Behavioral Modeling of High Power Amplifiers Based on Measured Two-tone Transfer Characteristics

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Multi-stage high power amplifiers generally have a large memory effect and high nonlinearity. The usual AM-AM and AM-PM measurement data cannot describe the large distortion characteristics in the presence of the system's large memory. A more accurate amplifier behavioral modeling method based on two-tone transfer characteristics is presented and the measurement setup for these characteristics is described. The measured data are modeled using the conventional AM-AM and AM-PM model to fit the measured amplitudes and phases of the fundamental, third-order intermodulation (IM3) and fifth-order intermodulation (IM5) components. This is a quasi-memoryless model. However, it provides a better description of memory effects and an accurate presentation of highly nonlinear characteristics than the same quasi-memoryless model based on the single-tone transfer characteristics.

It is very useful to simulate the system level performance of power amplifiers using a simple behavioral or mathematical model. Class A power amplifiers have normally been treated with the assumption of a memoryless (representation of AM-AM characteristics only) or quasi-memoryless (complex representation of both AM-AM and AM-PM characteristics) system.[16] However, accurate characterization and modeling of very high power amplifiers with an output power of over a few hundred watts are very difficult because of their high nonlinearity and large memory effects. The single-tone transfer characteristics (measured AM-AM and AM-PM characteristics) cannot properly describe the nonlinearity of these high power amplifiers because they have no memory information. However, the two-tone nonlinear transfer characteristics including the amplitude and phase responses of the fundamental, IM3 and IM5 components contain the highly nonlinear properties and are representative of the amplifier's large memory. Hence, the behavioral model based on two-tone transfer characteristics can reasonably predict the integrated average distortion for non-constant envelope signals (for example, p/4 QPSK and 16 QAM signals). For most high power amplifiers, the behavioral model based on single-tone transfer characteristics cannot even accurately predict the simple response of the amplitudes of the IM3 and IM5 in the two-tone test. W. Bosch, et al., reported on a case where a predistortion linearized amplifier with improved AM-AM and AM-PM characteristics did not provide any enhancement over two-tone intermodulation nonlinearity.[7] Therefore, a more accurate behavioral model based on two-tone characterization with phase information would be a better choice for modeling of multi-stage high power amplifiers.

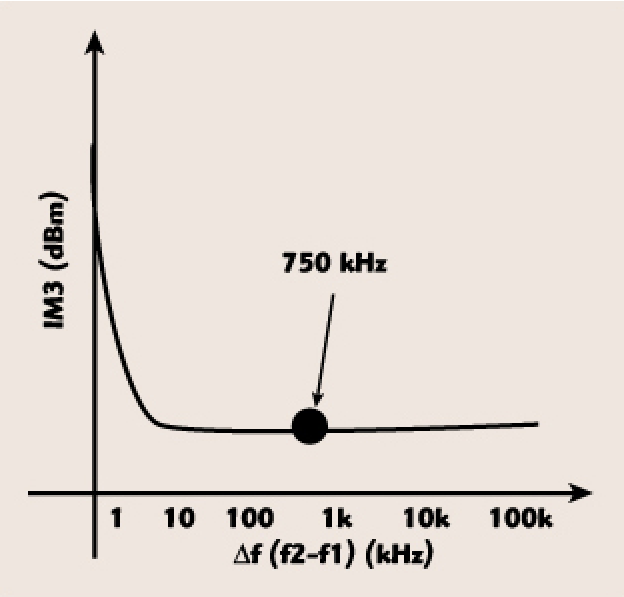
This article presents an accurate measurement and modeling technique for determining the two-tone transfer characteristics of high power amplifiers. For the measurements, the amplifier output is down-converted to an intermediate frequency and the relative phase is measured by comparison with a reference signal. The relative phases of the harmonic terms of a very low frequency amplifier are 0° or 180°. A low power GaAs MESFET amplifier at 750 kHz is used for the reference intermodulation (IM) generator. The measured two-tone data have been fitted to the conventional model of AM-AM and AM-PM distortion characteristics. A 500 W class AB multi-stage power amplifier is used for measurement and modeling. The measurement setup and sequence are described and the measured and modeled results are also shown.

WHY TWO-TONE CHARACTERIZATION?

