Simulating IMD in SiGe HBTs: How Good Are Our Models?

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ABSTRACT

Nominal transistor model parameters are found to be insufficient for reliably predicting intermodulation distortion (IMD) in heterojunction bipolar transistors. A method for optimizing the model parameters to give a more accurate simulation of IMD performance is outlined. Differences between transistor models are observed and analyzed by experimentally measuring IMD in silicon-germanium heterojunction bipolar transistors and comparing the results to computer simulations.

Keywords: intermodulation distortion, silicon-germanium, HBT, modeling

1 INTRODUCTION

High-speed heterojunction bipolar transistors (HBTs) have become an increasingly important element in microwave circuit design. In particular, silicon-germanium (SiGe) HBTs are playing a greater role in a variety of applications such as RF integrated chips, PCS handsets and digital radios, networking chips, and high-speed switching equipment [1]. Intermodulation distortion (IMD) impairs amplifier performance by introducing unwanted in-band signals, especially when amplifiers are driven with large input powers; it is also related to other figures of merit, such as ACPR. Therefore, accurately modeling the causes and effects of IMD is a critical factor in enhancing the performance of SiGe HBT circuits.

This work investigates how reliably some widely used transistor models simulate IMD, as well as attempts to determine which model parameters tend to dominate the nonlinear behavior of SiGe HBTs. With this knowledge, extra care can be taken when extracting those parameters that have a major influence on IMD modeling.

The initial step is performing computer simulations of the HBT to predict its IMD response under varying operating conditions. The starting point is the selection of a suitable transistor model and its accompanying parameter extraction procedure. However, the vendor-supplied model parameters are only nominal values that are averaged over many devices. In an effort to distinguish between contributions from the models themselves versus those from device variations, it is necessary to optimize individual device parameters with respect to measurements.

2 EXPERIMENTAL MEASUREMENTS

To provide the baseline data against which the model parameters are optimized, DC, S-parameter, and IMD measurements were collected from actual HBTs whose nominal model parameters were known. The devices were on-wafer NPN SiGe HBTs which were configured for common-emitter operation. Several devices near the center of the wafer were measured at an ambient temperature of T = 22.7 C. A semiconductor parameter analyzer was used to characterize the HBT's DC attributes, while S-parameters were measured with a network analyzer. Custom-written programs on a host PC controlled the instruments via GPIB.

The setup for IMD measurements is shown in Fig. 1. For the IMD data, two DC bias levels (I_B = 6 μA, V_{CE} = 2 V and I_B = 27 μA, V_{CE} = 2 V) and two sets of frequencies (f_1 = 1.7 GHz, f_2 = 1.701 GHz and f_1 = 2.9 GHz, f_2 = 2.901 GHz) will be presented. The power from the signal sources was swept from –25 to +13 dBm. The true input and output powers at the transistor terminals were computed with the aid of a power loss calibration table. This table was compiled by measuring the frequency-dependent power losses through the interconnecting cables, isolators, combiner, bias-Ts, and probes with a power meter.

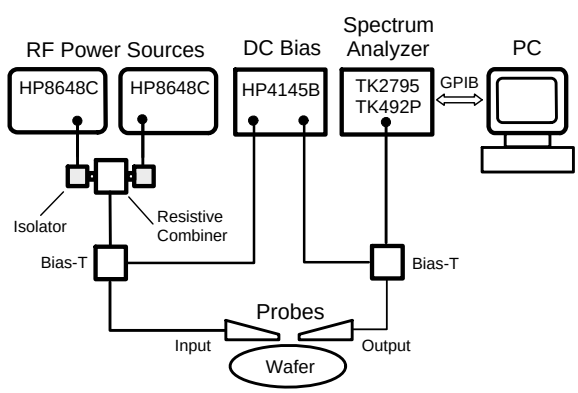

Figure 1: IMD measurement equipment setup

To ensure a proper IMD simulation model for the input and output loading of the HBT at the fundamental and harmonic frequencies, the input and output impedances as seen by the HBT device were measured at the mixing

frequencies using the network analyzer and utilized directly in the simulation software.

