Time-Frequency Characterization of Long-Term Memory in Nonlinear Power Amplifiers

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***Abstract* — This paper presents a new time-frequency characterization method for extracting the linear and third-order nonlinear parameters of a PA including long term memory. A dynamic frequency two-tone test signal is developed where the frequency separation between tones increases over time to enable third-order measurements over frequency from a single measurement. A measurement technique is presented using a single Vector Signal Analyzer (VSA) measurement to coherently capture both the test signal and the DUT output sequentially by switching between the two paths during the measurement. The linear and third-order characteristics of a nonlinear PA are estimated from measuring a sequence of dynamic two-tone signals which vary the relative phase of the input tones. Measurement results for the linear response are in good agreement with vector network analyzer (VNA) measurements. Third-order amplitude and phase characteristics are presented over a tone spacing of 1 kHz to 1 MHz centered at 2 GHz for three different power levels.**

***Index Terms* — Circuit modeling, intermodulation distortion, microwave measurements, time domain measurements, time-frequency analysis.**

I. Introduction

Measurements to identify and quantify memory effects in nonlinear power amplifiers are important for the optimization of linear power amplifier performance and to improve development of nonlinear behavioral models. Accurate measurements of third-order amplitude and phase response to modulated signals are necessary to determine the origin and nature of nonlinearity exhibiting long term memory. It was shown in [1] that the third-order response of a PA presenting memory can be characterized by performing a sequence of simple two-tone measurements where the tone spacing is stepped for each measurement. This characterization approach was based on the assumption that the fundamental frequency filtering and the second harmonic filtering components within the PA are constant over the tone spacing. In that case, the baseband contribution to the long term memory effects can be identified as the $F_2(\omega_2,-\omega_1)$ term in the intermodulation (IM) component of the PA output below:

$$Y(2\omega_2-\omega_1)=\left[K-2F_2(\omega_2,-\omega_1)\right]3X(\omega_2)X(\omega_2)X(-\omega_1)\,. \quad (1)$$

The procedure in [2] was used with a microwave transition analyzer (MTA) to characterize the amplitude and the phase of upper and lower IM components. MTA's synchronous two channel sampling capability enables simultaneous capture of a DUT's input and output. But due to the sub sampling nature of the RF frontend in MTA, the dynamic range is degraded by all the down-converted noise. Thus, the amount of repetitive measurements required makes the process complex and time consuming.

A new method is presented here to simplify and speed up the characterization process. It combines a single channel Vector Signal Analyzer (VSA) with a dynamic frequency two-tone signal to enable nonlinear characterization over frequency in a single measurement. Measurement dynamic range is improved due to the tuned narrowband frontend in the VSA. A dynamic time-frequency two-tone waveform is designed in conjunction with post processing to avoid spectral leakage. A simple hot switching technique circumvents the triggering uncertainty problem, which arises from sequentially capturing a DUT's input and output in a single channel measurement system. Linear and third-order characterization results for a 2 GHz solid state PA are presented over a tone-spacing of 1 kHz to 1 MHz.

II. Test System Configuration

A. Waveform Design

To simplify the sequence of two-tone measurements in PA characterization [2-3], waveform segments of varying tone spacing are concatenated together in an arbitrary waveform generator (AWG) and up-converted. The test signal is thus a frequency modulated two-tone signal with the tone spacing changing over time. It can be described mathematically as

$$x(t)=A\cos\left[2\pi\left(f_c-\frac{\delta(t)}{2}\right)t\right]+A\cos\left[2\pi\left(f_c+\frac{\delta(t)}{2}\right)t\right]. \quad (2)$$

where the function $\delta(t)$ determines the tone-spacing over time. Discrete frequency separation over time is defined by

$$\delta(t)=\sum_{k=0}^{N}\rho_k rect\left(t-t_k\right). \quad (3)$$

So for the duration of each t_k segment, the instantaneous spectrum can be considered a two-tone excitation.

The baseband interpretation of this modulation is that the two single sideband tones are moving away from each other over time. The two-tones and the IM products can then be measured and characterized over a wide range of tone spacing with one measurement using the VSA. Fig. 1 shows the composite envelope spectrum of the test signal segments. The two dimensional spectrum is calculated from the short time

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frequency transform. This type of time-frequency signal representation is present in Fig. 2 as a spectrogram plot.

