Revista Ingeniería, Investigación y Desarrollo, Vol. 16 Nº 2, Julio-Diciembre 2016, pp. 6-11, Sogamoso-Boyacá. Colombia
ISSN Impreso 1900-771X, ISSN Online 2422-4324

WAVEFORM MEASUREMENT IN MICROWAVE DEVICE CHARACTERIZATION: IMPACT ON POWER AMPLIFIERS DESIGN

Medición de las formas de onda en la caracterización de dispositivos de microondas: impacto en el diseño de amplificadores de potencia

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(Recibido marzo 29 de 2016 y aceptado mayo 27 de 2016)

Resumen
Este artículo describe un ejemplo de setup, para la medición de las formas de onda durante la caracterización load-pull de un dispositivo de microondas con alta capacidad de potencia. La significancia de está característica de la medición, se resalta al estudiar la forma en la cual puede ser utilizada, en el diseño de amplificadores de microndas con altas potencias de salida y alta eficiencia.

Palabras clave: electrónica de alta frecuencia, sistemas de medición de microondas, amplificadores de potencia.

Abstract
This paper describes an example of a measurement setup enabling waveform measurements during the load-pull characterization of a microwave power device. The significance of this measurement feature is highlighted showing how waveform engineering can be exploited to design high efficiency microwave power amplifiers.

Key words: High frequency electronics, microwave measurement systems, power amplifiers.

1. INTRODUCTION

The power amplifier is a crucial component in a high frequency transceiver, due to its impact on the total power consumption, linearity, and cost of the whole system. For this reason, a great effort is spent by the microwave research community to investigate and discover design techniques for the optimization of power amplifier performance.

Solid state power amplifiers are realized by properly terminating active devices through the use of matching networks [1, 2]. The frequency dependent optimum terminations can be determined by means of experimental characterization of the devices, in particular using load pull systems that measure the several figures of merit of the device (e.g., output power, efficiency, gain) while varying its load condition [3, 4, 5]. Enabling the observation of the voltage and current waveforms on the device allows designers to reach an even deeper understanding of the working mechanisms of the device, and permit a better relation between the power amplifier theory and the real device operation. In fact, most of power amplifier theoretical studies are based on current/voltage waveform considerations, for example dynamic load line [1, 2]. However, when operating at high frequency, many of these simplified approaches must be consciously applied, taking in consideration the impact of reactive effects of the device. For this reason, only a proper combination of theory and experimental characterization of the device enables a successful design of the power amplifier.

In section 2 it is shown how waveform engineering can be used to define high efficiency power amplifier basics, in particular continuous Class B/J modes. In section 3 of this paper an overview of a harmonic load

Cómo citar este artículo:
Quaglia, R., Bell, J., Cripps, S. & Tasker, P. (2016). Waveform measurement in microwave device characterization: impact on power amplifiers design. Revista Ingeniería Investigación y Desarrollo, 16 (2), pp. 6-11

pull characterization system is presented, showing its capabilities and limitations in terms of operating frequency, power, and accuracy. The waveform measurement features are carefully discussed. In section 4, some experimental results confirming the power amplifier theory are finally shown.

2. HIGH EFFICIENCY POWER AMPLIFIERS: WAVEFORM ENGINEERING

2.1 Waveforms in high efficiency power amplifiers

Narrow band power amplifiers are usually designed loading the active device with proper harmonic terminations. In fact, for these kinds of systems, a single tone analysis is sufficient to define most of the main features such as output power, power gain, DC power consumption and efficiency [1, 2]. Considering single-ended power amplifiers, they are usually categorized in classes. Linear classes are characterized by the active device working in fact as an amplifier, and not as a switch. Class A, AB and B are classified in relation to their bias point, while their fundamental load is purely resistive and all the harmonics are short-circuited. The observation of drain current/voltage waveforms (Figure 1 and 2) helps understanding why class B is efficient, and also allows to identify the load at which the efficiency can be maximized.

