RF I-V Waveform Measurement and Engineering Systems

- addressing the high power amplifier design challenge

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Abstract —This short paper presents an overview of the potential of RF Waveform Measurement and Engineering to support the developments of transistors, circuits and systems that rely on strong non-linear affects. To date these concepts have mainly been focused towards aiding the development of RF Power Amplifiers (RFPAs). This is because the performance of RFPAs both exploits (efficiency) and is limited (linearity) by strongly non-linear affects. RFPAs are a critical component in many systems; e.g. mobile communications, satellite communications and radar systems.

I. INTRODUCTION

RF Power Amplifier (RFPA) performance, output power, conversion efficiency and linearity, etc., is influenced by the transistor terminal voltage and current time varying waveforms. Thus *waveform engineering* should be driving the RFPA design process at all levels; transistor optimization, circuit design and system requirements. In practical RFPA design, waveform engineering is only a guiding principle; its direct application previously hindered by the lack of appropriate RF waveform measurements tools. The past 15 years has seen the maturing of RF voltage and current waveforms measurements systems. Coupling with impedance control hardware also enables experimental control (Engineering) of these terminal RF waveforms during measurements; *thus providing a practical RF Waveform Measurement & Engineering solution*. Application involves either the direct utilization of the measurement system in the design investigation/evaluation loop, or its indirect use by providing CAD accessible datasets or behavioral model parameters.

II. RF WAVEFORM MEASUREMENT

The most utilized microwave measurement tools supporting CAD design measure s-parameters, small signal parameters, are only of limited use in non-linear CAD design. Non-linear CAD design must include mixing (intermodulation distortion), compression (harmonic generation), etc. While this information, ideal for system evaluation, is provided by (Vector) Spectrum Analyzer and/or Power Meter; in this form it is again of limited use in non-linear CAD design. This explains the prevalence of “build and test” in the RFPA design cycle.

Initially RF Waveform Measurement capability was realized by integrating sampling scopes within conventional s-parameter measurement systems [1]. The Microwave Transition Analyzer (MTA) triggered the realization of standalone RF Waveform Measurement Systems [2]. Figure 1 shows the standard, full two-port, architecture of RF Waveform Measurement System, often referred to as a Non-Linear

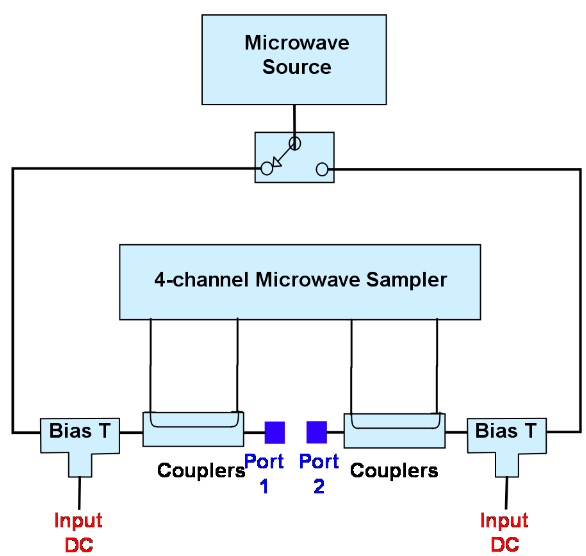

Fig. 1 Basic schematic of an RF Waveform Measurement and Engineering System [3].

Vector Network analyzer (NLVNA) now typically employed [3]. Presently receivers employed include four channel digital sampling scopes (i.e. Tektronix DSA + Mesuro M20), sampling down converters or 5 channel network analyzers (i.e. Agilent PNA-X). All systems are fully vector calibrated and provide for error corrected measurement of the time varying voltage and current waveforms present at the device under test (DUT) terminals, as shown in figure 2.

Calibration involves a two-step process [3] in order to determine the required eight-term error model shown in figure 3. First a VNA calibration process is employed to determine all but one of the required calibration coefficients, either ε_{10} or ε_{23}. VNAs only measures the ratio of quantities hence this one error term is not required and so is set to unity. The second calibration step involves the determination of this residual calibration term. Magnitude calibration is done with a calibrated Power Meter. Phase calibration is done by either assuming that the sampling receiver has an ideal phase response [3] or by employing a reference harmonic phase generator [4].

