A NOVEL MEASUREMENT METHOD FOR THE EXTRACTION OF DYNAMIC VOLTERRA KERNELS OF MICROWAVE POWER AMPLIFIERS

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ABSTRACT

A novel measurement method for the behavioral modeling of power amplifiers is presented. The proposed method is based on the use of a specific configuration of a vector network analyzer. The principle consists in measuring under two excitation, a parametric and a conversion gain of an amplifiers versus the magnitude of the large input signal carrier.

INTRODUCTION

With increasing complexity of signals travelling through RF and microwave analog devices, accurate measurement based system level (behavioral) models are rewarded. The difficulty for modeling nonlinear systems or subsystems like power amplifiers [5], linearizers or mixers, is to take into account the nonlinear memory exhibited in such equipments. Classical behavioral memoryless models made with AMAM and AMPM characteristics stay very poor, namely for wide band applications with complex modulated signals. Recently a new rigorous modified Volterra model [1] has been presented for accurate modeling of nonlinear distributed memory in subsystems like power amplifiers. This model is based on both single tone and two tones measurements. In this paper we present the required characteristics for building the model and the measurement setup used to practically extract the model. A particular highlight is made on the solution found to measure the two tones nonlinear complex frequency conversion gain which is one of the basis of the model. The solution proposed, based on the use of a vector network analyzer (VNA) doesn't require specific test equipment and is easy to introduce in an industrial environment.

THEORICAL CONSIDERATIONS ON DYNAMIC VOLTERRA APPROACH

At system level low pass equivalent signals are used and real signals are replaced by associated input/output complex envelopes $\hat{X}(t)$ and $\hat{Y}(t)$ (Fig. 1.) .

$x(t) = \Re e\left[\hat{X}(t)e^{j\omega_0 t}\right]$ $\qquad$ $y(t) = \Re e\left[\hat{Y}(t)e^{j\omega_0 t}\right]$

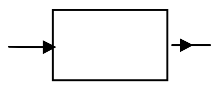

Fig.1: Nonlinear system with memory

As formerly described in [1] the output of a nonlinear system with memory could be expressed with sufficient accuracy as the first order development as following :

$$\hat{Y}(t) = \hat{Y}_{dc}(|\hat{X}(t)|)\, e^{j\Phi_{X(t)}} + \frac{1}{2\pi}\int_{-BW/2}^{BW/2} \hat{H}_1(|\hat{X}(t)|,\Omega)\hat{X}(\Omega)e^{j\Omega t}d\Omega + \frac{1}{2\pi}\int_{-BW/2}^{BW/2} \hat{H}_2(|\hat{X}(t)|,-\Omega)\, e^{2\Phi_{X(t)}}\, \hat{X}^*(\Omega)e^{-j\Omega t}d\Omega \quad (1)$$

where : BW is the modulation bandwidth, $\hat{X}(\Omega)$ the spectrum of input signal.

$\hat{Y}_{dc}(|\hat{X}(t)|)\, e^{j\Phi_{X(t)}}$ represents the purely static response of the system : this is the response calculated with Memoryless Model. $\hat{H}_1(|\hat{X}(t)|,\Omega)$ and $\hat{H}_2(|\hat{X}(t)|,-\Omega)$ are the Dynamic Volterra Kernels accounting for nonlinear memory effects, expressing the distance from the real response to the purely static one (without memory).

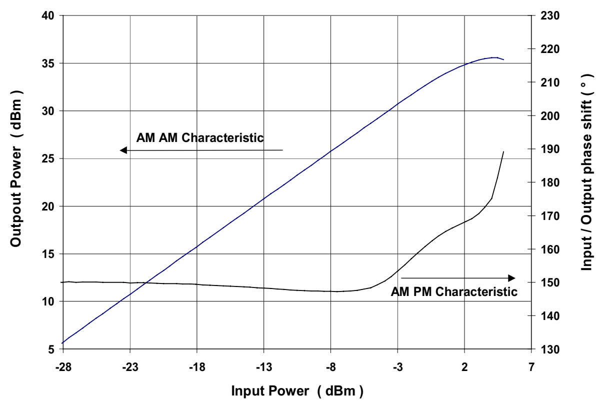

***Fig.2 :** Power Amplifier AMAM and AMPM Characteristics*

Measurement of static part of the model $\hat{Y}_{dc}(|\hat{X}(t)|)$ is easily done with classical AMAM and AMPM measurements performed on a nonlinear vector network analyzer at the center frequency ω_0 of amplifier, with an input sweept power. The typical shape of such characteristics is as shown in Fig.2 .

