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The Impact of Baseband Electrical Memory Effects on the Dynamic Transfer Characteristics of Microwave Power Transistors

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Abstract **— The inter-modulation distortion products can vary both in terms of amplitude and asymmetry due to the effects of baseband and 2nd harmonic impedance. This paper presents an investigation into the relationship between the IMD asymmetries caused by baseband impedance variation and the looping or hysteresis that can sometimes appear in the dynamic transfer characteristics of microwave power devices when subjected to modulated excitation. The investigation is carried out using a 2W GaN HFET bare die device characterized at 2.1GHz, and using IF active load-pull to clarify the role of baseband impedance on observed hysteresis in the dynamic transfer characteristics. Analysis is performed using the envelope domain in order to more effectively reveal the DUT's sensitivity to impedance environments and specifically electrical baseband memory effects.**

Index Terms **— Envelope domain, GaN, hysteresis, IF active load-pull, inter-modulation, memory Effects.**

I. INTRODUCTION

It is widely reported how electrical memory effects are caused by baseband, fundamental as well as 2nd harmonic impedance variation as a function of modulation frequency [1] and can cause significant variation in the symmetry and magnitude of inter-modulation products generated within a signal bandwidth. This spectral asymmetry leads to, and in some cases can be considered a direct consequence of an asymmetrical output modulation envelope that results in an observed hysteresis in the measured dynamic input voltage - output current transfer characteristics of the device - an effect often attributed to the presence of memory.

The third order inter-modulation (IMD3) products are of most interest, and for simple two-tone excitation comprise several contributors, some of which are mixed to IMD3 from different frequency bands. The interest here is mainly in the 2nd order non-linearity that causes components to mix to IMD3 from the baseband and 2nd harmonic band, and which can be affected by manipulating the impedances presented to these frequency bands [1]. Although the optimization of IMD3 terms is possible by controlling both the baseband and the second harmonic frequency components, in this work only load-pull of the low frequency baseband components is considered. In practical design, critical baseband impedances are usually determined by bias insertion networks, and typically extend from DC up to five times the modulation bandwidth. These impedances are notoriously difficult to maintain constant and as a consequence, are recognized as the main cause of bandwidth dependent memory effects observed in microwave power devices [1, 2]. The first part of this paper focuses on probing the presence of nonlinear memory effects by examining both the input voltage and output current modulation envelopes and the resulting dynamic transfer characteristics obtained for modulated two-tone stimulus using various tone-spacings. The second part focuses on the use and application of active 'IF' or baseband load-pull measurements in order to control baseband impedances and to remove 'conventional' electrical memory. Finally, the effect of device inherent linear delay reported in [3] is removed to allow the residual hysteresis in the device's output characteristics to be analysed.

II. MODULATED MEASUREMENT SYSTEM

Until recently, there has been a lack of measurement systems that can support comprehensive non-linear device investigations under the modulated excitations. The majority of systems focus either upon the magnitude of the frequency spectra or upon in-band spectral components using instruments such as Vector Signal Analysers. Although these are extremely valuable approaches, they generally fail to capture all of the out-of-band information contained within both the base-band (IF) and around the harmonics that is essential for accurate envelope domain representation and analysis [3].

The developed measurement system is capable of handling IF and RF power levels in excess of 100W which makes particularly relevant to the characterization of devices used in both mobile handset and base-station applications. The measurement system itself is shown in fig. 1 and consists of two main entities: the RF test-set and the IF test-set which are identical both in terms of component architecture and principle of operation. The architecture incorporates combined IF and RF capabilities allowing critically, the simultaneous collection of all four travelling waves at both IF and RF frequencies.

The simultaneous combining of coupled RF and IF components of the signal prior to the measurements is a key feature, and ensures phase coherence between the measured IF and RF components. The system is fully vector-error corrected, and can therefore account for any errors introduced due to losses, mismatches and imperfect directivities in the system, thus allowing for the measurement of the complete

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modulated voltage and current waveforms and impedances that exist at the DUT plane [2, 3]. The modulated measurement system shown in fig. 1 was used to perform the measurements where the significant baseband IF1 and IF2 components were actively suppressed. These 'active' IF loads were supplied via two phase coherent arbitrary waveform generators, which when amplified are capable of delivering 100W over a bandwidth of 10 KHz to 12 MHz.

