	4.56E-4	CB current gain (reverse)
τ	1.7 to 3.1 ps	transit time
I_{sF}	7.39E-26 A	Forward sat Current
I_{sR}	1.52E-22 A	Reverse sat Current
n_F	1.07	BE junction ideality
n_R	1.00	CB junction ideality
C_{jeo}	180 fF	E-B junction depl cap
V_{jeo}	1.64 V	E-B junction built in pot
M_{je}	0.5	E-B junction grading coeff
τ_F	1.03 pS	diffusion time (C_{be}^{diff})
C_{jco}	34 fF	B-C junction cap
V_{jco}	1.42 V	B-C junction built in pot
M_{jc}	0.5	B-C junction grading coeff
T_o	300 K	Active Device Temperature

IV. Results

Several HBT's from various sources have been tested. Typical measured and simulated IMD intercept points for a 2 finger, 2 by 20 μm emitter HBT [9] are shown in figures 4 and 5.

[3]Two nominally equivalent devices were measured in this work. The values in table I are for the first device. For the second device, R_b = 37 Ω and R_e = 7.3 Ω. All other parasitics were approximately the same for both devices.

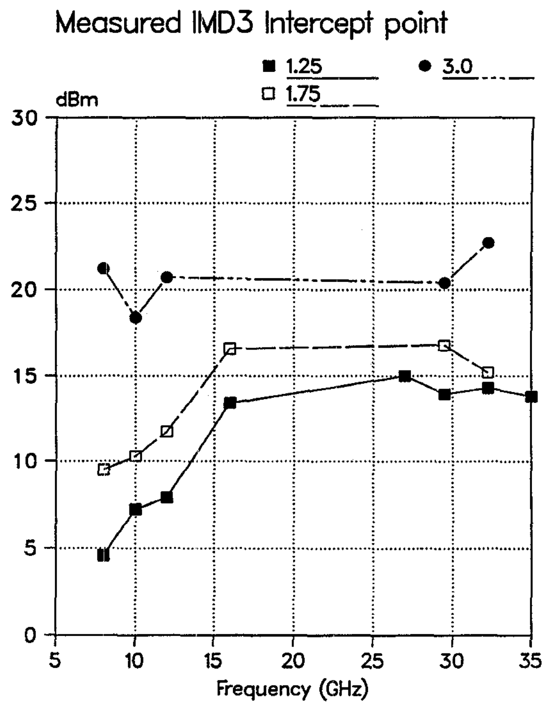

Figure 4: Measured third-order intercept point for various V_{ce}. I_c is 16 mA.

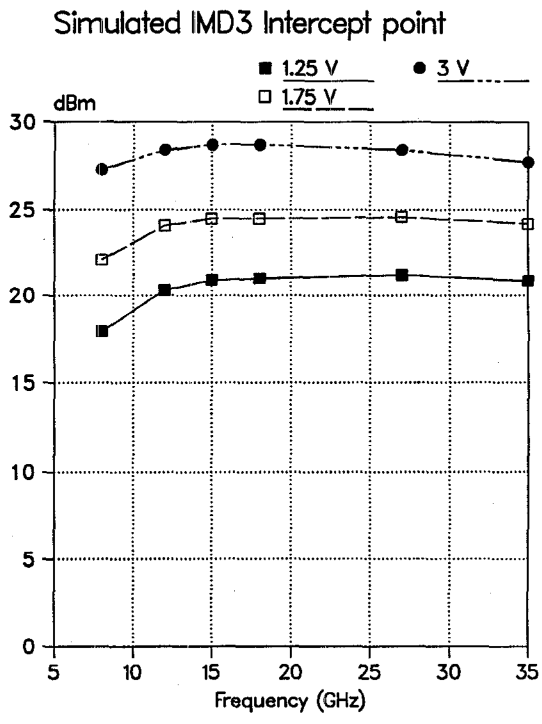

Figure 5: Simulated third-order intercept point for various V_{ce}. I_c is 16 mA.

Table III: Device Structure [9]

region	Al frac	dop	dop (cm^{-3})	μm
contact	0.0	n	2.E18	0.15
grading	0.0 - 0.3	n	1.E18	0.05
emitter	0.3	n	1.E17	0.05
base	0.	p	2.E19	0.1
collector	0.	n	1.E16	0.8
sub collector	0.	n	2.E18	1.5
SI substrate	0.		undoped	625

A collector current of approximately 16 mA was measured in all cases. At each frequency, the load was adjusted to its small signal optimum value based on S parameter measurements. Qualitatively, the measured and modeled trends are the same. The model tends to predict a higher intercept point than we measured. This disagreement stems from several simplifying assumptions used in the model. Maas suggests that the simple capacitance model for C_{be} used here may not be accurate at microwave frequencies [8]. Furthermore, nonlinearities in the current generator were neglected in this work. In Maas' work [8], the measured second and third-order intermods have been used to adjust the nonlinear model parameters in order to get better agreeement between theory and experiment. The rationale here is that the bias dependence of the model parameters can not be found accurately from "S" parameters alone.

Based on these comparisons and observations, we feel that this model is adequate for qualitative studies of intermodulation, but needs additional work to improve its accuracy. The model can, however, serve as a useful tool to help explain our measurements.

From our measured and modeled results, we have been able to draw several conclusions. Since only class A bias points were considered in this work, harmonic loading was not expected to be as significant as it is for class B bias points. This was verified using the computer model. Simulations at 8 GHz showed no more than 0.5 dB variation in third-order intercept point for variations in the second harmonic load and V_{ce}. During these calculations, the fundamental load was fixed.

As V_{ce} increased from 1.25 to 3 Volts, the intercept point increased. This can be explained with the help of our model. For low values of V_{ce}, the base collector junction was forward biased, resulting in a high base collector capacitance (C_{bc}) which is extremely nonlinear. At larger values of V_{ce}, the base collector junction was reversed biased. This resulted in a lower value of C_{bc} which is less nonlinear. Reduction in the nonlinearity of C_{bc} caused the intercept point to increase for these bias points. However, further increases in V_{ce} beyond 3 Volts are not expected to improve the intercept point by much because C_{bc} is already small and relatively linear at this point.

V. Conclusions

The frequency and bias dependence of the third-order intercept point has been presented for a typical HBT. A conventional tuner system was used for measurements from 8 to 16 GHz. Beyond 27 GHz, an active load pull system was used to circumvent insertion loss problems. Appropriate corrections to the active load pull intercept measurements were described. To aid us in understanding our measured results, a simple model which includes transist time effects was developed. From our measured and modeled results, we noticed that reductions in V_{ce} resulted in a reduction in third-order intercept point. This degradation was attributed to increased nonlinearity in C_{bc}.

VI. Acknowledgments

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[9] Device provided by Texas Instruments. [4]

[4]HBT development is being supported by the Naval Weapons Center, China Lake, California under contract no. N-60530-89-C-0300.