Augmented Behavioral Characterization for Modeling the Nonlinear Response of Power Amplifiers

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ABSTRACT — **It is shown a simple extension of the conventional behavioral characterization of amplifier nonlinearity can be used to quantify power amplifier performance including many memory effects. External variables that influence the amplifier behavior (such as power supply voltage, input bias or temperature) are identified. Measurements of gain and phase (AM-AM and AM-PM conversion) are subsequently made over a range of these external variables. The variation of the external variables is explicitly taken into account with linear equivalent circuits at baseband. The method is shown to be useful for the estimation of bias circuit effects and self-heating effects.**

I. INTRODUCTION

A topic of considerable research interest is the analysis of nonlinear behavior of power amplifiers using theoretical frameworks which extend the well-known behavioral model for narrow-band systems with memoryless nonlinearities [1-6]. This paper discusses a new framework for this analysis, in which memory effects associated with one or more physically-identified dynamic variables that influence the amplifier gain and phase are taken into account explicitly, by making use of measurements of amplifier response in single tone tests.

In this paper, the principles of the technique are first outlined. Subsequently the method is applied to calculate the intermodulation behavior of amplifiers in which the baseband frequency response of bias circuits is important [7], and of amplifiers in which self-heating effects are important [8]. The dependence of the intermodulation on spacing between tones is calculated. Application to power amplifiers in which the power supply voltage is intentionally varied in accordance with the output signal ("envelope tracking" or "dynamic supply voltage" amplifier [9]) is also described.

II. MODELLING APPROACH

In the conventional Behavioral Model (BM), the characteristics of an amplifier are specified completely by its behavior with single tone inputs, including gain vs input power, *G(Pin)* (associated with AM-AM conversion), and output phase vs input power, *Φ(Pin)* (associated with AM-PM conversion). An underlying assumption is that the amplifier gain and phase depend only on the instantaneous value of the input power.

In the Augmented Behavioral Characterization model (ABC model), the amplifier is characterized by its gain and phase response, which depend on the instantaneous input power as well as on an additional time-varying parameter, denoted *Z(t)*. For example, *Z(t)* can correspond to the instantaneous temperature of the amplifier, or the instantaneous power supply voltage. Explicit measurements or simulations can be used to determine the relationship between the gain and the additional parameter *Z*, as well as between the output phase and *Z*. Subsequently, the relationship between *Z(t)* and the instantaneous input RF power of the amplifier is measured or calculated. This relationship is approximated by a linear, time-invariant response, characterized by a finite number of poles (which correspond to the memory of the system). The output with arbitrary (band-limited) input signals with complex envelope $x(t)=a(t)\exp(j\phi(t))$ may then be computed by

1) computing the response *Z(t)* from *a(t)*;
2) computing *G(a(t), Z(t))* and *Φ(a(t), Z(t))*; and
3) determining $y(t)= G(t)x(t) \exp(j\Phi(t))$, the envelope of the output.

Output power spectral density may be computed with an appropriate Fourier Transform of this response. The computational algorithm is illustrated in Fig. 1.

The technique may be used to compute the intermodulation response of amplifiers with two-tone inputs. While in the conventional BM, the

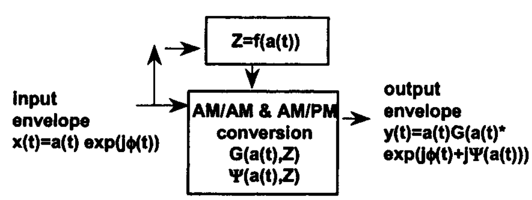

Fig. 1 Augmented Behavioral Model

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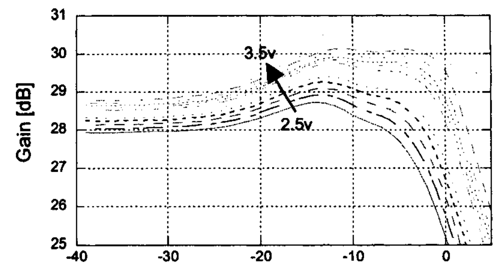
intermodulation response is independent of the frequency spacing between tones, in the present technique a dependence on frequency spacing can be determined through the time response of $Z(t)$. Differences between the amplitude of upper and lower sidebands are in general observed. As with the conventional behavioral model, the response to signals with arbitrary narrowband modulation may be also readily calculated.