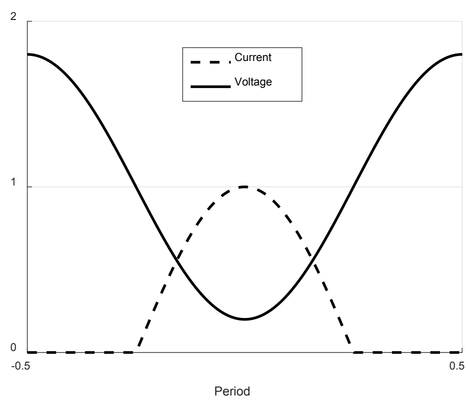

Figure 1. Current (dashed line) and voltage (solid line) waveforms in class B operation, when the fundamental load is equal to $0.8R_{OPT,B}$.

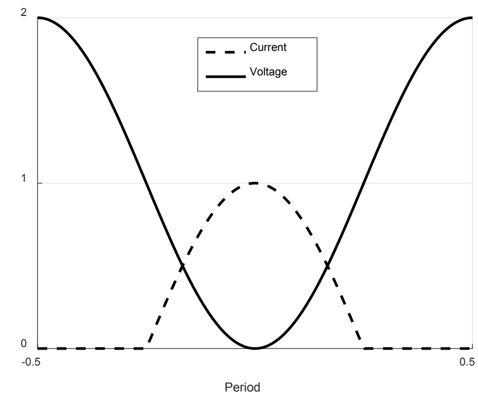

Figure 2. Current (dashed line) and voltage (solid line) waveforms in class B operation, when the fundamental load is equal to $R_{OPT,B}$.

In the presented figures the current is normalized to I_{MAX} and the voltage to the bias voltage V_{DD}. The optimum fundamental load $R_{OPT,B}$ for the class B is $2V_{DD}/I_{MAX}$, that allows a maximum output power of $V_{DD}I_{MAX}/4$ and an efficiency of π/4.

Figure 1 refers to a class B where the fundamental load is lower than R_{OPT}: the voltage minimum does not reach zero, and as a consequence the instantaneous dissipated power is larger than in Figure 2, where the load is fixed at R_{OPT}.

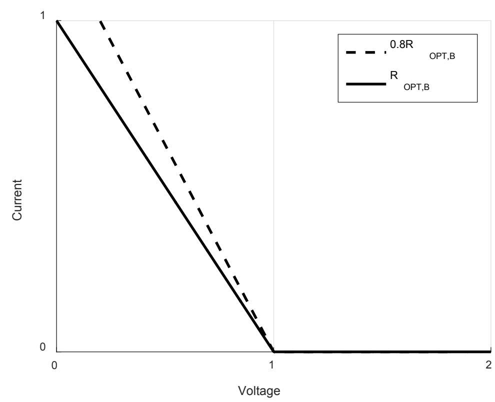

Figure 3. Dynamic load line in class B operation for fundamental load $0.8R_{OPT,B}$ (dashed line) and $R_{OPT,B}$ (solid line).

Figure 3 shows the dynamic load lines in the two load cases. The highlighted box represents the physical limits of the device. In reality, as can be seen in Figure 4, a real device is characterized by non-ideal output characteristics: as a first approximation, the box can be re-defined as shown. A first approximation can be seen on the minimum voltage that passes from zero to the so called knee voltage V_K.

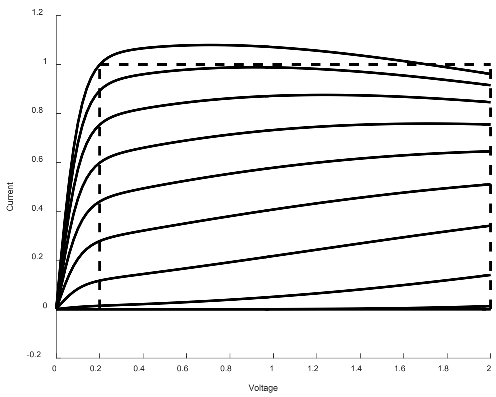

Figure 4. IV output normalized curved (solid lines) for a real device example. Dashed line: the box for the ideal design.

