GaN Transistor Large-Signal Characterization Under Multi-Frequency Excitation

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***Abstract*—Transmitters for high peak-to-average power ratio communication, including Doherty, outphasing, and envelope tracking, are increasingly using supply modulation to improve efficiency. This paper describes a technique to measure multi-frequency excitation of a transistor under supply modulation conditions. The measurement setup is used to characterize GaN transistors in large signal operation at X-band with 1-500 MHz low frequency excitation on the drain and is useful for supply modulator design.**

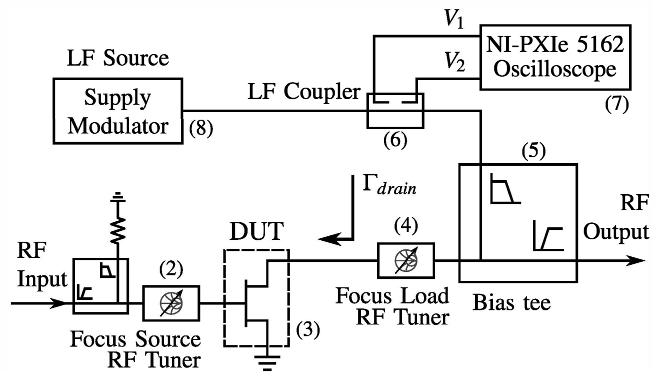
***Index Terms*—Supply modulation, microwave transistors, MMICs, multi-frequency characterization, power amplifiers.**

I. Introduction

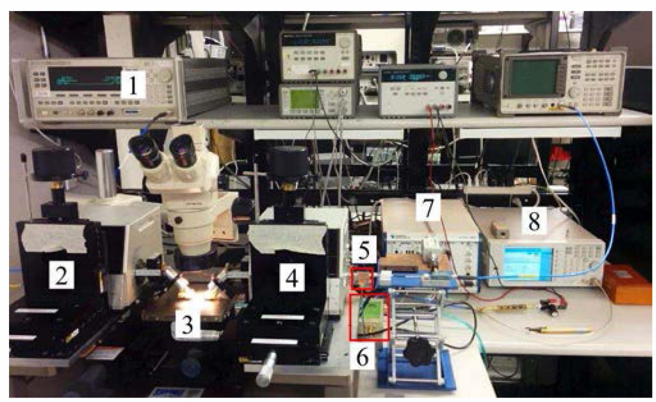
Wireless systems have increasingly complex modulation schemes and increasing signal bandwidths in order to improve capacity [1]. Such signals have high peak to average power ratios (PAPR) and it is a challenge to design an efficient transmitter that meets linearity requirements, especially for signal bandwidths exceeding a few tens of MHz. Power amplifiers that address this problem include the Doherty amplifier [2], outphasing [3], and various forms of supply modulation (SM) [4], [5]. Additionally, SM has also been shown to be beneficial to Doherty [6] and outphasing PAs [7].

Efficiency improvement by SM comes from decreasing wasted DC power when the output power of the RF power amplifier (RFPA) is reduced. The SM needs to provide sufficient power and appropriate voltage while following the signal envelope. The power from the SM is delivered to a dynamic load, but, most commercial nonlinear RF transistor models are not designed to predict low-frequency dynamic behavior at the drain supply port, where the drain supply port is considered as the third port. Transistor characterization in literature <10 MHz has been reported with a goal of modeling [8], including thermal and traps [9]. However, this is not helpful for large-signal models that can inform SM designers for frequencies $1<f_{LF}<500$ MHz. Multi-frequency 3-port measurements are therefore very useful for supply-modulated RFPA transmitter design.

The paper will discuss the measurement setup and then cover measurements on a bare die 0.15 µm GaN transistor. Static and large signal RF measurements will be presented. The purpose is to explore how the transistor acts under multi-frequency excitations, in particular when under supply modulation.



