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Waveform Engineering Applied to Linear-Efficient PA Design

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Abstract — Low-frequency, baseband effects in Power Amplifiers can become particularly important when steps are taken to improve operational efficiency through the application of 'envelope' based approaches such as Envelope Elimination and Restoration (EER) and Envelope Tracking (ET). The aim of this paper is to demonstrate how a broadband modulated time-domain measurement system, when used in combination with active IF load-pull, can be employed to gain valuable insight into the behaviour of high-frequency power transistors whilst operating under modulated conditions. Also considered is the interesting idea of how PA linearity can be improved using the very mechanisms that are employed to improve efficiency.

Index terms — Amplifier distortion, Amplifier linearity, Amplifier efficiency, Modulation, Power amplifier

I. INTRODUCTION

In order to achieve truly broadband, highly efficient linearization of increasingly complex PA architectures, baseband as well as RF effects must be carefully considered and taken into account [1]. This can be particularly important when working with complex, multiple-device architectures such as the Doherty PA, where successful design relies upon the precise and highly optimised interaction between two or more active devices, both in terms of both RF and baseband frequency components. One interesting approach presented in [2] exploits this interaction and connects the drain bias nodes of two similar PAs via a baseband processing circuit in such a way that the effects of baseband impedance on distortion are cancelled over a wide bandwidth.

The devices used within these types of structures and architectures may well be configured in different efficient or efficient-linear modes of operation such as inverse class-F or class-J, as well as using different types or versions of device. Such designs become challenging when steps are made to improve efficiency by the application of 'envelope' based approaches such as Envelope Elimination and Restoration (EER) and Envelope Tracking (ET). The latter has recently gained popularity and relies upon dynamically modifying the instantaneous DC applied to a device in response to a modulation envelope. Considered another way, these approaches directly modify the baseband impedance environment presented to a device through active baseband injection - an approach that through earlier work has already been shown to be able to significantly improve linearity [1][3].

It is worth considering therefore the idea of improving PA linearity using the very mechanisms that are employed to improve PA efficiency.

Whereas classical modulated analysis of active devices and power amplifiers usually involves observing the magnitude and symmetry of inter-modulation products as a function of varying tone-spacing excitation and drive [4][5], observing modulation envelopes directly - envelope domain analysis - offers an alternative approach to exposing problematic effects, and involves plotting the dynamic behaviour of key parameters such as gain, output power, efficiency and others in response to the modulation envelope. This representation can be highly intuitive and sometimes more representative of a device's behaviour whilst operating within a realistic environment. Analysis of time varying behaviour in the envelope domain, especially in comparison to CW equivalents, can often provide significant insight into a number of dynamic, non-linear processes including the presence or otherwise of PA or device related 'memory'[6].

II. MODULATED WAVEFORM MEASUREMENT SYSTEM

Continuous Wave (CW) waveform measurement and engineering has established itself as a highly effective design solution for the development of power amplifiers [7][8][9]. However, modern modulation schemes such as CDMA and OFDM demand characterisation over extended instantaneous bandwidths of up to 100 MHz. In order to cater for these evolving requirements, existing CW waveform measurement and engineering capabilities have been extended into the modulated domain. This allows not only for the optimisation of traditional parameters such as output power and efficiency, but also the direct and simultaneous observation of linearity, memory and the sources of memory. Until recently, there has been a lack of measurement solutions that support comprehensive investigations into the full consequences of modulated excitation, with the majority of systems focusing either upon the magnitude of the frequency spectra using Spectrum Analysers, or upon magnitude and phase of in-band spectral components using Vector Signal Analysers (VSAs). Although these are both extremely valuable approaches, they are not able to completely describe the devices full operating state as they do not capture out-of-band information that exists at both the base-band (IF) and around the harmonics of the carrier

frequency (RF). It is after all the vector summation of these individual components that results in the actual voltage and currents that develop at the nonlinear device's input and output terminals. The accurate capture of these waveforms is essential to develop accurate envelope domain representation and analysis. The approaches investigated in this paper have been made possible by the development of a modulated waveform measurement approach that allows the observation and control of all the frequency components (RF, IF¹ and DC) [10] produced by the device under test. The system architecture is capable of handling both low and high power IF and RF signals (1mW to 100W), which makes it relevant to the characterisation of devices used in both mobile handset and base-station applications. A simplified schematic of the measurement system itself is shown in Fig. 1