3 MODEL PARAMETER OPTIMIZATION

The computer simulations were done on Hewlett-Packard's MDS software [2]. The measured data were imported into MDS and the built-in MDS gradient descent optimizer was used to optimize the model parameters. For comparison, two transistor models were chosen: Gummel-Poon (G-P) [3] and Kull-Nagel (K-N) [4].

Since the DC attributes of an HBT have a direct impact on its IMD performance, a good forward-operation DC fit is imperative. A two-stage optimization process was used:

1. Optimize the DC parameters I_S, β_F, and n_F in the active linear range of the Gummel plot data ($V_{BE} \approx 0.6$ V to 0.85 V), with all other parameters kept fixed. The optimization goal is to minimize the relative error between the measured and simulated curves over the V_{BE} range.

2. After the first set of parameters is optimized, run another simulation to optimize the parameters I_{KF}, n_{KF}, and R_E in the high injection region ($V_{BE} \approx 0.85$ V to 1.1 V). All other model parameters, including the just optimized I_S, β_F, and n_F, are held constant. Since the K-N model has additional parameters (such as BEX and VO) that are intended to more accurately model quasi-saturation effects, these parameters are also optimized.

A plot of the relative errors in the DC currents for the Gummel-Poon model using both the nominal and DC-optimized parameters is shown in Fig. 2. Note that below $V_{BE} = 0.45$ V, currents were too small for our measurement equipment.

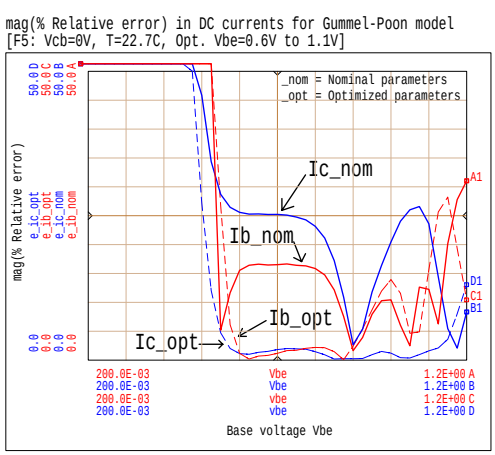

Figure 2: G-P Relative errors in DC currents plot

S-parameter simulation results showed good agreement with the measurements, so no attempt was made to further optimize the parameters with respect to S-parameters. An IMD simulation using MDS's harmonic balance feature was then performed with both the nominal and DC-optimized parameter sets for each transistor model.

4 IMD RESULTS

Fig. 3 shows the fit between the measured and modeled G-P IMD curves (f = 1.7 GHz) using the nominal parameter set (full line = measurements, dashed line = simulation). While the match in the fundamental is very good, there are large discrepancies in the output power for both IMD3 and IMD5. The mismatch is most prominent in the middle input power range, where up to 10 dBm differences are evident. From Fig. 4, running the IMD simulation with DC-optimized parameters makes the fundamental fit worse, but improves the mid-range fit in IMD3 and IMD5.

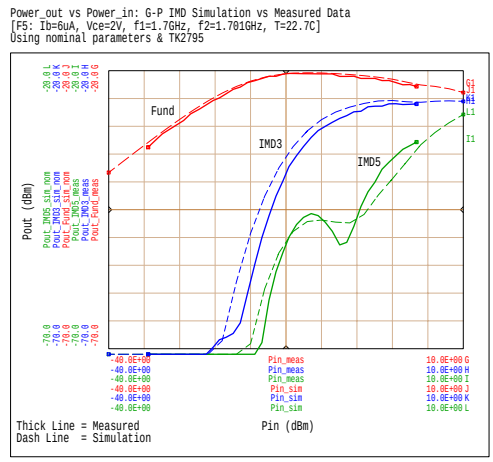

Figure 3: G-P IMD plot (f = 1.7 GHz, nominal)

