Behavioral Modeling of Quadrature Modulators for Characterization of Nonlinear Distortion

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Abstract— **A behavioral model of the nonlinear response of a microwave quadrature modulator is developed to investigate the impact of modulator nonlinearity on spectral regrowth of wireless communications signals. The nonlinear characteristic of each input is modeled by a complex power series. The model parameters are extracted from the single-tone amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) measurement data. The model was verified with an uplink WCDMA pilot signal applied to the quadrature modulator. The measured ACLR data is in excellent agreement with the modeled results.**

I. INTRODUCTION

Spectral regrowth is of great concern to the designers in modern wireless systems, where spectrally efficient digitally modulated signals are dominantly used. Nonlinear components in a cellular and personal communication system such as power amplifiers generate in-band and adjacent channel interferences due to spectral regrowth. The amplitude variation nature of a digital signal requires a highly linear RF transmitter to meet the stringent regulatory emission requirement at the cost of power efficiency. Therefore, an accurate and efficient method to characterize the nonlinear distortions of the nonlinear devices is important in designing and evaluating the wireless systems. One key figure-of-merit for spectral regrowth is adjacent channel power ratio (ACPR).

Modern wireless transmitters consist of a number of concatenated building blocks such as baseband processor, digital-to-analog converter (DAC), quadrature modulator, and power amplifier and each contributes to the total nonlinear distortions. Among all these components, the power amplifier is the largest contributor. Successful behavioral models have been done by many researchers for predicting the ACPR of power amplifiers [1-4]. These models are developed based on the AM-AM and AM-PM measurement. Quadrature modulator is another important contributor to the total distortions. In [5], the author modeled a quadrature modulator by extracting the model parameters with a pulsed DC signal input.

In this paper, the modeling technique for power amplifiers used in [1-3] was extended to a 3.4 GHz passive quadrature modulator. The nonlinear characteristics of the *I* and *Q* channels were modeled individually by complex power series behavioral model. The model was used to simulate the adjacent channel leakage ratio of an uplink WCDMA pilot signal. There is good agreement in the ACLR between the measurement data and the simulated results.

II. NONLINEAR BEHAVIORAL MODEL

Behavioral modeling is one approach to characterize the nonlinear distortions of a nonlinear device. A behavioral model is a compact representation of the circuit, suitable for system level simulation. It can be generated without knowing the detailed circuit structure and simulated fast and memory effectively. A behavioral model is usually developed based on either simulation or measurement. A measurement based development can capture actual nonlinear characteristics of a device since it is not affected by the inaccuracy of the underlying circuit models.

The basic structure of a quadrature modulator is shown in Figure 1. The local oscillator (LO) input, at the carrier frequency, is split into quadrature phase signals. The baseband input signals, *I* and *Q*, are mixed with the inphase and quadrature carrier signals separately and combined in-phase to generate linear quadrature modulation of the RF carrier.

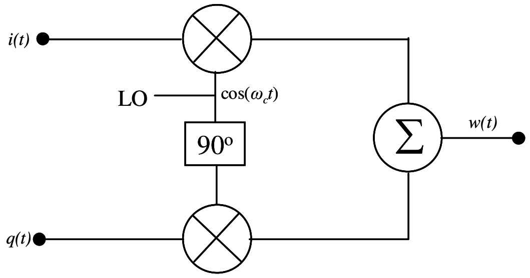

Figure 1 Block diagram of a quadrature modulator.

Assuming that the nonlinearity of the *I* and *Q* channels are isolated, they can be modeled as two independent bandpass nonlinearities. The baseband equivalent model of the quadrature modulator is shown in Figure 2.

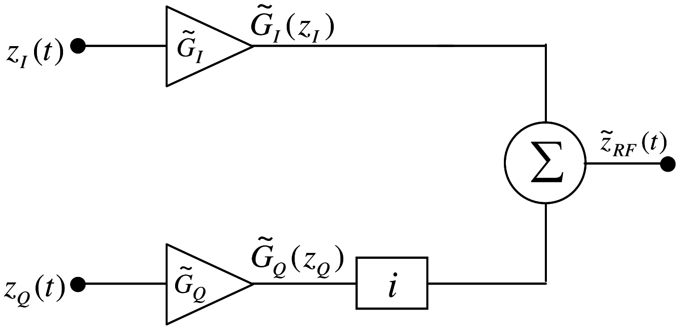

Figure 2 Baseband equivalent nonlinear model of quadrature modulator.