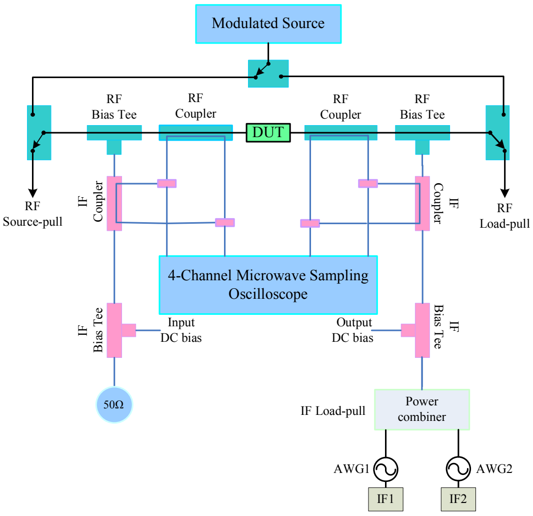

Fig. 1 Modulated waveform measurement system

III. MEASUREMENT RESULTS AND ANALYSIS

The measurements presented here were carried out on a 2W GaN HFET bare die supplied by CREE. For baseband electrical memory investigations, a two-tone stimulus signal with a centre frequency of 2.1GHz was used and the tone-spacing was varied between 1 and 10MHz. The device was biased at approximately 20% IDSS in Class-AB at a quiescent current of 130mA, and all significant RF signals were passively terminated into 50Ω. The characteristics were measured dynamically and found to be strongly dependent on the separation frequency.

$$A(\cos\omega_1 t+\cos\omega_2 t)$$
$$= 2A\cos\left[\left(\frac{\omega_1-\omega_2}{2}\right)*t\right]\cos\left[\left(\frac{\omega_1+\omega_2}{2}\right)*t\right] \qquad (1)$$

Where the modulation frequency, ω_m, is given by

$$\omega_m=(\omega_1-\omega_2)/2 \qquad (2)$$

To observe the dynamic behavior of the device whilst operating within a realistic operational environment, and in response to an applied modulated input stimulus signal, envelope domain analysis is used [3]. Fig 2 shows the fundamental current and voltage modulation envelopes for a P_{1dB}-3dB backed-off drive level , and clearly show that there is a significant phase delay between the input and output of the device at a tone spacing of 5MHz, whereas at 1MHz tone spacing, negligible phase delay was observed . At this backed-off drive level, the output power spectrum illustrated the low-level of baseband and near absence of 2ndharmonic distortion; a condition which unsurprisingly resulted in symmetrical IMD3 behaviour.

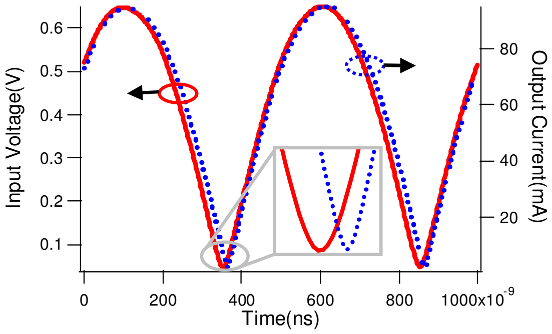

Fig. 2 Input voltage and output current envelopes at 5MHz tone spacing.

Fig. 3 shows a broadening in the dynamic transfer characteristic due to linear device delay as reported in [3]. It can be seen however that when the device is driven 1dB into compression, the observed nonlinearities are much more significant and appear as a soft, asymmetrical clipping of the output current envelope, which significantly increases the 2nd harmonic signal level and causes a significant baseband signal components to develop.

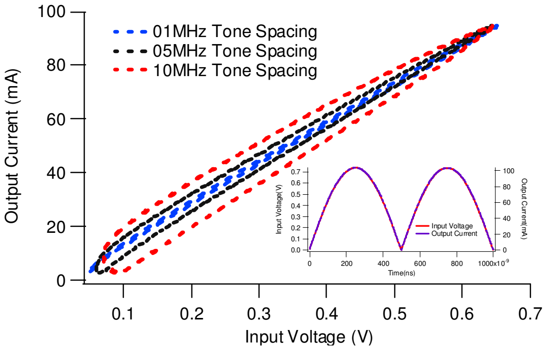

Fig. 3 Dynamic transfer characteristics at different tone spacings with input voltage and output current inset at 1MHz tone-spacing.

The asymmetrical envelops are shown in fig. 4 which are an explicit manifestation of presence of nonlinear memory effects at higher drive levels. The baseband signal generated from the device also includes higher order terms, and it is the asymmetric envelope shape that determines which IMD_3 product ($2\omega_2$-ω_1) or ($2\omega_1$-ω_2) will have the greater magnitude. The presence of these asymmetrical spectral current components manifest themselves as recognizable electrical memory effects and can be clearly seen in the envelope domain as significant looping at the top-end of the input voltage / output current transfer characteristic. The hysteresis in the dynamic transfer characteristics worsen with the increasing tone spacing and can be seen explicitly from fig. 5.