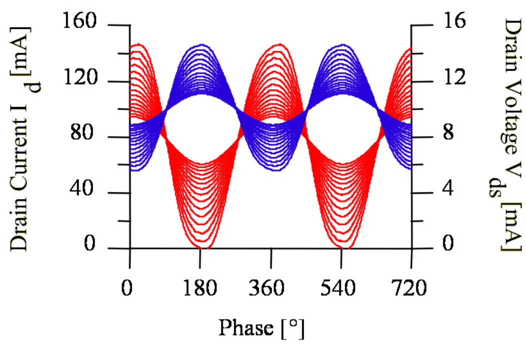

Fig. 2 Typical Measured, as a function of input power, RF Voltage and Current Waveform for a HFET.

III. RF WAVEFORM ENGINEERING

S-parameter measurements are generally performed into a known, fixed 50 ohm reference impedance. This does not impose any constraints in linear CAD design since the performance into arbitrary terminal impedances is computed via linear algebraic transformations. This is not the case for non-linear CAD design, hence the limited usability of s-parameters. This constrain also applied to RF Waveform Measurements. While the RF Waveforms contain non-linear information they cannot be used to simply compute non-linear performance into arbitrary terminal impedances.

This explains the initial use of RF waveform Measurement Systems simply as a tool to help develop or optimize non-linear transistor models [5,6]. Such models can then be used in non-linear CAD simulators, mainly utilizing harmonic balance concepts, to compute non-linear performance into arbitrary terminal impedances.

Unfortunately the RFPA design community has often found the model accuracy, hence usefulness of these CAD simulations, inadequate. They have placed more reliance on load-pull; the direct measurement of the key non-linear performance parameters, output power, gain, efficiency, linearity, etc. as a function of load impedances. Typically passive mechanical systems based on multiple stub tuners are used to achieve this variation of terminal impedances. Coverage of the impedance plane is limited by loses in these passive mechanical systems. To overcome these loses a number of active load-pull systems have been investigated [7]. However, they can often be prone to oscillations;, hence limiting their uptake.

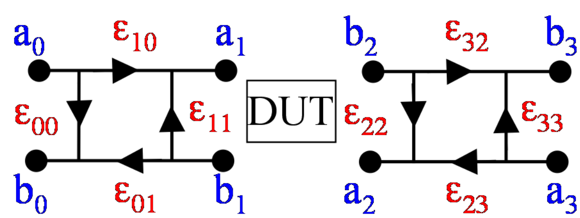

Fig. 3 Eight-term error model flow graph necessary for error correcting rf Waveform Measurement Systems.

RF Waveform Measurement Systems can, however, be integrated with such impedance control hardware [3,8]. The practical consequence of integrating experimental control (Engineering) of the terminal impedances is that RF incident traveling voltage waveforms can be modified (Engineered) during measurements; hence the term RF Waveform Engineering rather than source- or load-pull. It is important to note, however, if the stimulus signal is a single-tone CW signal then the RF Waveform generated by the non-linear DUT will also contain harmonics components. RF Waveform Engineering requires not only fundamental load-pull but also harmonic source- and load-pull. This highlights the fact that when investigating the behavior of a non-linear DUT, impedance variation investigation should not be limited to fundamental frequency alone.

Reviewing the fact that the role of this impedance variation is to engineer the RF incident traveling voltage waveforms led to the development of a relatively simple implementation shown in figure 4 [8]. To provide the required harmonic coverage, multiple RF sources are required since the impedance must be engineered at all of the RF waveforms spectral components. If the stimulus signal is a single-tone CW signal, confining the problem to the third harmonic allows for band-limited RF Waveform Engineering with a practical number of RF sources, i.e. six. Multi-tone stimulus will result in a significant increase in spectral components; RF Waveform Engineering of these signals cannot be addressed by simply increasing the number of RF sources.

