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Effect of Low Frequency Memory on High Power 12W LDMOS Transistors Intermodulation Distortion

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***Abstract*—**The increasing demand for higher data rates in wireless communication systems has led to the more effective and efficient use of all allocated frequency bands. In order to use the whole bandwidth at maximum efficiency, one needs to have RF power amplifiers with a higher linear level and memory-less performance. This is considered to be a major challenge to circuit designers. In this thesis the linearity and memory are studied and examined via the behavior of the intermodulation distortion (IMD). A major source of the in-band distortion can be shown to be influenced by the out-of-band impedances presented at either the input or the output of the device, especially those impedances terminated the low frequency (IF) components. Thus, in order to regulate the in-band distortion, the out of-band distortion must be controllable. These investigations are performed on a 12W LDMOS device characterised at 2.1 GHz within a purpose built, high-power measurement system.

***Keywords*—**Low Frequency Memory, Intermodulation Distortion (IMD).

I. INTRODUCTION

THE radio frequency (RF) power amplifier (PA) in base station systems is typically the most costly component. The increasing number of mobile users, combined with a growing demand for a higher data rate has driven RF designers to try and effectively utilise the entire allocated bandwidth to its maximum potential. This would require the designing of a linear power amplifier capable of producing a linear response over a wide bandwidth. Intensive research into the linearity of RF power amplifier of wireless communication has become a global focus.

The maximum allowable adjacent channel leakage ratio (ACLR) for mobile terminals are -33dBc and -43dBc for 5 MHz and 10 MHz respectively [1] [2]. Otherwise, distortion into adjacent channels and error in detection of the desired signal may occur. A typical value of carrier to intermodulation (C/I) ratio for a linear power amplifier is 30 dB or more [2] [3]. The main technology for the implementation of 3rd generation (3G) cellular systems is wideband code division multiple access (W-CDMA). Its ACLR is illustrated in Fig. 1.

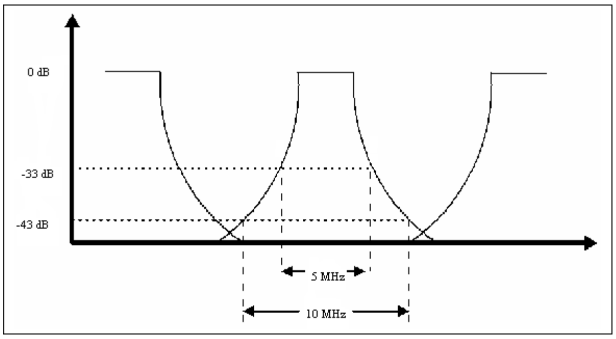

Fig. 1 Illustration of the maximum ACLR vs. output power allowed by 3GPP

To minimize the interference between the channels, the slope of the window should be ideally as sharp as possible, and the intermodulation distortion (IMD) ought to be kept to a minimum level.

To meet these challenging standards, RF power amplifier manufacturers and circuit designers must come up with a development approach allowing for high linear power amplifier behaviour, in order to use the whole available bandwidth in an efficient way.

Memory effects are defined as changes in the amplitude and/or phase of the distortion components, as a function of the input signal envelop frequency. In microwave Pas memort effects are generally attributable to a number of physical processes that involve thermal [4], electrical [5] and surface effects [6]. Electrical memory, particularly the base-band electrical memory effect, is generally considered to be the major contributor.

Full investigation of electrical memory effect requires a thorough examination of all impedances presented across the complete frequency spectral (preferably from DC to some of nRF). Unfortunately current commercial measurement systems do not accommodate low frequency impedance due to limitations in technology at these frequencies [7] [8] [9].

