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# Using X-parameters to Model Diode-based RF Power Probes

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***Abstract*— This paper presents a X parameter model for diode power probes that can be used for calibration purposes.**

**It will be shown that X parameters can be applied to diode power probes with significant gains in terms of behavior characterization.**

**This first tentative to apply X parameters is a step further in the calibration of power probes, when they are excited by modulated signals. Diode power probes are normally calibrated using a simple one-tone average power as the calibration quantity, but it was proved that this type of calibration can create measurement errors when the excitation is different from a pure sinusoid.**

**The use of more robust models to describe the power probe is thus an important point when calibrating it for operation with modulated signals.**

***Index Terms:* Diode Power Probe, Nonlinear black-box modeling, Poly-Harmonic Model, X-parameters, Power Measurement.**

## I. INTRODUCTION

High speed RF power probes based on diodes have been used for power measurements in RF systems. The nonlinear characteristic of the diode actually rectifies an RF signal, providing a representation of the RF power through an output DC voltage. Before performing actual measurements, diode probes must first be calibrated with a well known signal. The calibration process consists in obtaining a table with correction factors which will be further applied to measurements to obtain the correct DC voltage. For many years this calibration process has been carried out with a single sinusoidal signal that is quite satisfactory when the signal to be measured is also a single sinusoid [1-3].

However, modern wireless systems employ more sophisticated signals than single sinusoidal carrier. Wideband, multi-tone and complex signals such as M-QAM has been used. Hence, we have to question if one-tone calibration remains valid for measurements of other complex forms of signals. Actually due to the inherent nonlinearity of the diodes this is actually not true; we need to use other forms of calibration.

Recently in [4] and [5] it was proved that a calibration of a diode-based power probe with a single-tone sinusoidal signal does not guarantee proper calibration for N-tone signals or other complex forms of excitation. This is due to the so-called memory effects, the low-frequency response imposed by the power probe baseband impedance. This means that the nonlinear response of the power probe may not be constant over the bandwidth of the RF input signal and may affect the time domain evolution of the signal.

Memory effects in power amplifier are not a new theme. In power amplifiers these effects are associated with some time-varying operating conditions such as self-heating and bias-line modulation. Thus a new characterization procedure is fundamental to guarantee proper measurements. One of the possibilities is to use a simple nonlinear model to describe the inherent nonlinear behavior, and then calibrate the overall measurement using that same model. One of those possibilities is the so called X parameters [6]. Actually in [6] X-parameters are already used to characterize and model memory effects of wideband modulated signals in microwave power amplifiers.

In this paper, we will study the application of X parameters to diode power probes under multi-tone excitation. X parameters will be extracted using a two-tone signal capable of describing the diode probe behavior and predict the memory effects.

The paper will start with a brief overview of the black box models used, then the framework will be applied to a diode power probe, and finally some simulated and measured results will be obtained in order to validate our proposal.

## II. POLY-HARMONIC DISTORTION (PHD) MODEL AND X-PARAMETERS

The fundamentals of Poly-Harmonic Distortion (PHD) Modeling are introduced in [7] and a good overview is presented in [8]. PHD modeling is a black-box, frequency-domain modeling technique initially developed for microwave power amplifier characterization. The model approach relates each reflected wave from a non-linear DUT with all incident waves at all ports and harmonics. PHD can be seen as an extension of S-parameters for non-linear systems. PHD model is empirically extracted by exciting a DUT with external signals and measuring the response at the desired port-harmonic.

Being a block-box approach, this technique is technology and topology-independent and has the advantages of protecting intellectual property and potentially speed up design cycle and provide increased model accuracy since it can be extracted directly from devices. On the other hand, in principle, each model is only valid for conditions close to those used to extract the model, such as bias point, load and matching conditions and mainly excitation signal. For instance, a model extracted under single-tone excitation will only be valid for narrow band signals. The PHD model as presented in [8] is for one-tone case. In this work we will exploit the two-tone case since we are interested in studying the memory effects associated with wide-band signals.

