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Propagation of Compact-Modeling Measurement Uncertainty to 220 GHz Power-Amplifier Designs

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***Abstract* — We study the impact of measurement uncertainties in a heterojunction bipolar transistor (HBT) model and their consequences on the electrical performance under large signal conditions at 9 GHz. Then we use the model with uncertainties to verify the ability of our model to accurately predict the electrical performance of power amplifier designs at 220 GHz. We compare the measured performance of the power amplifiers with simulations and estimated range of performance.**

Index Terms — Semiconductor device modeling, Heterojunction bipolar transistors, Measurement uncertainty, Millimeter wave power amplifiers.

I. Introduction

Measurement uncertainties are not usually considered in the verification procedure of compact transistor models. This leaves open the possibility that observed differences between the actual and predicted behaviors of the transistor in the verification process are due to measurement errors, and not to the inability of the model to accurately predict transistor behavior.

The propagation of measurement errors through the model extraction process was investigated in [1-4] in several technologies. However, the impact of the propagation of measurement uncertainties through an entire circuit simulation has never been examined at millimeter-wave frequencies. Here, we investigate the propagation of measurement uncertainty through 220 GHz power-amplifier simulations and we compare with the measured performance.

II. Model Extraction with Measurement Uncertainty

We extracted a model of a heterojunction bipolar transistor (HBT) with a single 6 μm emitter fabricated at Teledyne Scientific with a state-of-the-art 250-nm process [5]. A full description of the extraction process and a model verification under 1 GHz large signal operating conditions was presented by Williams *et al.* in [4]. We performed I-V curve and scattering (S-) parameter measurements up to 110 GHz under a wide range of bias points to extract this model. On-wafer thru–reflect–line (TRL) standards were designed and used for the calibration of our S-parameter measurements, which Williams *et al.* argued improve the accuracy of HBT and CMOS transistor measurements in [6].

We used the ICCAP[1] Keysight software to extract the HBT model parameters based on the model architecture developed in [7-8]. We first extracted an HBT model that did not consider measurement uncertainty. We will refer to this model as the "nominal" model. Then, we used the NIST Microwave Uncertainty Framework [9] to add uncertainties to our measurements and propagate them through the ICCAP model extraction procedure. We considered 415 error mechanisms in our calibration process. Most of those error mechanisms were related to the geometry of the lines and the characteristic of the substrate and the conductor. The contact probe placement error and the VNA drift were also considered by performing two calibrations. Then, we performed a 250-iteration Monte-Carlo analysis to estimate the impact of these error mechanisms during the calibration process. Each Monte Carlo iteration led to the extraction of one HBT model. Consequently, we extracted 250 HBT models through ICCAP, each of them having a unique assignment of measurement uncertainties.

Finally, we created a single model in the ADS[1] Keysight software, which integrated the nominal HBT model and the 250 models with uncertainties. The user can choose to run the nominal HBT model or all the models at the same time.

III. Model Verification

The nominal model was verified in [4] using 1 GHz large-signal measurements under 50 ohms conditions. Here, we verified our HBT model with large-signal, multi-harmonic, load-pull measurements at 9 GHz. We used a conventional first-tier 2.4-mm short–open–load–thru (SOLT) calibration to perform the power and phase calibrations needed to fix the wave amplitudes and phases of the large-signal measurements. Then, we transferred these calibrations to the on-wafer reference plane by performing a second-tier TRL calibration.

We optimized the load at the fundamental and second harmonic frequency to obtain optimal electrical performance in terms of output power, gain and power-added efficiency

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[1]We identify commercial products only to accurately describe the experiments and analysis we performed. NIST does not endorse commercial products. Other products may work as well or better.

(PAE) when the transistor was saturated. The quiescent bias point was set to obtain a collector voltage V_c = 1.5 V and collector current I_c = 6 mA. Four harmonics were measured.

Fig. 1 illustrates a comparison between the 250 simulated HBT models with uncertainties and the measurements under the optimized load conditions (ZL_f_0=0.64/5º and ZL_2f_0=0.55/-175º). This simulation provided information regarding the expected range of performance. For example, we observed a very small spread in the range of the output power and the collector voltage waveform. However, under these specific conditions of DC bias points, loads and frequency, our HBT model with uncertainty showed a large expected range of PAE and current in the collector waveform in saturation.