The difficulty in investigating low frequencies is compounded by the fact that the biasing network should have constant, and ideally, zero impedance at all low frequency (IF) ranges. Otherwise, AC voltages may be generated and added to the power supply voltage, causing amplitude and/or phase modulation, and resulting in asymmetry in the IMD [3] [5]. In the case of a 5 MHz W-CDMA signal, for example, such a bias network needs to be constant and ideally at zero for at least eight decades of bandwidth. In contrast, designing a matching network with consistent impedance for the RF frequency and its first 10 harmonics requires only one decade of bandwidth. This highlights the complexity of bias network design.

In this work, the measurement of inter-modulation products resulting from two-tone excitation, performed as a function of varying tone-spacing is used as a reliable indicator of the presence of memory effects [10] [11]. The objective of this approach is to eliminate the sources of electrical memory and thus establish whether the measured 3rd and 5th order intermodulation distortion ($IMD_{3\&5}$) levels and symmetry become frequency independent over a wide range of stimulus tone-spacing. This is achieved by presenting a low baseband impedance environment across a wide modulation bandwidth. Such measurements has been made possible by the development and fabrication of a pioneering new modulated waveform measurement system which permits the gauging and engineering of all relevant frequency components, i.e. RF, baseband and DC [10] [7].

II. MEASUREMENT AND RESULTS

The main objective of this investigation was to present short circuit to both IF_1 and IF_2 simultaneously using a Freescale seventh generation (HV7) 12W LDMOS device. Termination of these frequency components into a short circuit would be desirable since it would minimize the overall in-band distortion as can be seen in Fig. 2. In this figure and just for a comparison between two extreme terminations, IF1 firstly terminated to short circuit (optimum) and secondly terminated to infinite impedance (worst case). The result of these two terminations indicates clearly that short circuiting low frequency (IF) components linearizes the device and hence is preferable. Termination into a short circuit would be possible, particularly for tone-spacing ranging between 0.37MHz and 7MHz. To achieve this active IF load-pull was employed to independently engineer different, frequency independent, impedance environments at the two significant IF components; IF_1 and IF_2. Fig. 3 illustrates just how effective the IF load-pull is in maintaining a frequency independent IF_1 and IF_2 short circuit impedance.

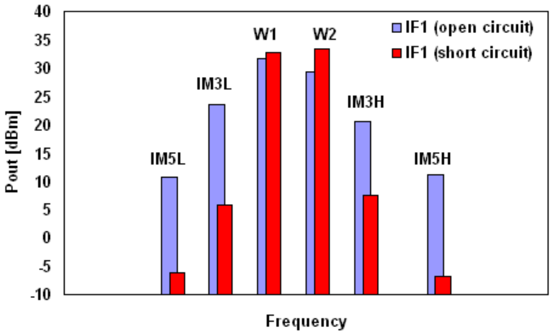

Fig. 2 Measured spectrum output power for (open circuit presented to IF_1) and (short circuit presented to IF_1)

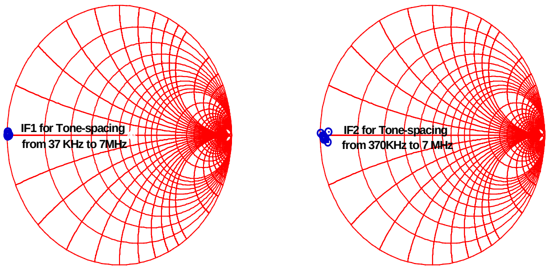

Fig. 3 Measured IF1 and IF2 vs. tone spacing

The measured RF two-tone spectral power performance where a short circuit is presented to both IF_1 and IF_2 is shown in Fig. 4. A typical behaviour, 1:1 slope for the two tones and approximately 1:2.4 for the IM3 inter-modulation components, is observed over a power sweep of some 30 dB. The slope of IM_3 will not however be 1:3 unless IM_5 inter-modulation components are set to zero. In this case the two-tone spacing is 5 MHz. The variation of measured IM_3 response as a function of IF impedance is clearly seen.

