LARGE-SIGNAL NETWORK ANALYSIS: GOING BEYOND S-PARAMETERS

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ABSTRACT

In this paper we present a new measurement solution for the characterization of high frequency devices under large signal operating conditions. It is shown how a device-under-test (DUT) is put under large signal operating conditions and how one then measures the voltage and current waveforms at the signal ports in order to completely and accurately characterize the DUT behavior.

INTRODUCTION

The S-parameter theory and the associated instrumentation revolutionized the high-frequency electronic industry. In fact S-parameters got so ingrained that many people believe they are omnipotent when it comes to solving microwave problems. One can not repeat enough, however, that their applicability is strictly limited to cases where the superposition theorem holds. In other words, S-parameters are only useful to describe linear behavior. For semi-conductor components this implies that the signal levels need to be small. Many applications today require the usage of signal levels which are significantly higher, e.g. power amplifiers. There is as such a need to "go beyond S-parameters". We call the realized ensemble of measuring and modeling tools "Large-Signal Network Analysis". In this presentation we will focus on the measurement solutions. The idea is to put a device-under-test (DUT) under realistic large-signal operating conditions and to acquire complete and accurate information of its electrical behavior. Having the right tools, it is then possible to analyze the network behavior. The realistic operating conditions are typically achieved by stimulating the device with synthesizers and by using tuning techniques.

DATA REPRESENTATIONS

Unlike S-parameters, different choices can be (need to be) made for the representation of the acquired data. The best choice will depend on the application. On one hand different "domains" can be used to represent the same data: the time domain, the frequency domain and the envelope domain. On the other hand, the measured data can be represented as a port current (noted I) and a port voltage (noted V), or as an incident (noted A) and a scattered (noted B) travelling voltage wave at that port. Since we assume that we are dealing with a (quasi) transverse electromagnetic mode of propagation the relationship between both sets of quantities is given by a simple linear transformation. A-B representations are typically used for near matched and distributed applications (system amplifier). V-I representations are typically used for lumped non-matched applications (individual transistors). In most cases a characteristic impedance of 50 Ohms is used for the wave definition. For certain applications other values are useful. An example is the black-box modeling of the behavior of a power transistor. In this case it is convenient to represent the fundamental at the output in an impedance which is close to the optimal match (typically a few Ohms).

SIGNAL CLASSES

In what follows we will explain what signal classes can be acquired with the existing "Large-Signal Network Analyzer" (LSNA) instrumentation. The oldest measurement solution deals with continuous wave one-tone excitation of 2-port devices, e.g. a biased field effect transistor (FET) excited by a 1GHz continuous wave (CW) signal at the gate, with an arbitrary load at the drain. Assuming that the device is stable (not oscillating) and does not exhibit subharmonic or chaotic behavior, all current and voltage waveforms will have the same periodicity as the drive signal, in this case 1 ns. This implies that all voltage and current waveforms (or the associated travelling voltage waves) can be represented by their complex Fourier series coefficients. These are called the spectral components or phasors. One calls the 1GHz component the fundamental, the 2GHz component the 2nd harmonic, the 3GHz component the 3rd harmonic,… The direct current (DC) components are called the DC-bias levels. In practice there will only be a limited number of significant harmonics. The measurement problem is as such defined as the determination of the phase and amplitude of the fundamental and the harmonics, together with the measurement of the DC-bias.

Recently, the class of signals that can be measured with a LSNA was extended to the periodically modulated version of the previous example of a CW signal. As an example, consider the same FET transistor whereby one modulates the 1GHz signal source, such that the modulation has a period of 10kHz. The voltage and current waveforms will now contain many more spectral components. New components will arise at integer multiples of 10kHz offset relative to the harmonic frequency grid. In practice significant energy will only be present in a limited bandwidth around each harmonic. The resulting set of frequencies is called a "dual frequency grid". Note that in this case each frequency is uniquely determined by a set of two integers, one denoting the harmonic frequency, and one denoting the modulation frequency. E.g. harmonic index (3,-5) denotes the frequency 3GHz - 50kHz. The measurement problem will be to determine the phase and the amplitude of all relevant spectral components of current and voltage.