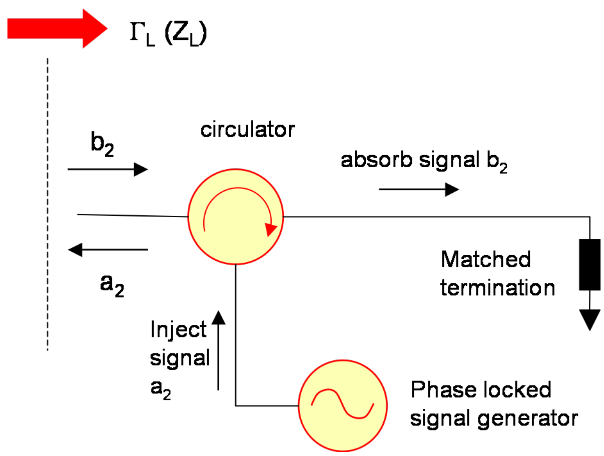

Fig. 4 Variable Load Emulation: Basic open loop active load-pull configuration [8].

Also, while the open loop active load-pull solution is not prone to oscillations [8] it requires an iterative adjustment of the additional RF sources power levels and relative phases however to emulate a given load termination; this is time consuming. This can be overcome by providing, as shown in figure 5, some base-band feedback (envelop signal) to allow for automatic adjustment of the additional RF sources magnitude and phase; this approach is referred to as envelop load-pull [9]. It can also address the multi-tone signal issue provided that the feedback loop has sufficient envelop bandwidth; this is typically 10 times the modulated bandwidth of the stimulus multi-tone signal [10].

The alternative solution would be to perform the rf waveform synthesis directly in the time domain using an Arbitrary Waveform Generator (AWG). The very recent introduction of a Microwave Arbitrary Waveform Generator (Tektronix AWG [39]) has just made this feasible, thus allowing for a very compact and simple rf Waveform Measurement and Engineering system, shown in figure 6, to emerge [11].

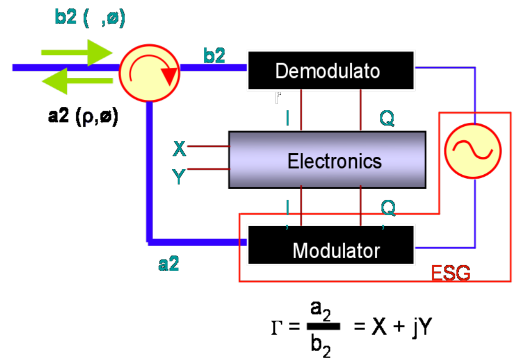

Fig. 5 Typical basic architecture of a Envelop Load-Pull System. [9]

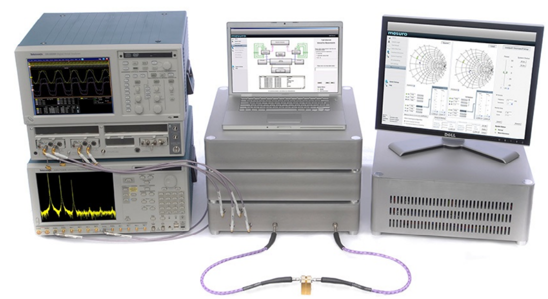

Fig. 6 Compact rf Waveform Measurement and Engineering system from Mesuro [11] which utilizing the Tektronix AWG.

IV. Transistor Characterization

RF Waveform Measurement and Engineering Systems can be used to fully investigate the transistors dynamic non-linear response at microwave frequencies. It can thus support technology optimization, selection, modeling and utilization as well as the investigation of trapping problems and reliability.

Consider for example the optimization of the emerging GaN HFETS. Fabricated RF Power GaN transistors often have disappointing RF power performance; generally associated with both surface and buffer trapping. Conventional microwave measurements, whether linear or large signal, only measure their consequences; transconductance and output conductance dispersion, RF power loss and/or decreased efficiency. This is not the case with an RF Waveform Measurement and Engineering Systems, as shown in figure 7 [12]. Here CW measurements are performed while sweeping the RF fundamental load impedance from a low (short) to a high (open) impedance. The RF knee walkout is clearly observed associated with surface traps. Additionally, if this measurement is repeated for increased drain voltage the increased knee walkout is clearly identified.

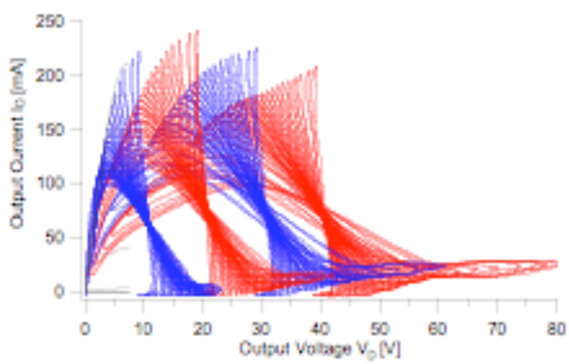

Fig. 7 RF fan diagrams, showing measured knee walkout [12].