Fig. 5 summarizes the $IM_{3\&5}$ behaviour at these two different IF impedance states for different values of tone spacing ranging between 0.37MHz and 10 MHz, at a single drive level (Pref 1), this power level corresponds to a point 1dB below the 1dB compression point.

The behaviour of the two output tones (ω_1 and ω_2) is clearly observed to be almost independent of both the tone spacing frequency and IF termination. However, modulation frequency independence was only observed between 4 and 7 MHz.

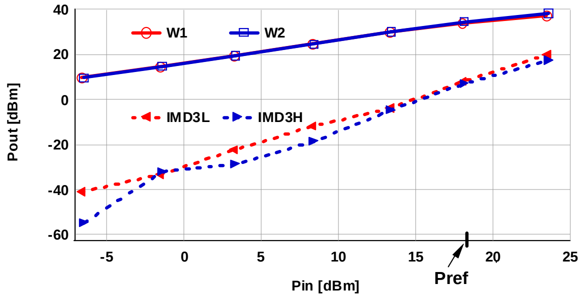

Fig. 4 Measured two-tone power sweeps for 5MHz frequency separation for2 IF$_1$=IF$_2$=0Ω

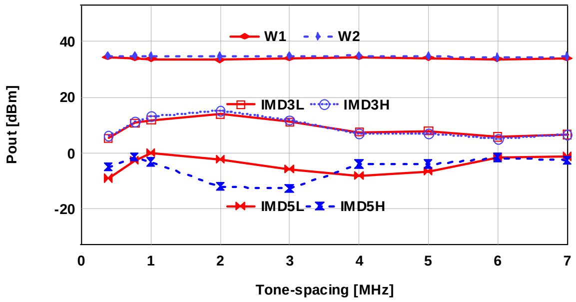

Fig. 5 Measured fundamental and IMD power for two impedanceIF$_1$=IF$_2$=0Ω at different two-tone frequency separations at a constant drive level of 1dB below the 1dB compression point (see Pref 1 in Fig. 4)

The frequency variation observed below 4 MHz is not related to variation in base-band impedance and thus must be associated with other memory sources; i.e. thermal, surface trapping, package parasites.

In order to investigate the repeatability of the previous device measurements, especially the inter-modulation distortion (IMD$_{3\&5}$) behaviour when both IF$_1$ and IF$_2$ were terminated to short, the output power of the fundamental (ω_1 and ω_2) and IMD$_{3\&5}$ were measured at different input drive levels of 6 dB below the 1 dB compression point with a short circuit presented to IF$_1$ and IF$_2$. As can be seen from Fig. 6, the similarity between the IMD$_{3\&5}$ behaviour in either case of an input power of 1dB or an input power of 6 dB below the compression point is observed.

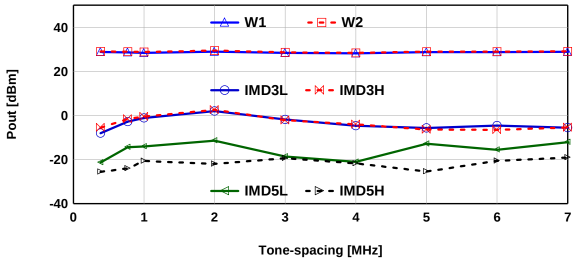

Fig. 6 Measured fundamental and IMD power vs. Tone-spacing at a constant input drive level of 6dB below the 1 dB compression point

So far the device discussed in this work have been characterized by the magnitude of its IMD only in order to describe their behaviour as a memory-less devices. However, this is only true if its phase is also memory-less (frequency independent). Because the device used in this paper is packaging device in order to measure its absolute phase it must be first de-embedded and this is beyond the scope of this work. However, relative phase investigations are possible. The absence of this package de-embedding step makes it impossible to look at the terminal voltage and currents for the RF frequency components as was done previously at IF. Fig. 7 plots the measured values of the relative inter-modulation IMD$_{3L\&H}$ phase when both IF$_1$ and IF$_2$ were terminated to short as a function of tone-spacing at a fixed input power level corresponding to a point 6 dB below the 1 dB compression point. The slope of the two output tones (ω_1 and ω_2) and IMD$_{3L\&H}$ is approximately constant for all two-tone frequency spacing. Therefore, this device can be classified as a memory-less device and only exhibits a constant group delay, for frequency ranging from 0.37 KHz to 7 MHz.

