Envelope Domain Analysis of Measured Time Domain Voltage and Current Waveforms Provide for Improved Understanding of Factors Effecting Linearity

David J. Williams, Jonathan Leckey* and Paul J. Tasker
Cardiff School of Engineering, Cardiff University, Cardiff, UK. E-mail: Williamsdj2@cardiff.ac.uk
*Celeritek UK Ltd, Belfast Northern Ireland, UK

Abstract: A detailed understanding of the factors affecting amplifier linearity can be obtained by performing envelope domain analysis on measured time domain voltage and current waveforms. Analysis of the input and output time varying envelopes provides for a direct observation of amplifier linearization through IF (baseband) source pull.

I. INTRODUCTION

It is widely acknowledged that the primary aim of amplifier design for mobile communication systems is the realisation of high performance amplifiers capable of delivering high output powers with increased efficiency, and linearity. This is driving the development of a number of measurement tools; large signal network analysers (LSNA), vector signal analysers (VSA), etc., required to support this development.

LSNA or time domain waveform measurement systems have now been developed to the point where they now allow for the investigation of the non-linear behaviour of transistors and amplifiers under modulated excitation [1]. These systems have enabled the effect of source and load impedance, including the IF (baseband), on the output performance, including output power, efficiency and linearity to be investigated in the time domain. Previously studied work [1] has demonstrated how the effect of the output IF (baseband) impedance on amplifier performance could be correlated to the interaction of the dynamic load lines with the I-V characteristics.

This study shows how the analysis of these time domain waveforms in the envelope domain, effectively providing the designer with a four channel VSA, can provide further insight into how the interaction of the transistor with the source and load impedances, can influence the amplifier performance particularly with respect to linearity.

II. MEASUREMENTS AND ANALYSIS

Measurements were performed using the system described in [1]. This allows for the error corrected measurement of the input and output voltage and current waveforms under modulated excitation. In addition this system provides for the variation of the source and load impedances including the IF (baseband) components. Using this system measurements were performed to study the effects of IF (baseband) impedance on the device performance under two-tone excitation. The stimulus frequencies were 830MHz and 840MHz and the device used was a 2x3x27 geometry HBT device biased in class B with a collector voltage of 3.5V. While using the non-linear measurement system to measure the full spectral content of the two-tone AM modulated signal, the performance was modified by source pulling and then load pulling the 10MHz IF difference component. Note, all other frequency components were terminated passively with a nominal 50Ω system impedance.

It has previously been demonstrated that the efficiency and the output power of the device is maximised when an IF short circuit is presented to the output of the device [1]-[3]. In addition it was also found that the IF impedance presented to the source and load also has a significant effect on the Linearity of the device, demonstrated in figure 1 for the load and figure 2 for the source.

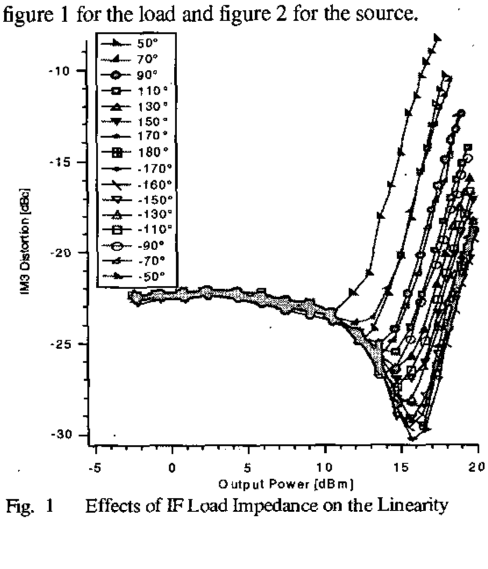

Fig. 1 Effects of IF Load Impedance on the Linearity

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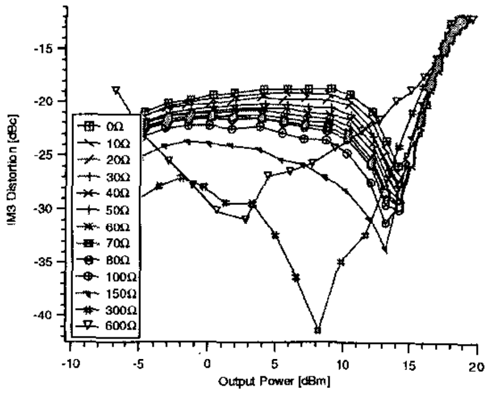

Fig. 2 Effects of IF Source Impedance on the Linearity

Linearity in this case is quantified in terms of the worst-case IM3 component for a given output power. Analysis of these measured results with reference to the dynamic load-lines showed that the IF load impedance can only influences the linearity of the device once the dynamic load lines interact with the knee region. Since a short circuit IF load impedance minimized the interaction with the knee region in the transistor I-V characteristic, hence, producing the most linear performance.