Nonlinear transfer functions $\hat{H}_1$ and $\hat{H}_2$ are however extracted from specific characterization as shown in Fig 3. The signal at the input of the device is constituted of two tones at different frequencies ω_0 and $\omega_0 + \Omega$ having different amplitudes.

The first tone, depicted as a pump, is fixed at the mid band frequency ω_0(carrier frequency). The pump power $\left|\hat{X}_0\right|$ is swept from small signal region of amplifier to strongly nonlinear region. The second tone, depicted as a probing signal at frequency $\omega_0 + \Omega$, has a constant amplitude fixed in linear region of amplifier. The modulation frequency Ω is swept for covering the entire bandwidth of the amplifier.

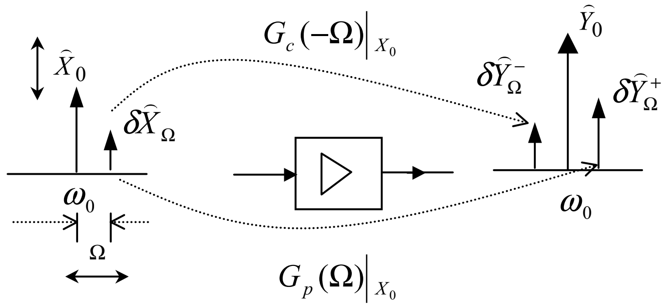

***Fig. 3 :** Signal setup for model extraction*

The resulting signal at the output of the device is composed of three tones. We are especially interested in the two tones $\delta\hat{Y}_\Omega^+$ and $\delta\hat{Y}_\Omega^-$. Indeed building nonlinear transfer functions $\hat{H}_1$ and $\hat{H}_2$ consists of calculating the following ratios :

$$H_1\left(\left|\hat{X}_0\right|,\Omega\right)=\left[\frac{\delta\hat{Y}_\Omega^+}{\delta X_\Omega}-\frac{\delta\hat{Y}_{(\Omega=0)}^+}{\delta X_{(\Omega=0)}}\right]_{FOR\ INPUT\ POWER\left|\hat{X}_0\right|} \qquad H_2\left(\left|\hat{X}_0\right|,-\Omega\right)=\left[\frac{\delta\hat{Y}_\Omega^-}{\delta X_\Omega}-\frac{\delta\hat{Y}_{(\Omega=0)}^-}{\delta X_{(\Omega=0)}}\right]_{FOR\ INPUT\ POWER\left|\hat{X}_0\right|} \quad (2)$$

In facts $\frac{\delta\hat{Y}_\Omega^+}{\delta X_\Omega}$ is a small signal parametric gain *Gp* at the frequency $\omega_0 + \Omega$ where the parameter is the input power of pump $\left|\hat{X}_0\right|$. In the same time $\frac{\delta\hat{Y}_\Omega^-}{\delta X_\Omega}$ is a frequency conversion gain *Gc* from the input frequency $\omega_0+\Omega$ to the output frequency ω_0-Ω also depending of input power of pump $\left|\hat{X}_0\right|$. Hence equation (2) becomes :

$$H_1\left(\left|\hat{X}_0\right|,\Omega\right)=G_p(\Omega)\big|_{|X_0|}-G_p(0)\big|_{|X_0|} \qquad H_2\left(\left|\hat{X}_0\right|,-\Omega\right)=G_c(-\Omega)\big|_{|X_0|}-G_c(0)\big|_{|X_0|} \quad (3)$$

Measuring complex parametric gain *Gp* could be done without any problem with a vector analyzer, as it is done for AMAM and AMPM characteristics, because input and output signals are at the same frequency.

However directly measuring *Gc* is difficult with a VNA, because input and output signal are not at the same frequency. The extraction of such a characteristic necessitates an intermediate reference signal as it will be shown in the following.

A close look to eq. (3) could provoke some interrogation. Of course it is impossible into a practical measurement to determine *Gp(0)* and *Gc(0),* because in the case where Ω=0, the pump signal and the probing signal are at the same frequency at the input of the device and result on a unique single tone signal.