The output signal having a memory effect is determined by both the real time input signal and the previous input signals, and it causes a drastic variation of the nonlinear behavior of power amplifiers. The effects of nonlinear behavior due to memory effect are an asymmetric IM spectra between lower (2f1-f2 for IM3) and upper (2f2-f1 for IM3) components and IMD characteristic variation for different tone spacings (”f). The asymmetry of the IMD spectra is not discussed in this article because it can be avoided by proper stage matching (to avoid multiple reflection) and well-designed bias circuits (low frequency harmonic termination -- resistive or short).

The IMD variation for different tone spacings due to large-time-constant memory effects is mainly caused by the thermal time constants of the high power amplifiers.[7,8] Generally, IM3 variation characteristics for various tone spacings are shown in Figure 1, based on the results of Lu, et al.[8] From the graph, IM3 drastically decreases and settles down as the tone spacing (▯ f) is increased. Hence, the single tone characteristics, which can be treated as asymptotically zero tone spacing, cannot represent the average distortion of a high power amplifier with a large memory. On the other hand, the two-tone characteristics with proper tone spacing (750 kHz in this experiment) better represent the nonlinear behavior of power amplifiers. Therefore, the behavioral model based on properly measured two-tone transfer characteristics will predict the integrated adjacent channel emission characteristics of the high power amplifier when it is applied to the modulated signals (for example, WCDMA, CDMA-2000).

Fig. 1 Conventional IM3 characteristics vs. tone spacing for a two-tone input case in the presence of a large memory effect.



MEASUREMENT OF THE TWO-TONE TRANSFER CHARACTERISTICS

A four-stage amplifier is built for Korea's wireless local loop (WLL) band of 2.37 to 2.40 GHz. Its final stage consists of four balanced 130 W LDMOS FETs (Motorola's MRF21120 RF LDMOS FET). It is a push-pull-type configuration with class AB operation. The other three stages are arranged to drive the final stage amplifier. The peak output power at the 1 dB gain compression point is approximately 500 W and the overall gain is 44.5 dB. The operational average output power is 45 W for a WCDMA signal with a chip rate of 8.192 Mcps. Figure 2 shows a line-up diagram of the main amplifier used for measurement and modeling.

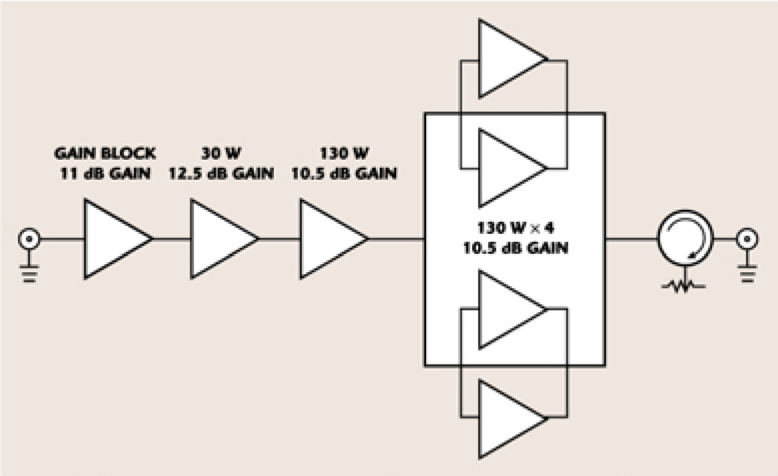
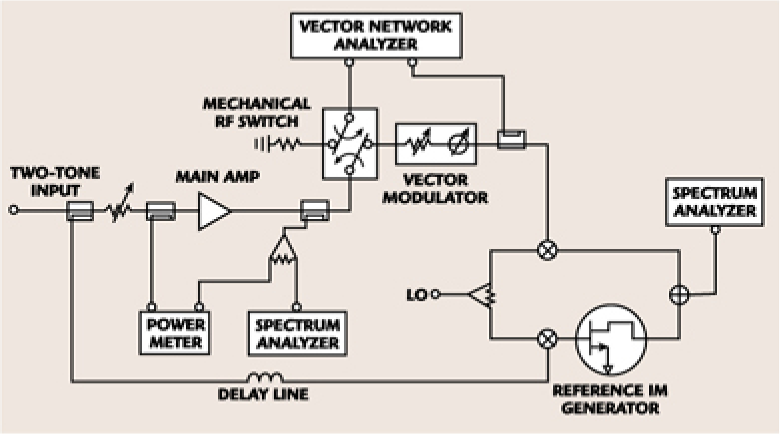
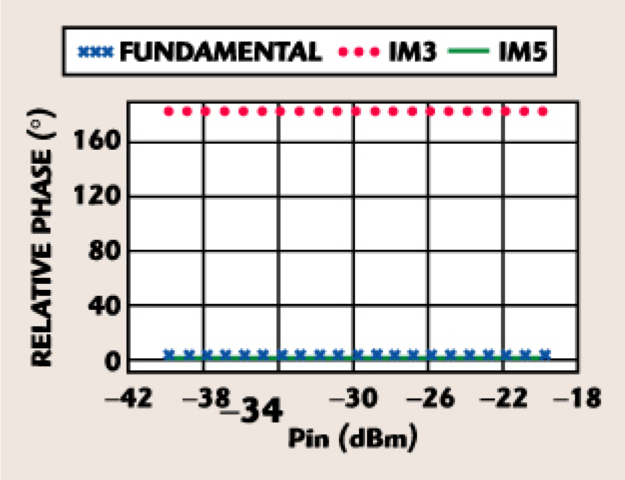