The PHD formulation states that for a given DUT there is a set of multivariate non-linear functions $F_{pm}(.)$ that relates all the input components $A_{qn}$ with the output components $B_{pm}$ , where $q$ and $p$ range from one to the number of network ports $Q$ where $m$ and $n$ range from zero up to the highest harmonic index N [8]. This is formally expressed as:

$$\mathrm{B_{pm}} = \mathrm{F_{pm}}(\mathrm{A_{11}}, \mathrm{A_{12}}, \dots, \mathrm{A_{1N}}, \dots \mathrm{A_{21}}, \mathrm{A_{22}}, \dots, \mathrm{A_{2N}}, \dots \mathrm{A_{Q1}} \dots \mathrm{A_{QN}}) \quad (1)$$

Agilent has recently introduced a commercial implementation of the PHD framework named X-parameters. The basic equation for one-tone X-model can be described as [9]:

$$B_{pm} = X^{F}_{pm}\left(\left|A_{(11)}\right|\right) + \sum_{qn,qn\neq(1,1)}^{QN} X^{S}{}_{pm,qn}\left(\left|A_{(11)}\right|\right)P^{+m-n}A_{qn} + \sum_{qn,qn\neq(1,1)}^{QN} X^{T}{}_{pm,qn}\left(\left|A_{(11)}\right|\right)P^{+m+n}\mathrm{conj}(A_{qn}) \qquad (2)$$

where: $X^{S}{}_{pm,qn}(.)$ and $X^{T}{}_{pm,qn}(.)$ are the S-type and the T-type X-parameter respectively, providing the contribution to the reflected wave at output port *p*, harmonic *m* due to the incident wave at input port *q*, harmonic *n*. $X^{F}_{pm}\left(\left|A_{(11)}\right|\right)$ is the component of the output due to the large signal input ($A_{11}$) so it is indexed only with respect to the receive port-harmonic *pm*. $A_{qn}$ is the incident wave at port *q*, harmonic *n* and $B_{pm}$ is the reflected wave at port *p*, harmonic *m*. *P* is defined as being $e^{j\varphi(A_{11})}$ where $\varphi(A_{11})$ is the phase of $A_{11}$.

$X^{F}$, $X^{S}$ and $X^{T}$ parameters can be directly extracted from a DUT by performing a convenient number of excitations and response measurements. Figure 1 shows a basic setup to extract the one-tone PHD/X-parameters model from a general DUT. The source 1 is used to inject the large signal $A_{11}$. Source 2 provides the small signal stimulus. By using broadband bi-directional couplers The LSNA/NVNA measures all relevant incident and reflected waves needed for model identification.

In order to incorporate the DC bias behavior, the PHD framework is accomplished with two additional equations that relate the DC bias voltage and current with incident waves. In this work we'll focus our attention in the DC voltage equation [8-10] which can be adapted to study the power probe RF-DC conversion characteristic [10]:

$$V_i = X_i^{V}\left(\left|A_{(11)}\right|, I_{DC}\right) + \sum_{(j,l)\neq(1,1)}^{JL} \mathrm{Re}\left(X^{Z}{}_{i,jl}\left(\left|A_{(11)}\right|, I_{DC}\right)A_{jl}\right) \qquad (3)$$

Where $X_i^{V}\left(\left|A_{(11)}\right|, I_{DC}\right)$ is the DC voltage measured at port *i* under large-signal operating conditions. This is the non-linear contribution taken when all RF ports j=2..J are matched (ideally) at all the harmonics l=1..L, a bias current $I_{DC}$ is applied to DC port i and a large signal $A_{11}$ is applied to port 1 harmonic 1. $X^{Z}{}_{i,jl}\left(\left|A_{(11)}\right|, I_{DC}\right)$ is the X-parameter providing the small signal contribution to the DC voltage at port *i* due to the small signal incident wave at port *j* harmonic *l*, $A_{jl}$. $V_i$ is the total DC voltage at port i. Both $X_i^{V}(.)$ and $X^{Z}{}_{i,jl}(.)$ are dependent on the large input signal at port 1 harmonic 1, $A_{11}$ (which can be seen as a strong signal biasing) and on the DC current biasing at port *i*, $I_{DC}$.