The response to varying the IF source impedance is more complicated. Before the dynamic load lines interact with the knee region increasing the IF source impedance produces a significant improvement in linearity. However, once the dynamic load lines interact with the knee region the opposite is true. In addition, at a given output power level there is an optimum IF source impedance that will produce a linear amplifier response. For example, at a finite real impedance of 300Ω the IM3 products can be significantly reduced, achieving a null at a given drive level, corresponding to an output power, in this case of 8dBm. Figure 3 shows the measured dynamic load lines under this optimum IF source termination compared with the worst case, short circuit IF termination, showing clearly that this improved linearity is not associated with the interaction of the transistor I-V knee region. The improved linearity can be better explained by considering a Taylor series expansion to the third order for the output current in terms of the input voltage, shown by equation (1).

$$I_{Out} = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 \qquad (1)$$

The effect of IF source pull is to add a component to the voltage stimulus at the difference frequency, hence the stimulus voltage can now be described by equation (2).

$$v_i = C + B\cos(\omega_2 - \omega_1) + A\left[\cos(\omega_1) + \cos(\omega_2)\right] \qquad (2)$$

In this case the IM3 products are described using equation (3) Hence it is possible to reduce the IM3 products, theoretically to zero by varying the value of B, using the IF source pull for a given drive A and bias C, cancelling the two a_2 and a_3 IM3 components.

$$I_{IM3} = a_2(AB) + a_3\left(\frac{3}{4}A^3 + \frac{3}{4}AB^2 + 3ABC\right) \qquad (3)$$

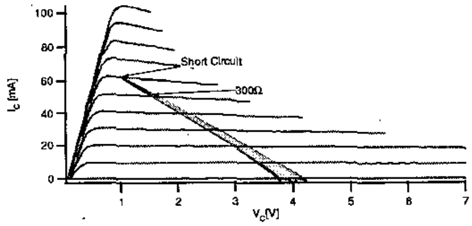

Fig. 3 Dynamic load lines for two different IF source impedance

III. ENVELOPE ANALYSIS

Measuring the full spectral content of the voltage and current waveforms using the large signal measurement system provides both magnitude and phase information, however analysis of these waveforms in the time domain becomes difficult due to the frequency difference between the IF component and the RF carrier, producing a large number of zero crossing points within the envelope of the signal. Hence the overlaying of waveforms generated as a result of increasing input power becomes difficult to understand. Alternatively the analysis of the spectral contents could be performed in the frequency domain using the magnitude and phase, however again as the number of tones in the modulated signal increases so does the spectral complexity. Analysis of modulation measurements can be achieved using Envelope analysis [4] where the time varying complex envelope of the carrier is computed, using the modulation domain components consisting of the in phase I(t) and the quadrature phase Q(t) components computed using equations (4) and (5). Once computed an IQ-plot of the I(t) and Q(t) can, for example, be used to generate an IQ constellation diagram [5].

$$I_n(t) = \sum_{i=-m}^{m} \rho_{n+i}\cos(i\omega_{IF}t - \phi_{n+1}) \qquad (4)$$

$$Q_n(t) = \sum_{i=-m}^{m} -\rho_{n+i}\sin(i\omega_{IF}t - \phi_{n+1}) \qquad (5)$$

In addition using the computed I(t) and Q(t) components of the carrier the magnitude and phase of the envelope can be reconstructed using equations (6) and (7).

$$A_n(t)=\sqrt{I_n(t)^2+Q_n(t)^2} \tag{6}$$

$$\phi_n(t)=\tan^{-1}\left(\frac{Q_n(t)}{I_n(t)}\right) \tag{7}$$

Figure 4 presents the measured I(t) and the Q(t) waveforms for the output current in terms of an IQ-constellation plot for two different IF source impedances, the normal case of a short circuit and the optimum case of 300Ω, at an output power of 8dBm. In figure 4 the output I(t) and Q(t) waveforms, are phase referenced to the input voltage stimulus, shown in figure 5. This AM modulated input voltage signal, as expected has only a small Q(t) component. The main AM modulated I(t) components in both IM source impedance cases are almost identical. This is to be expected since the stimulus signal about the carrier was not intentionally varied. The small discrepancies observed in the shape of the two Q(t) waveforms result from slight differences in the magnitudes of the high and low IM3 components present at the input. Since it can be assumed that the carrier components remain unchanged, the advantage of measuring the full spectral contents of the stimulus voltage signal provides a means of observing the predistorted signal required to linearize the device, shown in figure 6 and can be described by equation (2).

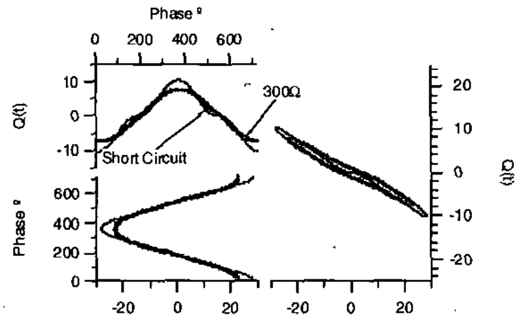

Fig. 4 Comparison of the output current I(t) and Q(t) waveforms as a result of presenting a Short Circuit and a finite IF Source Impedance.

