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Understanding Base Biasing Influence on Large Signal Behavior in HBTs

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Simulations with extracted large-signal model parameters can accurately predict the performance of heterojunction bipolar transistor (HBT) circuits

Large-signal behavior of HBT devices can depend strongly on the type of source used to bias the base of the devices. Understanding of this behavior is advanced using sample device measurements and model simulations. The device used is a wafer-level InGaP/GaAs HBT represented with a modified Gummel-Poon non-linear model. Results show that the use of constant voltage source allowed for a higher power gain compression as compared to constant current-source use. Once properly setup, simulations with the extracted non-linear model accurately predict power compression behavior for either base source type.

Introduction

The type of biasing applied to the base of a bipolar transistor can have a strong impact on device characterization and modeling. Thus, it is important to understand the type of source bias applied to the base of the bipolar transistor in the intended application. Heterojunction bipolar transistors (HBTs) are current controlled active devices, in contrast to field effect transistors (FETs). Although HBTs are current controlled devices, modeling of HBTs also requires using voltage source measurements for best practice extraction and validation of model parameters. In this work, the dependency of large signal characterization with bias conditions will be analyzed and validated with example measurements and model simulations.

HBTs consist of two different semiconductor junction layers. Examples include InGaP and SiGe. HBTs provide many advantages over conventional silicon bipolar junction transistors (BJTs) such as larger current gain and higher cutoff frequencies. As a result, HBTs are widely used for digital and analog microwave applications. For designers of RF circuits, it is imperative to use reliable large signal models that are developed from measurements under various bias conditions of the device for reliably accurate prediction of the circuit performance.

Biasing circuits used for BJTs or HBTs circuits are generally designed to either provide a constant base current or a constant base voltage to the transistor. In modeling bipolar transistors (BJTs or HBTs), an engineer with a well equipped laboratory will generally have the flexibility to setup bias circuits with either configuration. On the collector side, constant collector voltage, with monitored collector current would be the most common approach. The choice of constant base current or constant base voltage biased measurements can affect both the modeling and the results of modeled to measured validations performed to explore model accuracy.

In this work, I-V (current-voltage) and power sweep measured gain data are compared for various base sourcing setups. The variability of RF output power compression behavior with bias type is specifically explored with the goal to add understanding to what causes these differences and to provide some guidance with respect to avoiding pitfalls that can occur with improper setup of measured and/or simulation benches. A related paper [1] from this research focused on the impact of these effects on device modeling, particularly in connection to correct assignment of ther-

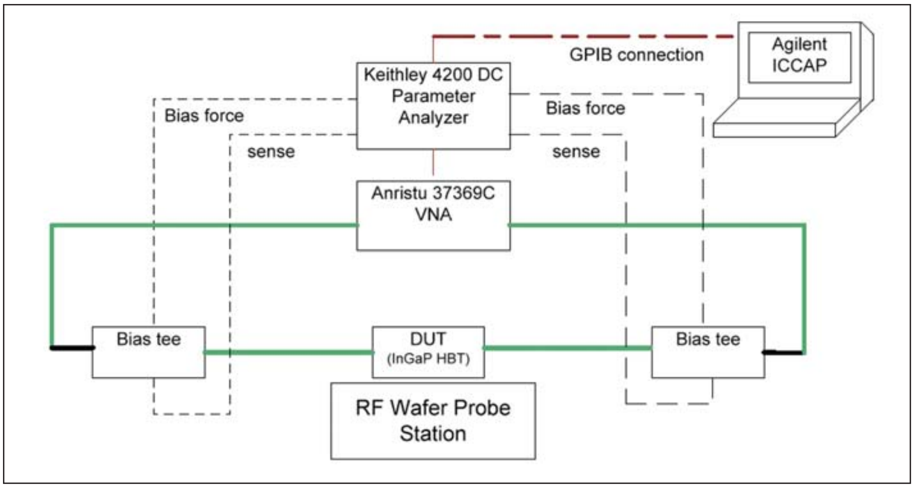


Figure 1 · DC/RF parameter test configuration for tansistor model development.

