A STUDY OF THE EFFECT OF ENVELOPE IMPEDANCE ON INTERMODULATION ASYMMETRY USING A TWO-TONE TIME DOMAIN MEASUREMENT SYSTEM

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Abstract An error corrected two-tone time domain measurement system has been developed and combined with a low frequency active source and load-pull system to investigate the effects of all impedance terminations, IF and RF, on the linearity and efficiency of power transistors. Measured data is presented on a HBT biased in class B stimulated by a two-tone signal while actively load pulling the low frequency IF component.

I. Introduction

It has been acknowledged that the key challenge in amplifier design for mobile communication systems is the realisation of amplifiers, which provide high output power, linearity and efficiency. Experimental source and load-pull measurement systems have been developed to study the effects of fundamental and harmonic terminations on device performance, output power, and efficiency, under large signal operation [1]. Modulated signals, however, contain additional high frequency and low frequency IF components, due to intermodulation. Hence, when using these measurement systems to study linearity these additional frequency components and their terminations must be included. For example, previous work [2,3], has indicated that the IF impedance, presented at the device plane by the bias network can, influence the high frequency third order intermodulation asymmetry.

In this paper we present a time domain measurement system capable of measuring the full spectral content (IF and RF) of the voltage and current resulting from two-tone excitation. Additional functionality is achieved by combining this system with an active source and load-pull architecture that includes not only harmonics but also the ω_2-ω_1 IF intermodulation component.

To demonstrate the system, measurements have been conducted to study the effect of the IF terminations on the third order intermodulation distortion produced by a Heterojunction Bipolar Transistor.

II. Measurement System

The measurement system developed is shown in figure 1. It combines two systems, a high frequency system and a low frequency IF system. The high frequency measurement system is based on the HP-MTA (Microwave Transistor Analyser), a two channel sampling scope, which is identical in both construction and operation to that demonstrated by Tasker, et al [4]. It operates between 0.5GHz and 40GHz, the lower frequency is set by the directional couplers and so does not include the needed IF band. The low frequency system is identical in design and operation, and is required to measure the IF ω_2-ω_1 component and its harmonics. An oscilloscope is used in this case to measure the incident and reflected voltage waves between 200kHz and 100MHz.

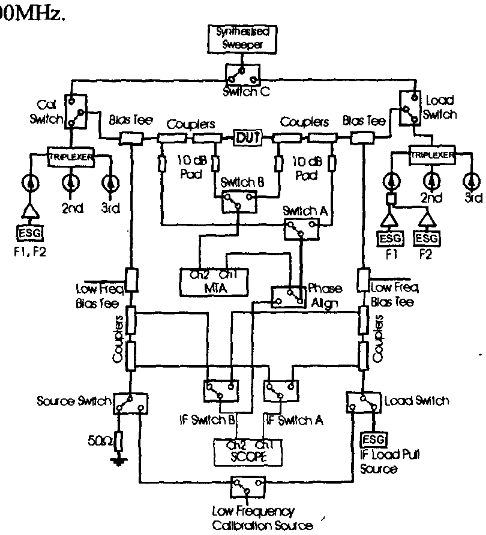

Fig. 1. Schematic of the Measurement System

The frequency components of the measured *a* and *b* voltage waves from both the oscilloscope and the MTA systems are error corrected in the frequency domain before being converted to absolute voltage and current time domain waveforms at the device terminals. Calibration of each system is conducted separately and consists of an on wafer two-port error calibration using a

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SLOT calibration for the low frequency oscilloscope system and a TRM calibration for the high frequency MTA system. Since s-parameter calibration alone only provides travelling wave ratios, it is therefore necessary to perform an absolute power/phase calibration at a defined reference plane within each system, details of which are discussed in reference [1].

Common triggering between the oscilloscope and MTA is achieved by means of an additional measurement, where the MTA is used to measure the IF signal directly. In addition, it is not possible to trigger the MTA when no IF signal is present. This is resolved by triggering measured data within the measurement system software.

