

Linearity Enhancement of GaN HEMTs under Complex Modulated Excitation by Optimizing the Baseband Impedance Environment

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Abstract — This paper demonstrates how the linearity performance of a 10W GaN HEMT can be dramatically improved by actively engineering the baseband impedance environment around the device. An important refinement to existing active load-pull measurement capability is proposed that allows the precise and independent control of all significant baseband and RF components that result from the amplification of a complex 9-carrier multi-sine modulation. The synthesis of constant, modulation frequency independent negative baseband impedances, resulting in specific baseband voltage waveforms has delivered a 24dB improvement in ACPR compared to the classical baseband short case, even when the device is operating with RF components terminated into a non-optimal 50Ω RF environment. This linearization concept is further investigated through the broadband emulation of a class-J impedance environment around a single device. Using this enhanced system and a two-tone modulated excitation, optimum baseband loads are identified that result in a 18.5dB and 24dB improvement in IM₃ and IM₅ inter-modulation products respectively, again relative to the case of a traditional IF short circuit. The significance of this last observation is that unlike the 50Ω case, the optimum class-J IM₃ and IM₅ baseband impedances disperse, becoming reactive and moving away from the real axis.

Index Terms — Active load-pull, memory effects, baseband, harmonics, power device.

I. INTRODUCTION

The continuing evolution of the wireless standards such as WiMAX and Long Term Evolution (LTE) is driving the need for power amplifiers (PAs) to be able to accommodate multiple modulation schemes at multiple frequencies, and also demands spectral efficiency to meet ever-increasing linearity requirements. These standards invariably impose higher peak-to-average power ratios (PAR), which typically require increasing degrees of back-off to maintain good linearity, thus reducing the efficiency of the power amplifier considerably. As an example, the PAs used in LTE systems, employing orthogonal frequency division multiplexing (OFDM) need to accommodate scalable bandwidths ranging between 1.4 MHz and 20 MHz, with PAR in the region of 10dB [1].

In such wideband applications, any variation in baseband impedance over bandwidth can cause adverse effects in terms of device linearity performance where intermodulation distortion (IMD) levels can vary asymmetrically with signal bandwidth - these problems are generally termed memory

effects [2]. In such case, filtering because it is too close in frequency to the desired signal cannot generally reduce the resulting IMD. Additionally, the reduction of IMD through simple pre-distortion linearization can become rather difficult when the side-bands become asymmetrical, since the simple pre-distorter assumes symmetrical IMD characteristics according to tone spacing. With the increasing signal bandwidth and PAR associated with modern wireless communication standards; it is frequently observed that pre-distortion linearization becomes very PA and modulation standard specific [3]. In addition, when PAs are driven into compression, pre-distortion algorithms have difficulty in capturing the true compression characteristics of the PA as the memory effects increase [3]. This highlights the fact that these bandwidth dependent baseband impedance effects on memory behavior are an important problem that needs further investigation. To further investigate such effects and their influence on the linearity performance of a device, a high-power modulated waveform measurement system has been developed and demonstrated in [4-8].

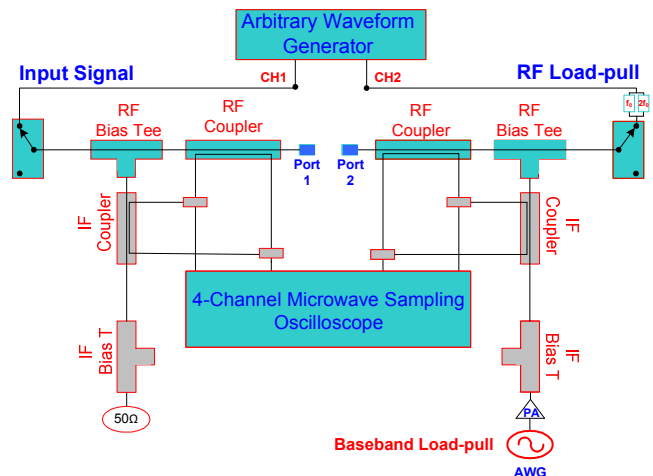


Fig. 1 Modulated waveform measurement system with the capability of active RF and IF load-pull.