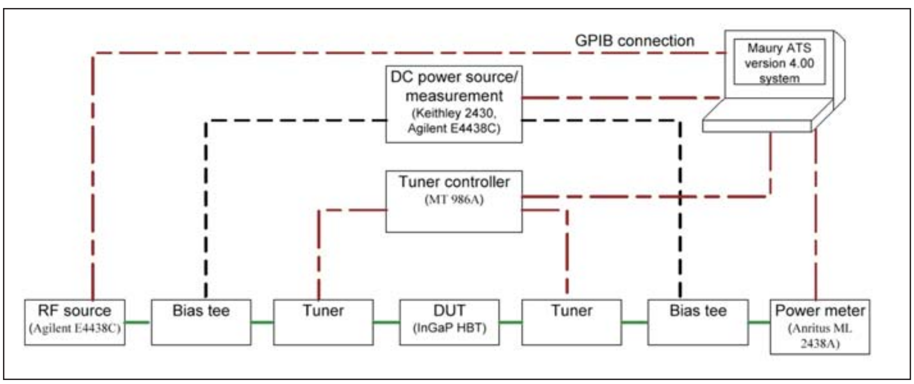
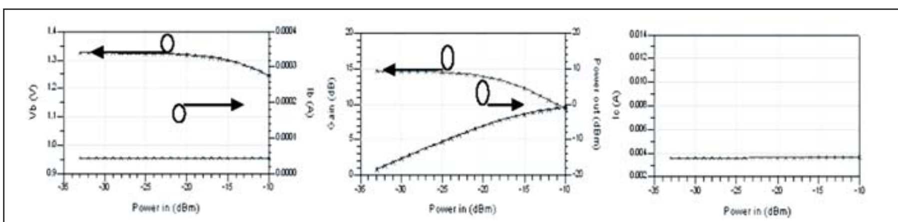
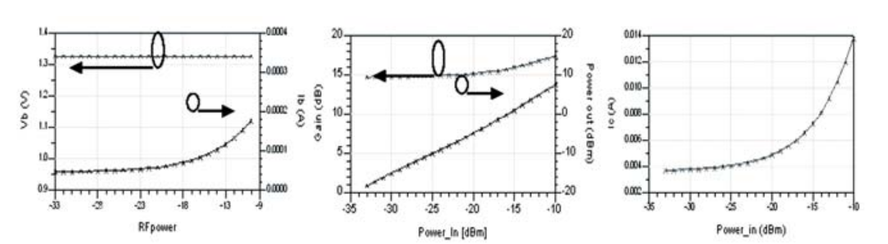


Figure 2 · Test configuration for power sweep measurements. (Tuners set to 50Ω condition for the results presented.)



(a) The measurement data with biasing a constant current (Ib = 43.5 μA) on the base.



(b) The measurement data with biasing a constant voltage (Vb = 1.32 V) on the base.

Figure 3 · The 50 ohm power sweep measurements of the InGaP HBT with different constant bias condition on the base with the RF frequency, 3.5 GHz and the bias condition V_{ce} = 5 V and I_c = 3.6 mA.

mal-related model parameters. Confidential – unpublished research.

About the Devices and Models Used in This Study

To illustrate HBT base bias source effects, sample HBT device measurements and corresponding model simulations are used. The device used in this study consists of a wafer-level InGaP/GaAs HBT, represented in simulations with a non-linear model extracted using a modified Gummel-Poon model template [2]. The test bench used for development of this type of model by Modelithics is shown in Figure 1. This transistor model development bench consists of a Keithley 4200 DC parameter analyzer, a 40 GHz Anritsu 37369C Lightning vector network analyzer and an RF wafer probe station (e.g., J microTechnology Personal Probe Station™.) Force/sense bias tees are used to best ensure device-level voltage/current (e.g. Anritsu SC6772) measurement accuracy. This system is fully automated using Agilent Technologies ICCAP data acquisition and modeling software [3]. (Note: An important component of this solution is the ICCAP compatible software driver that is available for the Keithley 4200.)