The computer controlled active source and load-pull system, also included in figure 1, has been realized using a number of Agilent ESG series signal generators, since they provide for the ability to computer control both the signal magnitude and phase via the GPIB Bus. This solution provides unfortunately an open loop architecture. Software feedback is required to realise and maintain the desired source or load reflection coefficients [5].

III. Measurements And Discussions

Two-tone measurements, (830 and 840 MHz) were performed, in the time domain, on a 2x3x27 geometry HBT biased in class B with a collector voltage of 3.5V. Power sweeps were performed while actively load-pulling the lower 10MHz IF component. A sequence of measurements were performed where the magnitude of the IF reflection coefficient, ρ^{IF}, was held constant at unity while the phase was varied from 0° to 360° in 20° steps. All other harmonics and mixing terms were terminated passively with a nominal 50Ω impedance.

Figure 2 shows how the IF impedance significantly influences the maximum efficiency and output power. Analysis of the waveforms shows that these results can be explained by noting that the output IF current component is generated by the HBT's non-linear internal current source [7], while the output voltage component present depends also on the terminating IF impedance. The output power and the efficiency is dramatically reduced, for example, when the IF impedance approaches an open circuit. At the open circuit point the output voltage wave is dominated by the IF voltage component which then suppresses the RF modulated signal components. From this graph we can see that maximum efficiency occurs for an IF termination of 180° as expected.

In addition, the phase of ρ^{IF} has a significant effect on the asymmetry of the 3^{rd} order, $2\omega_2-\omega_1$ and $2\omega_1-\omega_2$, IMD terms. Figure 3 shows the measured magnitude and, for the first time, measured phase difference of the resulting IMD terms. Symmetrical IMD terms, independent of IF impedance, are observed up to a critical drive level. At higher drive levels asymmetry is observed, the degree of which is a function of drive level and IF impedance. The graph shows a maximum asymmetry is produced when the phase of ρ^{IF} has either a 90° or –90° phase angle and is minimized as this phase angle passes through the 180° point. This observation confirms the mathematical analysis and discussions in references [2,3], which predict that the ideal envelope termination required for symmetrical IMD terms is a short circuit (180°). This is only the case where the output power is below the 1dB compression point, marked in figure 3. Above this point asymmetry occurs independently of IF impedance, possibly caused by higher order mixing products.

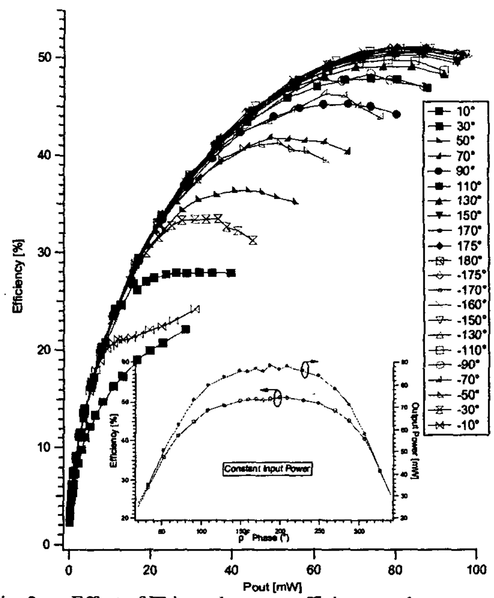

Fig. 2. *Effect of IF impedance on efficiency and output power*

Having vector IMD information makes it possible to determine the amount of asymmetry contributed to by the IF mixing, using the vector model, see figure 3, defined in [3]. The analysis shows that only the magnitudes of the mixing terms change with drive level and IF impedance, the phase is almost constant until the critical drive levels are reached. From the critical drive levels to the 1dB compression point the variation in magnitude and phase with IF impedance is observed. Only above the 1dB compression point is the IMD term found to be dependent on the IF impedance.

Using the measured voltage and current waveforms it is possible to investigate the cause of the asymmetry in the IMD products. Figures 4 and 5 depicts the dynamic load lines generated by a swept input power superimposed on the DC-IV characteristics, for two cases, where i) the IF is terminated by a reactive impedance (90°), figure 4, and ii) the IF is terminated by a short circuit (180°), figure 5.

