Capturing Asymmetry in Distortion of an RF System Using a Multislice Behavioral Model

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Abstract—**Baseband effects result in asymmetrical distortion of RF communication signals through the interaction of baseband-related distortion with in-channel distortion. Here, a behavioral model architecture that captures these asymmetries and can be implemented in a variety of circuit and system simulators is presented. The architecture has two or more slices with each slice corresponding to different frequency bands or multiple parallel nonlinear processes. Each slice could comprise any conventional narrow-band functional model. Here, the behavioral model is extracted using AM–AM and AM–PM measurements for the first slice and phase and amplitude measurement of intermodulation components for the second slice.**

Index Terms—**Asymmetrical distortion, baseband-related distortion, narrow-band functional model.**

I. INTRODUCTION

THE successful development of RF systems relies on the ability of behavioral models to accurately predict system performance. Measurement-based behavioral models have been used to capture this complex behavior with multiple model architectures and techniques [1]–[3]. The measurements typically used include single-tone AM–AM and AM–PM measurements, and two-tone tests. While the former pair captures both the amplitude and phase of the nonlinear response of the fundamental, the latter is typically used to measure the amplitude only of the spectral products in the distorted response.

Without the phase of the system response captured, a model cannot track the behavior arising from the multiple nonlinear processes within a device as these add vectorially to produce the total output. This also impacts the evaluation magnitude-based metrics such as adjacent channel power ratio (ACPR). Several authors have addressed the need to capture the phase of the intermodulation (IM) products to properly account for observed nonlinear effects [4] and [5]. Such measurements however are quite difficult.

Measuring the phase of the additional frequency content produced by a nonlinear system under discrete-tone stimulation arises from the lack of a reference signal at the system input. Several measurement techniques have been developed to address this problem with varying degrees of success and capability. A review of these techniques can be found in [6]. Also in [6], we developed a simple relative phase measurement method for capturing the phase of IM products resulting from discrete-tone stimulus. In the following, we present the incorporation of this phase information into a multislice behavioral model of a high-power amplifier and show how this model captures distortion asymmetries.

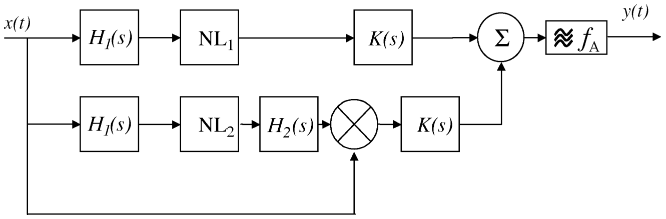

Fig. 1. Multislice model with first slice composed of single-tone fit and second slice capturing even-order baseband contributions to IM products.

II. MULTISLICE MODEL

In [7], the authors presented a multislice behavioral model architecture. The model has real linear and nonlinear networks and so can be used in many simulators including transient, harmonic balance, transient envelope or system-level. The multislice model employs multiple parallel branches of Wiener–Hammerstein structures to account for the multiple nonlinear processes present within a circuit. A two-slice version is shown in Fig. 1. The Wiener–Hammerstein structures comprise memoryless nonlinearities between ideal linear networks. In the architecture of Fig. 1, the first slice represents the traditional approach in which for example, an odd-order polynomial fit to single-tone AM–AM, AM–PM measurements could be used as in this letter. Higher-order branches in the model make use of an ideal multiplier that allows the model to capture nonlinear operation involving a series of nonlinear effects at different frequencies. The second slice, for example, captures baseband effects and the mixer in effect translates baseband effects resulting from even-order distortion, to the RF frequency by mixing the baseband products with the input signal. It is this mixing operation that can result in asymmetrical phase contributions to RF distortion.

The translation in frequency of even-ordered nonlinear products from baseband frequencies to that of the distortion frequencies of odd-ordered nonlinear effects results in the interesting phenomenon of IM asymmetry. It is simple to show that the IM products resulting from strictly odd-ordered mixing of the stimulus tones or from even-order harmonic production mixing with the stimulus always produce symmetrical (in both amplitude and phase) IM product contributions. In this letter, we consider operation and measurements with a two-tone stimulus at ω_1 and ω_2. (We have previously shown that models derived

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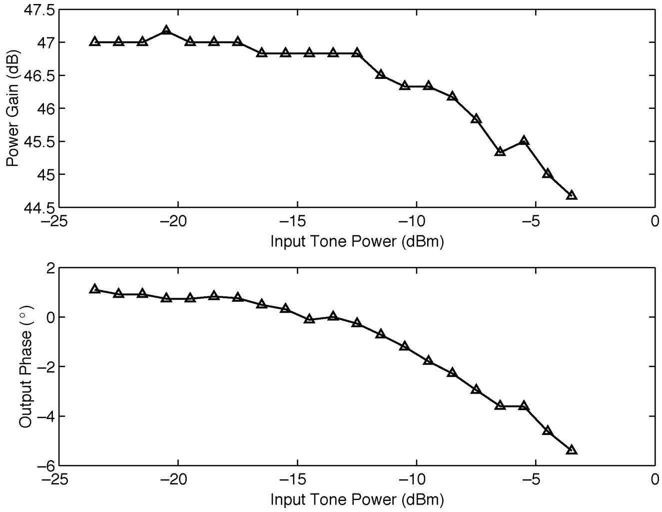

Fig. 2. Measured complex gain of amplifier under single-tone stimulus.