Fig. 2 Class AB high power amplifier module for measurement and modeling.

The measurement setup is shown in Figure 3. This setup requires a two-tone signal generator, a vector network analyzer, a two-input power meter and two spectrum analyzers. The reference IM generator is Agilent's ATF21186 low power MESFET and operates at a center frequency of 750 kHz. At this low frequency the memory effect of the device can be ignored because its nonlinear capacitances are nearly open-circuited and the propagation delay is negligible. Hence, the device has no AM-PM characteristics and its fundamental, IM3 and IM5 components show no phase variations with input power level changes. This characteristic is verified with two-tone harmonic balance simulation using the large signal model of the device. Figure 4 shows the results of this simulation. The phases of the fundamental, IM3 and IM5 signals are constant throughout input power level changes up to the 1dB gain compression point. The fundamental and IM5 signals have equal phase and IM3 is 180° out of phase because the third-order volterra series coefficient (gm3) has a negative sign.



▲ *Fig. 3 Measurement setup for two-tone transfer characteristics.*

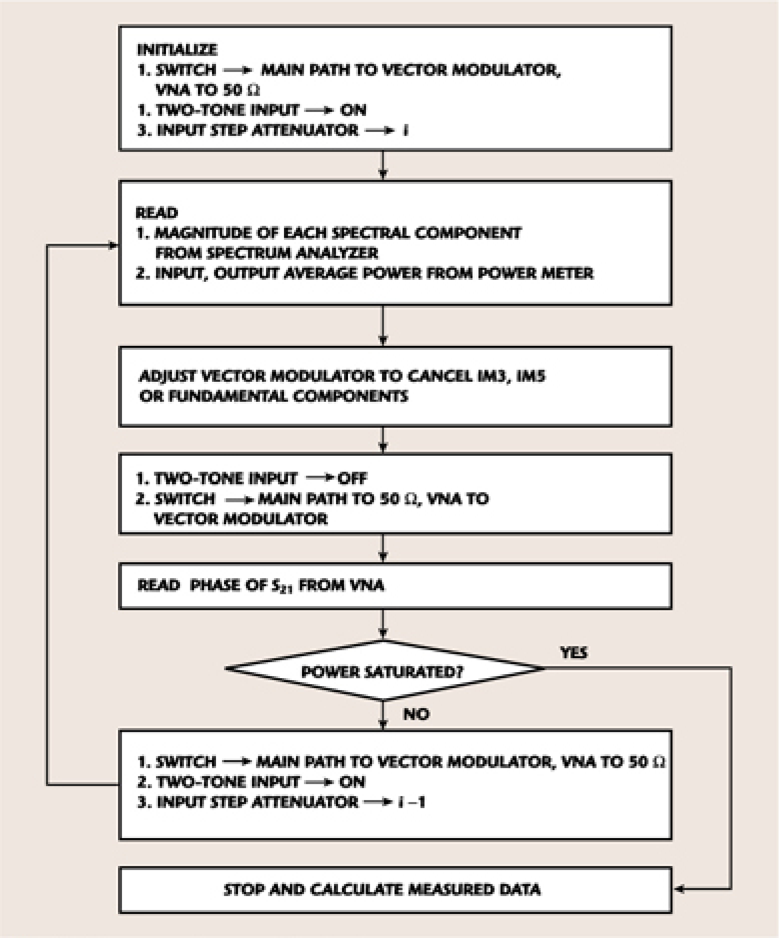


▲ *Fig. 4 Simulated relative phases of fundamental, IM3 and IM5 of reference IM generator vs. two-tone input power level at 750 kHz center frequency.*