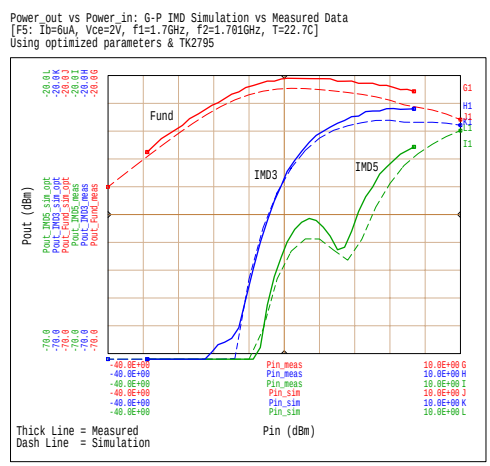

Figure 4: G-P IMD plot (f = 1.7 GHz, optimized)

Interestingly, the measured and simulated IMD curves can be made to match more precisely if some of the optimized model parameters, namely I_{KF}, n_{KF}, and R_E, are "tweaked". The difference between the nominal and tweaked parameter values can range from ± 10 to 70 percent, though the typical value is around 35%. The final result of manually tweaking these parameters is displayed in Fig. 5.

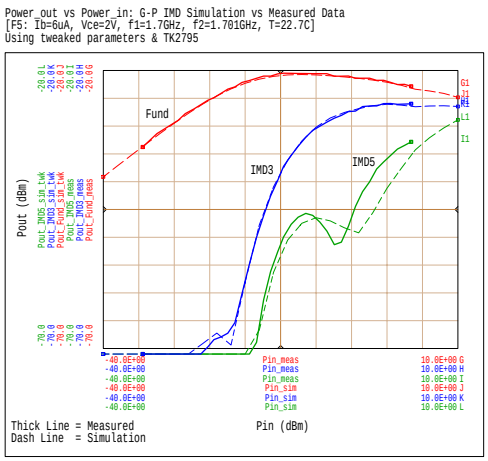

Figure 5: G-P IMD plot (f = 1.7 GHz, tweaked)

For frequencies in the 1 to 2 GHz range at both DC biases, doing a two-stage DC parameter optimization followed by some judicious parameter "tweaking" gives a better IMD fit than using the nominal parameters alone. In particular, I_{KF} and R_E have a substantial influence on IMD characteristics at mid-to-high input powers. The adjusted values for I_{KF}, n_{KF}, and R_E do have an effect on the DC fit as seen in Fig. 6 and Fig. 7. The relative error between the measured data and the simulation using tweaked parameters is noticeably worse than when using the optimized parameter set. However, the tweaked parameters still generally provide a better DC fit than the nominal parameters. This tradeoff is acceptable if increased IMD model accuracy is desired.