Next to the frequency and time domain, other representations can be useful for describing modulated measurements. One commonly used example is the so-called "envelope domain". This representation is used in so-called "envelope simulators". The idea is to write the signal as the superposition of a set of time-dependent complex phasors. One has one time-dependent phasor for each of the radio frequency (RF) carriers, in our case the fundamental and all of the harmonics. These complex time domain functions are often called IQ-traces, where I refers to the “in phase” or real part and Q to the “in quadrature” or imaginary part. This representation is very natural to digital modulation people. An appropriately sampled IQ-trace results e.g. in one of the typical constellation diagrams, such as 16-QAM,… Figure 1 illustrates the time domain and envelope domain representations. It represents the output wave of an RF integrated circuit which is excited by a modulated 1.8GHz carrier. The properties of the actual modulation that is used in the example are similar to the properties of a typical “code division multiple access” (CDMA) signal.

The oscillating waveform is the time domain representation. This waveform does not correspond, however, with the physical signal. In reality hundreds of carrier oscillations occur before there is any noticeable deviation in the envelope. As such a realistic representation would look like a black blur of ink. In order to interpret the time domain data, the ratio between the modulation time constant (microseconds) and the carrier time constant (nanoseconds) is artificially decreased. This allows to visualize how the carrier waveform changes throughout the envelope. Note for instance the clipping which occurs at the highest amplitudes. The other, smoother, traces which also occur on the figure are the amplitudes of the time dependent phasor representations of the fundamental and the 2nd and 3rd harmonic. Note how the amplitude of the fundamental phasor becomes larger than the peak-voltage of the time domain waveform at the high amplitudes. This is the well known typical behavior for a clipped waveform. It can be explained by the presence of a significant third harmonic, which is in opposite phase relative to the fundamental (note that the phase is not indicated on the figure).