The two-tone input signal, which has a tone spacing of 100 kHz, is tapped to the reference path. The tone spacing is carefully chosen to consider the transient response of IMD with tone spacing in the two-tone signal and the integrated adjacent channel power (ACP) contributed by different delta-frequencies in the CDMA signal. The main path signal passes through the step attenuator for input power level control, and is then coupled to power meter A for monitoring the input power. The main amplifier output signal is attenuated and coupled to power meter B for monitoring the output power and to the spectrum analyzer for relative power measurements of IM3 and IM5. The vector modulator, which consists of a variable attenuator and variable phase shifter, is used to adjust the amplitude and phase of the fundamental, IM3 or IM5 components of the output signal in order to cancel the corresponding reference signal component at the adder.

Finally, the output signal and the reference signal are down-converted to approximately 750 kHz. The down-converted reference signal is amplified by the reference IM generator and the reference IM terms are generated. The output and reference signals are canceled using an analog adder circuit. This low frequency part may well be shielded to block out environmental noise. The vector network analyzer measures the required phase variation of the vector modulator for the cancellation by reading the phase of S_{21}. The mechanical RF switch connects and disconnects the loop without breaking calibration.

The complete flow of the measurement sequence is shown in Figure 5. For initialization, the vector network analyzer port 1 is connected to a 50 O load and the main path is connected to the vector modulator by a mechanical RF switch, the two-tone input is on and the input step attenuator is set to an appropriate starting power level. The input and output powers are read from the power meter and the relative amplitudes of the fundamental, IM3 and IM5 signals are acquired from the spectrum analyzer. Next, the vector modulator is adjusted to cancel the fundamental, IM3 or IM5 components. After the adjustment has been completed, the two-tone input is turned off at the signal generator and the RF switch changes the connection of vector network analyzer port 1 to the vector modulator and the main path to a 50 O load in order to measure the relative phase variation of the vector modulator. After reading the phase of S_{21} from the vector network analyzer, the RF switch connects the main path to the vector modulator, the two-tone input is switched on, and the input step attenuator is set to increase the input power level.



▲ *Fig. 5 Measurement sequence flow chart.*

This sequence is repeated for the fundamental, IM3 and IM5 phase measurement until the output power of the main amplifier is saturated. The measured data provide the relative phase variations of the fundamental, IM3 and IM5 components of the main amplifier. The reference IM3 phase offset of 180° is de-embedded from the measured relative phase of IM3.

BEHAVIORAL MODELING USING AM-AM AND AM-PM FUNCTIONS

The measured two-tone characteristics are fitted to the general quadrature AM-AM and AM-PM nonlinearity model. The nonlinear transfer function of the power amplifier is formulated as

$v_{out}(t) =$
$A[v_{in}(t)] * \exp\{j * *[v_{in}(t)]\}$ (1)

where

$v_{in}(t)$ = input envelope signal
of power amplifier
$v_{out}(t)$ = output envelope signal
of power amplifier

In this experiment, the AM-AM distortion function is modeled using a modified sine series from the work of A. Leke and J.S. Kenney[5] and the AM-PM distortion function is a rational polynomial. AM-AM and AM-PM functions used in this experiment are represented as

$$A[v_{in}(t)] = a_0 \bullet v_{in}(t) + \sum_{n=1,2,3\ldots} a_n \bullet \sin[(2n-1) \bullet \xi \bullet v_{in}(t)] \qquad (2)$$

$$\Phi[v_{in}(t)] = \frac{\sum_{n=0,1,2\ldots} b_n \bullet v_{in}(t)^n}{1 + c_0 \bullet v_{in}(t)^2 + c_1 \bullet v_{in}(t)^4} \qquad (3)$$

