GaAs Based HBT Large Signal Modeling Using VBIC for Linear Power Amplifier Applications

Marcel Tutt
Motorola DigitalDNA Laboratory
EL720
2100 E. Elliot Rd.
Tempe, AZ 85284
Phone: (480) 413-6671, FAX: (480)413-4453, e-mail: Marcel.Tutt@motorola.com

ABSTRACT:

The relevant performance parameters that a large signal device model must predict for linear power amplifier design have been identified. The VBIC model was applied to Gallium Arsenide based Heterojunction Bipolar Transistors and shown to accurately predict all of these performance parameters.

INTRODUCTION

Modern communication systems use complicated digital modulation schemes such as Offset Quadrature Phase Shift Keying (O-QPSK) which put extremely demanding performance requirements on power amplifier circuits (PA's). These PA's are required to provide needed transmit power while maintaining adequate linearity and efficiency. Good linear performance and good efficiency always requires compromise in the circuit design. Gallium Arsenide Heterojunction Bipolar Transistors (GaAs HBT's) have demonstrated good performance for such PA applications. This establishes the need for a large signal model for GaAs based HBT's suitable for use in linear PA design. Although considerable work has been done to address GaAs HBT large signal models as exemplified by [1,2,3,4], little work has been done to completely demonstrate the adequacy of the models for predicting all relevant parameters that are required by PA circuit designers. This includes self-heating, DC behavior, small signal behavior, output power, power added efficiency (PAE), phase shift through the device and distortion. Furthermore, the model must be able to predict all of these as a function of the input terminating impedance (also referred to as input tuning) and output terminating impedance (also referred to as output tuning).

The VBIC [5] bipolar junction transistor model is a candidate for GaAs HBT modeling for several reasons. First, self-heating is incorporated in the model. Second, it provides a base current model that is a better approximation to the actual device than that which is used in the conventional Gummel-Poon (G-P) model. Third, the collector current and base current are not related through a fixed current gain as in the G-P case. Fourth, it is available in commercial circuit simulators (e.g. ADS from Agilent). Although the reverse operation of GaAs HBT's is not described properly, this is not a limitation because the device is always operating in the forward active region. To date, this model has not been demonstrated to predict all of the necessary parameters for linear PA design.

This work identifies all of the parameters that a large signal model must predict in order to demonstrate the suitability of a given model. Furthermore, it describes the results of applying the VBIC model to GaAs based HBT's for the purpose of modeling their large signal operation for linear PA design. The results clearly demonstrate the usefulness of the VBIC model applied to GaAs based HBT's for linear PA applications.

PARAMETERS of INTEREST

In order for a device model to be useful it must be able to predict all of the necessary parameters required in linear PA design. What these parameters are and why they are of importance are reviewed here. First, the output power (P_{out}) of the device is the most important parameter. The model must be able to predict P_{out} as a function of input power (P_{in}) for all practical input terminating impedances and output terminating impedances. The ratio of P_{out}/P_{in} is the gain, G, of the device. PA design will require that the model be able to predict the transistor G well into compression, say 6dB compression. This corresponds to where the gain of the device has been reduced 6 dB below the value of G when the P_{in} is quite small (i.e. tuned small signal case). Second, the model must be able to predict the DC operating point as a function of applied DC bias. This is needed in order to verify that the circuit is biased properly. It is also needed in order to design active bias circuitry. Third, the model must be able to predict the PAE of the device which is a measure of how well the device/amplifier converts DC power to useable microwave power. PAE is vitally important to linear PA's used in portable equipment such as cellular phones where it directly impacts talk time. It is defined according to the following expression:

$$PAE(\%) = \frac{P_{out} - P_{in}}{P_{DC}} x100$$

P_{out} and P_{in} are defined above. P_{DC} is the total average DC input power when P_{in} is applied to the device. This requires that the model be able to predict the average DC bias under large signal excitation. Fourth, the model must be able to predict the distortion of the transistor. This is required because many PA applications today require detailed knowledge of the circuits' distortion. While most large signal models have dealt with different aspects of some of the parameters referred to above, none have dealt with distortion.

Distortion is very difficult to validate because different measures are used for different modulation schemes. Historically, the Third Order Intercept (TOI) has been the most common measure of device linearity. This was determined by applying two equal amplitude signals,

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closely spaced in frequency, to the transistor and then measuring the third order intermodulation products. Today, there are other measures that are also significant. For instance, line amplifiers for cable TV use a measure called Composite Triple Beat, while cellular phone designers will use Adjacent Channel Power Ratio (ACPR) when designing linear PA's for Code Division Multiple Access (CDMA) modulation schemes. It is very time consuming to evaluate a model's ability to predict distortion under all imaginable conditions. Fortunately, for all modulation schemes in use today, it is possible to determine the level of performance that can be expected by having knowledge of the G vs P_{in} (AM-AM conversion) and the relative phase shift through the device as a function of P_{in} (AM-PM conversion).