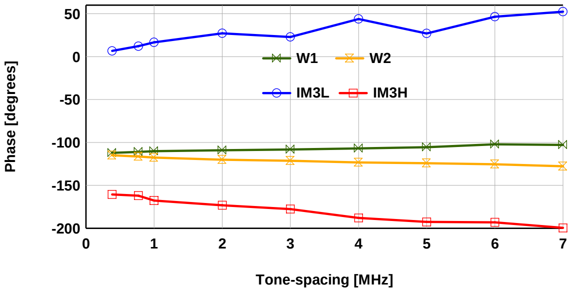

Fig. 7 Measured fundamental and IMD phase when terminating IF$_1$ and IF$_2$ to short at different tone-spacing frequency at a constant input drive level of 6 dB below the 1 dB compression point

So far analysis of the base-band impedance magnitude shows that IF impedance can considerably influence the device performance and more importantly its linearity. In this section investigation into the influence of the phase of IF reflection coefficient at a magnitude of unity (at the edge of the Smith chart) will be examined.

Based on the results of the previous measurements, an investigation of the effect of the IF base-band impedance, (particularly the most significant components IF$_1$ and IF$_2$), on the output power and linearity is performed there is a need to optimize the base-band impedance environment, rather than to just present short circuits [10] as is usually assumed. Such an investigation would examine and support the observation made in the previous passive and active load pull measurement, that IF$_2$ impedance was considered to be the primary cause of the observed variation in IMD response.

To do this investigation the value of the IF$_2$ impedance was varied while fixing the IF$_1$ at a short circuit. The variation of IMD$_{3\&5}$ responses versus IF$_2$ impedance for 12W LDMOS at 5MHz tone spacing is shown in Fig. 8. These results clearly show that variations in IF$_2$ impedance, which is four times the modulation frequency, modify the levels of IM$_{3\&5}$ intermodulation components. The results also indicated that there is an optimum IF_2 impedance that minimizes the $IM_{3\&5}$ terms. The optimum IF_2 impedance is 135° [12].

A similar response is obtained if the IF_1 impedance is varied while the IF_2 impedance is held constant. The variation of $IMD_{3\&5}$ responses versus IF_1 impedance at 5MHz tone spacing is shown in Fig. 9. The optimum IF_1 impedance is not necessary short circuit (180°) but found to be 225°.

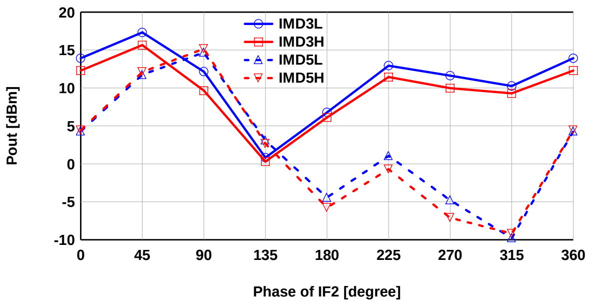

Fig. 8 Measured IMD magnitude vs. phase of IF_2 for 5MHz frequency separation with IF_1 held a constant short

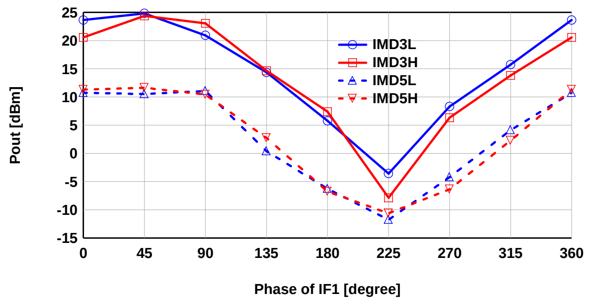

Fig. 9 Measured IMD magnitude vs. phase of IF1 for 5MHz frequency separation with IF2 held a constant 50Ω