where

* = input scaling factor

a_n = AM-AM expansion parameters

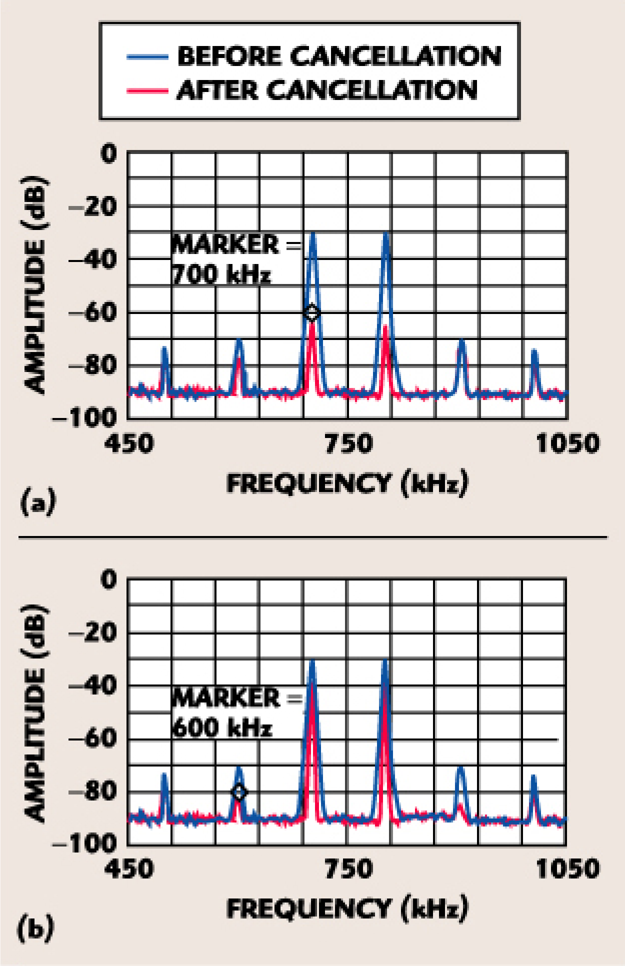
b_n, c_0 and c_1 = AM-PM expansion parameters

To extract the model parameters, all of the AM-AM and AM-PM coefficients are optimized to fit the measured amplitudes and phases of the fundamental, IM3 and IM5 simultaneously throughout the input power level range. As the nonlinearity and memory effect of the amplifier increase, more amplitude and phase modulation coefficients are required to fit the measured data. Twenty-seven parameters are used to represent amplitude modulation and 16-parameters, including c_0 and c_1, to represent phase modulation of the class AB 500 W high power amplifier.

The rather large number of parameters used in this experiment is essential for accurately predicting the substantial nonlinearity of the multi-stage class AB high power amplifier. It may require more parameters to fit the rapidly changing data than that based on single-tone transfer characteristics. It means that the single-tone-based model cannot provide an accurate description of the highly nonlinear characteristics and the results may be very sensitive to the measurements, model functions and function parameters. The model parameters are optimized in Agilent's Advanced Design System (ADS) using the symbolic defined device (SDD) function.