(a)



(b)

Fig. 1: (a) Simplified block diagram of experimental setup. The transistor is driven at the RF carrier frequency, while the drain is simultaneously excited at a baseband frequency (1-500 MHz) to act as a supply modulation signal. The numbers correspond to labels in Fig. 1b. (b) Photograph of setup with labeled 1) RF source, 2) gate tuner, 3) probe station with DUT, 4) drain tuner, 5) bias tee, 6) low frequency coupler, 7) oscilloscope, 8) low frequency source.

II. Multi-Frequency Measurement Setup

The test system shown in Fig. 1 was developed to measure low frequency impedances in a wide bandwidth (~1-500 MHz) while simultaneously measuring the RF performance of a DUT. The RF path uses scalar power measurements and a spectrum analyzer to distinguish multiple tones at RF frequencies. Fundamental frequency carrier tuners (operating from 8-50 GHz) are used to adjust the RF loading of the

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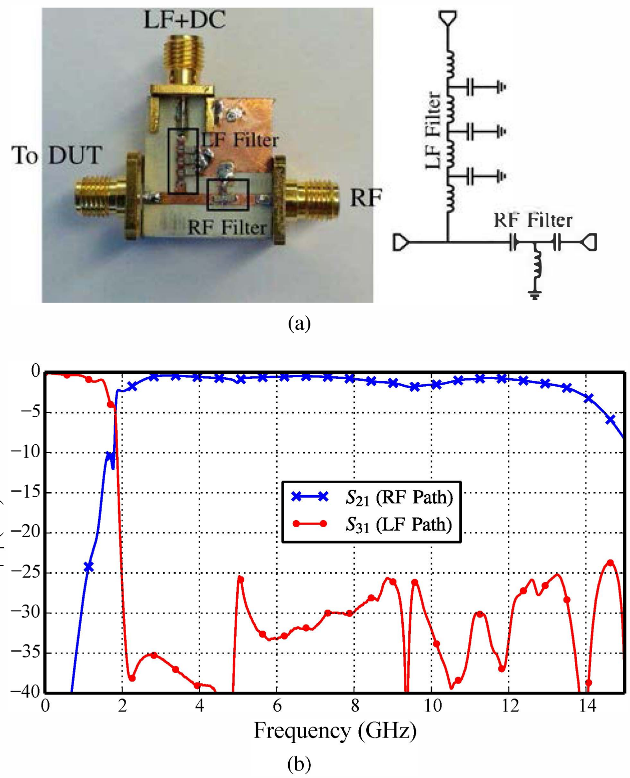

Fig. 2: (a) Photograph and circuit diagram of wideband bias tee which operates as a diplexer. (b) Measured performance of the bias tee.

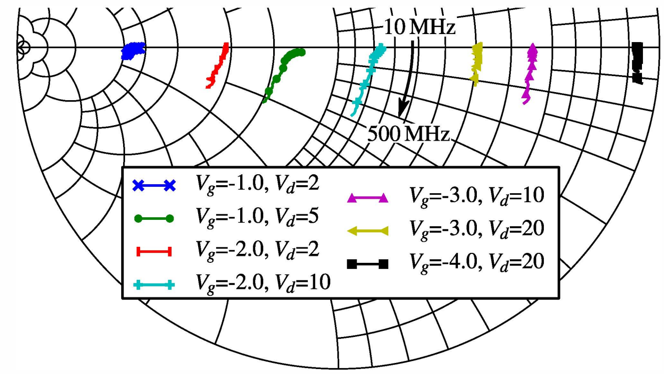

Fig. 3: Measured complex impedance from 10 MHz to 500 MHz of a few bias points of the 10x90 μm transistor plotted on an admittance grid. The lower gate bias voltage curves can easily be fit by a RC in parallel. The higher gate biases (-1 and -2 V) have an inductive part in addition to the RC indicating other effects under high current.

transistor. Below 500MHz, the tuner's effect on the LF waves is negligible. In the low frequency path, the NI PXIe-5162 10 bit, 5 GS/s oscilloscope is used to acquire the time-domain waveform. For this setup, the LF signal is AC coupled onto the DC drain voltage line and a simple signal generator injects the low frequency signal. The entire DC + LF block can be replaced with a supply modulator that simultaneously supplies the DC and LF signals without re-calibration. The RF used in this paper is 10.7 GHz, which is far from the LF of <500 MHz. This allows adequate impedance tuning of the probe station tuners and simpler filter design of the bias tee to differentiate the RF and LF signals. A similar bias tee on the gate side of the transistor to terminate the LF impedances from DC-500 MHz.