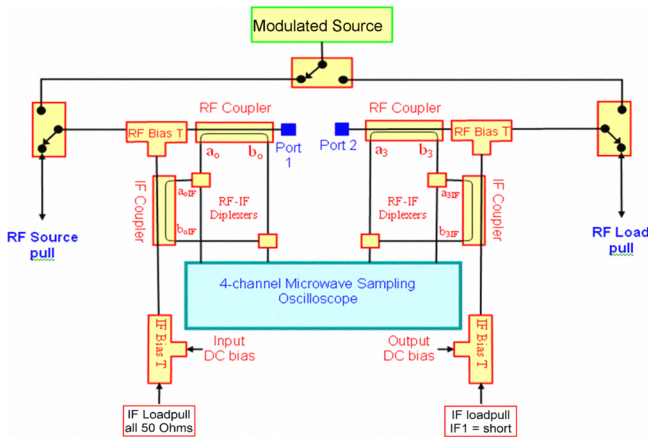


Fig. 1 Schematic of the modulated measurement system

The modulated measurement system consists of the RF test-set and the IF test-set, which are identical in terms of both component architecture and principle of operation. This combined IF and RF architecture allows the collection of the four travelling waves both at IF (a_1^{IF} , b_1^{IF} , a_2^{IF} and b_2^{IF}) and RF (a_1^{RF} , b_1^{RF} , a_2^{RF} and b_2^{RF}) frequencies. Combination of the coupled RF and IF components of the signal prior to measurement by the broadband sampling oscilloscope is achieved using diplexers, and is a key feature that ensures phase coherence between measured IF and RF components. The system is fully vector-error corrected and can therefore account for any errors introduced due to losses, mismatches, imperfect directivities and delay in the system, thus allowing the measurement of the complete modulated voltage and current waveforms and impedances that are presented at the input and output of the DUT. For the measurements shown in this paper, the system was calibrated over a bandwidth, of 50 MHz at baseband and around the fundamental and first three harmonic frequencies.

¹ Here, the term IF refers to the frequency components that exist in the baseband as a result of modulation. These may exist as a result of mixing, or be actively injected using active IF load-pull.

The specific focus of the measurement activities discussed in this paper was to investigate the impact of active baseband impedance conditions upon device linearity. For this reason, the fundamental and all harmonic frequency components were terminated into 50 Ohms. The IF load-pull architecture used here provided active impedance control of the most significant IF components; IF1 and IF2. This was achieved using an 80 MHz arbitrary waveform generator in combination with a high-power (200W), 1-10 MHz power amplifier. All measurements were performed on a CREE CGH40010 10W GaN device within a custom 50 Ohm test fixture. Calibrated reference planes were established at the package plane using a two-tier approach with error terms initially generated using a TRM coaxial calibration and then embedded with the extracted s-parameters of each half of the test fixture.

III. APPLICATION OF THE MEASUREMENT SYSTEM

Building upon previous work [7][12], the aim of this measurement activity was to explore in more detail the impact of baseband impedance upon linearity, and specifically 3rd order inter-modulation product magnitude and symmetry. Whereas previous work focussed primarily upon emulating passive baseband impedances inside the smith-chart, such as those that may be presented by an actual bias insertion network, this work was carried-out with an ET application very much in mind, where both positive (inside the Smith chart) and negative (outside the Smith chart) baseband impedances can be presented to the significant IF components.

The first investigation involved biasing a CREE CGH40010 10W GaN device in class AB ($IDQ=250$ mA), using a drain bias voltage of 16V and exciting with a symmetrical 2-tone modulation centred at 2.1 GHz. A reduced value of V_d was used to represent a typical ET application, and the magnitude of the excitation limited to emulate a backed-off drive condition. In this way, the device remained largely linear with no significant load-line / knee boundary interaction occurring.