The model result is the envelope of the modulator RF output, which can be obtained by the quadrature summation of the envelopes of the *I* and *Q* channel outputs,

$$\tilde{z}_{RF}(t) = \tilde{G}\left[z_I(t)\right] + j\cdot\tilde{G}\left[z_Q(t)\right] \tag{1}$$

since

$$\tilde{z}_{RF}(t)e^{j\omega_c t} = \tilde{G}\left[z_I(t)\right]\cdot e^{j\omega_c t} + \tilde{G}\left[z_Q(t)\right]\cdot e^{j(\omega_c t+\frac{\pi}{2})} \tag{2}$$

where ω_c is the carrier frequency.

$\tilde{G}_I$ and $\tilde{G}_Q$ are complex transfer characteristics of the nonlinearities of *I* and *Q* channel respectively, both described as envelope complex power series [1-3].

$$\tilde{G}_I\left[z_I(t)\right] = \sum_{n=0}^{N} \tilde{a}_{I,2n+1} z_I^{\;2n+1} \tag{3}$$

$$\tilde{G}_Q\left[z_Q(t)\right] = \sum_{n=0}^{N} \tilde{a}_{Q,2n+1} z_Q^{\;2n+1} \tag{4}$$

where $\tilde{a}_{I,2n+1}$, $\tilde{a}_{Q,2n+1}$ are the complex power-series coefficients and 2N+1 is the highest order of the nonlinearities. A quasistatic nonlinear device can be accurately characterized by a complex power series model when there is no significant memory within the signal bandwidth, implying flat frequency response and no PM-AM conversion. The complex power series coefficients are obtained by fitting a polynomial to the single-tone AM-AM and AM-PM characteristics, as described in [1]. However, only the odd-order envelope coefficients can be extracted from single-tone complex compression measurement (AM-AM and AM-PM), but fortunately, the odd-order terms are the most important since the intermodulation distortions in-band and adjacent to the desired channel are produced by the odd-order terms.

To obtain the complex power series coefficients $\tilde{a}_{I,i}$ and $\tilde{a}_{Q,i}$, first the complex power series $\tilde{b}_{I,i}$ and $\tilde{b}_{Q,i}$, which relates the complex envelope of the input (a phasor of a single-tone signal) to the complex envelope of the output at the carrier frequency (a phasor of a single-tone signal), need to be extracted by fitting a complex polynomial to AM-AM and AM-PM measurements of *I* and *Q* channel separately. For modulators, the major source of nonlinear distortions is the baseband transconductor, which produces the instantaneous responses of the baseband inputs. All of such responses, including not only the fundamental terms, but also the nonlinear terms, are upconverted to the carrier frequency by the subsequent LOs. Therefore, unlike power amplifiers, instantaneous complex power series coefficients $\tilde{a}_{I,i}$ and $\tilde{a}_{Q,i}$ need to be used for modulators. As described in [1], $\tilde{a}_{I,i}$ and $\tilde{a}_{Q,i}$ can be derived from $\tilde{b}_{I,i}$ and $\tilde{b}_{Q,i}$ using the following relationships:

$$\tilde{a}_{I,2n+1} = \tilde{b}_{I,2n+1}\,\frac{2^{2n} n!(n+1)!}{(2n+1)!} \tag{5}$$

$$\tilde{a}_{Q,2n+1} = \tilde{b}_{Q,2n+1}\,\frac{2^{2n} n!(n+1)!}{(2n+1)!} \tag{6}$$

In [6], the authors measure the AM-AM and AM-PM characteristic of a baseband to RF quadrature modulator by applying a sweeping DC offset to the *I/Q* modulator. One limitation of this approach is that the finite carrier suppression performance of the *I/Q* modulator greatly limits the measurement dynamic range since the DC offset is upconverted exactly to the carrier frequency. In this paper, instead of using a sweeping DC offset signal, a baseband 10 kHz sinusoid signal with an exponential amplitude ramp was utilized to measure the AM-AM and AM-PM characteristic of *I* and *Q* channel. The measurement setup is shown in Figure 3.

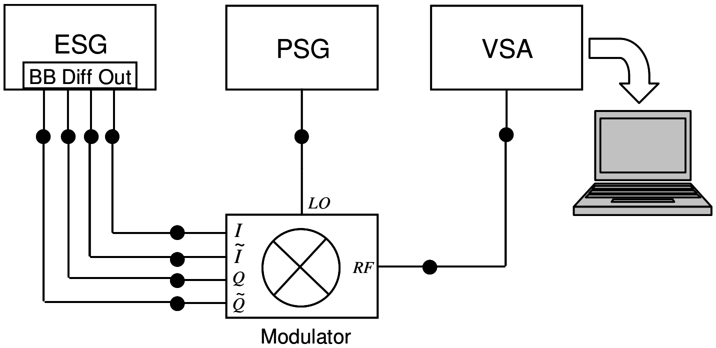

Figure 3 Measurement setup for AM-AM and AM-PM characterization and ACLR measurements.