Initial extraction for the model to be utilized in the study described here was performed in Agilent ICCAP and then refined and finalized using Agilent Technologies Advanced Design System (ADS) software [4] for best fit to measured IV data, bias-dependent *S*-parameters and power compression measurements. All the simulations shown were performed using this model within ADS.

Large Signal Behavior with Different Biasing Schemes

To explore the impact of base current biasing on device behavior, power compression measurements were performed with base biasing applied with a Keithley 2430 current/voltage source meter along with the power measurement setup of Figure 2. An Agilent E4438C voltage supply was used as the constant voltage source used for collector biasing, and for base-biasing for the case of constant base voltage source use. Maury Microwave's ATS (ver 4.00) measurement software was used to automate the bias-dependent power measurements using the load/source pull power test system of Figure 2. The Maury ATS system has the ability to perform 50Ω input/output power sweep measurements by setting the input and output tuners to the nominal 50Ω condition. This was done for simplicity for the purposes of this paper.

Even though the nominal input voltage, and small-signal quiescent bias current are set to be the same for the HBT for both cases (constant base current or voltage source use), different large signal behaviors are observed depending on the type of source used to bias the base. 50Ω power sweep measurements of the InGaP HBT are shown in Figure 3. Two measurements were performed: one with with a constant base current (I_b = 43.5 µA) applied, and then with a constant base voltage (V_b = 1.32 V) used to achieve the same collector current (I_c = 3.6 mA). These results are shown in Figures 3a and 3b, respectively.

As mentioned, HBTs are current controlled active devices. If a constant current is applied on the base, the power sweep measurement shows a typical gain compression behavior at high input power, and the collector current is almost constant across the entire input power range as shown in Figure 3a. However, it is observed that the collector current increases exponentially with increasing RF input power level when a constant voltage is applied on the base as shown in Figure 3b.

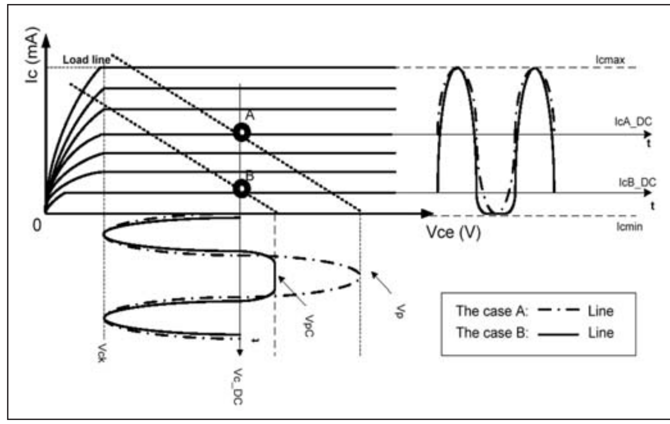


Figure 4 · Idealized voltage—current waveforms at the output of an ideal BJT/HBT.

It is well known that power gain compression is caused by nonlinearity of the transfer characteristics of an active device. One of the causes of this nonlinearity is