In facts this is not a problem. Indeed *Gp(0)* and *Gc(0)* are the nonlinear parametric gain and the conversion gain of the amplifier considered as memoryless. For this reason these two nonlinear transfer function could be easily obtained in simulation by applying the setup depicted in Fig.3 to the measurement based memoryless static part of the model obtained at center frequency ω_0 with AMAM and AMPM characteristics (Fig.2).

MEASUREMENT OF NONLINEAR FREQUENCY CONVERSION GAIN

The problem faced for measurement of complex frequency conversion gain is that tones to be characterized are not at the same frequencies. This problem has found some solutions presented in [3] for signals constituted of harmonic tones and in [2] for any kind of signal with low frequency conversion and a time domain measurements. However solutions proposed require specific equipment or rather complicated calibration procedures.

Here the measurement procedure proposed for model extraction is not a fully and absolute determination of all phase relations between tones at input or output of the device, but a more simple characterization allowing recording of phase evolution as well as amplitude evolution of the different tones at input and output ports of the device with swept input power. Distance between tones is not limited to any size. The few unknown relations not directly obtained by measurements are resolved both by general knowledge of phase relations in two tones fed nonlinear devices as well as optimization.

The proposed principle is based on the use of a modified vector network analyzer, used in receiver mode [4] , calibrated with a classical SOLT procedure and power calibration. In this operation mode, the analyzer is capable of measuring power of any tone constituting input or output device spectrum by using an internal power reference, as it could be done by a spectrum analyzer. For this reason determination of input output power relation between tones for procedure depicted in Fig. 3 is not a problem. In other words $|$*Gp(Ω)*$|$ and $|$*Gc(-Ω)*$|$ are directly determined by vector analyzer without any difficulty.

Furthermore determination of phase Φ(*Gp(Ω)*) is easy to do because it is a simple S21 measurement, tones being at the same frequency at the input and output of the device.

The difficulty takes place in the extraction of the phase Φ(*Gc(Ω)*) because input and output tones are not at the same frequency. The principle used for this measurement is to use a reference fixed signal constituted of all necessary spectral frequencies. This signal is placed on a reference port of network analyzer, and input or output tones of devices are measured relatively to the reference signal, as shown in Fig. 4 . The key for this measurement is to force the reference to stay constant in amplitude and phase during extraction. In this case we have eq. (4) .

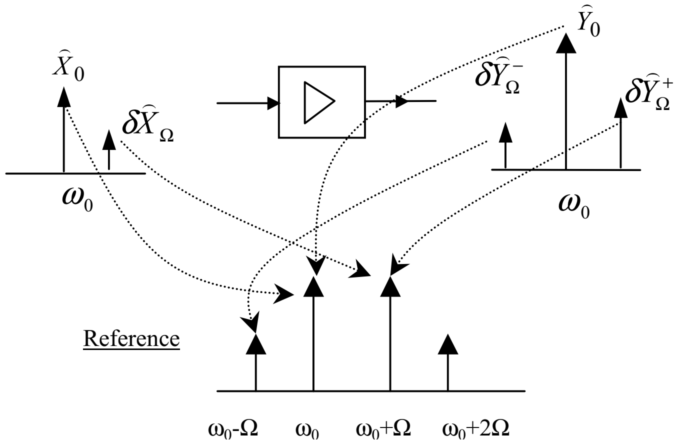

Fig. 4 : *Input Output relations using reference signal*

$$G_c(-\Omega)\Big|_{|X_0|} = \frac{\delta\hat{Y}_\Omega^-}{\delta X_\Omega} = \frac{\delta\hat{Y}_\Omega^-}{Ref(\omega_0-\Omega)} * \frac{Ref(\omega_0+\Omega)}{\delta X_\Omega} \quad (4)$$