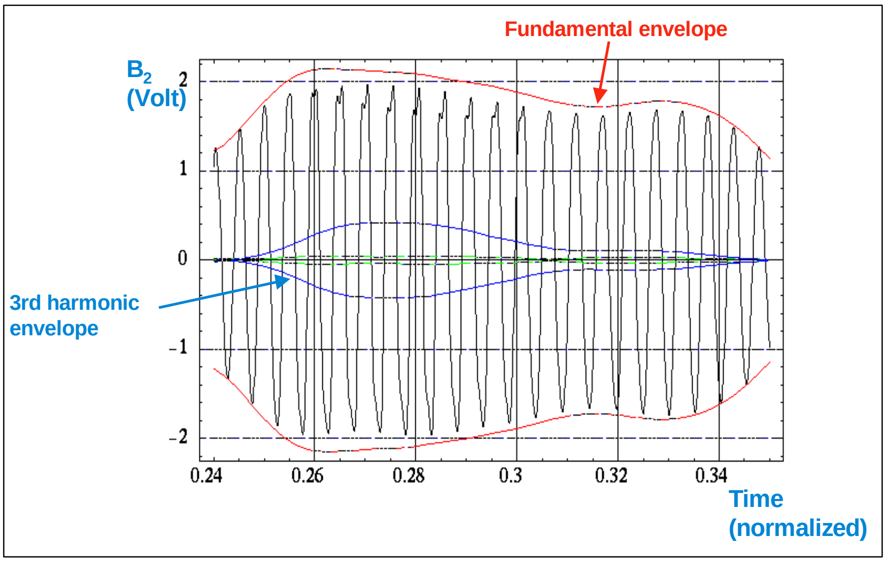

Fig.1 Representation of a modulated signal

LARGE-SIGNAL NETWORK ANALYZER HARDWARE

The first report on a LSNA set-up dates from 1988. Markku Sipila reports of a measurement system to measure the voltage and current waveforms at the gate and drain of an RF transistor. He uses a 2-channel 14GHz oscilloscope and one coupler at the input. Since that time several researchers reported on LSNA's: Kompa & Van Raay, Lot, Demmler, Tasker, Leckey, Wei and Tkachenko, Verspecht. Many references can be found in [1]. The hardware architecture of the LSNA instrument build by Agilent Technologies is relatively simple. 4 couplers are used for sensing the spectral components of the incident and scattered voltage waves at both DUT ports. The sensed signals are attenuated to an acceptable level before being sent to the input channels of a 4 channel broadband frequency converter. This RF to “intermediate frequency” (RF-IF) converter is based upon the harmonic sampling principle and converts all of the spectral components coherently to a lower frequency copy (below 4MHz). The input bandwidth is 40GHz. The resulting IF signals are digitized by a set of 4 high-performance analog-to-digital converters (ADCs). A computer does all the processing which is needed to finally end up with the calibrated data in the preferred format (A/B or V/I, time, frequency or envelope domain). The specifications of the LSNA at present: the calibrated RF frequency range equals 600MHz-20GHz, the maximum RF power equals 10Watt, the maximum bandwidth of the modulated signal equals 8MHz. The repetition frequency of the modulation is typically a few kHz. Note that synthesizers and tuners for the signal generation can be (need to be) added externally. A schematic of the system architecture is represented in Figure 2. Although not shown in the figure for reasons of simplicity, DC bias circuitry is also present.

CALIBRATION ASPECTS

During an experiment we want to know the exact phases and amplitudes of a discrete set of spectral components appearing at the DUT signal ports. These quantities are called the "DUT quantities". Unfortunately we do not have direct access to these quantities. The only information we can get are the uncalibrated measured values. These are called the "raw quantities". The calibration procedure is based on the assumption that there exists a linear relationship between the raw measured spectral components and the actual spectral components at the DUT signal ports. It is assumed that the error has two independent sources of error: a high frequency (RF) error, caused by all of the RF hardware up to the sampling switch, and a low frequency (IF) error which is caused by the low pass filter characteristic of the RF-IF converter and the transfer characteristic of the analog-to-digital converters. First the IF correction is applied to the raw data. Next the RF correction is applied. The RF correction is described by a 16-element matrix. At present one assumes that there is no cross-coupling between port 1 and port 2, which implies that 8 elements of the calibration matrix are equal to 0. The elements of the calibration matrix are determined in three steps: a classical vector network analyzer (VNA) calibration (to determine the "RF relative error"), an amplitude calibration and a harmonic phase calibration. Note that one needs to determine the matrix for all frequencies of interest. The RF error is related to the high frequency hardware (couplers, cables, probes) and is much more sensitive to external influences than the IF error. It is recommended to perform this calibration before each measurement session and at least once a day. For coaxial measurements a classical "short-open-load-thru"" procedure is used for the relative error, while a "line-reflect-reflect-match" is being used for an on wafer calibration. The amplitude calibration is performed by means of a power meter and the harmonic phase calibration by means of a phase reference generator. This is a repetitive pulse generator which is characterized by a broadband sam-

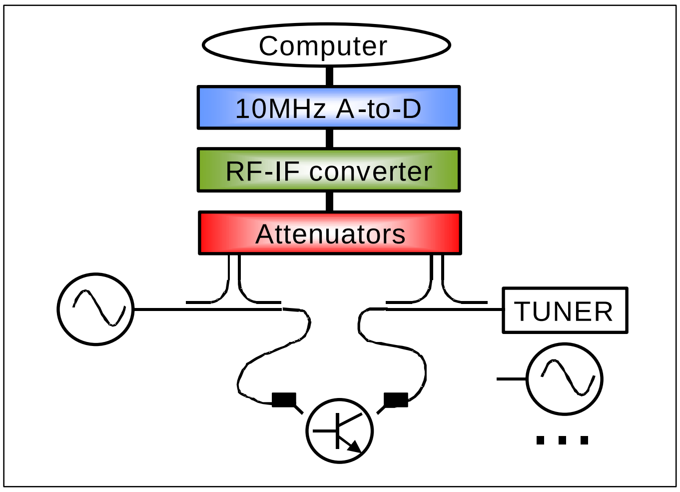

Fig. 2. Schematic of the LSNA

pling oscilloscope. A discrete Fourier transformation returns the phase relationship between all of the relevant harmonics (up to 20GHz). The sampling oscilloscope on his turn is characterized by the so-called "nose-to-nose" calibration procedure, which was invented by Ken Rush (Agilent Technologies, Colorado Springs, USA) in 1989. At this moment, the National Institute of Standards and Technology is investigating the phase calibration process mentioned above.