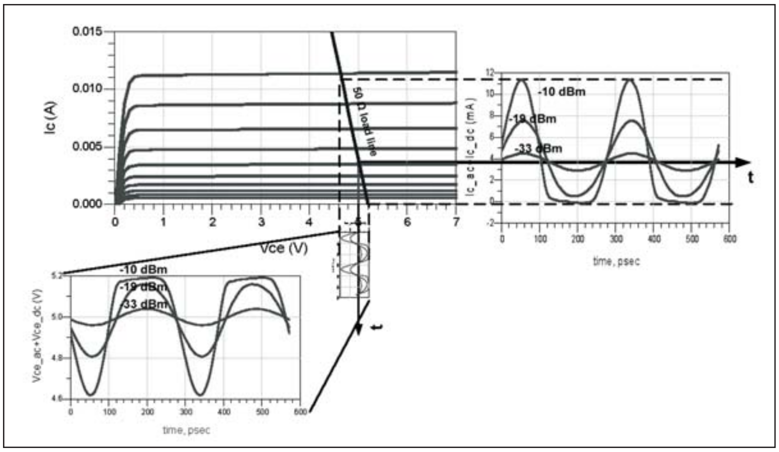


Figure 5 · Simulation showing the AC collector current and voltage waveform with various input RF power levels.

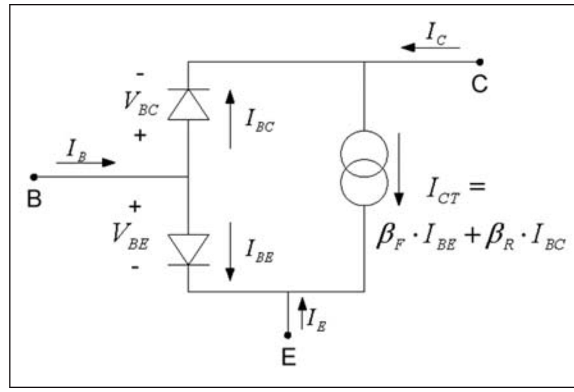


Figure 6 · The non-linear hybrid-π version of the EM1 model.

device heating due to power dissipation. But the main cause of the gain compression is overdriving the input RF signal beyond linear operating region of the device. This leads to the clipping of the output RF signal. Thus the RF power gain compression depends on the quiescent bias point at the output of the device. Under large-signal operation this quiescent bias condition can change due to DC rectification of the large ac signal caused by the non-linearity of the device. In particular, for the example studied here the operating current is seen to increase with increasing power for the constant voltage case under high drive levels, but is held constant for the constant current case. (By the way, observations of a changing bias current during *S*-parameter measurements can be a hint that the RF power levels are too high for small signal measurements!

The dependence of the power gain compression on the output quiescent bias point can be explained by the ideal I_c-V_{ce} characteristics of a BJT/HBT (without self-heating, breakdown, and early voltage) shown in Figure 4. The two cases of the output bias condition are defined as "***A***" and "***B***" in the I-V curve to illustrate AC current and voltage waveform behavior at the output of an ideal BJT/HBT device. This viewpoint is similar to illustrations of FET behavior given by Walker [5]. The amplified voltage and current waveform at the output of a device can be considered to swing along the load impedance line. So if the voltage and current waveform is large enough to hit the minimum and maximum boundary of the device operation region the waveforms will be clipped. As a consequence, the quiescent bias point ***A*** can achieve a higher power gain compression point than the point ***B*** as shown in Figure 4 because the quiescent bias point ***A*** allows more room to swing the waveform without clipping. Generally, the largest non-clipped signals can be supported by a "Class A" bias condition of around one half of the maximum current (bias condition ***A***); however, many very useful non-linear modes of operation are commonly used that allow partially clipped operation to occur, including classes B, AB, D, E and F [6]. Bias condition ***B*** would be considered a class AB bias condition.

For verification of the theory, the extracted model was used to simulate collector voltage and current waveforms with varying input power levels as shown in Figure 4. Results for small-signal at –33 dBm, 1 dB compression power at –19 dBm, and 6 dB compression point at –10 dBm input power are shown. For simplicity, the model was simulated without considering self-heating effects.