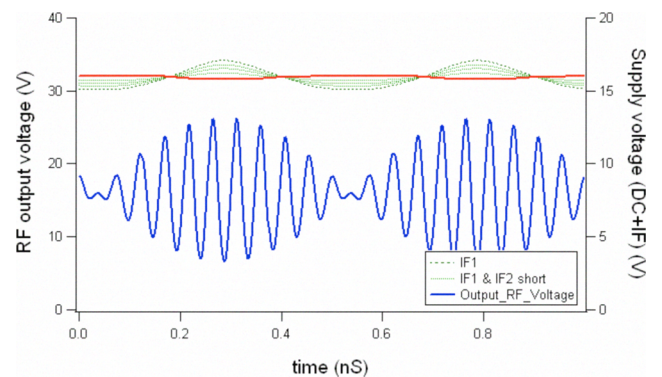


Fig. 2 measured modulated output voltage waveform and supply voltage.

Fig. 2 shows the measured voltage waveform present at the device plane², where the ‘backed-off’ and linear operating condition is evident from the limited voltage peak-to-peak

² Note that folded sampling approach used [5] allows individual cycles of RF to be visible inside the modulation envelope.

swing between 8V and 28V - well away from the device's knee voltage at approx 4V.

IF1 and IF2 loads were then actively synthesised and swept together over the measurement grid shown in Fig. 3 and Fig. 4. The supply voltages comprising DC+IF, that correspond to the cases of IF1 and IF2 load along the real axis are shown as the upper traces in Fig. 2. These are plotted relative to the right-hand axis, and are not to scale. The reference case is shown as a central, solid red line where both IF1 and IF2 are terminated into short circuits. The most negative IF1 load point results in approximately a 2V p-p IF waveform established on a 16V supply rail.

For each of the measurement points, the bias and drive level was maintained constant, and the IM3 behaviour measured. Due to the linear operation of the device and the dynamic range limitations of the system (60dB), it was not possible to accurately measure the IM5 behaviour.

Contours of IM3 high and low are shown in Fig. 3 and Fig. 4 respectively, and indicate that interestingly, separate local optimum IF loads for linearity exist some way outside the Smith chart, and that for this device, a 15-20 dB improvement in IM3-high magnitude exists for this load in comparison to the reference case where IF1 and IF2 are terminated into short circuits, as may be the case for example when using a conventional video bypass bias network arrangement. A slightly smaller improvement and different optimum load is observed for IM3-low.

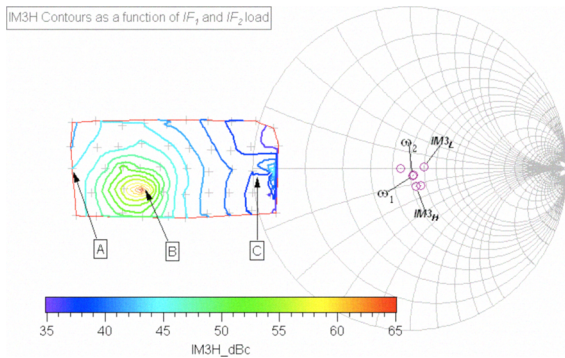


Fig. 3 IM3-high contours as a function of IF1 and IF2 load

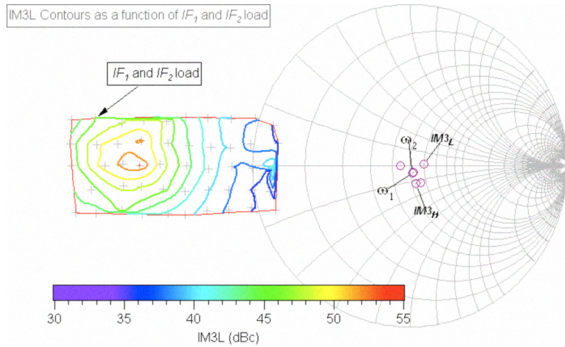


Fig. 4 IM3-low contours as a function of IF1 and IF2 load

Access to the envelope domain allows the dynamic analysis of other device parameters such as gain and drain efficiency as a function of the applied modulation envelope. Fig. 5 shows for example how the gain changes throughout the cycle of modulation for the three cases of IF1 & IF2 load identified by points A, B and C in Fig. 4: point A - significant IF 'ET-like' component, point B - the identified optimum for minimum IM3L and point C - a near IF short circuit.