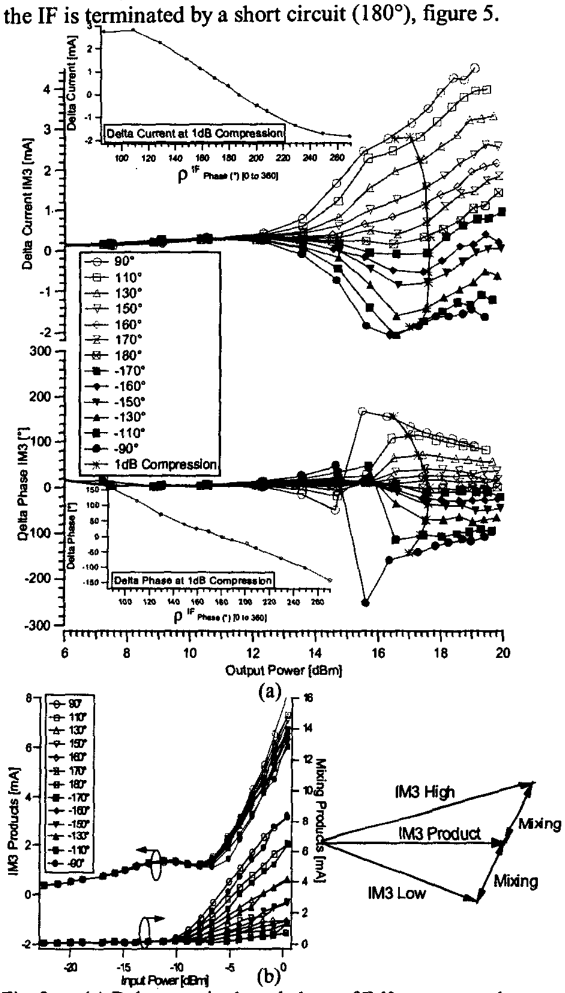

Fig. 3. (a) Delta magnitude and phase of IM3 current products vs. output power. (b) Measured vector intermodulation and mixing products vs. input power. With the Vector Model.

The waveforms in region 2 are the measured load lines at the critical drive level where asymmetric features begin to occur in the output power spectrum. At lower drive levels, region 1, it can be seen that the dynamic load lines do not interact with the knee region, in this case the IMD products are symmetrical regardless of the IF impedance. At higher drive levels, region 3, the dynamic load lines interact with the knee region. The degree of interaction is now a function of the IF impedance. The reactive IF impedance produces significant looping which maximises the interaction, in fact the load lines now track the knee region. The IF short circuit minimises the looping effect, hence the interaction with the knee region is reduced. The final load line, region 4, corresponds to the 1dB compression point.

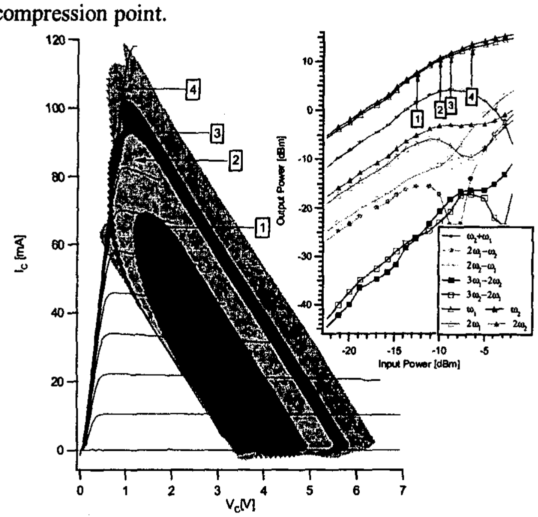

Fig. 4. Dynamic load lines and output power spectrum for reactive IF impedance (90°)

The results clearly show that asymmetry in the IMD products as a function of IF impedance requires input drive levels that cause an interaction between the dynamic load lines and the knee region. This is because it is the interaction with the knee region that causes the HBT's dynamic transfer characteristic to be dependent on the time varying output voltage, hence producing the mixing behaviour considered in references [2,3] as the source of asymmetric IMD products.