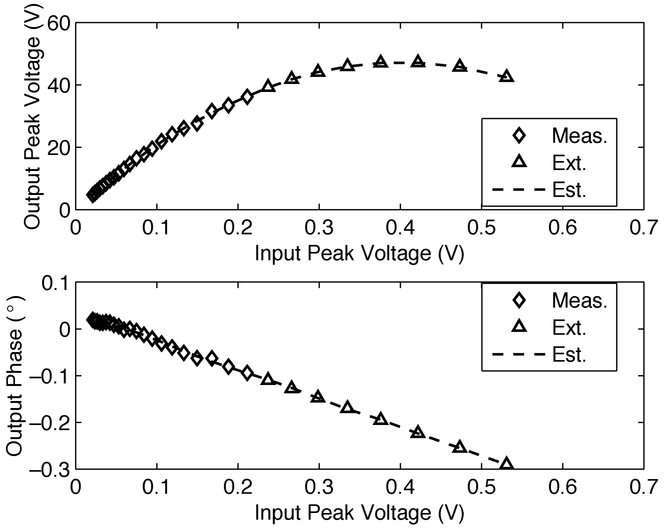

Fig. 3. Odd-ordered polynomial fit with complex coefficients for extrapolated AM–AM, AM–PM measurements.

from two-tone characterization can be used to represent the response to digitally-modulated signals [2] and [3].) Therefore, the symmetrical contributions result in both the upper and lower products (e.g., the third-order (IM3) products at $2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$) having the same phase and amplitude. Baseband translation to the spectrum around the stimulus signals however, produces vectors that add in a complex conjugate sense to the appropriate upper and lower IM products, thus generating IM products that are either asymmetric in amplitude, phase, or both.

III. MEASUREMENTS AND MODELING RESULTS

Using single-tone measurements, the measurement technique described in [6], and the multislice development in [7] the unilateral nonlinear transfer function for the IM3 products of a high-power amplifier was developed. Input power of the single-tone and the two-tone stimuli were swept over identical levels using a single apparatus, thus the peak power for the two-tone data was 6 dB higher for the same power setting between the single and two-tone measurements. A 5-W mini-circuits amplifier, (ZHL-5W-1) was used with the one-tone characteristics shown in Fig. 2. Under two-tone stimulus with a separation frequency of 10 kHz, ($f_1 = 450$ MHz), this amplifier did not exhibit amplitude asymmetry in the IM3 products. The phase of these terms, however, did exhibit asymmetry above an input power of −14 dBm. For our purposes here, only a single frequency separation and set of tone frequencies were used to collect the data.

A. First Slice Extraction

Using the single-tone AM–AM, AM–PM measurements, an odd-ordered polynomial with complex coefficients was extracted. To account for the higher input range of the two-tone data, the single-tone data was extended by extrapolating the measured complex voltage gain. The complex polynomial fit to the measured and extrapolated AM–AM, AM–PM is shown in Fig. 3. The output of the first slice under two-tone stimulus showed that this portion of the model tracked the IM3 amplitude well (<0.5-dB error) over much of the power range, with an underestimate (<3 dB) of the amplitude at the upper end of the input power range. The predicted phase of the response also tracked the general trend of the upper and lower IM3 products, but as expected could not track the asymmetric phase response of the amplifier. The error in the fit of the response calculated by the first slice to the measured data was then used in extracting the second slice parameters.

B. Second Slice Extraction

The second slice sought to capture the phase asymmetry between the upper and lower IM3 tones and account for the difference in IM3 amplitude between the measured data and first slice output. The measured symmetric amplitude and the asymmetric phase response of the amplifier pointed to a baseband impedance effect embodied by the linear network $H_2(s)$ in the multislice architecture. $H_2(s)$ is a real network with even-amplitude response and odd-phase response around dc. The filter acts on the even-ordered nonlinear output such that positive and negative frequency components at baseband are added with conjugate phase to the IM products of the first slice after upconversion by the ideal multiplier. This results in IM3 products with symmetric amplitude and asymmetric phase. To produce the appropriate baseband contribution to the amplifier IM3 output, the difference between the measured IM3 data and the estimated IM3 output predicted by the first slice was fit with an even-ordered complex polynomial, taking into account the effect of the ideal multiplier. The result of fitting this difference and summing the output of the two slices in the complex domain is displayed for the magnitude in Fig. 4 and the phase in Fig. 5. The fit reproduced phase asymmetry of the upper and lower third-order products within 1° for a wide range in the input stimulus, with a maximum error at the largest input power levels of 3°. The amplitude match for the IM3 products was better than 0.5 dB over the entire input power range. The results demonstrate that a multislice model composed of only a fit to the odd-order and baseband nonlinear contributors can successfully capture both amplitude and phase