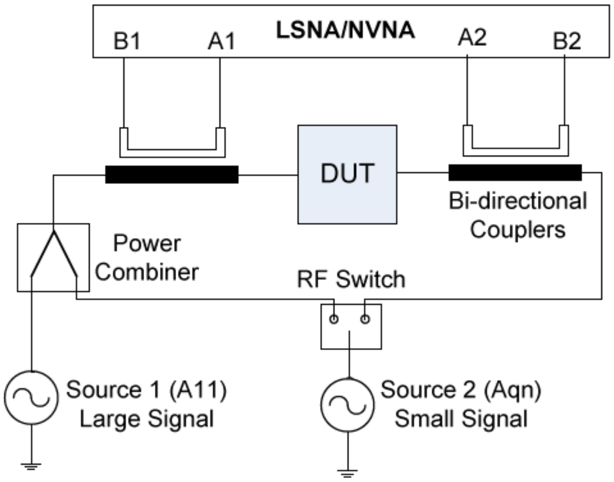

Fig. 1 PHD/X-parameters model extraction setup

Previous formulation was presented with respect to the one-tone case. However, the case that really matter in memory effects studies is the multi-tone case, so we will extrapolate the DC equation for the two-tone model:

$$V_i = X_i^{V}\left(\left|A_{(110)}\right|, \left|A_{(101)}\right|, Bw, I_{DC}\right) + \sum_{k,k\neq(1,1,0),(1,0,1)}^{JL} \mathrm{Re}\left(X^{Z}{}_{i,k}\left(\left|A_{(110)}\right|, \left|A_{(101)}\right|, Bw, I_{DC}\right)A_{k}\right) \qquad (4)$$

$A_{110}$ and $A_{101}$ are the two large signal incident waves at port 1 at $\omega_1$ and $\omega_2$ respectively. Here, the X-parameters have a dependency on the two large input tones $A_{110}$ and $A_{101}$ and on the frequency spacing between them $B_w$. *k* is the combination of port-frequency mixing term for incident waves, *k*=101 stands for port 1 (first digit), fundamental $\omega_2$ (combination of last two digits: $0.\omega_1+1.\omega_2$). Unlike the one-tone case where the small stimulus is applied only at the harmonics of the fundamental $\omega_1$, when extracting the X-model, here the stimulus must also be applied at all the mixing term frequencies of interest. Figure 2 depicts the setup to extract a two-tone X-parameters model from our diode power probe.