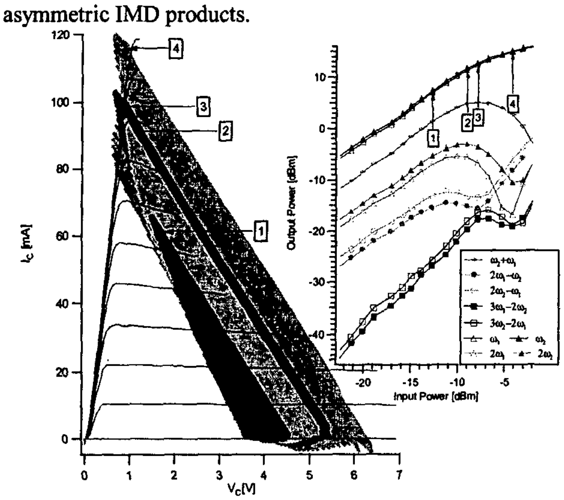

Fig. 5. Dynamic load lines and output power spectrum for IF short circuit (180°)

Figures 6 and 7 depict the corresponding output current waveforms. Waveform 1 is where the device is driven below the critical level. At this point an undistorted modulated envelope is observed. As the drive level is increased to the critical level, waveform 2, the current waveform envelope, see figure 7, has adopted a squared up feature, this is further exaggerated as the drive level is increased to the 1dB compression point, waveform 4. These features are again consistent with interaction of the knee region.

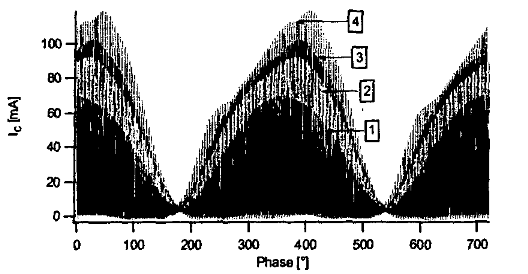

Fig. 6. Current waveforms for reactive IF impedance at 90°

While the magnitude of the IMD products are symmetrical the current waveforms are also symmetrical, terminating the IF with a reactive component of 90° dramatically changes the shape of the envelope, see figure 6, as a result of the voltage leading the current during the interaction with the knee region, this process is reversed when the ρ^{IF} phase angle is moved from 90° to –90° producing a mirror of the waveforms shown. However, it is this asymmetric envelope shape that determines which IMD product $2\omega_2$-ω_1 or $2\omega_1$-ω_2 will have the greater magnitude.

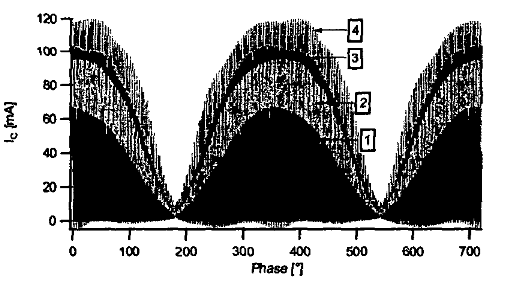

Fig. 7. Current waveforms as a result of an IF short circuit

IV. Conclusions

A measurement system has been developed which enables the measurement of all the spectral components of a modulated two-tone signal in the time domain, including the IF component. This system enables both the magnitude and the phase of all the intermodulation products to be measured.

A detailed investigation using active load-pull of the fundamental IF component has provided an insight into the importance of the envelope termination, hence the amplifiers bias network design at the IF frequency on the RF performance: power, efficiency and linearity. Analysis of the measured current and voltage waveforms and resultant dynamic load lines has provided detailed insight into the causes of the asymmetry in the IMD distortion. The measured waveforms confirmed previous mathematical analysis that a mixing process, which is in fact caused by modulating the transistor dynamic transfer characteristic at the IF frequency, can produce asymmetrical IMD products. This effect can be eliminated by terminating the IF current components into a short circuit.

Acknowledgements

The authors would like to thank Celeritek for the funding, co-operation and for providing the devices.

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