↓ ↓

2 Ratios measured by VNA: $\mathbf{M_1}$ $\mathbf{M_2}$

The ideal reference generator would be a three tones generator with perfectly known amplitudes and phase relationships and having the capability of selecting any frequency spacing : for example from 100 Hz to 1 GHz. Hence determination of *Gc(-Ω)* would be complete and absolute. However such a standard signal is difficult to obtain. We decided to use as reference signal a more simple to obtain signal constituted of intermodulation of the two tones at ω_0 and $\omega_0+\Omega$ passed through a nonlinear amplifier.
Therefore exact phase relation between $Ref(\omega_0+\Omega)$ and $Ref(\omega_0-\Omega)$ is not known, but reference staying constant, measurement of relative drift of Φ(*Gc(Ω)*) versus input power $\left|\hat{X}_0\right|$ is known using both measurements M_1 and M_2 with an undetermined constant K : $\Phi(M_1 * M_2)\Big|_{|X_0|} = \Phi\left(G_c(-\Omega)\Big|_{|X_0|}\right) + K$ (5)

On the other hand we are interested in evolution of Φ(*Gc(-Ω)*) with input power $|X_0|$, and K is independent of $|X_0|$. So the evolution of measurement (5) with $|X_0|$ gives us the evolution of $\Phi\left(G_c(-\Omega)\Big|_{|X_0|}\right)$ with $|X_0|$. In fact the constant K corresponds to the unknown value of Φ(*Gc(-Ω)*) for very small input power.
Determination of K is done afterwards by a numerical treatment. Indeed, given the model (1), we know that this model is a very good representation of amplifier response at least for the quasi linear region of amplifier. Thus, a model is build for a given modulation frequency Ω, with an arbitrary small signal phase K on Gc. Then an optimization is performed for minimizing model error compared to single tone power measurement at frequency Ω in quasi linear region of the amplifier. The phase corresponding to this minimum is found to be always unique and gives us the value of K.

MEASUREMENT SETUP

The bench corresponding to the extraction methodology described above is finally relatively simple, as shown in Fig 5. It is important to note that in this bench, reference signal, pump and probing signals are coming from same sources. This method avoids any problem of phase coherence, or jitter between reference signal and input signals used to feed the DUT.
The method described in the previous paragraph is applied to characterize the amplifier under test with f1 placed at the center bandwidth of amplifier and f2 covering step by step the entire bandwidth of amplifier. For each step of f2, variable attenuator allows to sweep input power of the device from linear to strongly nonlinear region of DUT.

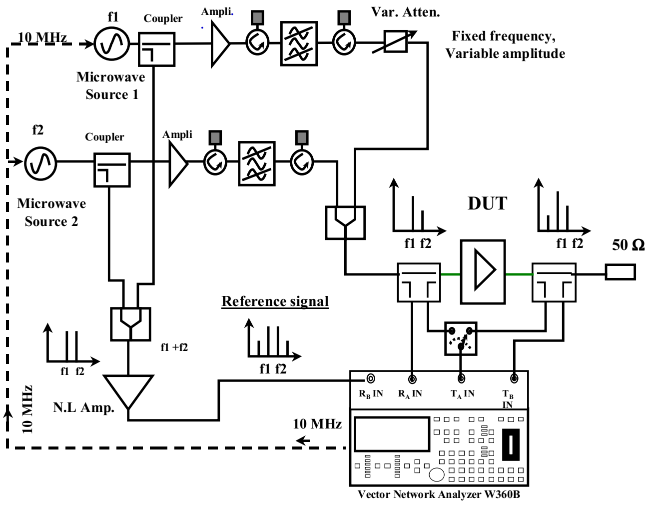

Fig. 5 : *Measurement setup*

APPLICATION

The behavioral modeling of a L band (1.5 GHz) Hybrid 4 Watt power amplifier for space applications has been achieved with this method. Static part of the model has been extracted with AMAM AMPM measurements at center frequency of amplifier bandwidth (Fig. 2). Dynamic kernels are obtained by measurements of nonlinear parametric gain and frequency conversion gain by the described technique. The next figures show the obtained characteristics for Gp and Gc for a swept input power. For each curve the probing signal has been swept in frequency from -10 MHz to +10 MHz around the carrier pump signal at 1.53 GHz.