The work presented in [6] shows that the class B PA mode is in reality a particular case of a continuum of modes, where the optimum fundamental load can actually be a complex impedance $Z_1=(1+j\beta)R_{OPT,B}$ while the second harmonic is loaded by $Z_2=-j\beta\pi 3/4R_{OPT,B}$. The parameter β is in the range -1 to 1. This set of modes is named the class B/J continuum, and is characterized by constant output power and efficiency. The ideal current waveform is, across the entire continuum, the same as that of class B; some possible voltage waveforms are shown in Figure 5, and they belong to the family of equations (1-cosθ)(1+βsinθ).

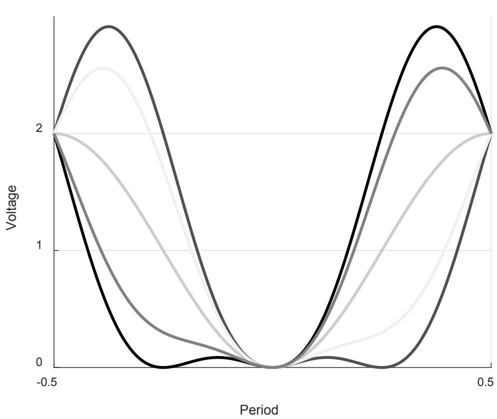

Figure 4. Set of normalized voltage waveforms of the B/J continuum.

All these waveforms graze zero (or the knee voltage in a real device), meaning that they never enter the clipping region, hence maintain low distortion. This is just a case of how engineering the waveforms can achieve interesting PA properties. Other examples of high efficiency linear classes are the class F [7], the continuous class F [8], and the second harmonic tuned PA [9].

2.2 Load pull characterization system

Figure 4 shows a block diagram of the multi-harmonic active load-pull system in use at the centre for high frequency engineering, Cardiff University. Two channels of the Agilent Vector Network Analyser (N5242A) are used to receive the 4 scattering waves at the input and output DUT ports. These receivers are narrowband, so every harmonic frequency components is sampled sequentially rather than at the same time. The ratio between waves is sufficient to determine S-parameters of the DUT. In order to enable proper absolute power measurement, the received absolute level must be recorded. Moreover, the measurement of voltage and current waveforms can be reconstructed from the harmonic components of the scattering waves, but it is necessary to measure the phase relation at different harmonics. To this aim, the Comb Generator connected at port 3 is used as a stable phase reference, and it permits the reconstruction of the waveforms by combining all harmonic components with a properly corrected phase.

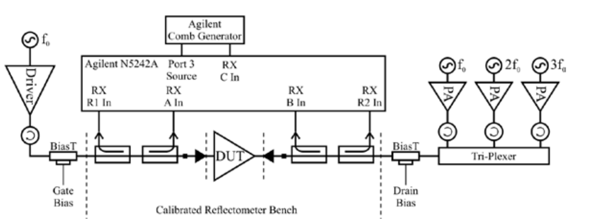

Figure 4. Block diagram of the active harmonic load pull system.

The input signal is provided by a microwave source, and amplified if necessary by a driver PA. A circulator is used to minimize the effect of mismatch on the driver and avoid PA damage in case of high VSWR. The active load pull system, in this case inspired by the work of [10], is based on the concept that the device "sees" the load a_2/b_2. While b_2 is determined by the device operation, a_2 can in fact be controlled by injecting power with another source whose amplitude and phase can be controlled. Again, if the source power is not enough, an amplifier is needed, and the circulator is in this case of crucial importance. The extension to multi-harmonic is achievable by using a multiplexer that separates fundamental and harmonics, and by using harmonic sources. On both input and output bias-tees are used to provide DC voltage and current to the DUT.

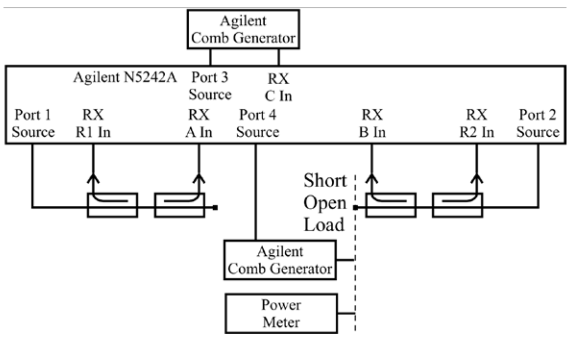

Figure 5. Power and phase calibration of the VNA receivers.