The effects of varying the impedance presented to the two most significant baseband components; IF1 and IF2 that are generated as a result of 2-tone excitation has been shown in [4-7], where the device is driven at a relatively backed-off level, 1dB below the 1dB compression point. However, when

the device is driven more deeply into compression with more complex excitations, significantly more mixing terms are generated, and in order to achieve a sufficiently broadband IF termination, significant modification of the load-pull measurement system has been required in order to accurately account for higher order baseband components. For this work, this impedance control is being achieved in the time domain using a single wide-band arbitrary waveform generator (AWG) to synthesise the necessary waveforms that result in a constant and specific IF impedance environment across a wide IF bandwidth. The RF synthesizer used in the modulated waveform measurement system depicted in Fig.1 is a Tektronix AWG7000 Arbitrary Waveform Generator, and is used to synthesize both fundamental excitation and harmonic load-pull signals simultaneously, in the time domain. Using this instrument and its two independent yet coherent channels, the waveform measurement system is capable of maintaining independent and constant impedance control for each individual tone across both the IF and RF impedance environment, and over a wide modulation bandwidth. The approach adopted in this work is to actively engineer the baseband signal environment in order to achieve specific, modulation frequency independent impedances over a bandwidth of at least ten times the modulation bandwidth. The first part of this paper confirms and demonstrates that substantial linearity improvement can be achieved using this approach, when using a complex 9-tone excitation, as has already been shown for case of two-tone in [8]. As expected, for the GaN device considered, and for this degree of compression, the measured linearity significantly improves when specific negative baseband impedances are presented. The second part of this paper demonstrates the emulation of a modulated class-J PA, through the application of modulated RF active load-pull. This has been done to investigate the effectiveness of using this baseband linearising approach in improving PA linearity when the fundamental and reactive harmonic loads presented to the device become highly reactive. It is worth mentioning that although such 'negative' baseband impedances are non-realiseable using conventional, passive designs, this is not the case when considering active, baseband injection architectures such as Envelope Tracking (ET).

II. LINEARITY MEASUREMENTS AND ANALYSIS

All the measurements presented in this section are for a CREE CGH40010 discrete 10W GaN HEMT device, characterized at the centre frequency of 2GHz, within a custom built 50Ω test fixture. This fixture was calibrated over a relatively wide 50 MHz baseband bandwidth, and over 100 MHz RF bandwidths centered around the fundamental, second and third harmonics, with both baseband and RF calibrated reference planes established at the device's package plane. This allowed the accurate and absolute measurement of all the significant voltage and current spectra generated at the input and output of the device. Modulated measurements under nine

tone stimuli at PAR of 9.54dB were performed using a 2MHz modulation frequency, with the device class-AB biased. Respective drain and gate bias voltages of 28V and -2.05V resulted in a quiescent drain current of 250mA ($I_{DSQ} \cong 5\% I_{DSS}$). The device was driven into approximately 1.5dB of compression whilst delivering a peak envelope power (PEP) of 41dBm with fundamental and harmonic components terminated into a nominal impedance of 50Ω, at both input and the output. It should be noted that the broadband 50Ω load was used in this case to simplify the required measurement architecture. Although this is a non-optimal load condition, it was considered sufficiently representative for the linearity analysis presented here. Active IF load-pull was then used to synthesize a range of IF reflection coefficients in order to quantify the effects of the broadband baseband load impedance environment on the non-linear behavior of the DUT.

The optimum IF impedance for the best linearity, as has been identified in [8], lies some way outside the Smith chart. Fig. 2 illustrates a set of measurements where the broadband IF impedance was held constant for all baseband tones and swept over a measurement grid, including the short circuit condition. For each of the measurement points, the bias and drive level was maintained constant.