When measuring the AM-AM and AM-PM characteristic of the *I* channel, an electrical signal generator (ESG) generates a baseband 10 kHz exponential ramp sinusoid signal, which is supplied to the differential *I* ports of the *I/Q* modulator via the baseband differential *I/Q* output port of the ESG. The *Q* channel input of the quadrature modulator is set to zero. The 10 kHz sinusoid is upconverted to RF carrier and the complex envelope of the RF output at 10 kHz offset to the carrier frequency is measured by the vector signal analyzer (VSA). For example, if the carrier frequency is 3.4 GHz, the complex envelope at 3.40001 GHz is measured. A sinusoid signal is generated by the power signal generator (PSG) and supplied to the LO port of the quadrature modulator. The measurement of the AM-AM and AM-PM characteristic of the *Q* channel is similar as the *I* channel.

An 11th-order complex power series was fitted to AM-AM and AM-PM data of the *I* and *Q* channel of the *I/Q* quadrature modulator, respectively. The input power is swept from -19.7 dBm to 7.7 dBm. The quality of the fit of the *I* and *Q* channels are shown in Figure 4 and Figure 5 respectively.

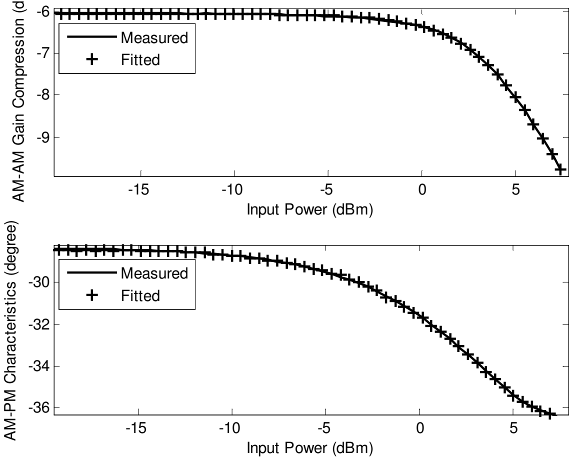

Figure 4 Measured and predicted AM-AM and AM-PM characteristics of *I* channel.

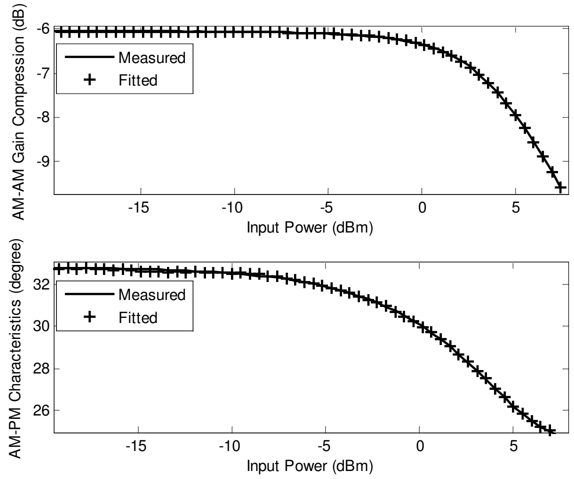

Figure 5 Measured and predicted AM-AM and AM-PM characteristics of *Q* channel.

The complex power coefficients $\tilde{b}_{I,i}$ and $\tilde{b}_{Q,i}$ of order N=11 for *I* and *Q* channel are listed in Table 1.

Table 1 Behavioral Model Complex Coefficients

$b_{I,1}$	0.21902 - 0.11795i
$b_{I,3}$	-0.04031 - 0.07836i
$b_{I,5}$	-0.20183 + 0.22120i
$b_{I,7}$	0.25182 - 0.16466i
$b_{I,9}$	-0.10023 + 0.03510i
$b_{I,11}$	0.0073026 + 0.00487i
$b_{Q,1}$	0.20877 + 0.13458i
$b_{Q,3}$	0.03905 - 0.05375i
$b_{Q,5}$	-0.24993 - 0.11594i
$b_{Q,7}$	0.22611 + 0.19584i
$b_{Q,9}$	-0.067246 - 0.10671i
$b_{Q,11}$	-0.0005899 + 0.018832i

III. SIMULATION AND MEASUREMENT RESULTS

The *I*/*Q* quadrature modulator being characterized is a diode-ring structured passive RF modulator. The *I*/*Q* baseband bandwidth is from DC to 250 MHz and RF frequency range is 3300 - 3700 MHz. It is suitable for use with WCDMA and WLAN applications. A WCDMA uplink pilot signal was applied to the model. The measured ACLR data was compared with the simulation results to validate the accuracy of the complex power series model in characterizing the nonlinear distortions of the *I*/*Q* modulator.