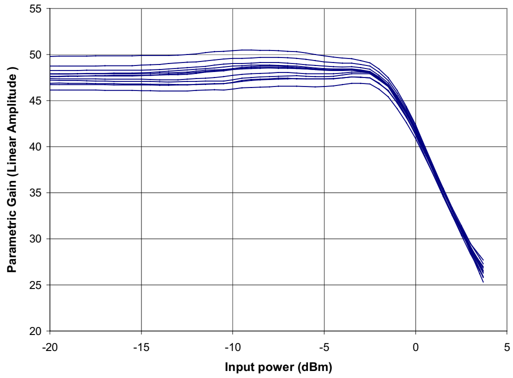

Fig. 6 : *Amplitude of Parametric Gain for modulation frequency of +/- 10 MHz around pump*

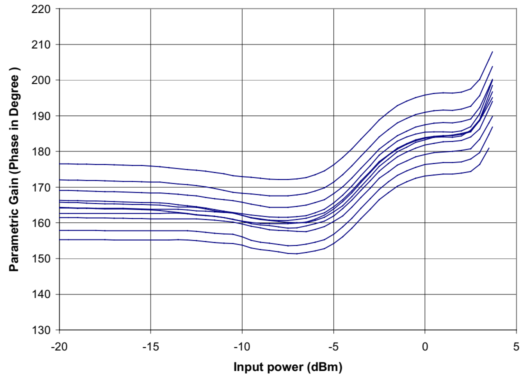

Fig. 7 : *Phase of Parametric Gain for modulation frequency of +/- 10 MHz around pump carrier*

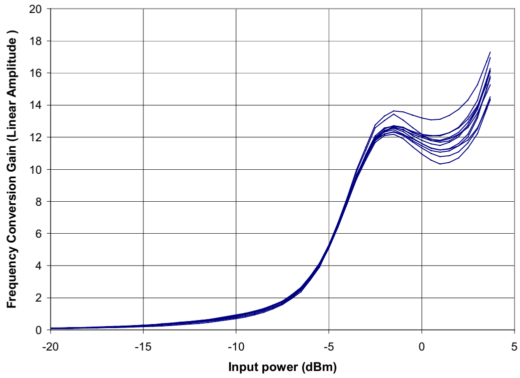

Fig. 8 : *Amplitude of conversion Gain for modulation frequency of +/- 10 MHz around pump carrier*

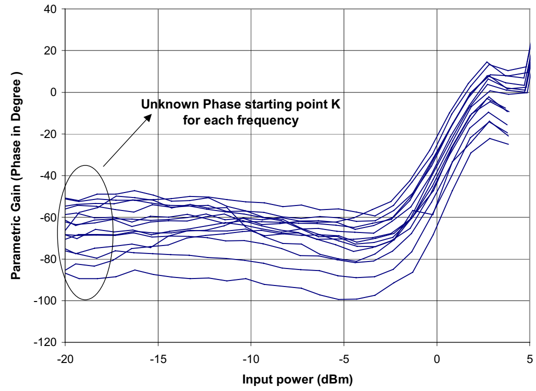

Fig. 9 : *Phase of Conversion Gain for modulation frequency of +/- 10 MHz around pump carrier*

After the previously described numerical optimization on the model build with parametric gain and conversion gain, the small signal phases K for conversion gain are recovered for each modulation frequency as shown in the next graph . With this information Φ(*Gc(-Ω)*) is now completely known, and behavioral completely determined.

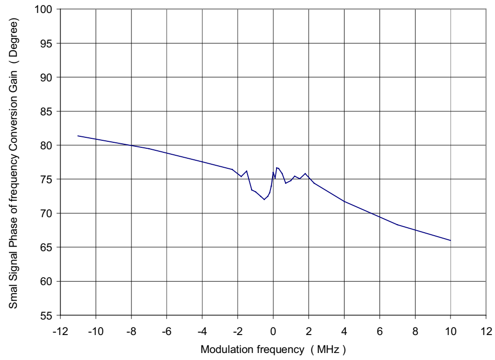

Fig. 10 : *Distribution of Small signal values (K) for phases of Frequency conversion Gain at each modulation frequency*

CONCLUSION

A simple and easy to carry out measurement principle has been exposed for nonlinear behavioral model extraction. The particularity of the method proposed is to allow nonlinear frequency conversion gain measurement both in phase and amplitude. Application to dynamical characterization of a power amplifier has shown that method could give rather accurate results. Based on a nonlinear vector network analyzer this measurement setup doesn't necessitate complicated calibration procedure or specific equipment. Hence it could easily be introduced in an industrial environment.

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