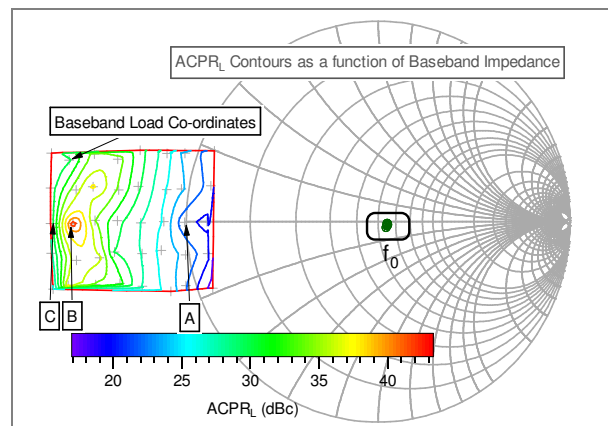


Fig. 2 Measured lower adjacent channel power linearity contours as a function of IF reflection coefficient (Γ_L).

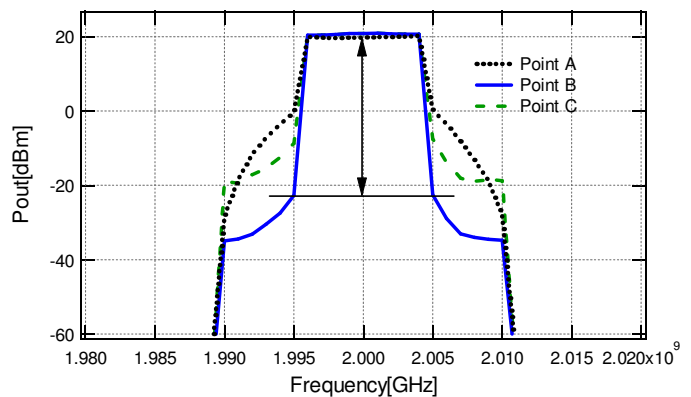


Fig. 3 Measured output power spectrum as a function of IF reflection coefficient (Γ_L).

The optimum loads for $ACPR_L$ and $ACPR_H$ lie on the real axis and are almost identical in terms of their position and the degree of linearization they offer. The contours of $ACPR_L$ are plotted in Fig 2 and show that at point-B, the linearity is found to be -43dBc , which is approximately a 25dB improvement over the classical short circuit case (point-A). From the output power spectrum depicted in Fig. 3, it can be clearly seen that terminating all the significant IF components at point-B significantly improves the device's linearity over a 10MHz bandwidth, to a level of approximately -43dBc . This confirms that this method of baseband linearization is not only applicable to two-tone excitations, but can also apply to far more complex, multi-sine signals with high degrees of PAR.

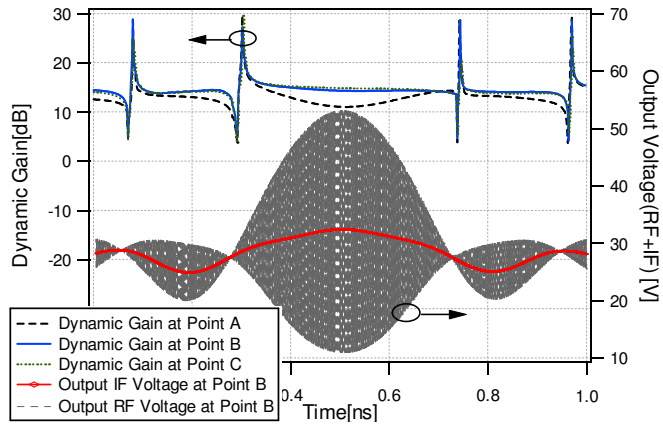


Fig. 4 Envelope domain [5] representation of gain as a function of IF reflection coefficient (Γ_L) at the identified points, alongside RF and baseband voltage waveforms.