The main reason for the power compression extension observed in the constant base voltage case (see Fig. 3) is the increase in DC collector current with increasing power, which allows for a higher value of non-clipped output current and voltage waveforms to be supported on the load impedance line. The following sections examine how high input power signals increase the collector

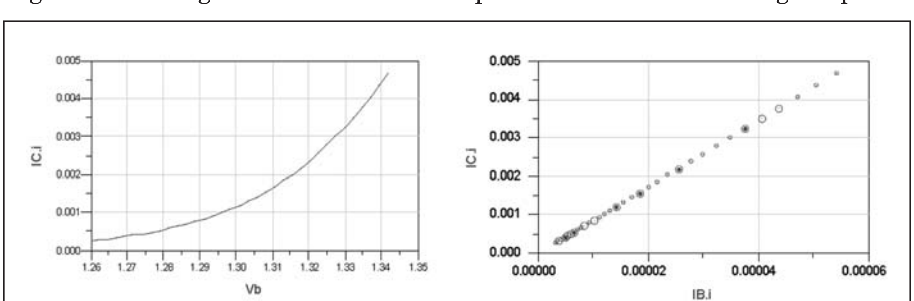


Figure 7 · The simulation of the I_c vs V_b and the I_c vs. I_b for the example InGaP/GaAs HBT (with self-heating effects deactivated.

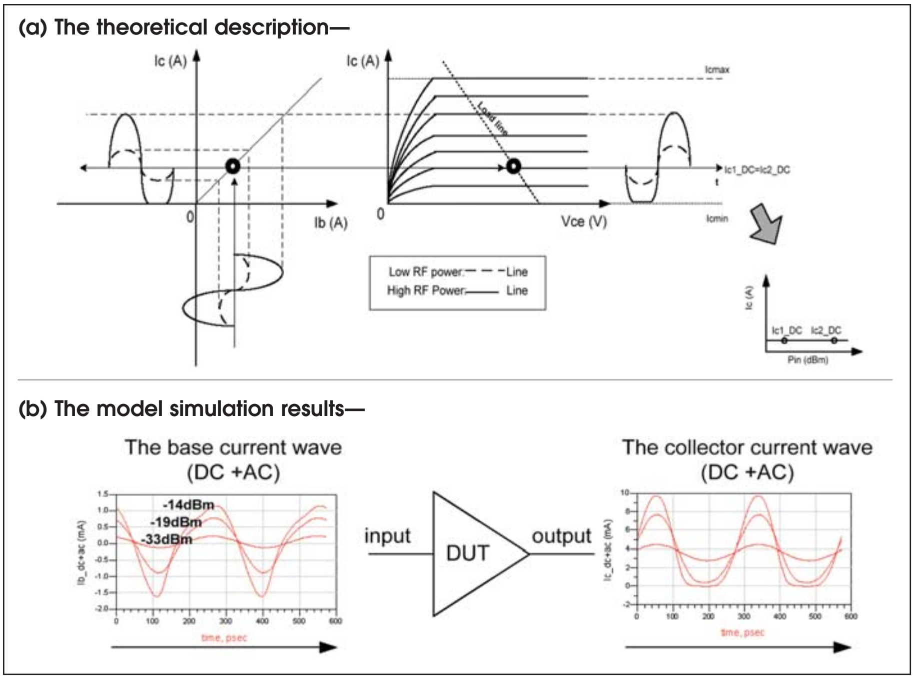


Figure 8 · The input current and output current waveform with a constant base current.