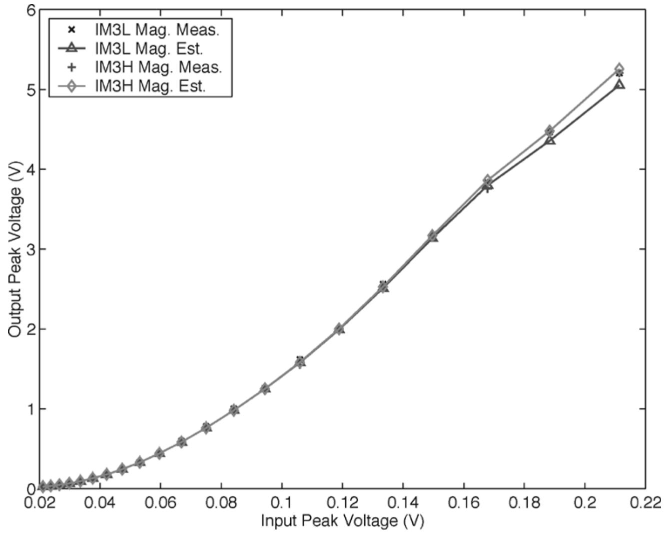

Fig. 4. Fit to measured IM3 amplitude using multislice model.

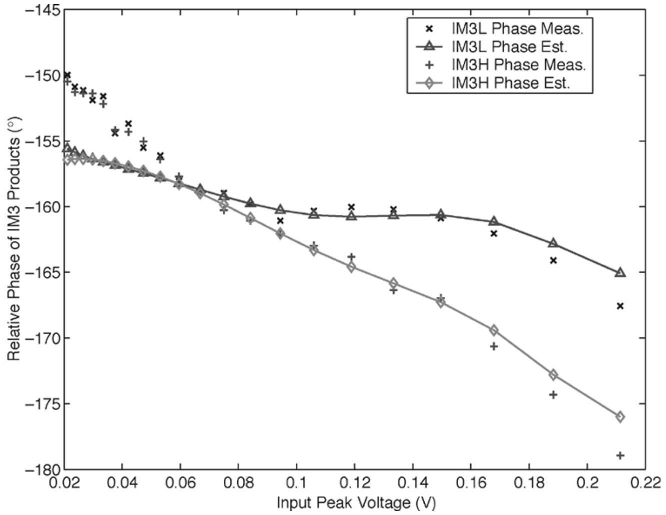

Fig. 5. Fit to measured IM3 phase using multislice model.

of the IM products of a narrowband communications system even in the presence of phase asymmetry.

The plot in Fig. 6 shows the measured and modeled upper and lower IM3 products in the logarithmic power domain on a polar plot. The IM amplitudes have been offset such that they are positive for the purposes of using polar coordinates. From this figure the phase asymmetry and the behavior of the IM distortion with increasing power are clearly discernible.

IV. CONCLUSION

Here, we have demonstrated the use of an IM3 phase measurement system and a multislice behavioral model architecture to capture phase asymmetry resulting from the upconversion of baseband effects. The good agreement between the measured

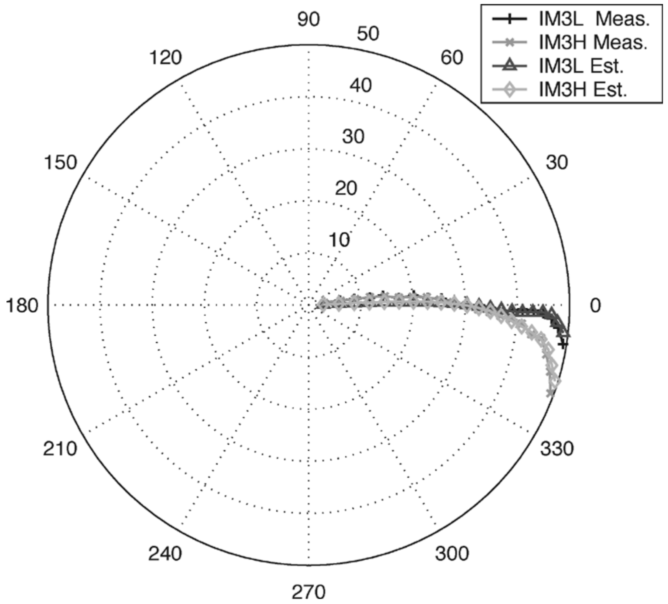

Fig. 6. Fit to measured IM3 phase and amplitude, (amplitudes offset such that they are nonnegative), with multislice model displayed in polar coordinates.

data and the model output using only two slices demonstrates the ability of this architecture to capture complex behavior using only simple measurements and straightforward model parameter extraction. Extension of this model to capture the complete response of a system under test including harmonic production, dependence on stimulus bandwidth, and stimulus frequency would require measuring additional spectral output and adding the appropriate model slices. However, at the subsystem level microwave systems are bandlimited to the RF channel of interest and a two-slice model is sufficient to capture the distortion response.

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