10 W Broadband Load-Pull for GaN/AlGaN Characterization

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Abstract — In this paper we will discuss different load-pull techniques under two tone excitation with wide bandwidth (10 MHz). In our measurements a two tone signal with 10 MHz separation will be used with different load configurations. Due to the large bandwidth of the excitation signal each tone as well as the IMD (intermodulation distortion) products will have a different load condition. In the following experiments 4 load configurations will be used and the results will be compared also a load configuration which gives identical load condition at each of the two tones and terminates the IMD products with 50 Ω will be demonstrated.

I. INTRODUCTION

GaN/AlGaN material system is a strong candidate for manufacturing high-power high-efficiency and high-linearity RF power transistors for 3G base stations due to its superior electrical properties. The high saturation electron velocity (1.5 × 10^7 cm/s), wide bandgap (3.4 eV), and high breakdown field strength (35×10^5 V/cm) of the GaN/AlGaN system result in record power densities [1]. In 3G networks WCDMA air interface is used with a carrier bandwidth of approximately 5 MHz. The base station can use up to 4 carriers, where they are combined and amplified together by a common power amplifier. Characterizing GaN HEMTs excited with broadband complex modulated signals requires the use of two-tone signals with broad bandwidth. Performing load-pull on high power transistors services two purposes. The first is to find the optimum impedance required to achieve the required performance characteristics such as output power level, efficiency and IMD level. The second purpose is creating large signal behavioural models [2]. Performing load-pull requires a load whose impedance can be varied in a controllable way. In previous studies [3] two tone load-pull was performed with frequency spacing of 5 MHz but the reflection coefficient was assumed to be same as for the center frequency. In [4] multi tone load-pull was performed with maximum bandwidth of 3.2 MHz. In all of the cases the reflection coefficient was assumed to be identical for all the signal components. In this paper the effect of variation of reflection coefficient in relation to the load configuration will be demonstrated.

II. SYSTEM REALIZATION

The system used in performing the measurements is shown in Fig. 6. This system was first reported in [5] is extended to be able to perform harmonic load-pull and also the power capability is raised to 10 W in [6]. It is based around MTA (microwave transition analyzer), the MTA is a 2 channel high speed sampling scope, through the MUX unit and the bidirectional couplers fitted at the input port and the output port the incident and reflected waves at both ports can be measured also the MTA can measure the relative phase between the input port and the output port as well as the harmonics at each port enabling complete measurement of phase and magnitude for nonlinear devices. The bidirectional couplers are fitted with 20 dB attenuators at the coupling ports providing a total attenuation of 40 dB. For linear operation of the MTA the input at any of its 2 channels should be limited to 0 dBm. In this way this setup is capable of measuring signals up to 40 dBm (10 W). The measurement system sensitivity is -50 dBm and it has a dynamic range of -50 dB. Fig. 1 shows the result of a power sweep on the GaN HEMT used in the following experiments. The Device is terminated with a 50 Ω termination and operating at class B with supply voltage of 20 V and bias current of 150 mA.

III. LOAD-PULL CONFIGURATIONS

The load configuration used in load-pull measurements determines the phase and magnitude of the load reflection coefficient at each component of the output signal. Load configurations can be divided into two main categories passive loads and active loads. In case of single tone load-pull the magnitude of the reflection coefficient that can be achieved using passive tuners is limited by losses to be less than 1. This limitation can be overcome by using active loads. Active loads can achieve magnitudes for the reflection coefficient greater than 1 by arbitrarily generating the reflected wave. Performing load-pull using two tone signals especially with large tone separation (> 5 MHz) is critical because the load configuration affects the phase of the reflection coefficient seen by each signal component since each signal component has a different phase velocity. In the following sections load-pull will be performed using four configurations under two tone signal with tone separation of 10 MHz. To compare between the different configurations a target impedance is specified and the load configuration is tuned to achieve this target impedance at one tone. At the same time the levels of the
signal components (the main two tones and the 3rd and 5th order IMD) are measured as well as the reflection coefficient at these components. The first target reflection coefficient is 0.41∠105.5°, the same measurements will be repeated with another target reflection coefficient of 0.27∠19°. The Device is biased for class B operation with supply voltage of 20 V and bias current of 150 mA. Not all configurations can achieve the same reflection coefficient for both tones, leading to variation in IMD levels and main tones levels. Having the same reflection coefficient for both tones is important for modelling purposes to isolate the effect of the termination impedance from the effects associated with the transistor’s nonlinear capacitances. To get a true picture of the output levels of the two tones as well as the levels of the IMD products at large bandwidth, software power levelling for the input tones is used to ensure the same level for the input tones, any difference of the output levels of the output tones will be due to the transistor.

A. Passive Tuner

In this configuration a passive tuner from Maury is used. Fig. 3 shows that at large frequency spacing the phase shift between the two reflection coefficients is inevitable because of the length of the tuner (although the tuner is mounted directly without cables to the setup). At the same time the magnitudes of the reflection coefficients of the two tones are identical (the tuner is of high quality and has a very low $S_{11}$).