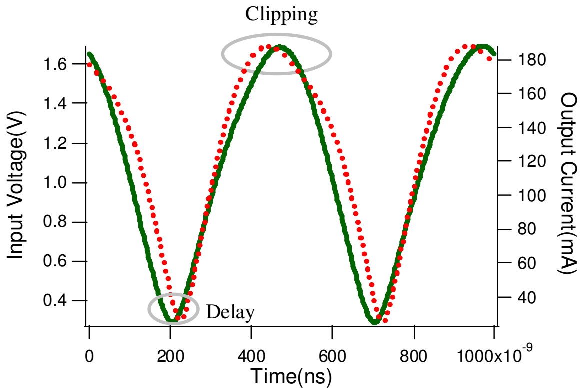

Fig. 4 Input voltage and output current envelops at 5MHz tone-spacing.

In this first case, the significant baseband frequency components are to be expected and are due to the fact that the significant baseband current components are termination into a relatively high broadband impedance of 50 Ohms. These are clearly the most significant contributor towards the observed electrical memory effects.

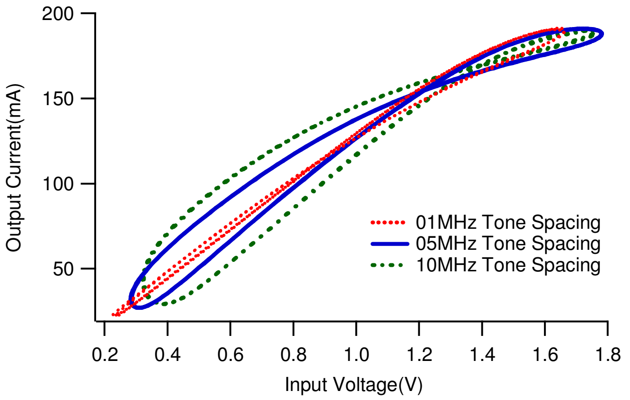

Fig. 5 Dynamic transfer characteristics at different tone spacings for compressed drive level.

IV. APPLICATION OF IF ACTIVE LOAD-PULL

In a practical PA design, the first instinctive step is to nullify or cancel these unwanted baseband voltage components, preventing any contamination or 're-modulation' of the output bias supply. Therefore, the termination of these frequency components into short circuits is usually desirable and the normal course of action. For the measurements presented in this paper, active IF load-pull has been used as means of controlling the contribution of the significant baseband components (IF1 and IF2). The validity of this approach in maintaining a constant low-frequency impedance environment is reported in [2] where IF1, which is twice of the modulation frequency and IF2, which is four times the modulation frequency were actively load-pulled. In the work presented here, frequency independent IF1 and IF2 short circuit impedances were maintained for different tone separation and at a single drive level. The observed variation in impedanc is very small and can be seen from Fig. 6 to be less than 0.005 in magnitude and approximately 0.1degrees in phase over the entire IF bandwidth.

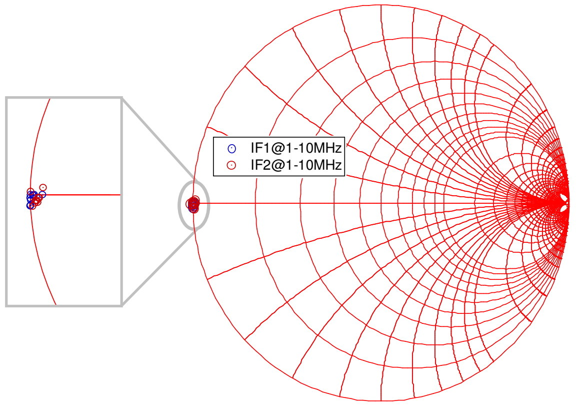

Fig .6 Measured IF$_1$ and IF$_2$ impedaces on Smith chart at different tone-spacing.

The behaviour of the carrier tones (F1 and F2) is clearly independent of the tone spacing as shown in Fig. 7. It is also evident that a reduction in IMD$_3$ components appears to have been possible by providing the IF short circuit impedance for frequency ranging from 1MHz to 10MHz. This is due to the fact that the non-negligible baseband electrical memory effects are greatly reduced.

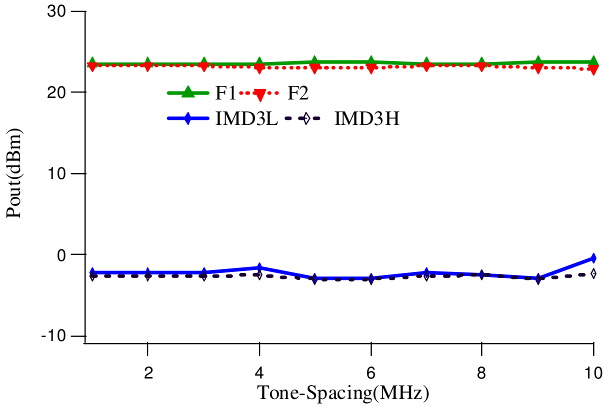

Fig. 7. Measured fundamental and IMD3 power for different tone-spacing at constant drive level of 1dB compression point.