Network analyser-based microwave measurements are characterized by a calibration procedure that is needed to move the reference plane of the measurement from the VNA port to the actual DUT ports [3]. For example, 2-port vector calibration using known 1- and 2- port standard is necessary for measuring the S-parameters at the DUT plane. For load pull systems, and in particular when waveform measurements are required, added parameters are needed to calibrate the absolute power levels and the phase relation between harmonics at the DUT plane. In the specific case, the receiver at port 2 is firstly calibrated in power and phase using a power meter and another Comb Generator, fed by the source of port 4 (see Figure 5). Then, a 1-port Short-Open-Load (SOL) calibration is performed, using coaxial standards compatible with the power meter and Comb Generator connectors, to calibrate the reflectometer bench at port 2.

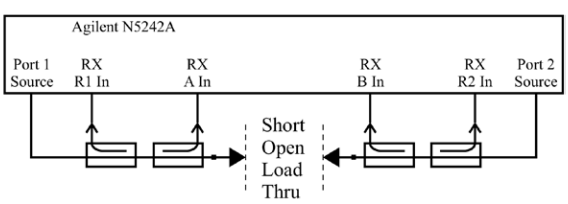

Figure 6. On-wafer 2-port VNA calibration.

A second calibration step is used to move the reference planes to the DUT plane that in our case will be connected with wafer probes. A full Short-Open-Load-Thru (SOLT) calibration with on-wafer standards is performed, see Figure 6.

The system is controlled by specific software developed by Mesuro Inc. that manages both the calibration and measurement procedures. Once the system is calibrated, the DUT can be connected and biased, and the software allows the control and sweep of drive and load conditions, recording the wave harmonic coefficient, that contain all the information needed for the computation of output power, efficiency and gain.

2.3 Waveform measurements in high efficiency power amplifier modes

A 0.5um GaN HEMT device with 1mm gate periphery has been characterized using the described measurement setup. The device was operated with a drain bias of 20V and fundamental frequency of 2 GHz. Fundamental, 2nd, and 3rd harmonic load pull was performed. Figure 7 shows the fundamental load pull contours for output power.

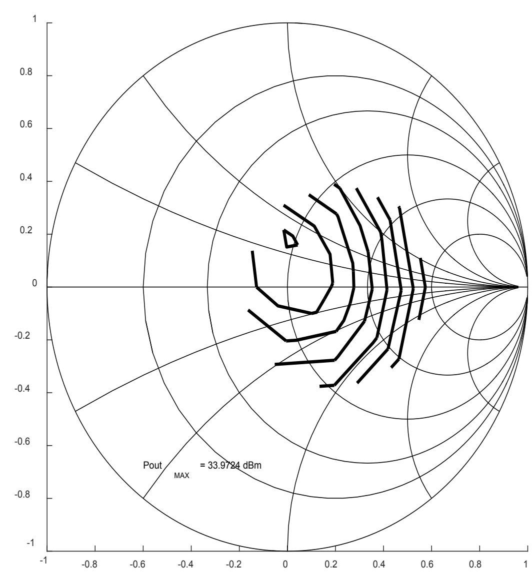

Figure 7. Measured output power contours on fundamental load at 3dB compression. The maximum output power is 33 dBm, with corresponding efficiency of 48%, contour step of 0.5 dB. Second and third harmonic at 0 Ω.

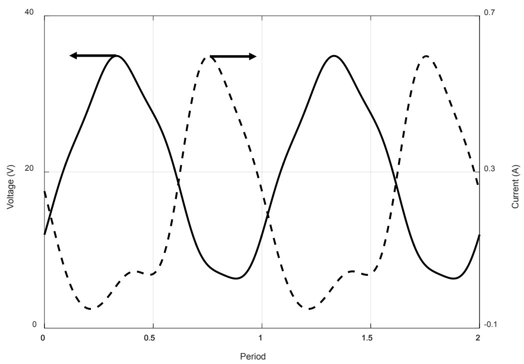

Figure 8. Measured current (dashed line) and voltage (solid line) waveforms, de-embedded at the intrinsic plane, on the optimum load with shorted 2nd and 3rd harmonics.