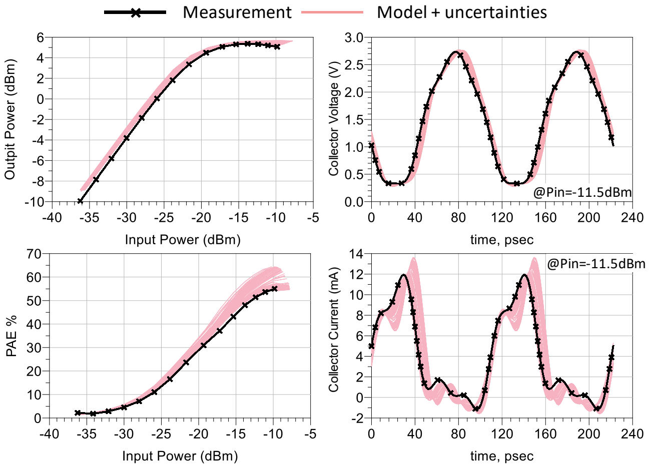

Fig. 1. Simulated HBT model with uncertainties versus load-pull measurements of a 6 µm HBT transistor. The load pull at the 9 GHz, fundamental and second harmonic loads were optimized.

Plotting the 95% confidence interval for the electrical performance of the transistor offers a convenient approach to investigate uncertainty in the model.

Fig. 2 illustrates the standard uncertainty related to the output power, PAE and the collector current and voltage waveforms at saturation. The standard uncertainty for the output power remains around 0.15 dBm in a linear operation, then drops when the transistor enters compression and increases up to 0.4 dBm at saturation. A standard uncertainty of 8% in PAE was simulated at saturation. We found significant variations in the DC collector current for the 250 Monte-Carlo models in saturation. This was largely responsible for the significant variation observed in the simulated PAE. We also observed that the simulated collector voltage and current waveforms at saturation presented a significant standard uncertainty at a time corresponding to the half period of the signal. This was due to uncertainties in the Kirk-effect model, and the contribution of the higher-order harmonics was mainly responsible for the uncertainties observed in the fall time of the collector current waveform. We also verified our model under different load conditions at 9 GHz and 16 GHz, and under small-signal conditions up to 110 GHz.

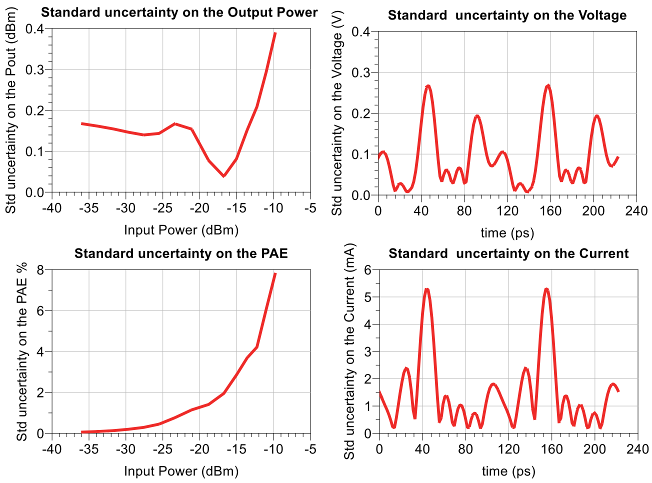

Fig. 2. 95% confidence interval for the output power (top left), collector voltage waveform at saturation (top right), PAE (bottom left) and collector current waveform at saturation (bottom right), resulting from a 9 GHz load-pull simulation of the HBT model with uncertainties included.

IV. Propagation of Uncertainty to Power-Amplifier Design at 220 GHz

We performed circuit simulations of two 220 GHz power amplifiers with our HBT model. The circuit consisted of a one-stage power amplifier, made up of 8 HBT transistors in parallel, and a four-stage power amplifier, made up of 40 HBT transistors. Fig. 3 shows the two 220 GHz MMIC power amplifiers.

Cheron, *et al.* originally simulated and designed these two common-base power amplifiers using the model provided by the foundry and showed measured performance in [10]. All the passive circuits were simulated with ADS/Momentum[1] Keysight software.