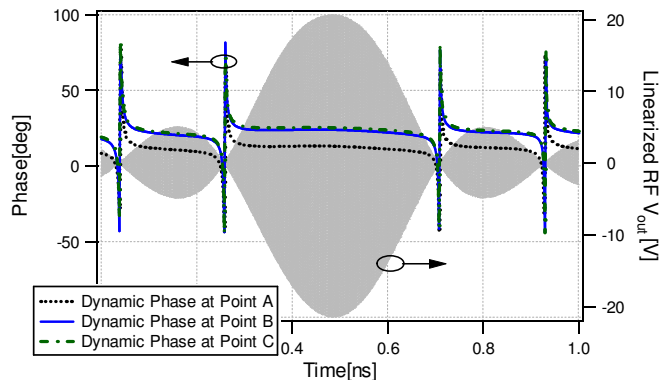


Fig. 5 Measured envelope phase ($\angle b_2 - \angle a_1$) as a function of IF reflection coefficient (Γ_L) at the identified points with linearized output RF voltage at point-B inset.

Fig. 4 shows the dynamic changes in gain over the modulation cycle for the three cases of baseband load reflection co-efficient, identified by points A, B and C in Fig. 2. It is clear from this graph that the negative IF impedance presented at point-B results in an increased and almost constant gain and improved linearity. The effect of the baseband voltage at point-B in shaping and 'positioning' the

output voltage waveform can clearly be seen. Setting the baseband load at a short circuit (Point-A) results in a significant depression in the dynamic gain envelope. Whilst point-C delivers almost the same envelope gain as point B, the linearity is reduced by approximately 13dB.

The phase shown in Fig.5 is defined here as the difference between measured a_1 and b_2 modulation envelopes, and its dependency on negative baseband impedance is shown in Fig. 5. It should be noted that the discontinuities observed in both the envelope gain and phase traces are measurement artifacts that occur due to the effect of linear delay as the magnitude of the modulation envelope approaching zero. Interestingly, there is a phase variation of approximately 18° between point-A and point-B, and this remains relatively constant over the entire period of the modulation cycle. The peak envelope efficiency is depicted in Fig. 6, and shows a maximum improvement of 8.1% for point-B compared to the short circuit case. This observation shows that presenting a negative impedances at point-B increases the achievable peak output power and has thus enables a higher efficiency than is possible at point-A.

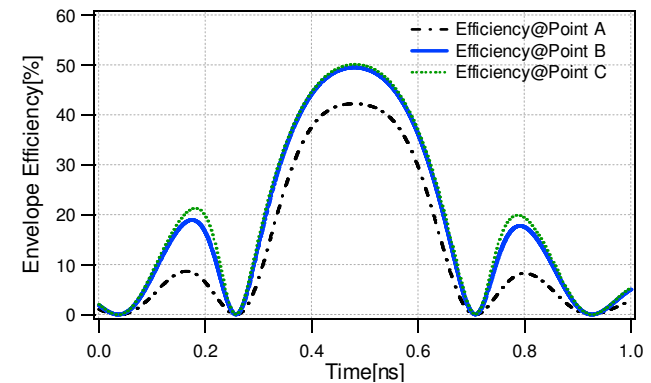


Fig. 6 Dynamic peak efficiency envelopes at an identified baseband loads.

III. EMULATION OF CLASS-J MODE OF POWER AMPLIFIER

In order to further investigate the suitability of this efficiency enhancing and linearizing technique under a realistic PA mode of operation, a class-J RF impedance environment was emulated. The device was biased in deep class-AB, driven into approximately 2dB of compression and excited using a 4MHz spaced two-tone modulated excitation centred at 2GHz. With knowledge of the device's intrinsic and extrinsic parasitics, the required class-J impedances were emulated and presented to the package plane [9]. This involved maintaining constant, specific impedances for both fundamental tones as well as the tones ($2\omega_1, 2\omega_2$) located around the 2nd harmonic.