Measurements under such conditions show a notable reduction in IMD$_3$ asymmetry and confirm the validity of IF active load-pull in maintaining a constant baseband impedance for the two significant baseband components IF1 and IF2 over the bandwidth of at least four times the modulation frequency. The baseband voltage components are greatly suppressed whilst maintaining the short-circuit baseband impedance for significant baseband components. Under such conditions, the IF load-line was almost completely vertical with only slight current variation present. This condition resulted in negligible looping in IF load-lines as the RF load-line follows the same trajectory in and out of the boundary conditions; consequently this reduced the hysteresis in the dynamic transfer characteristics.

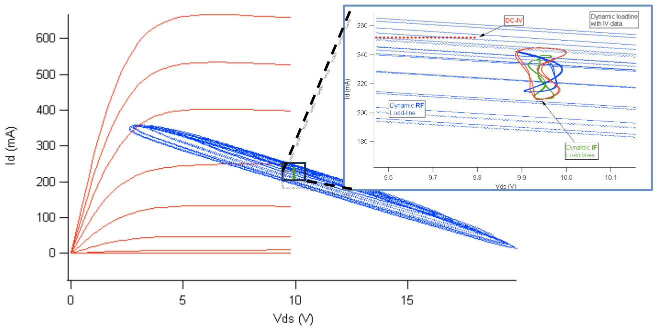

Fig. 8. Dynamic RF load-line with the IF loadline inset at different tone spacings.

V. Delay Adjustment Estimation

The device's linear propagation delay has to be accurately computed so that the input and output envelopes can be time aligned. The delay is computed and applied to the output envelope, and fig. 9 shows that the envelopes can be perfectly aligned at their minima. There appears non-quasi static envelope distortion however even after terminating the significant baseband components into short circuits. This alignment changes the shape of the transfer characteristics such that the broadening at the bottom is diminished whilst the looping in the upper part of the characteristic remains.

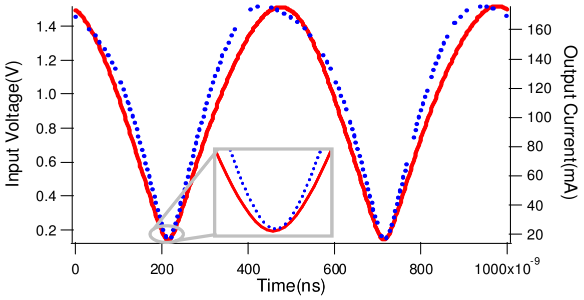

Fig. 9 Delay compensated output current envelope at 5MHz tone spacing.

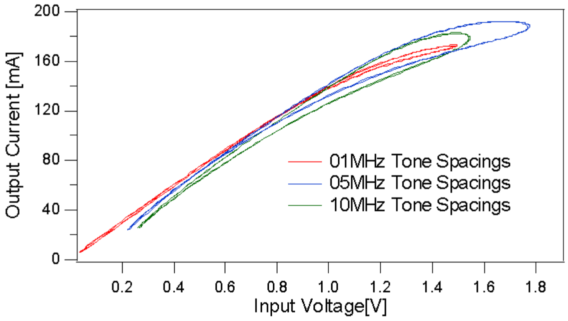

Fig. 10 Delay compensated dynamic transfer characteristics at different tone spacings for slghtly different drive level at 5MHz tone spacing.

Interestingly however, in the case of IF short circuit termination, it was observed that the approach of shorting these low-frequency voltage components is effective in influencing the IMD asymmetry, suggesting that the hysteresis in the dynamic transfer characteristics can also be minimized by terminating the significant baseband components IF1 and IF2 into short circuits. The residual spread remains in the dynamic transfer characteristics as can be seen from fig. 10 for certain bias conditions, and is most probably attributable to non-linear device delay or other sources of memory, specifically trapping effects, thermal effects [4][5], and in this case, is not due to electrical baseband memory effects.

VI. Conclusion

In this paper, envelope domain analysis is performed for different drive levels and is used to investigate the effect of baseband electrical memory on envelope distortion and on the measured dynamic transfer characteristic.

At a backed-off drive level with the device operating linearly, symmetrical modulation envelopes are observed. When driven into compression, these envelopes become asymmetrical however. Using IF active load-pull to control the behaviour of the significant baseband components, IMD_3 asymmetry can be significantly improved, an effect due to the suppression of baseband electrical memory. The causes of this 'electrical' effect may be understood by analysis of the IF dynamic load-lines - any significant looping in the IF load-line will result in different trajectories of the RF load-line through the static IV characteristic, for different parts of the modulation cycle. The suppressed baseband voltages translate to greatly reduced hysteresis for lower tone spacing, significant hysteresis remains for higher tone spacing.

Acknowledgment

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