A TRL is performed at RF frequencies with S-parameter measurements of the input and output RF networks for power meter offsets. At LF frequencies, a short-open-load (SOL) with an absolute power calibration is performed coaxially before connecting to the drain tuner probe station. De-embedding to the DUT requires an additional SOL calibration using an impedance substrate standard. The sampling frequency and number of points used in the FFT is kept constant throughout the calibration and measurement giving a discrete frequency grid.

The bias tee is of particular interest for wide-bandwidth signals as it must be designed to pass the low frequency content to the transistor while blocking the same content from leaking out to the RF load. The function of the bias tee is similar to a diplexer. For the measurements presented in this paper, the bias tee is a parallel combination of a small DC blocking capacitor (in the RF path) and a 7th order low-pass filter (in the LF path) shown in Fig. 2. The bandwidth of the low-pass filter is 1 GHz, designed to pass large bandwidth supply modulation signals. As the low-pass filter requires large inductance and capacitance values, parasitics of the elements causing resonances in the RF band are the primary limitation for a wide bandwidth bias tee. Additional elements (an inductor and capacitor) are used in the RF path to help flatten the frequency response in the RF band. Measured performance is shown in Fig. 2b. There is 1 dB of insertion loss through the RF path and <0.3 dB loss through the LF path. The match is better than 40 dB at LF and 10 dB at 10.7 GHz.

III. Transistor Multi-Port Measurements

A. Static Bias

A 10x90 μm GaN transistor on TriQuint's 0.15 μm process is characterized under static bias conditions. First, the device is measured under small signal low-frequency excitation with no RF input, effectively tracing the IV curves of the device while simultaneously measuring the drain impedance. The results for a few bias points are shown in Fig. 3. As expected, the equivalent impedance is that of a parallel RC circuit. However, the higher current bias points have a distinct series inductive part that indicate that there are other effects besides a bias-dependent resistance and capacitance.

B. Dynamic Measurements

Sourcepull and loadpull were performed on the 10x90 μm device to find the optimum fundamental frequency RF terminations for maximum PAE at 10 GHz and V_d=20 V. The peak PAE RF load is $25.0 + j34.2$. Measured output power and efficiency contours are shown in Fig. 4a. Over various RF input powers and at each loadpull point, the low frequency impedance is measured (Fig. 4b). The value of the real impedance varies not only with the RF load, but with the RF input power as well. For example, lower impedance values

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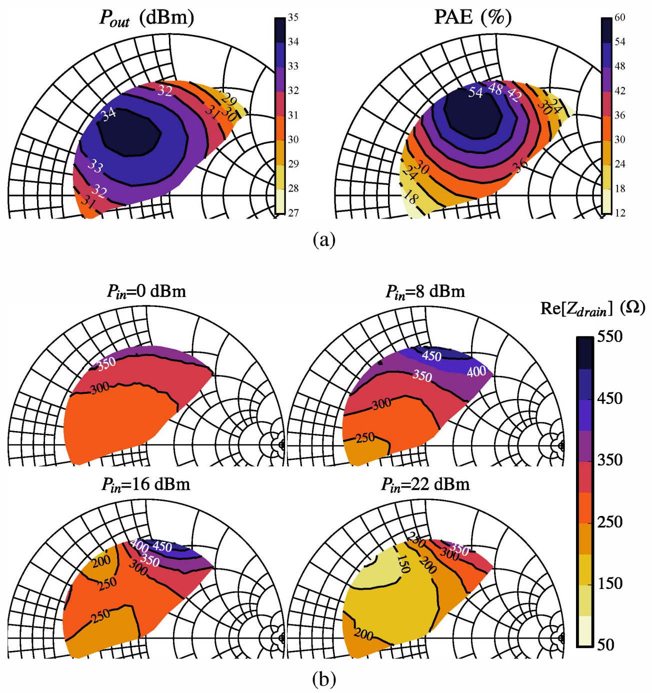

Fig. 4: (a) Measured RF loadpull performance on 10x90 µm transistor at 10 mA/mm. (b) Re[Z_d] at 10 MHz plotted versus RF impedance at various input powers.