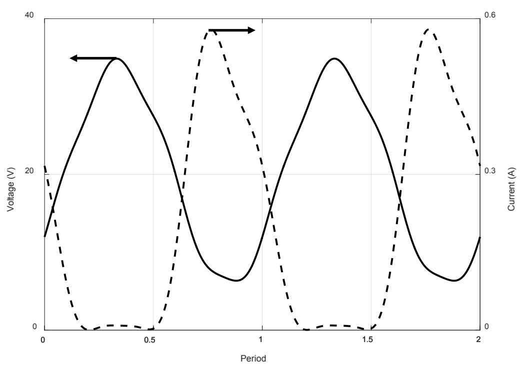

Figure 8. Measured current (dashed line) and voltage (solid line) waveforms, de-embedded at the intrinsic plane, on the optimum load with shorted 2nd and 3rd harmonics.

As expected, the optimum load is not purely real, since the load pull is performed at the extrinsic device plane. From this measurement it is possible to have a rough estimation of the output capacitance of the device, and perform very simple de-embedding that just compensates for this capacitance. Figure 8 and 9 show the measured current and voltage waveforms, before and after de-embedding of an equivalent capacitance of 0.4 pF, respectively. In the de-embedded case, the current practically always stands above zero, and is anti-phase to the voltage. The current waveform is not a perfect truncated sinusoid, due to many factors. First, while the source generates a sinusoid with high spectral purity, the device input non-linearity and the trans-conductance characteristic apply a distortion. Another source of distortion is due to the output characteristics that result in waveform clipping. The voltage waveform is distorted as well, due to the fact that only 2nd and 3rd harmonics are shorted, while higher harmonics are loaded with a different uncontrolled impedance. Experience however suggests that the impact of harmonics higher than the third is usually negligible in narrowband amplifiers.

Figure 9 shows the importance of de-embedding to the current generator device plane by comparing the dynamic load lines with and without de-embedding. The de-embedded load-line is more similar to the expected by theoretical considerations.

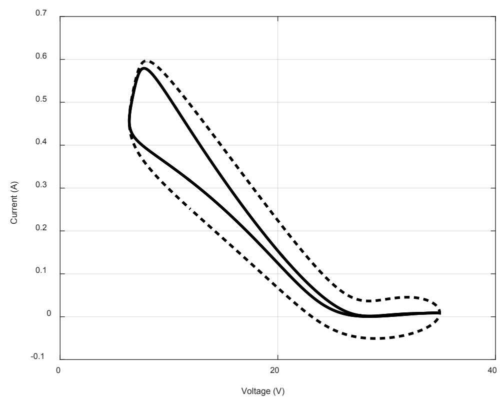

Figure 9. Measured dynamic load lines, without (dashed line) and with (solid line) de-embedding.

Finally, a set of harmonic loads on the B/J continuum is also tested, in particular with β=0.25. The measured waveforms are shown in Figure 10, and correspond to an output power of 33 dBm and an efficiency of 50%.

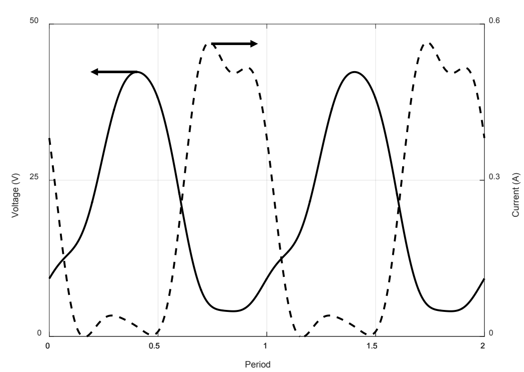

Figure 10. Measured current (dashed line) and voltage (solid line) waveforms, de-embedded at the intrinsic plane, on the load for B/J continuum, with β=0.25.

3. CONCLUSION

In this paper, the capabilities of a microwave harmonic load-pull setup have been discussed. In particular, the experimental characterization of a GaN HEMT power device has evidenced the advantages deriving from the possibility to measure the current and voltage waveforms on the device ports.

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