III. APPLICATION TO BIAS CIRCUIT EFFECTS

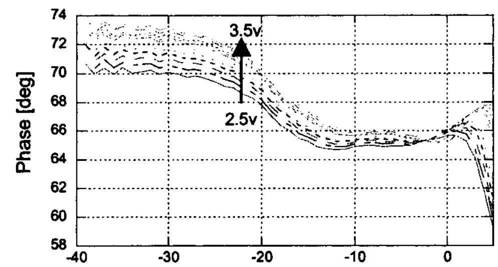
As an example of the method application, the nonlinear response of a commercial two-stage CDMA amplifier operating at 836.5MHz in two-tone tests with various bias circuits was analyzed. Previous works has shown that bias circuit terminations at baseband influence RF nonlinearities [7]. The behavior of gain and phase vs input power were measured (in one tone tests) for a variety of power supply voltage values, Vcc. Fig.2 (a) shows the variation of gain vs input power as Vcc is varied. Regions of gain expansion and of gain compression can be seen; the gain and saturated output power are both relatively strong functions of Vcc. The corresponding behavior of phase vs input power and Vcc are shown in Fig.2 (b). This behavior was represented as a 2-dimensional table in Matlab. The variation of Icc, the current drawn from the power supply, was also measured as a function of input power, as shown in Fig. 3. The substantial rise of current with increasing input power is expected for Class AB operation.

With these inputs, the variation of Vcc with time imposed by the external bias circuit could be accurately modeled. A simple external bias circuit consisting of an L, C combination as shown in Fig. 4 was used. It was intentionally varied in order to study the bias circuit influence on amplifier nonlinearity. Gain and third-order intermodulation in two-tone tests were measured with the 1uF capacitor present or absent. Results of IM3 are shown in Fig.5 (b).

The ABC model was used to theoretically calculate the results of the two tone tests, for comparison with the experiment. Using an input envelope waveform $x(t)=2\cos(\delta\omega t)$ (where $\delta\omega$ is the frequency spacing between input tones), the value of Ic(t) was calculated based on the measurements of Fig.3. The corresponding variation of Vcc(t) was calculated from the linear equivalent circuit of Fig. 4 (adding a linear resistor to correspond to the amplifier input current variation with voltage). Subsequently the results of Fig. 2 were used to compute the variation of gain and phase with time. Finally, the output envelope was determined and FFTs were computed to determine the fundamental output power and distortion products. Fig. 5(a) shows the computed output for the cases where the bias capacitor is present and where



(a)



(b)

Fig.2: Measured variation of (a) gain and (b) phase with input power, with Vcc as a parameter, for commercial PA

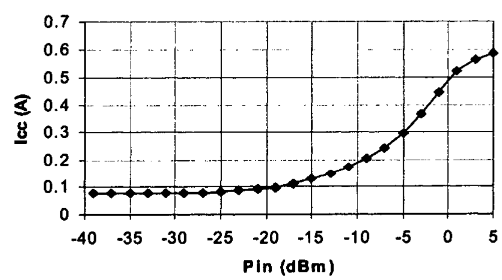


Fig. 3 The variation of Icc with Pin

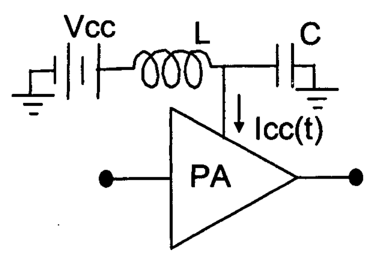


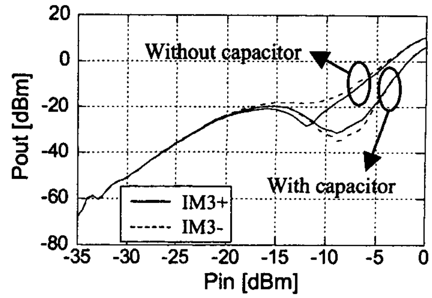
Fig.4: Schematic diagram showing bias circuit

it is removed. Good agreement is found over most of the range. The computations and experiment show that the IM3 is a function of tone spacing, and that in general IM3+ (at $2f_2$-f_1) has different amplitude than IM3- (at $2f_1$-f_2). The full depth of the "notch" in IM3 is not calculated properly. It is likely that the representation of the equivalent bias circuit in this complex 2 stage amplifier is not fully accurate.

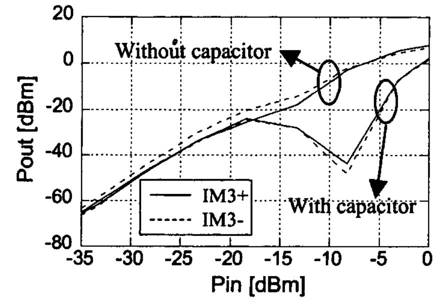
The results of Fig. 2 and 3 can also be used to analyze the nonlinear response of dynamic supply voltage or envelope tracking amplifier operation [9]. In this approach, the power supply voltage is intentionally adjusted according to the input power via a fast dc-dc converter, in order to maximize amplifier efficiency. It has been shown that if gain or phase response of the amplifier change significantly with bias voltage Vcc, then the DSV technique introduces distortion. Using the ABC model outlined above, the distortion thus introduced can be estimated, and appropriate signal predistortion can be applied to minimize its effects. Kobayashi has also shown that if Vcc is varied by using a high efficiency switching DC-DC converter, then converter output noise at the switching frequency (ripple) can corrupt the amplifier output. It is also possible to calculate the output distortion using the ABC model, and apply suitable input predistortion signals to minimize its effects.