Both of these quantities are measured and modeled using single tone excitation. The AM-AM conversion is simply the gain of the transistor as a function of input power level. This is typically measured and modeled well into gain compression (at least 3dB). The AM-PM measurement involves measuring the phase shift of the input signal as it is amplified at various input power levels. Phase is not commonly measured in most power characterization systems because it is considerably more difficult to measure than AM-AM conversion and requires that modifications be made to most existing test systems to incorporate a vector network analyzer.

It is well known that the device performance is also dependent on the harmonic termination conditions as well as the fundamental termination. For example, the second harmonic should be terminated into a short circuit to obtain maximum PAE. Thus the model must also properly represent the harmonic performance of the device.

RESULTS

The VBIC model was applied to a GaAs/AlGaAs HBT consisting of 3 emitter fingers having dimensions of 3µm by 100µm resulting in a total emitter area of 900µm^2. The DC parameters for the VBIC model were extracted from the DC characteristics of the HBT. Figure 1 shows that good agreement is obtained between measured and modeled I_C versus V_{CE} characteristics. Of special note, the negative slope of I_C versus V_{CE} is the result of device self-heating and not the result of a negative resistance.

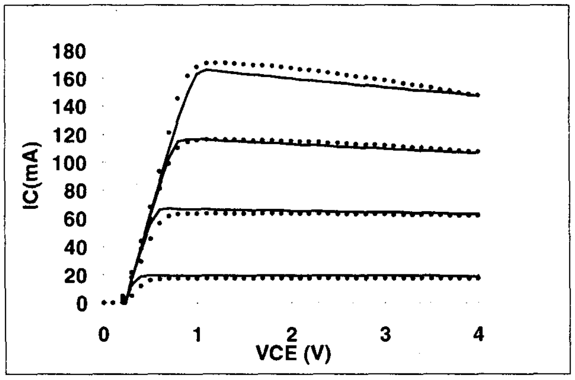

Fig. 1: Comparing measured (dots) and modeled (lines) IC-VCE characteristics of a 3(3µmx100µm) GaAs HBT.

The relevant AC parameters for the VBIC model were extracted using S-parameter data. Large signal measurements were made with an ATN on-wafer loadpull system. It enables the devices' terminating impedances to be varied at both the input and output. An HP8510 vector network analyzer is integrated into the system enabling complete characterization of fundamental and harmonic terminations. In addition, the system can measure phase shift through the device as a function of input power.

As a first test of the large signal simulation capability the device was terminated into 50Ω and the P_{out}, and average DC bias conditions were measured as a function of input power at 1.9GHz. This case is of interest because we are able to insure that the harmonic impedances are essentially 50 ohms as well. Figure 2 shows the measured and modeled gain and PAE as a function of P_{in}. The measured small signal gain is approximately 13dB and the modeled small signal gain differs by less than 0.3dB even at 7dB compression. The measured and modeled PAE are also in very good agreement over the entire range of input powers. The maximum PAE is approximately 42% and occurs at nearly 3dB compression. The good agreement obtained for the PAE results indicate that the average DC base and collector currents are accurately predicted by the model.

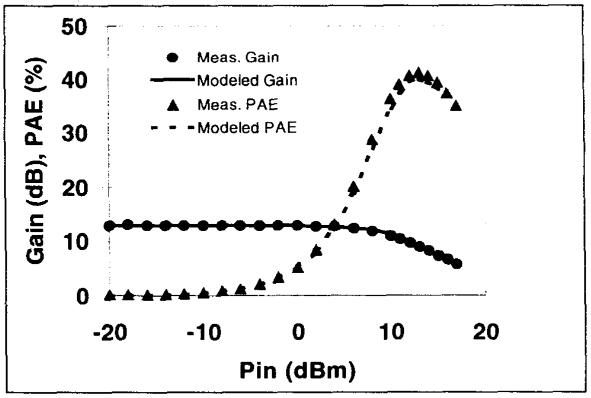

Fig. 2: Comparing measured and modeled large signal data with the HBT terminated into 50Ω

Next the device's input and output terminating impedances were adjusted for maximum stable power gain. The harmonic terminating impedances were also recorded for 2 harmonics. Figure 3 compares the measured and modeled results into more than 14.5dB compression. Under these tuning conditions the gain is increased to 22dB. This is 9dB greater than the case where 50Ω terminations were used. The difference between measured gain and modeled gain is less than 0.7dB for all values of input power. Measured and modeled PAE are also in very good agreement. The peak measured PAE is 47% and the peak modeled PAE is 42%. As the device enters deep gain compression, the measured and modeled PAE have their greatest discrepancies. This isn't considered to be much of a problem, since these devices would never be operated this far into compression. The measured and modeled collector currents are shown in figure 4. For small P_{in}, the measured and modeled currents are in excellent agreement. As the device approaches compression, the collector current increases as a result of self-biasing, however, the modeled current tends to be slightly larger than the measured current. Additional optimization of the model parameters may improve the agreement. The model was also investigated for the maximum PAE tuning case. Again, the results were very good in all cases except that the modeled average DC collector current was higher than the measured collector current. However, this did not occur until nearly 5dB into compression. This is typically well beyond where the device needs to operate.