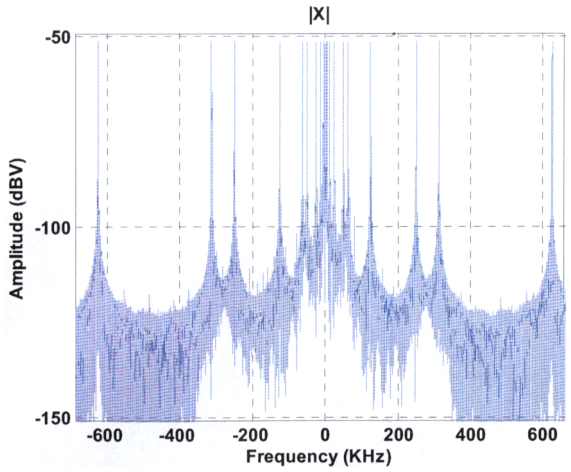


Fig. 1: Composite spectrum of dynamic time-frequency two-tone signal.

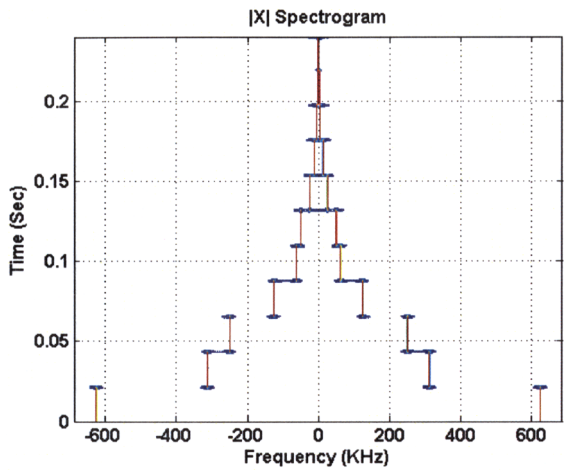
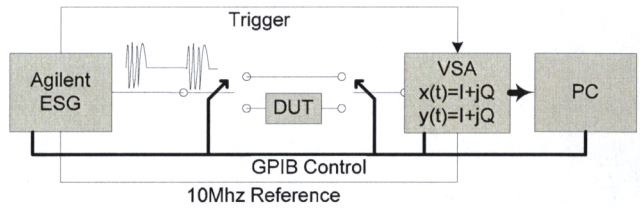


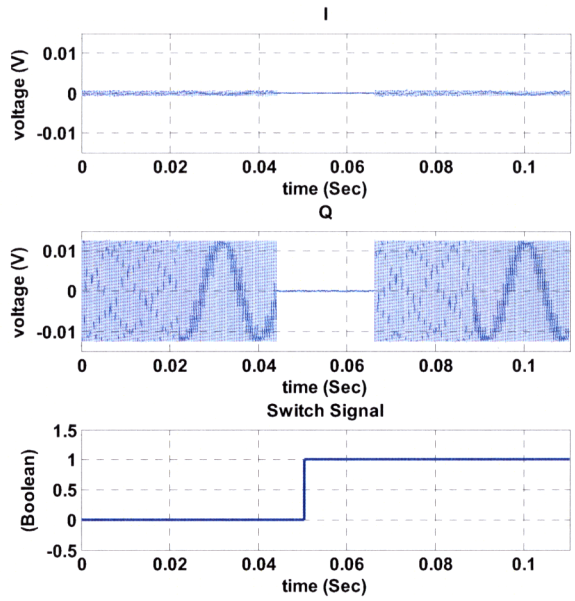
Fig. 2: Spectrogram of dynamic time-frequency two-tone signal.

B. VSA Measurement

Determination of the third-order characteristic K – $F_2(\omega_2,-\omega_1)$ from (1) requires coherent measurement of both the input signals $X(\omega_1)$ and $X(\omega_2)$ and the output response. A single channel VSA cannot simultaneously measure the input and output waveforms. Separate input output measurements suffer from significant triggering uncertainty [4] imposed on subsequent measurements. Alternatively, a switch is used to sequentially measure the input and output signals during one VSA measurement thereby providing coherent sampling of both signals. The test signal is constructed as one continuous waveform sequence, and the triggering is done only once at the start of the test signal. The dynamic time-frequency two-tone test waveform is repeated twice during the sequence with blank interval inserted between the two to allow settling time for the RF switch and to minimize RF power during the switching event as shown in Fig. 3.b. Now the sampler time base in the ADC module coherently relates the phase between recorded input and output. The test setup and waveforms are shown in Fig. 3.



(a)



(b)

Fig. 3: a) Test setup and b) test signal sequence.

Signal to noise ratio (SNR) of the recorded signal needs to be taken into consideration when determining the actual duration for each tone spacing segment. For equal number of two-tone cycles, the segment duration is smaller for higher tone spacing. Thus, the bigger DFT frequency bin collects more noise and SNR degrades for higher tone spacing. Uniform time duration for each tone spacing is chosen as a result.