It is clear from this graph that the negative IF impedance presented at point-A results in the higher gain, yet the load at point-B offers improved linearity, at least in terms of IM3 behaviour. The load at Point-C causes significant distortion in the dynamic gain envelope, which is unsurprisingly reflected in the poor linearity performance.

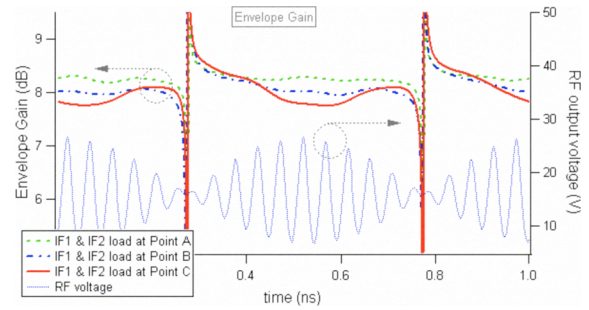


Fig. 5 Envelope gain profiles for IF1 and IF2 loads in positions A, B and C identified in on Fig. 4. RF voltage envelope is also shown for reference

IV. EXTENDING SYSTEM APPLICATION TO ENVELOPE TRACKING EMULATION

The analysis in the previous section is interesting from a linearity perspective, yet it is limited in that it explores performance only in a backed-off condition. Synthesising negative IF impedances does allow us to understand however how this investigation can be extended from simple linearity investigations to full ET emulation. In this next measurement sequence, the same device has been excited, this time using a symmetrical 3-tone signal centred at 2.1 GHz, resulting in 100% AM modulation with an envelope frequency of 1 MHz. The Device was driven into approximately 2dB of compression with fundamental and harmonic output components terminated into a passive 50 Ohm load. At this frequency, the optimum output impedance for power is approximately 25+j10 Ohms, and although the device is not operating into the optimal fundamental load impedance, it is considered sufficiently representative for this analysis.

Three separate measurement cases were considered; case-1 (reference case): $V_d=24V$ and IF1 and IF2 components actively terminated into short circuits, case-2: $V_d=20V$, injected IF1=8Vp-p and IF2 terminated into a short circuit, and finally case 3: $V_d=16V$, injected IF1=16Vp-p and IF2 again terminated into a short circuit.

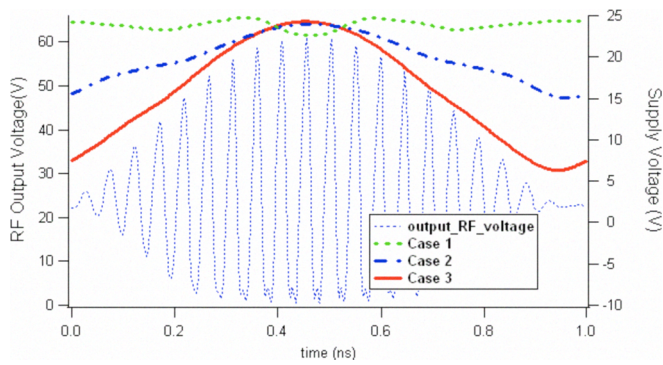


Fig. 6 measured supply voltages for the three cases of IF load, together with RF output voltage waveform - note that different scales are used.

These combinations of static DC supply and injected IF1 component ensure that the peak supply voltage remained as close as possible to a static 24V, as shown in Fig. 6, thus allowing meaningful comparison between the three cases.