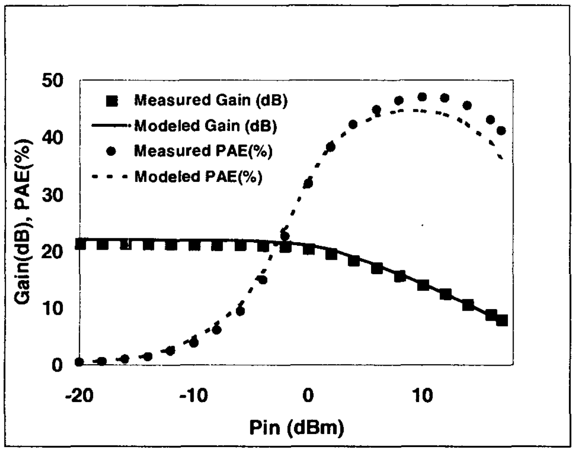

Fig. 3: Comparing measured and modeled large signal data with the HBT tuned for max. stable gain.

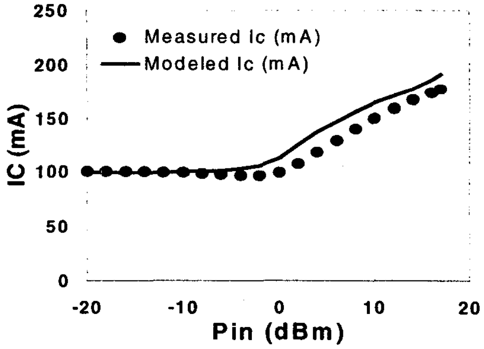

Fig. 4: Measured and modeled collector current as a function of P_{in}

Finally, distortion properties were investigated using AM-AM conversion and AM-PM conversion. As mentioned before, the AM-AM conversion term is merely the gain versus P_{in} relationship. The AM-PM was measured using the vector network analyzer during all of the power sweep measurements. The modeled AM-PM conversion was determined using a large signal simulation of the device and monitoring the phase change with input power. Figure 5 shows the measured and modeled AM-PM conversion for the maximum stable power gain. The modeled AM-PM conversion and measured AM-PM conversion agree to within one degree up to 2dB compression. The error is less than six degrees up to 14.5dB compression. Similar results were also obtained for 50 Ω termination conditions and maximum PAE tuning conditions. These AM-PM conversion results along with the excellent results obtained for the AM-AM conversion indicate that we should be able to get very accurate distortion results. To verify this, the ACPR was calculated for CDMA handset applications. The behavioral model in [6] was used for this work.

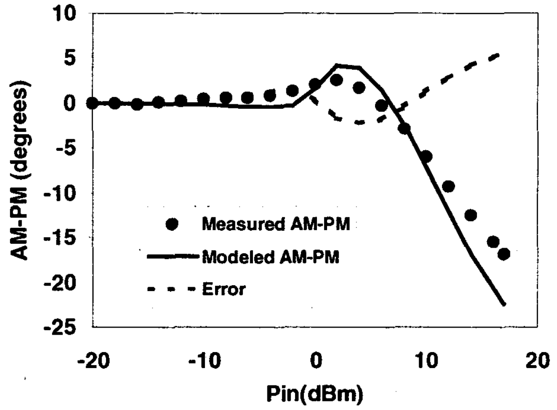

Fig. 5: Comparison of the measured and modeled AM-PM conversion as a function of Pin. The error is also shown on the plot.

Figure 6 compares the calculated ACPR using measured and modeled data. The results are within 1.5dB of each other. This is considered to be very good. Similar results were obtained for the maximum PAE case.

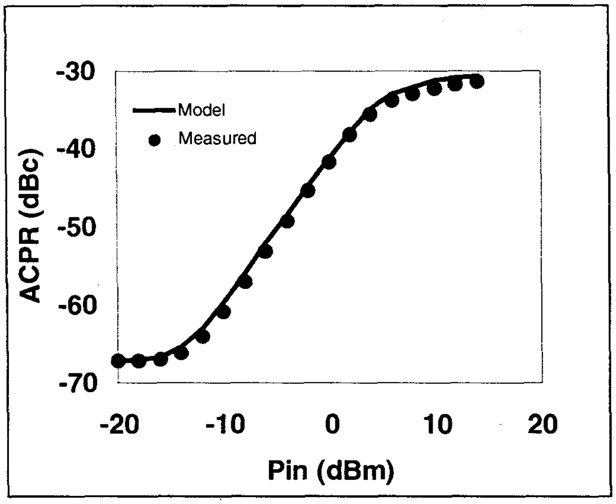

Fig. 6: Comparing ACPR calculated using a behavioral model using measured and modeled AM-PM and AM-AM data.

CONCLUSIONS

The relevant parameters that a compact, large signal device model must predict for linear PA design have been identified. Next, the VBIC model was successfully applied to GaAs based HBT's for the purpose of modeling device performance under tuned large signal conditions. Relevant parameters including P_{out}, gain, PAE, bias and AM-PM were used to validate the performance of the model. Of particular interest is the means for addressing distortion measures using the AM-AM conversion and AM-PM conversion. This is attractive because it requires only single tone simulation and not the more complicated multi-tone or envelope simulators.

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