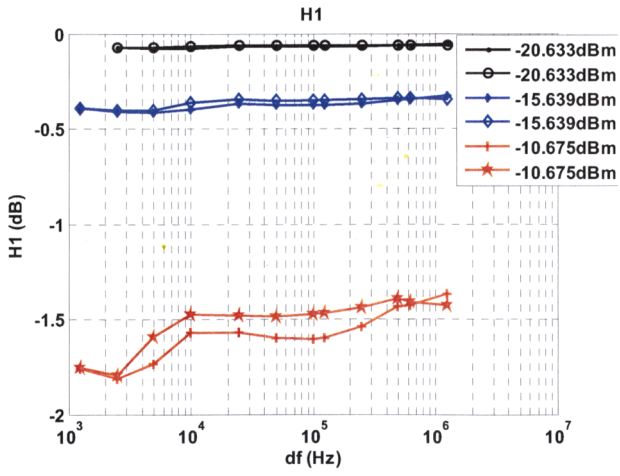
The recorded signal is analyzed by dividing the time domain envelope waveform into individual tone spacing segments. Then the amplitude and phase of the upper and lower IM component is extracted from the FFT result for each segment. The number of captured IQ data points chosen for

the FFT must maintain periodicity in order to avoid spectral leakage. It needs to be an integer multiple of the number of IQ data points captured during a two-tone cycle. The lowest tone spacing achievable is limited by the memory depth of the AWG. For 8 Msa of memory and sampling rate of 1.25 Gsa/S, 1 kHz tone spacing is possible.

III. Characterization Verification and DUT Measurements

To verify the measurement setup and extraction technique, a test was conducted with a digitally generated nonlinearity applied to the input signal. The verification waveform sequence contained the input signal followed by the blank switching period and the digitally distorted waveform. To estimate the digitally imposed a_3 coefficient, the response needs to be normalized by the amplitude of the input waveform, as if relating a_3 and IM3. After 50 averages for dynamic tone spacing from 1 kHz to 1 MHz, the error in estimating the amplitude and phase of a_3 is 5% for magnitude and 5 degrees for phase.

The method presented in [1] was applied to a 2 GHz medium power amplifier to determine the values of the linear and third-order response with memory at different input power levels. The results are shown below in Fig. 4 – 5. Note the increased gain compression in the linear characteristic and the growing contribution of the third-order response as input power increases. At narrow tone spacing below 10 KHz, the phase asymmetry in third-order characteristic converges to what a typical AM-AM and AM-PM measurement of quasi-static response would yield. The linear response results, shown in Fig. 4, clearly indicate gain compression and approximately 6 degrees of AM-PM change. The third-order results in Fig. 5 show the magnitude response changing significantly at 1.5 dB of gain compression while the phase response rotates about 5 degrees and the separation in phase appears to increase versus increasing tone-spacing.



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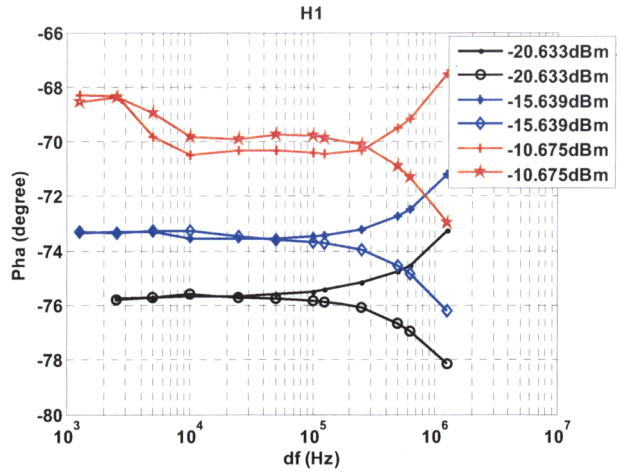
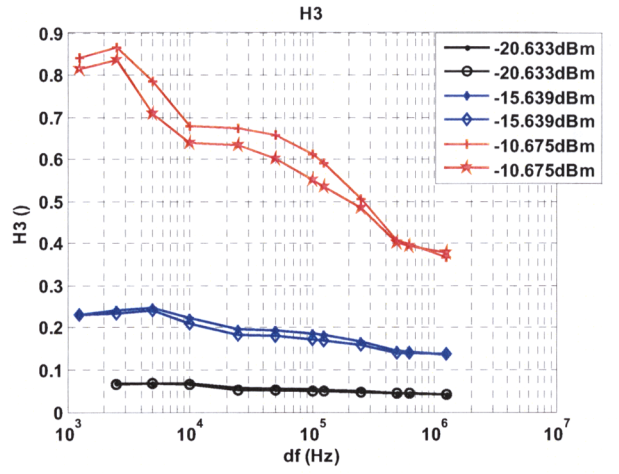


(b)

Fig. 4: Estimated linear a) magnitude and b) phase characteristic.