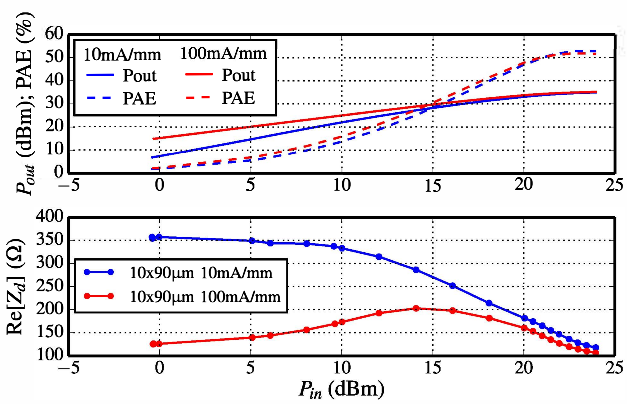

Fig. 5: Drain impedance of a 10x90 µm GaN FET over RF input power at 10 mA/mm (class B) and 100 mA/mm (class AB). The low frequency excitation is 10 MHz in this example. Depending on the bias point, the impedance variation can vary more than 250 Ω.

occur near the maximum output power RF load. At the optimal PAE RF load, the real part of low-frequency impedance at the drain is measured as the RF input power is swept, Fig. 5. Re[Z_d] is seen to greatly vary depending on RF input power and bias voltage ranging from 350 Ω to just over 100 Ω. Under RF compression, however, the resulting impedance is nearly the same, around 110 Ω.

IV. Discussion

The data shown above illustrates the type of measurements needed to model the behavior of a transistor under multi-frequency excitation. Additional variables include carrier frequency, low-frequency signal level, and bias. Similar measurements can be performed on an amplifier and an example is shown in Fig. 6 together with simulations using an Angelov based transistor model which gives good RF results. However, the low-frequency impedance gives non-physical results as can be seen as the sharp decrease in real impedance as the power amplifier enters into saturation at 22 dBm RF input. This paper details a measurement technique for transistors under multi-frequency excitation and is an initial step in the direction of a complete multi-frequency transistor model for dynamic supply applications.

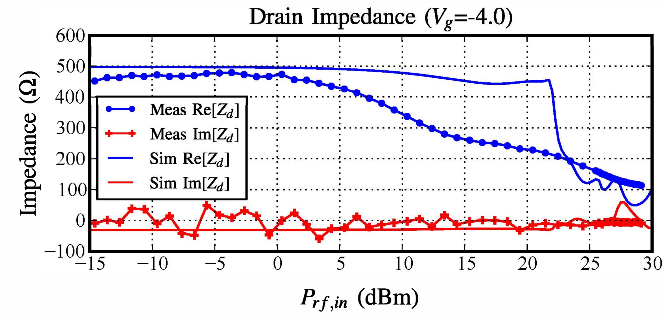

Fig. 6: Measured and simulated impedance of a MMIC power amplifier in [10]. The behavior of the bias line resistance in simulation is non-physical and is not seen in measurement.

As mentioned, supply modulation is an effective method for improving efficiency on its own or in conjunction with Doherty or outphasing PAs. In the case of envelope tracking, the data presented in this paper is a useful tool for determining trade-offs between RFPA and supply modulator efficiency during design. For example, to limit the large impedance variation over input power shown in Fig. 5, a class-A/AB bias point might be chosen, but limits the RFPA maximum efficiency. In contrast, for high-efficiency PA operating modes (class-B, class-F/F^{-1}, class-E) the bias point is very near pinch-off which will give large impedance swings when a typical communication waveform a transmitted.

V. Acknowledgment

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