The Q(t) component present at the output of the device is mainly the result of the rotation of the IQ-constellation diagram. This rotation is caused by delays in the transistor causing the RF carrier to be phase delayed compared to the AM modulation. The looping observed in the IQ-constellation diagram for the optimum point demonstrates a slight asymmetry between the two output carrier components.

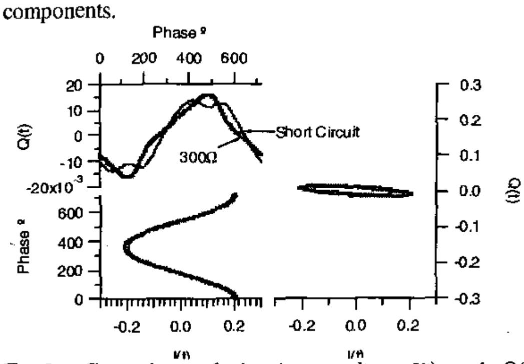

Fig. 5 Comparison of the input voltage I(t) and Q(t) waveforms as a result of a Short Circuit and a finite IF source impedance

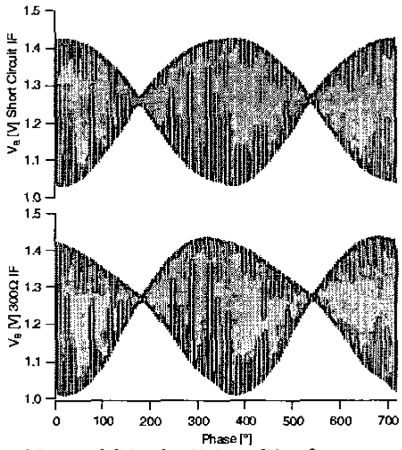

Fig. 6 Measured Stimulus Voltage Waveforms containing the full spectral contents.

Redefining the time reference allows rotation of the IQ-constellation diagram to the real axis. In this case the Q(t) component reduces to a very small value, similar to the input. Where all the AM modulation information is contained in the I(t) term. The measured output I(t) waveform obtained for the two IF source impedance conditions, are shown in figure 7. In the case of the short circuit IF source impedance distortion is clearly observed in the waveforms, however when terminating the source impedance with the optimum termination of 300Ω an undistorted output signal results.

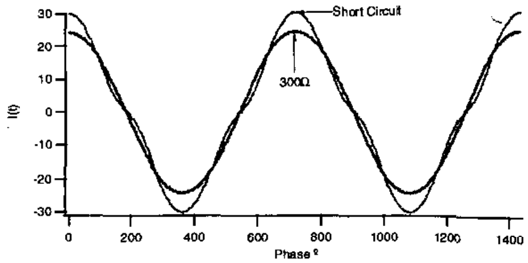

Fig. 7 Output current I(t) waveforms for two periods, after phase rotation minimised the Q(t) component. The linearisation caused by the optimum IF source impedance is clearly observed.

Using the magnitude of the output current envelope and the input voltage envelope, generated using equation (6), allows the waveforms to be analysed in terms of an effective device transfer characteristic. This is shown in figure 8, where the output current is plotted as a function of the input voltage, for different IF source impedances. At low IF impedances it can be seen that this transfer characteristic has a diode like characteristic which has expansion at high drive levels, where at a high IF impedance, 600Ω the transfer characteristic is compressed at high drive levels. The 300Ω IF impedance effectively linearizes the device resulting in a linear transfer characteristic at the carrier frequency. Plotted in this form demonstrates that in fact there is a slight overcompensation at 300Ω hence the optimum impedance must ideally be slightly less than 300Ω hence a further reduction in IM3 components is possible.

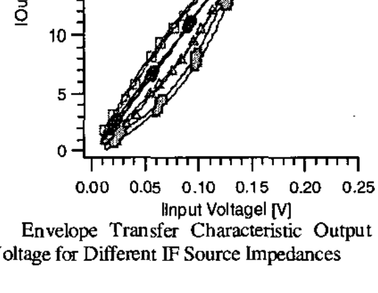

Fig. 8 Envelope Transfer Characteristic Output Current vs Input Voltage for Different IF Source Impedances

IV. CONCLUSIONS

Time domain measurement systems, combined with source-pull and load-pull, can now be utilised to analyse the large signal non-linear behaviour of transistors under modulated excitation. Analysis of this time domain data has been developed to include envelope domain processing. This provides for improved insight into how the interaction of the transistor source and load impedance affects linearity. An example is discussed which shows how presenting modulated time domain waveform data in the envelope domain has allowed, for the first time, the IF source pull linearisation of the amplifier at the carrier frequency to be directly observed in the time domain.

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