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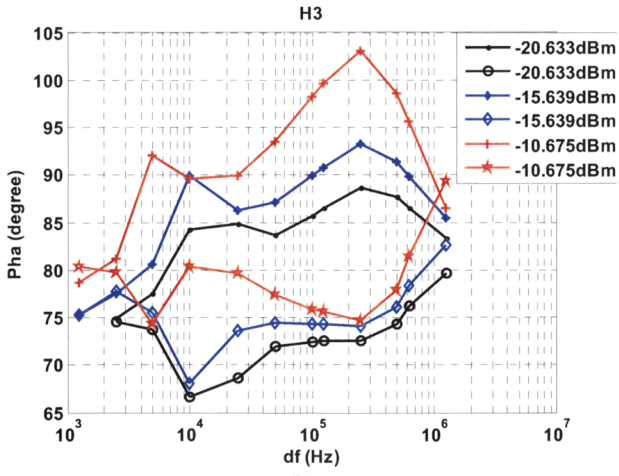

(b)

Fig. 5: Estimated third-order a) magnitude and b) phase characteristic.

The above linear results were compared to the S21 measurement at small input power from the VNA. Fig. 6 shows that the result from the new measurement method is in good agreement for gain and absolute phase. Note the output of the PA is attenuated to maximize measurement SNR while maintaining the same VSA settings for both the input/output signals.

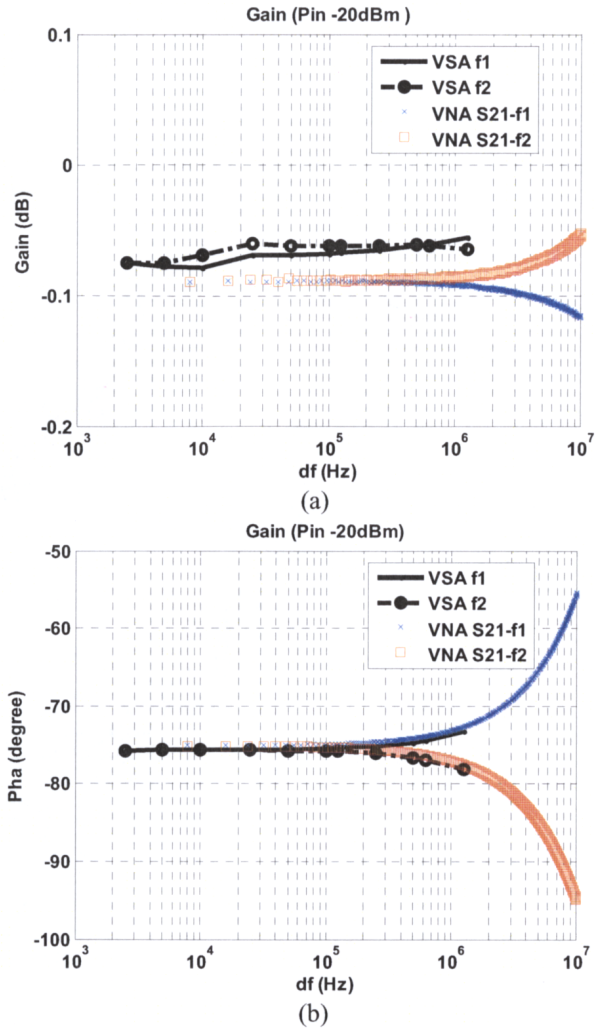

Fig. 6: Comparison of estimated linear characteristic with S21 in a) magnitude and b) phase.

V. Conclusions

A new characterization method for PA memory evaluation was presented. The presented technique utilizes a VSA measurement with a dynamic frequency two-tone signal to enable nonlinear characterization over frequency in a single measurement. Previous capabilities achieved using a Microwave Transition Analyzer is expanded, and the process is simplified. This method was applied to a medium power amplifier to extract the linear and third-order characteristic over a range of tone separations.

VI. Acknowledgement

This material is based upon work supported by the U.S. Army Research laboratory and the U.S. Army Research Office as a Multi-disciplinary University Research Initiative on Standoff Inverse Analysis and Manipulation of Electronic Systems under grant number W911HV-05-1-0337.

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