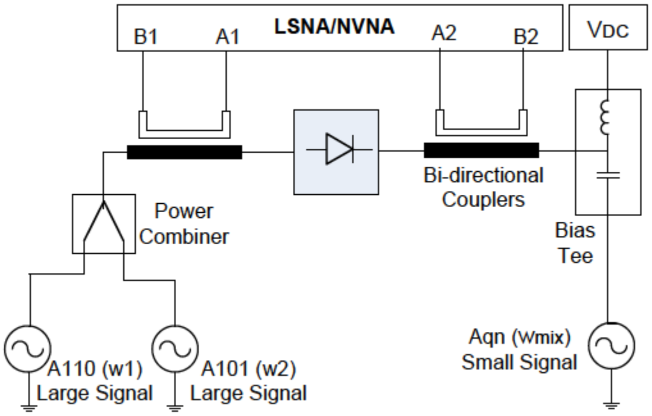

Fig. 2 Simplified setup to extract a two-tone X-model

## III. X PARAMETERS APPLIED TO DIODE POWER PROBES

To study the application of X parameters to a diode power probe, we will consider the basic circuit of Fig.3. The power probe itself is composed by an RF diode followed by a filter which is often realized by a single grounded capacitor acting as an RF feed or a quarter wavelength microstrip stub. Additionally, a matching circuit (omitted in this analyses) is used to improve the probe performance, we are assuming perfect matching at port 1 ($B_1$=0). In order to clearly mimic the effect of baseband impedance a load impedance $Z_{res}$ is inserted in the circuit. The overall probe output load impedance $Z_L$ exhibits a low-pass behavior and resonates at 1.5MHz as shown in Fig.4.

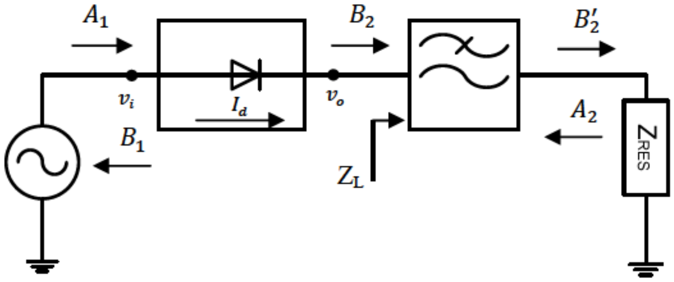

Fig. 3 Simplified power probe

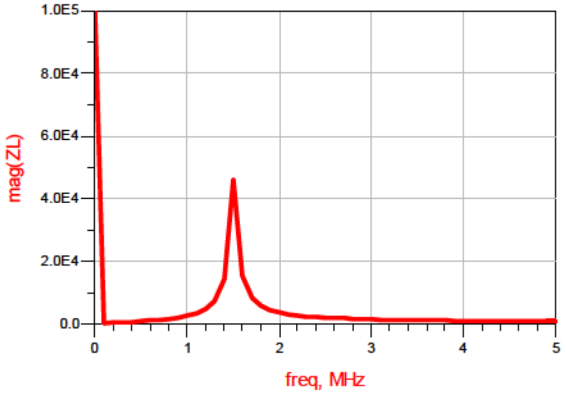

Fig. 4 Amplitude of impedance $Z_L$ (Ohm)

In order to simplify the pure mathematical analysis, we will first approximate the diode model by a polynomial series expansion around a quiescent point truncated to forth order. The current through the diode $I_d$ is thus given by:

$$I_d = I_s + k_1 v_d + k_2 v_d^2 + k_3 v_d^3 + k_4 v_d^4 \tag{5}$$

$$\text{whereby } v_d = v_o - v_i \tag{6}$$

Exciting the circuit with a two-tone signal, $A_1=\{A_{110}, A_{101}\}$ and considering the nonlinear relation (5), the reflected wave at port 2, $B_2$ will have spectral components at DC, $\omega_2-\omega_1, 2(\omega_2-\omega_1), 2\omega_1-\omega_2, \omega_1, \omega_2, 2\omega_2-\omega_1, 2\omega_1, \ldots$ :

$$B_2 = \{B_{2m11}, B_{2m22}, B_{22m1}, B_{210}, B_{201}, B_{2m12}, B_{220}, \ldots\} \tag{7}$$

Assuming that $Z_L \approx 0$ for RF frequencies (low-pass filter behavior), then $B_2'$ and $A_2$ will be:

$$B_2' = \{B_{2m11}, B_{2m22}\} \tag{8}$$

$$A_2 = \{\Gamma_{2m11} B_{2m11}, \Gamma_{2m22} B_{2m22}\} \tag{9}$$

Where $\Gamma_{2m11}$ and $\Gamma_{2m22}$ are the reflection coefficients at $Z_{res}$ seen by the components of $B_2'$ at $\omega_2-\omega_1$ and $2(\omega_2-\omega_1)$ respectively. The reflected low-frequency signal $A_2$ will affect the DC signal and is responsible for the long term memory effect in diode-probe excited with wideband signals. Furthermore, the DC value at port 2 will depend on the bandwidth of the input signal.