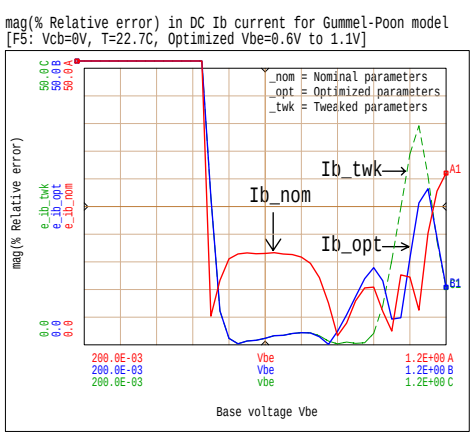

Figure 6: G-P Relative errors in Ib current

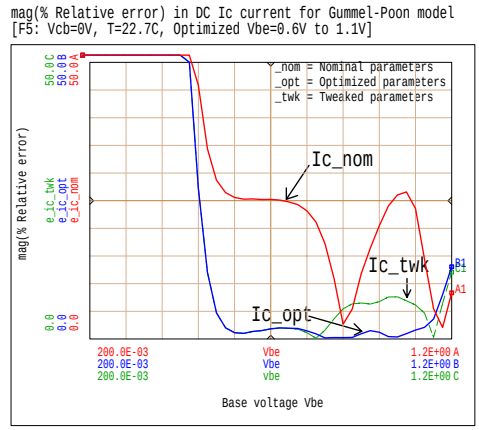

Figure 7: G-P Relative error in Ic current

At f = 2.9 GHz and using nominal parameters, both transistor models show major disagreement between the measured and modeled IMD curves, particularly for IMD3 and IMD5. For this frequency, trying to get a better match by optimizing and tweaking the parameters is much more difficult. In fact, both the G-P and K-N models require nearly doubling the value of R_E to get a reasonable IMD3 match, while the IMD5 fit remains poor. Fig. 8 shows the measured K-N IMD3 curve at 2.9 GHz, along with the simulated curves using nominal, optimized, and tweaked parameters for comparison. Exactly how R_E is able to control IMD is not yet fully understood, but potential explanations are that larger values of R_E enhance the current cancellation in the base-emitter junction of the HBT [5], or that possibly feedback provided by R_E linearizes the circuit [6].

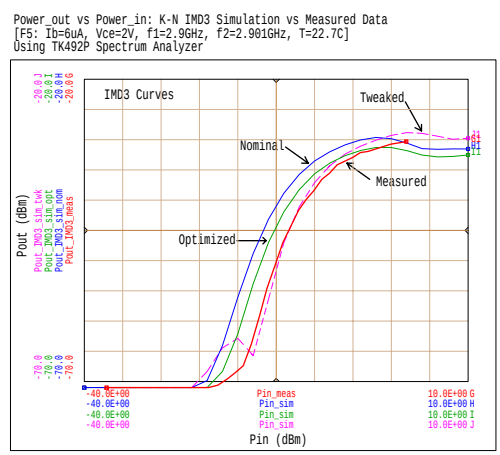

Figure 8: K-N IMD3 comparison plot (f = 2.9 GHz)

Finally, whereas differences between the G-P and K-N models are negligible at 1.7 GHz, substantial differences become evident at 2.9 GHz. For the K-N model, I_{KF} and R_E lose much of their ability to influence the simulated IMD curves unless the VO parameter (part of the quasi-saturation modeling parameters) is increased

simultaneously. Unfortunately, this also heavily distorts the modeled DC characteristics of the SiGe HBT, with I_C and I_B diverging strongly from their measured values. While the G-P model's predicted IMD curves also degrade in accuracy at the higher frequencies, the discrepancies are not as pronounced, and I_{KF} and R_E can still be used to obtain a better match. It is expected that such a parameter optimization technique will be progressively less successful as the frequency increases, since nonlinear capacitive effects, for example, will become more prominent.

5 CONCLUSIONS

At lower frequencies such as f =1.7 GHz, simulations of SiGe HBTs using nominal model parameters produce differences in IMD3 of up to 10 dBm, relative to measured data. The differences become significantly worse as the frequency rises to f = 2.9 GHz. More accurate IMD simulations are obtained after the model parameters are optimized to have a good DC fit to a given device's measured data. Further improvement requires parameter tweaking for IMD. Based on our comparison and analysis of simulation and measurement results, the I_{KF} and R_E parameters dominate the IMD behavior for both the Gummel-Poon and Kull-Nagel models. In the lower microwave frequency range, adjusting the values of I_{KF} and R_E improves the IMD match while keeping a very good DC fit. At higher frequencies, the interactions among the parameters and their effect on IMD and DC simulation accuracy become more complex, and parameter tweaking for IMD is not as successful. Nonetheless, IMD measurements should, in some form, be included in parameter optimization if good IMD simulation outcomes are expected. Our results also suggest that the Gummel-Poon model, due to its simplicity, is easier to "tweak" than the Kull-Nagel model.

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