Equation 1 gives an estimate of the reflection coefficients phase difference between the two tones. For the first target reflection coefficient (left side of Fig. 3) we have $\Gamma_f = 0.413\angle105.9°$ and for the other tone $\Gamma_{f2} = 0.42\angle93.67°$ and the output power of the tones differ by 1 dB.

B. Active Closed Loop

To overcome the problem of losses and inability to cover the whole range of passive loads an active closed loop is used. In this load configuration shown in Fig. 4 a part of the output power is coupled out then amplified, phase shifted and then feed again to the output of the DUT.

In this setup we have a total reflection coefficient equals to $\Gamma_{loop} = \frac{S_{11}S_{21}}{1 - S_{22}\Gamma_{loop}}$ (2)

$S_{11}$ is the eigen reflection coefficient of the sampling coupler, $S_{12} = S_{21}$ (reciprocity) is the transmission coefficient of the sampling coupler and $|S_{22}| \ll 1$ because of the circulator between the attenuator and the sampling coupler, as a result we have

$$\Gamma_l = S_{11} + S_{12}^2 |\Gamma_{loop}| e^{-2j\beta l}$$ (3)

here $l$ represents the length of the loop. As can be seen from equation 3 that the phase of the reflection coefficient is a function of the length of the loop and phase velocity of the wave. For the first target reflection coefficient (left side of Fig. 5) we have $\Gamma_{f1} = 0.42\angle105.5°$ and for the other tone

$$\Delta\phi = j2\Delta\beta l = j2\pi l(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})$$ (1)
\[ \Gamma_{f_2} = 0.36\angle 60.15^\circ \] and the output power of the tones differ by 1.64 dB here the difference is bigger than the case of passive tuner due to magnitude and phase variation.

C. Single ALM

In this setup shown in Fig. 6 a single ALM is used to control the reflection coefficient of both tones. ALM is an Automatic load module, it is an IQ modulator which receives a signal split into I (In phase) and Q (Quadrature phase) components. By varying the amplitude of the inphase and quadrature phase components the phase and amplitude of the signal can be changed independently. These ALM modules are based around Siemens chip PMB 2202.

In our experiment the control voltage which controls the vector generator (VG) is optimized to get a certain reflection coefficient at one tone and then levels and reflection coefficients at the other tone and the IMD products are measured. Because of the varying envelop of the two tone signal the IQ modulator suffers from internal distortion and produces 3rd and 5th order IMD products, Producing reflected waves at these products and thus terminating these products at the output with an impedance other than 50 \( \Omega \). For the first target reflection coefficient (left side of Fig. 7) we have \( \Gamma_{f_1} = 0.41\angle 104.9^\circ \) and for the other tone \( \Gamma_{f_2} = 0.34\angle 109.15^\circ \) and the output power of the tones differ by 1.4 dB.

D. Double ALM

Using two ALM modules, one for each tone as shown in Fig. 8 we can control each tone independently from the other tone. This configuration allows us to obtain arbitrary termination for each tone, also terminating the IMD products with a match. Fig. 9 shows that the reflection coefficients of the two tones are identical in both cases of \( \Gamma = 0.41\angle 105^\circ \) (left side) and \( \Gamma = 0.27\angle 19^\circ \) (right side) and also the output power for the two tones are identical. The IMD products in this setup are terminated with a match. It can be seen that terminating the IMD products with a match results in the highest IMD level in all the previous configurations.

IV. Narrow Band Load-Pull

A conventional load-pull with a passive tuner under two tone signal with frequency separation of 100 kHz \( (f_1 = 2.13995 \text{ GHz}, f_2 = 2.14005 \text{ GHz}) \) is performed. The device is biased...
for class B operation and the input power is 3 dBm which is equivalent to 3 dB backoff (1 dB compression is at 6 dBm Fig. 1). Fig 10 shows the impedance seen by each tone on the smith chart as well as the output power levels and the C/IMD (carrier to intermodulation ratio) levels. in case of narrow frequency spacing the impedance contours coincide over each others also the power levels are the same for the two tones. $\Gamma_{C/IMD}$ and $\Gamma_{Pout}$ shows the reflection coefficients equivalent to maximum C/IMD and output power level respectively.

![Figure 10](image1)

Fig. 10. Load reflection coefficient (Smith chart left). Output power (top right), C/IMD (bottom right) with respect to tuner parameters

Fig. 11 shows constant power and IMD contours. The point $\Gamma_{Opt}$ is the optimum reflection coefficient which gives 20 dBm of output power and 34 dB of C/IMD. For the same transistor under 50 \(\Omega\) termination the output power is 20 dBm and the C/IMD is 30 dB.

![Figure 11](image2)

Fig. 11. Constant power and IMD contours with respect to tuner parameters

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