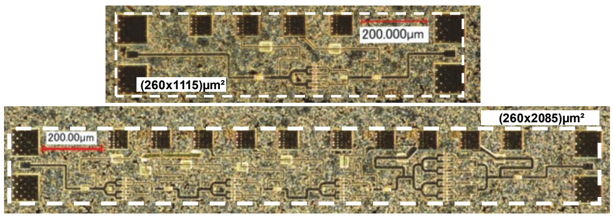

Fig. 3. Photograph of the 1-stage MMIC power amplifier (top) and the 4-stage MMIC power amplifier (bottom).

We compared the output power of the one-stage power amplifier, simulated using a model with uncertainties and using the measured data from [10]. In Fig. 4 we first observed a large expected range of output power from the model with uncertainties. We simulated up to 4.1 dBm of standard uncertainty in the output power at 208.5 GHz under linear operation, and 2.5 dBm at 222 GHz in saturation. In both cases, our simulated 95% confidence intervals overlapped the measurements. We observed that the simulation results from the nominal model and the average of the Monte-Carlo simulations better agreed with the measurements at saturation.

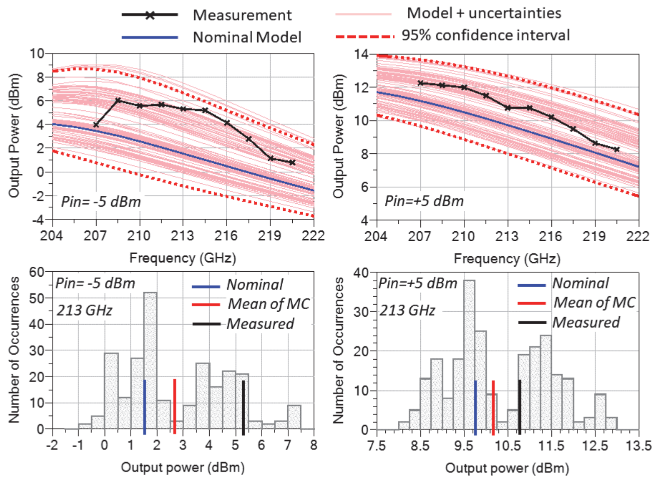

Fig. 4. 1-Stage PA: Simulations for a nominal model and a model with uncertainties versus measurements of the output power under linear operation (top left) and at saturation (top right). Histograms of Monte-Carlo simulations of the output power at 213 GHz under linear operation (bottom left) and in saturation (bottom right).

We compared the measured output power and power gain of the four-stage power amplifier with the simulated performance, using the nominal HBT model and the model with uncertainties, in Fig. 5. The two first stages of this power amplifier operate in a linear state when the last stage was saturated. The behavior of the simulated performance was similar to our observations of the one-stage power amplifier: (1) the simulated performance using the nominal HBT model is lower than the measured data; and, (2) we observed a large spread in the output power and power gain when we applied our model with uncertainties.

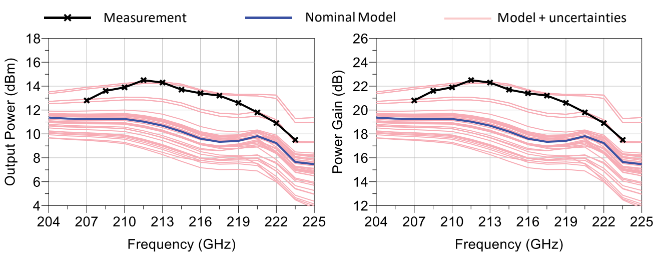

Fig. 5. 4-stage PA: Simulated performance using a nominal model and a model with uncertainties versus measurements.

We investigated the model parameters of the 250 HBT models we extracted. We determined that the models give a model parameter *TFC0* significantly higher than the nominal and provided a higher output power in this circuit simulation. The parameter *TFC0* is related to the definition of the low current transit time in the collector. The distribution of the *TFC0* model parameter illustrates that the ICCAP extraction procedure, using our set of measurements, failed to extract properly the model parameter *TFC0*, which is a critical parameter when the model is used at millimeter-wave frequencies.

V. Conclusion

For the first time, we used an HBT model with uncertainties in power-amplifier circuit designs at 220 GHz to predict the circuit's expected range of performance. We illustrated how useful the propagation of correlated measurement uncertainties during the model extraction process and design is in providing estimates of the expected range of electrical performance of complex circuit designs at millimeter-wave frequencies.

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