III. APPLICATION TO SELF-HEATING EFFECTS

Self-heating of power amplifiers is widely recognized to influence the distortion behavior of amplifiers, leading to intermodulation products in two-tone tests that are a function of tone spacing [8]. The ABC model can be applied to nonlinearities arising from self-heating effects, taking explicit account of the thermal time constants of the power transistors. As an example, the self-heating influence on the two-tone intermodulation behavior of a simple HBT amplifier, operated in Class A, was analyzed and compared with experiment. Fig. 6 shows on-wafer measurements of gain and phase vs output power for a GaInP/GaAs HBT, at several temperatures. The data demonstrate that although the gain and phase vary only gradually with output power, as expected for a Class A system, there is a significant temperature dependence to the results. The power dissipated in the transistor was also measured as a function of input power (by monitoring the power-added efficiency). In order to compute the thermal effects on distortion, an equivalent thermal circuit was used, as shown in Fig. 7 (with a single thermal time constant); values of Rth and Cth were chosen to correspond to the device geometry. The intermodulation results in two-tone tests were computed by (1) calculating the transistor power dissipation as the input envelope varied; (2) computing the temperature response of the



(a) Predicted Results



(b) Experimental Results
Fig. 5: Predicted and Measured IM3 with and without the bias circuit capacitor

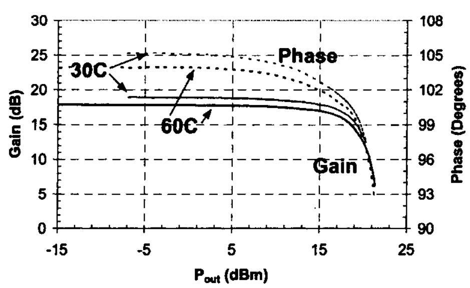


Fig.6: Measured variation of gain and phase with output power at several temperatures

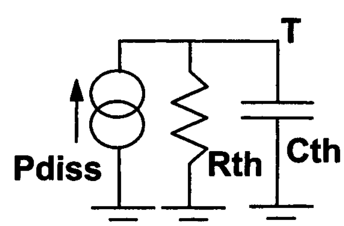


Fig. 7: The equivalent thermal circuit

transistor based on the linear equivalent circuit model; then (3) determining the overall gain and phase variation in time, based on the temperature dependent gain. Fig. 8 shows representative computed temperature variation for different tone spacings (with period larger than and smaller than the thermal time constant). The computed IM3 results at a representative output power of 0 dBm, for tone spacings of 0.1MHz, and 10MHz are shown in Table 1. Also shown are experimental results for these two tone spacings. The predicted intermodulation results are of the right order of magnitude (although there is error related to the accuracy of measuring gain flatness in this highly linear amplifier). More importantly, both theory and experiment show a variation of IM3 with tone spacing, in a rather unexpected sense. For small tone spacings, the self-heating effect is largest. However, the lower frequency IM3 values are smaller than the results for higher frequency. We interpret the result to correspond to the fact that the sign of the self-heating effect is that of a gain expansion because in the Class A amplifier, as the power output increases, the temperature decreases, leading to a gain increase. This gain expansion compensates for some gain compression, which is the dominant device-related nonlinearity.

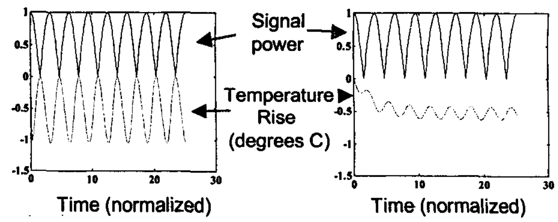


Fig. 8: The computed temperature for (a) 0.1MHz and (b) 10MHz

Table 1: Computed and Measured IM3 at 0dBm output

Tone Space	Computed Results	Experimental Results
0.1MHz	-73dBm	-72dBm
10MHz	-65dBm	-70dBm

IV. LIMITATIONS AND EXTENSIONS OF THE TECHNIQUE

The framework presented here is limited to only narrowband signals, although it is possible that extensions to broader frequency ranges may be possible following procedures currently under investigation [3,5,6]. It is also not well suited to account for the effects on distortion of terminations at harmonic frequencies [5]. It is naturally applicable in systems in which one or more external dynamic variable affecting gain can be identified. In addition to analysis of intermodulation in amplifiers, the technique may be worthwhile to predict the upconversion of noise in oscillators and amplifiers.

V. CONCLUSION

A model is described which offers a simple way to quantitatively predict memory effects influencing amplifier nonlinearity, based on straightforward measurements. The model is capable of accounting for strong amplifier nonlinearities such as saturation effects (while, by contrast, Volterra series are more naturally applicable to weak nonlinearities). The model only considers contributions to memory effects associated with low frequency response (rather than harmonic effects or narrow-band resonances). It benefits, however, from the fact that the physical effects responsible for the system memory are explicitly identified and measured. The ABC model can be expected to contribute to improved understanding and mitigation of power amplifier nonlinear behavior.

ACKNOWLEDGEMENT

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