The results in figure 7 also shown that this particular technology has an additional buffer problem, hence poor pinch-off that also leads to an identical degradation of RF power performance. Via the optimization of the iron doped buffer design this pinch-off problem was eliminate [12].

V. Amplifier Design

High efficiency power amplifier design is actually quantified in terms of waveform engineering. Amplifier efficiency can be improved if circuit termination impedances can be found that allow the transistor to generate or support half rectified sinusoidal waveforms and/or square waveforms. For example, the inverse class F solutions requires simultaneous a square waveform output current and a half rectified waveform output voltage. Figure 8 shows the measured (engineered) RF waveforms achieved using a 10W GaN HFET, clearly indicating that the transistor can support this mode of operation, hence deliver the RF output power required (>10watts) with a very high power added efficiency (>80%) [13, 14].

In addition to confirming the correct (desired) waveforms it also provided the designer with the desired input and output matching circuit impedances necessary at the fundamental, second harmonic and third harmonic. The designer now has all the information necessary to design an appropriate microwave matching circuit and assemble the amplifier, once assembled the amplifier was simply characterized giving a measured performance identical to that predicted; i.e. a first pass design success [13, 14].

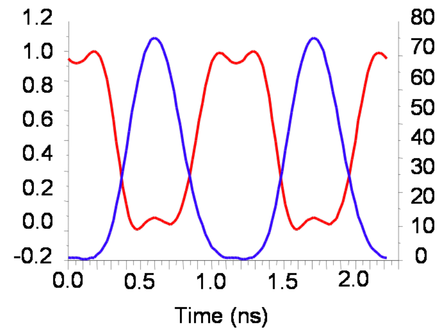

Fig. 8 Engineered RF waveforms showing GaN HFET operating in inverse Class F [13, 14].

Recent publications, stimulated by RF waveform measurement and engineering investigations, have highlighted the possibility of new, previously undescribed, optimal waveform solutions [15]. This is evidence of how the introduction of RF waveform measurement and engineering systems into the RF power amplifier design process has stimulated a revival in the theoretical mathematical analysis of RF waveforms.

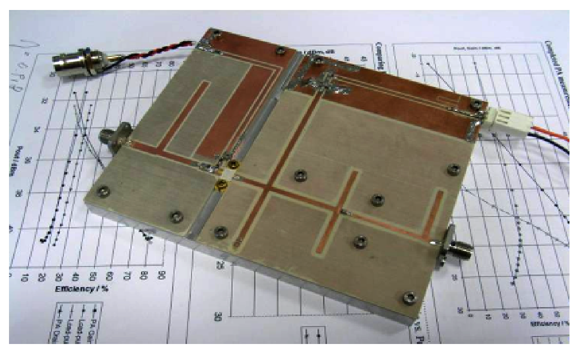

Fig. 9 Fabricated inverse Class F amplifier [13, 14].

VI. Transistor Modelling

The initial use of RF Waveform Measurement Systems was to help develop or optimize non-linear transistor models. Its ability to support model development is advanced considerably by the addition of RF Waveform Engineering. For example, this enables the full device I-V plane to be investigated via load-impedance variation rather than DC bias point when validating conventional analytical models or extracting the transistors non-linear state functions [16].

RF waveforms, measured as a function of the load impedance, can also provide datasets that be used directly, via a waveform data lookup model within the CAD design tool [17]. Alternatively experimental waveform datasets are transformed into behavioral model datasets [17-19]. All these models can then be used in non-linear CAD simulators, mainly utilizing harmonic balance concepts, to compute non-linear performance into arbitrary terminal impedances.

VII. Conclusions

RF I-V Waveform Measurement and Engineering Systems are now finally enabling practical waveform engineering to be directly undertaken. This measurement capability extends the characterization opportunities for both high frequency/speed transistor technology developers and circuit/system designers; *terminal waveforms are the unifying theoretical link between transistor technology, circuit design and system performance.* A more extended discussion of this topic can be found in [20].

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