At this point we are able to exploit equation (4) on the prediction of the DC component appearing at port 2:

$$\begin{aligned} &V_2 = \\ &X_2^V(|A_{(110)}|, |A_{(101)}|, Bw, I_{DC}) + \\ &\mathrm{Re}(X^Z{}_{2,2m11}(|A_{(110)}|, |A_{(101)}|, Bw, I_{DC})\Gamma_{2m11} B_{2m11} + \\ &X^Z{}_{2,2m22}(|A_{(110)}|, |A_{(101)}|, Bw, I_{DC})\Gamma_{2m22} B_{2m22}) \end{aligned} \tag{10}$$

$X_2^V(.)$, $X^Z{}_{2,2m11}(.)$ and $X^Z{}_{2,2m22}(.)$ are the X-parameters which can be experimentally extracted from the real circuit as explained in section II, $\Gamma_{2m11}$ and $\Gamma_{2m22}$ can be directly measured and $B_{2m11}$ and $B_{2m22}$ result also from measurements.

## IV. EXTRACTING X-PARAMETERS MODEL FROM SIMULATIONS AND MEASUREMENTS

X-parameter models can be extracted both from circuit-level simulations using a harmonic balance-based simulator, and from real circuits (using directly an NVNA or using incident and reflected waves measured with an LSNA). The extracted X-model can be further used in circuit simulation tools. As stated before, X-models potentially speed up simulation and designs and are IP-protected. In this section we extract the X-model of a power probe from its circuit-level design (Fig.5).

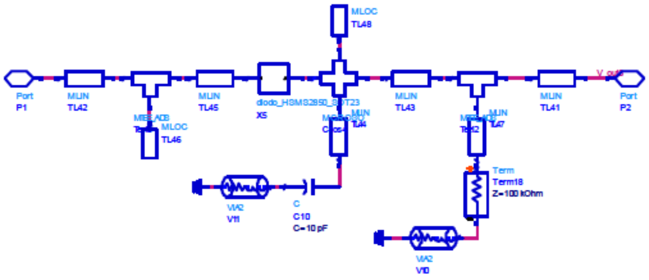

Fig. 5 - Power probe simulated circuit.

The DUT shown in Fig.5 was inserted in a simulation setup similar to the one presented in Fig.2 in order to extract a two-tone X-model as formulated by equation 10. The extracted model is valid for an input power ranging from -30dBm to -0dBm and frequency spacing between the carriers ranging from 300kHz to 4.8MHz.

To validate our model and to prove that it will be able to accommodate memory effects on diode probes we performed a simulation with a circuit similar to Fig.3 where we inserted a low-frequency resonance to mimic the memory effects. Considering the model (10) and the measured incident and reflected traveling waves A's and B's, we computed the X-modeled DC voltage at the probe output. This is depicted in Fig.6 by the crosses red curves. The solid blue curves are the DC voltage obtained directly with HB simulator. As can be seen there is a good degree of agreement between extracted X-model and original circuit-level model. Actually it is also seen that the X parameter model represents well the change of DC values with frequency separation, visible near 1.5MHz.

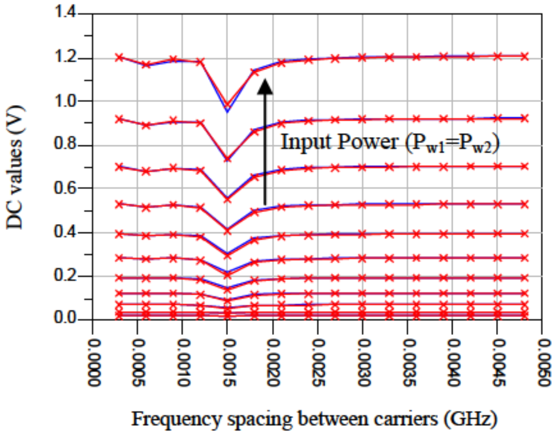

Fig. 6 DC voltage (V) at the probe output as computed by X-model (red crosses) and by ADS HB simulation (solid blue)

We then use a Large Signal Network Analyzer, LSNA, and a setup similar to Fig.2 in order to evaluate the DC value of the power probe, and the result is presented in Fig. 7.