The measurement results documented in the previous section clearly indicated that significant linearity benefit can be gained by optimizing the baseband impedance environment, as opposed for example to simply presenting a short circuit. For this class-J investigation, the IF impedance

presented to all significant baseband tones was swept over a similar measurement grid, again including the short circuit condition, and again extending outside the Smith chart. The IMD contours are plotted in Fig. 7, and similarly show that the optimum IF impedance for reduction of IMD resides outside the Smith chart. Importantly in this case however, the measurement shows that optimum baseband impedances are different for IM_{3L} , IM_{3H} , IM_{5L} and IM_{5H} and these are not, as was the case in the previous 50Ω measurement, co-located on the real axis. The optimum IM_{3L} and IM_{3H} baseband termination is found to be -43.2dBc and -45.5dBc respectively, and is approximately 18.5dBc better than the case where usual short circuit is provided to all the significant baseband components. But from an $IM5$ perspective, the optimum IM_{5L} and IM_{5H} showed the minimum distortion products which were found to be -59.3dBc and -61.1dBc respectively.

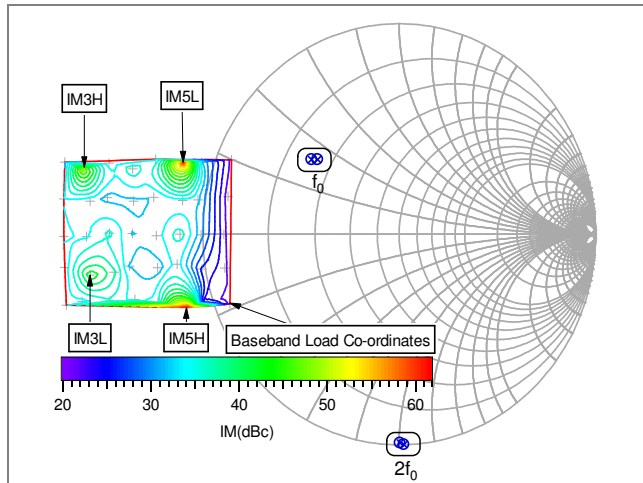


Fig. 7 Measured IM linearity contours as a function of IF reflection coefficient (Γ_L).

Fig. 8 shows the baseband voltage waveforms that result when the IF impedances for best $IM3$ low and high linearity are presented to the device. Although the magnitude and shape of both waveforms is similar, the phase is clearly different.

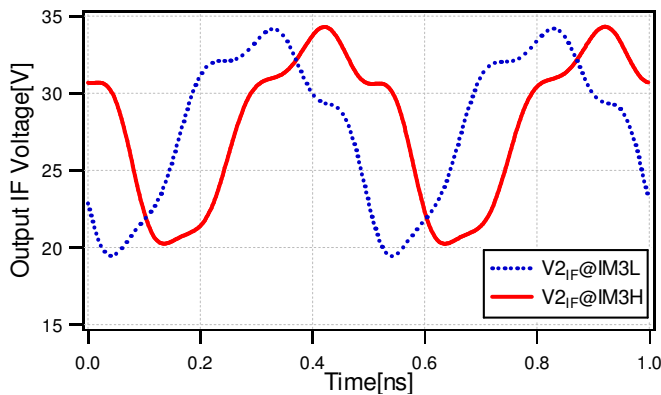


Fig. 8 Baseband voltages that resulted for the best $IM3$ linearity performance.

VII. Conclusion

Linearity investigations and analysis of 10W GaN HEMT under complex multi-tone excitations have shown that the optimum impedance for best linearity lies some way outside the Smith chart. The results show that for a 9-tone stimulus, the presentation of specific baseband loads can deliver a linearity improvement of 24dB and an efficiency improvement of 8.1% , relative to the baseband short-circuit case.

To investigate the suitability of this baseband linearizing approach to real-world PA architectures, the measurement system was used to emulate a class-J impedance environment, and the results suggest that although linearity can be improved, the optimum impedances become dispersed and move away from the real axis. This important observation may have large implications for the linearization of emerging, broadband PA architectures, especially when these involve efficiency enhancing techniques such as envelope tracking.

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