Plotting the measured (RF, IF & DC) time-domain voltage vs. time-domain current yields a complete dynamic load-line which can be used to describe the trajectory of the modulated envelope relative to the device's DC characteristic. This intuitive view shows the actual voltage and current behaviour at the calibrated reference plane, and importantly, the nature of any interaction between the envelope and device boundary conditions. This is a familiar plot in CW waveform engineering yet adds an extra dimension to modulated analysis as it can show interesting effects such as self-bias, and in the case here of an emulated ET environment, the proximity of the load-line to the knee region. Fig. 7 below shows the full dynamic load-lines for the three cases considered, along with the IF load-line trajectories, which have been added by plotting and overlaying the baseband current vs. the baseband voltage waveforms. These clearly show the degree of baseband voltage (horizontal) and current (vertical) variation throughout the modulation cycle. The IF load-line itself can be considered as the component that 'pushes' or 'pulls' the dynamic RF load-line, in the case of electrical memory, asymmetrically into the knee region, and in the case of ET, into more efficient parts of the characteristic. A Perfect IF short would result in a straight, vertical IF load-line, and the shape of the IF load-line allows scope for baseband waveform engineering and optimisation for example of the proximity of dynamic RF load-line to knee boundary region.

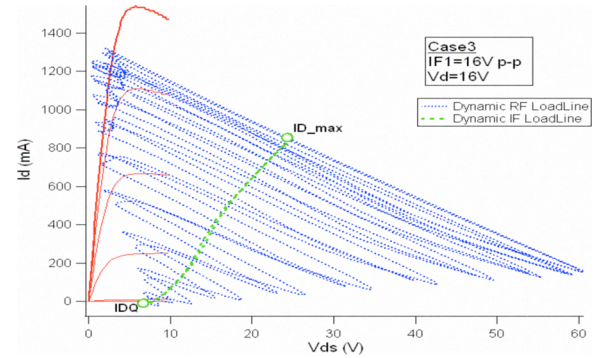
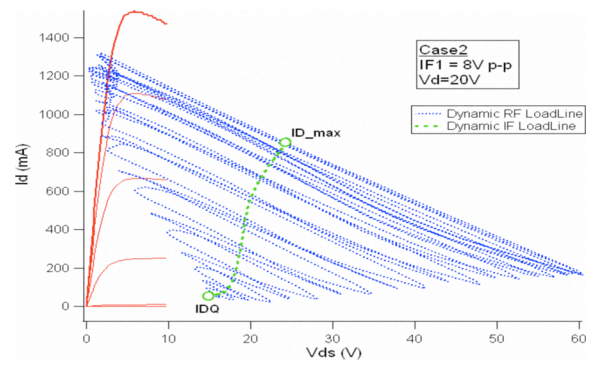
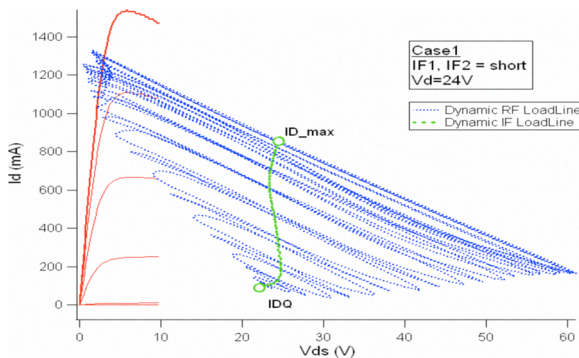


Fig. 7 RF and IF dynamic load-lines overlaid on DCIV characteristic for Case-3

Fig. 8 shows the extracted gain envelopes for the three cases, and how at the central point in the envelope where the DC supply voltage is the same at 24V, the gain is the same, albeit compressed. This plot also shows however that for other parts of the envelope, the dynamic gain can be very different. This effect is consistent with previous, CW based observations, where the gain for this device has been seen to reduce with reducing drain voltage.