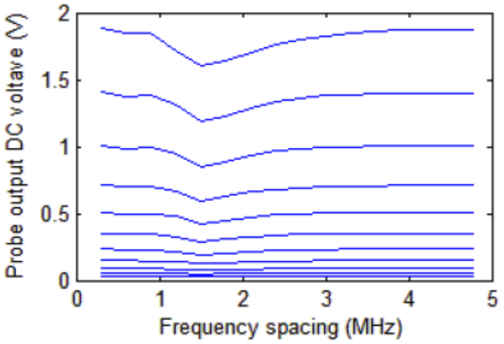

Fig. 7 Measured DC voltage (V) at the probe output.

From Fig.7 it is clear that the measured data actually present the same behavior as the simulated ones, representing well the DC dependency with the bandwidth changes. Nevertheless, some difference is also visible in the absolute value of the DC output, that can be attributed to a discordance between the chip and package diode model used in the simulations and real diode behavior. It should also be noticed that the real measurement setup is more complex than the one used in simulation, for instance, some components like the bias-tees or the bidirectional couplers are not considered in simulations since all the relevant values can be taken directly from simulation probes.

## V. CONCLUSIONS

In this paper we presented the application of X parameters to diode power probes modeling. It was shown that X parameters represent well RF to DC conversion, and that it is possible to use X parameters to characterize power probes, even when in presence of memory effects.

It is expected that this model can be used for calibration proposes in the future.

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## REFERENCES

[1] M. Kanda and L.D. Driver, "An isotropic electric-field probe with tapered resistive dipoles for broad-band use, 100 kHz to 18 GHz", IEEE Trans. Microwave Theory Tech., vol. 35, no. 2, pp 124- 130, Feb 1987.

[2] M. Kanda, "Standard probes for electromagnetic field measurements", IEEE Trans. Antennas Prop., vol. 41, no. 10, pp. 1349-1364, Oct 1993.

[3] J.M. Ladbury and D.G. Camell, "Electrically short dipoles with a nonlinear load, a revisited analysis", IEEE Trans. Electromagnetic Compatibility, vol. 44, no. 1, pp. 38-44, Feb 2002.

[4] Hugo Gomes, Alejandro R. Testera, Nuno Borges Carvalho, Mónica F. Barciela and Kate A. Remley, "The Impact of Long-term Memory Effects on Diode Power Probes", International Microwave Symposium, May, 2010, Anaheim, CA, USA.

[5] David Adamson, Daniel Bownds, Alva Fernández, Edward Goodall, David Humphreys, "The response of electric field probes to realistic RF environments", International Microwave Symposium, May, 2010, Anaheim, CA, USA.

[6] Agilent Application Note "Memory Effects in Microwave Components - X-Parameters to Characterize and Model Long-Term Memory Effects of Wideband Modulated Signals", May 2010

[7] Jan Verspecht, "Black Box Modelling of Power Transistors in the Frequency Domain"

[8] Jan Verspecht and David E. Root, "Polyharmonic Distortion Modeling", IEEE microwave magazine, June 2006

[9] X-Parameter Measurements, http://na.tm.agilent.com/pna/nvna/NVNAWebHelp/XParameter_Measurements.htm#config

[10] X-parameters equations, http://edocs.soco.agilent.com/display/ads2009U1/XnP+Components+%28X1P+-+X10P%29