EXAMPLE APPLICATIONS

Investigating transistor reliability under realistic operating conditions is the first application we mention. On Figure 3 one sees the voltage and current time domain waveforms as they appear at the gate and drain of a FET transistor. These measurements were done applying an excitation signal of 1GHz at the gate. The signal amplitude is increased until we see a so-called breakdown current. It shows up as a negative peak (20mA) for the gate current, and as an equal amplitude positive peak at the drain. We actually witness a breakdown current which flows from the drain towards the gate. This kind of operating condition deteriorates the transistor and is a typical cause of transistor failure. By our knowledge Figure 3 shows the first measurements ever of breakdown current under large-signal RF excitation. A second application is the verification of large-signal models which are derived from S-parameter and DC measurements. A third application is the identification of "Black-Box Frequency Domain" models. The idea is to do a set of frequency domain measurements which covers a specific application (e.g. a narrowband 1.9GHz power amplifier). Based upon the acquired data one can then fit so-called describing functions. These are the multi-dimensional complex functions which describe the relationship between the incident and the scattered spectral components. Consider for instance a power transistor. There will be a mathematical relationship between the incident A's and the scattered B's. The complex functions which describe this relationship are called the describing functions. The problem of building a black-box model is to perform a relevant set of measurements and to fit these functions. Depending on the application, several fitting techniques can be used such as artificial neural nets, polynomials, splines,…. The black-box frequency domain models based on the describing functions can accurately describe many large-signal effects: e.g. compression characteristics, amplitude modulation to phase modulation (AM-PM) conversion, power-added-efficiency, harmonic distortion, fundamental and harmonic loadpull behavior, time domain voltage and current waveforms, self biasing effects, spectral regrowth….

CONCLUSIONS

The "Large-Signal Network Analyzer" presented in the above allows to accurately and completely characterize the large-signal behavior of microwave and RF devices. The data is very useful for modeling purposes.

REFERENCES

[1] Jan Verspecht, Frans Verbeyst, Marc Vanden Bossche,"Network Analysis Beyond S-parameters: Characterizing and Modeling Component Behaviour under Modulated Large-Signal Operating Conditions," *56th ARFTG Conference Proceedings, Broomfield, Colorado, USA, December 2000.*

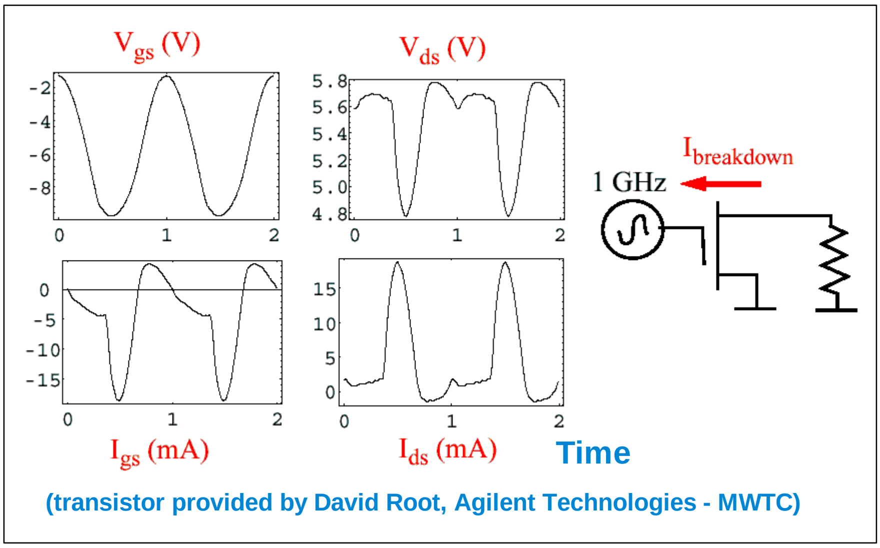

Fig. 3. Measurement of breakdown current