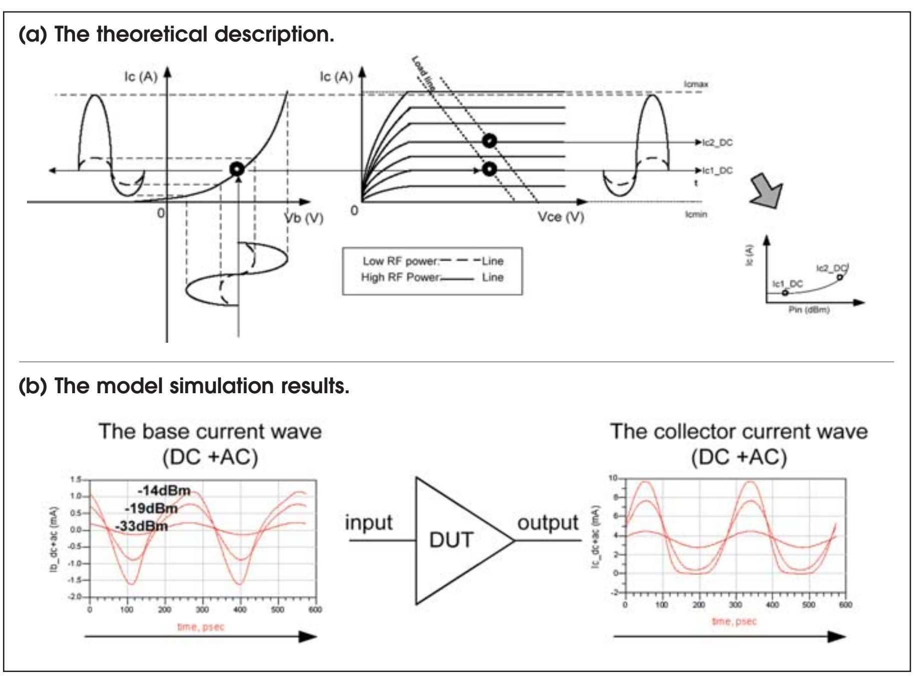


Figure 9 · Input voltage and output current waveform with a constant base voltage.

current when a constant base voltage is applied to bias the device. This illustration assumes that the initial bias puts the device in a "Class AB" low current operating region.

The Influence of RF Input Power on Base Current and Voltage

Most intrinsic DC equivalent circuit models of HBTs are developed based on the Ebers-Moll (EM) model, which is essentially a DC model that does not consider characterization of charge storage. The non-linear hybrid-π version of the EM1 model is shown in Figure 6. The diode currents on the base side become:

$$I_{BC} = I_S\left(\exp\left(\frac{V_{BC}}{V_t}\right)-1\right) \qquad (1)$$

$$I_{BE} = I_S\left(\exp\left(\frac{V_{BE}}{V_t}\right)-1\right) \qquad (2)$$

And the output current at the collector, is given by

$$I_{CT} = \beta_F \cdot I_{BE} - \beta_R \cdot I_{BC} \qquad (3)$$

For simplified analysis of the non-linear characteristics at the base, the equation (1-2) can be considered as the main input current source because in the normal active region the reverse-biased diode between the base and the collector becomes a near open circuit. In other words the collector current is an exponential function of base-emitter voltage and a linear function of the base current. Simulations are shown in Figure 7.

Figure 8a shows how the collector current waveform is clipped with a high RF signal for the constant base current condition. If the base current maintains a constant value with high RF input power, the base current waveform can have a negative swing. During this time the collector current cannot flow at the output of the device. The model simulation shows the base current wave and the collector wave in Figure 8b. The three different input power levels mentioned above are used for the harmonic balance simulation.

On the other hand, when a constant base voltage is applied, the collector current wave does not clip so quickly since the upper collector wave can be extended. This expansion is aided by the fact that the collector current is an exponential function of the base voltage as shown in Figure 9a. The model simulation is shown in Figure 9b for the same case.

Summary

The dependence of the RF power compression behavior of HBTs on the type of biasing used to supply the base voltage or current has been examined experimentally and with simulations. It is seen that higher power compression levels can be supported in general by use of a constant base voltage source that allows the current to expand with increasing power levels. Since both base current and voltage sources can support the same small-signal quiescent operating current, it is an area that can be subject to confusion or misinterpretation. Consistency in biasing setup is of primary importance for successful large-signal circuit design, and particulary for comparing power swept measured to modeled results.

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