The results show that not only IF1 but also IF2 can modify the value of the inter-modulation distortion components. Thus to achieve modulation frequency independent response the base-band impedance must be engineered to be frequency independent over a bandwidth that must be at least four times that of the modulation frequency. The results also indicate that there are separate, optimum IF1 and IF2 impedances that can minimize IM_3 and IM_5 terms simultaneously. The measurement results also show optimum base-band impedance is not necessarily zero but could probably be a complex impedance instead. This important observation has large implications for modern PA linearisation techniques, as well as requiring careful consideration when designing PA bias networks. For applications utilizing wide modulation bandwidths this will become a serious design constraint.

To get insight into the device, it is important to measure data in time-domain. For example, the measured drain voltage and drain current waveforms at the device plane for 5MHz tone-spacing are shown in Fig. 10 and Fig. 11. Note the distorted drain voltage waveform in fig 10 when IF1 load was maintained at $\Gamma_{L_{IF1}}=1\angle 45^{0}$ and IF2 to 50Ω (the worst case see Fig. 9) with comparison to the better drain voltage waveform shape in fig 11 when IF1 load was maintained at $\Gamma_{L_{IF1}}=1\angle 225^{0}$ and IF2 to 50Ω (the best case see Fig 9). This can be attributed to the variation of IF1 impedance.

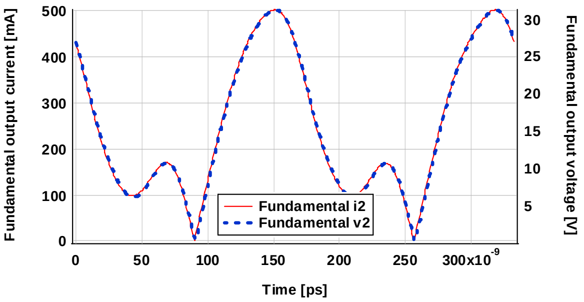

Fig. 10 Measured drain voltage and current waveforms for 5MHz tone-spacing and IF1 load was maintained at $\Gamma_{L_{IF1}}=1\angle 45^{0}$ and IF2 to 50Ω

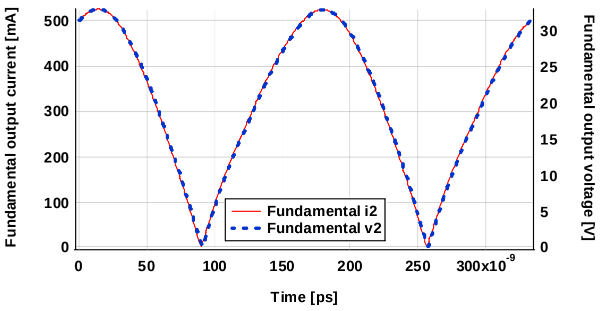

Fig. 11 Measured drain voltage and current waveforms for 5MHz tone-spacing and IF1 load was maintained at $\Gamma_{L_{IF1}}=1\angle 225^{0}$ and IF2 to 50Ω.

III. CONCLUSION

This paper presents detailed two-tone modulated measurements. These measurements clearly demonstrate how electrical memory, introduced by non-ideal low-frequency base-band impedances, represent the most significant factors in overall observed memory effects related to high-power LDMOS PA design. The results show that the bandwidth over which the base-band impedances need to be controlled must be extended to at least four times the modulated bandwidth. The results also highlight optimum IF impedance terminations that minimize overall in-band distortion. This important observation has significant implications for modern PA linearisation techniques, as well as requiring careful consideration when designing PA bias networks. For applications utilizing wide modulation bandwidths this will become a serious design constraint.

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