ACLR is a key parameter in quantifying the effects of the nonlinear devices on the transmit quality of the WCDMA signals. ACLR is defined as the ratio of the total power within the desired information bandwidth to the total power in an adjacent channel bandwidth, with a frequency offset away from the carrier frequency by: 1) 5 MHz, and 2) 10 MHz [7]. In this paper, the ACLR @ 5 MHz was measured and simulated.

The ACLR measurement test setup is shown in Figure 3. The uplink WCDMA pilot was generated using the build-in 3GPP WCDMA personalities of the ESG. The corresponding baseband *I*/*Q* signals were advanced to the *I*/*Q* quadrature modulator via the baseband differential output ports of the ESG. The ACLR was measured by the VSA. The baseband input power of the WCDMA signal ranges from -11.5 dBm to 8.5 dBm in the ACLR measurement. The gain compression characteristics of the *I*/*Q* modulator excited by the WCDMA signal is shown in Figure 6. For the WCDMA signal, the *I*/*Q* modulator goes into gain compression region at an input power of around 1 dBm.

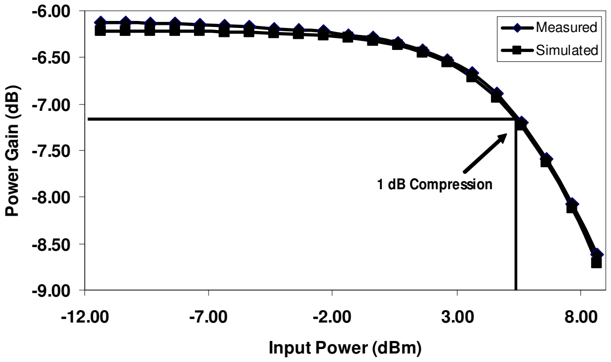

Figure 6 Measured and simulated gain compression characteristic of the *I*/*Q* modulator excited by a WCDMA uplink pilot signal.

The measured versus the simulated ACLR for the upper sideband is shown in Figure 7. There is an excellent agreement (within 1 dB difference) between the measured and the simulated ACLR when the modulator is within the nonlinear region, indicating that the complex power series model predicts the nonlinear distortion characteristics of the quadrature modulator very accurately.

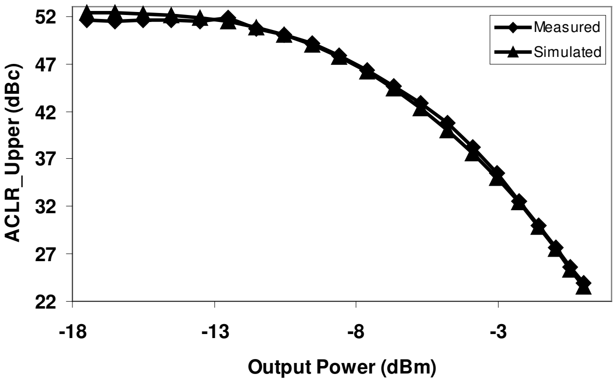

Figure 7 Measured and predicted ACLR (upper sideband) for a WCDMS uplink pilot signal.

The measured versus the simulated ACLR for the lower sideband is shown in Figure 8. The ACLR of the upper sideband and the lower sideband are very close for both the measured data and simulated results. The symmetry indicates that there is no significant memory in the modulator, which validates our assumption for the memoryless model.

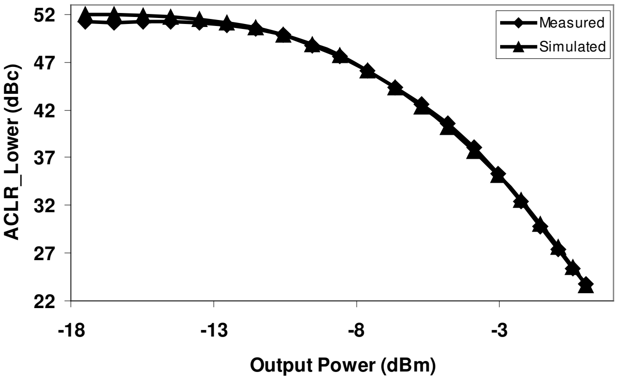

Figure 8 Measured and predicted ACLR (Lower Sideband) generated by a WCDMA uplink pilot signal.

IV. CONCLUSION

An envelope behavioral model for accurate characterization of the nonlinear distortion of a quadrature modulator excited by digitally modulated signals has been presented. An odd ordered complex power series model was developed based on single-tone AM-AM and AM-PM measurements of each baseband input. An uplink WCDMA pilot signal was applied to the model. The measured and simulated ACLR has an excellent agreement, which indicates that our AM-AM and AM-PM measurement-based behavioral model can accurately predict the spectral regrowth of a quadrature modulator.

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