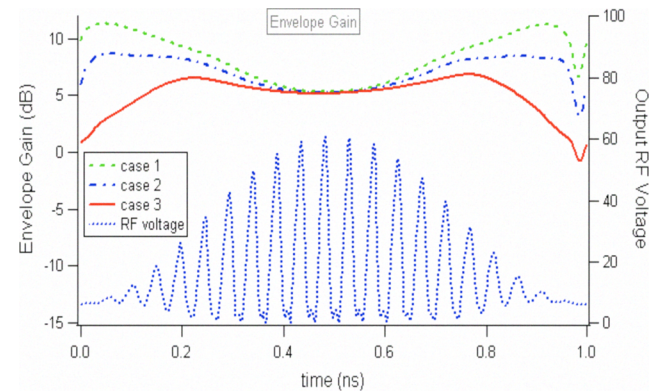


Fig. 8 Comparison of gain envelopes for the three cases

As with gain, it is possible to show the efficiency as a function of the envelope, and Fig. 9 shows a comparison of the three cases. Although it is clear from this graph that the applied ET does improve the average efficiency, it is also clear that the improvement is surprisingly small. In trying to explain this, it must be remembered that in each case, the device is driven

fairly hard into compression, and no improvement can be expected in this region of the envelope. Although improvement is apparent around the envelope 'skirts', as mentioned, it maybe isn't as large as one would expect. This is again probably explained by the fact that for this device, the gain, output RF power and hence efficiency reduces with reducing drain voltage.

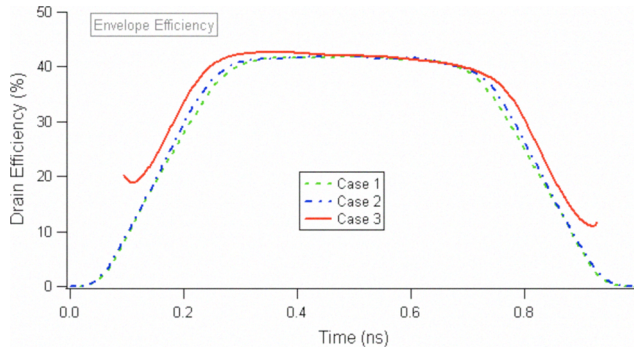


Fig. 9 Comparison of drain efficiency envelopes for the three cases

The linearity in terms of measured IM3 and IM5 mixing terms is shown in Table 1, which indicates that there is an approximate 10dB improvement in IM3 for case 1 compared to the reference IF1=IF2=short case, and only a slight improvement in IM5 for case 2.

case	IM5l dBc	IM3l dBc	w1* dBm	wc dBm	w2 dBm	IM3h dBc	IM5h dBc
1	31.93	23.62	27.42	33.57	27.46	24.43	31.23
2	47.46	16.32	27.13	34.29	27.22	16.53	43.57
3	41.57	12.77	27.04	34.95	27.10	12.94	41.02

Table 1 - linearity for the three cases

V. CONCLUSIONS

The aim of this paper has been to demonstrate that a broadband modulated time-domain measurement system, when used in combination with active IF load-pull, can be employed to gain valuable insight into the behaviour of high-frequency power transistors when operating under realistic conditions. With the increasingly popular application of ET in mind, the specific objective has been to question the impact of both positive and negative baseband impedance upon measured linearity, and to examine the idea of how PA linearity can be improved using the very mechanisms that are employed to improve efficiency.

In the case of a 'backed-off' device, contours of IM3-high and IM3-low indicate separate local optimum IF loads that lie some way outside the Smith chart, and for this particular device, a 15-20 dB improvement in IM3-high magnitude is observed in comparison to the reference case, where IF1 and IF2 are terminated into short circuits.

Whereas dynamic RF load-lines are a familiar plot in CW waveform engineering, the inclusion of baseband voltage and current to these plots adds an extra dimension that shows interesting and useful modulated behaviour, such as self-bias,

and in this case of an emulated ET environment, the proximity of the load-line to the knee region, which may of course be optimised. For the ET analysis, where significant a significant IF component is injected, it is shown how plotting the envelope efficiency and gain can be useful in understanding device behaviour. In this case, it is clear from these time domain plots that there is an overall reduction in gain and hence output power with the application of an envelope tracking voltage - an effect that is largely explained by the fact that for this device, the gain reduces with reducing drain bias voltage.

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