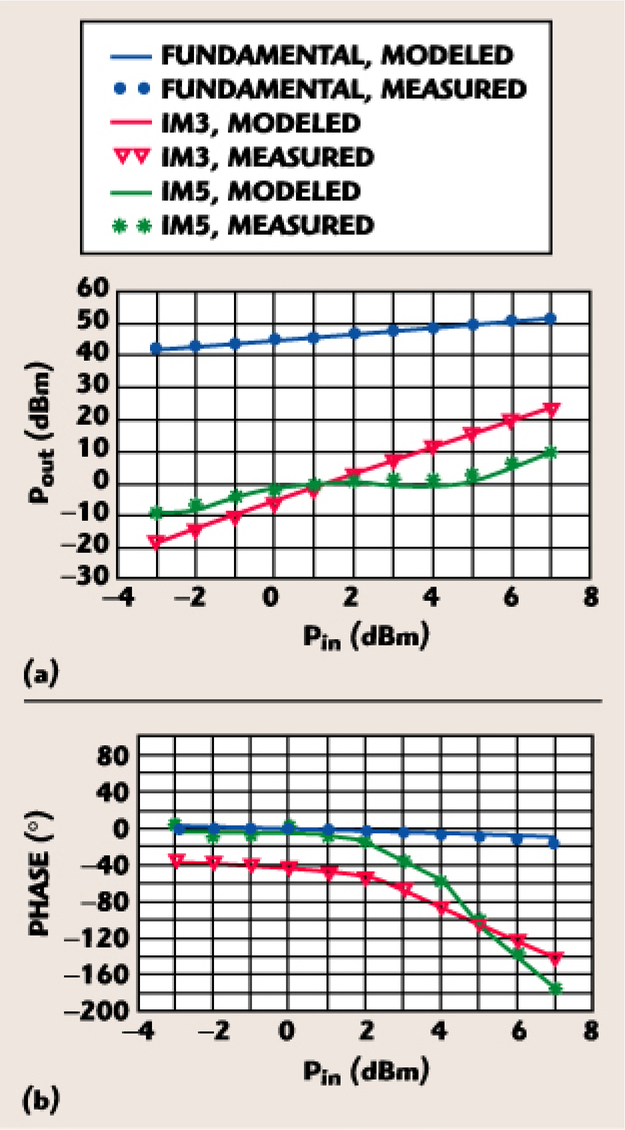
MODELING RESULTS

Figure 6 shows the spectra of the output before and after cancellation by the vector modulator at an average output power of 50 dBm for fundamental and IM3 cancellation. To measure the relative phases, more than 30 dB cancellation has been achieved for the fundamental components. A 30 dB cancellation provides approximately a ±1.8° phase error range, if the amplitudes of the two branches are perfectly matched. However, for IM3 and IM5, the cancellation cannot reach as high as 30 dB at a low input power level due to the noise floor level of the spectrum analyzer. In the case of 15 dB cancellation, for example, the relative phase error range is increased to more than ±10° if the amplitudes of the main path and reference path are perfectly matched. But the relative phase error range can be drastically reduced (to ±1.5°) when the amplitude mismatch between the two branches is about 1.7 dB and a 15 dB cancellation is maintained. To obtain highly accurate measurement data of the relative phases of fundamental, IM3 and IM5 components, a proper amplitude mismatch condition should be applied.



▲ *Fig. 6 Measured spectra of amplifier output before and after cancellation; (a) fundamental cancellation and (b) IM3 cancellation.*

Figure 7 shows the measured and modeled amplitude and phase characteristics of the high power amplifier under test. The two-tone average output powers of the fundamental, IM3 and IM5 signals are plotted in Figure 7(a). The measured and modeled relative phases are plotted in Figure 7(b). The first measurement point of fundamental is set to zero phase and the others are calculated to have relative values. As the power level approaches the saturation point, the phases of IM3 and IM5 vary greatly. The measured and modeled two-tone characteristics are in agreement.



▲ *Fig. 7 Measured and modeled two-tone transfer characteristics of high power amplifier; (a) amplitude and (b) phase.*

To verify this model, the measured and modeled adjacent channel power ratios (ACPR) of a WCDMA signal are compared. To accurately predict the ACPR of the high power amplifiers, an exact modeling of the amplitudes and phases of the fundamental, IM3 and IM5 components is inevitably required. A WCDMA signal with a chip rate of 8.192 Mcps and average output power of 45 W is used for the verification. The measured data are compared with the simulated data in the WCDMA co-simulation setup of the ADS using data flow and envelope simulations simultaneously. As shown in Figure 8, the measured and modeled ACPRs have a very similar trend.

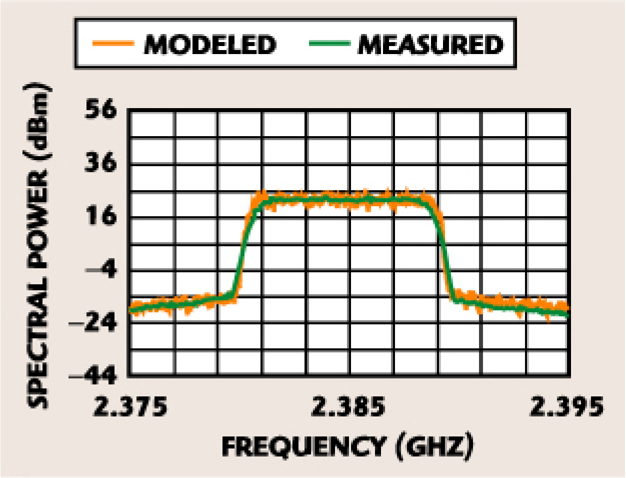


Fig. 8 Measured and modeled WCDMA responses with a chip rate of 8.192 Mcps and average output of 45 W.

CONCLUSION

A new, accurate method for measuring and modeling two-tone transfer characteristics has been presented to take into account the memory effect of high power amplifiers. For phase measurement, a reference IM generator at a very low frequency was used. The two-tone harmonic balance simulation shows the accuracy of the relative phase of the reference IM generator. The complete measurement setup and sequence have been described. For the experiment, a multi-stage high power amplifier with 500 W peak envelope power and 44.5 dB gain was employed. The relative phases of fundamental, IM3 and IM5 components were measured. The measured data of IM3 and IM5 are very smooth and continuous, and vary greatly as the power level approaches the saturation output power.

These measured two-tone amplitudes and phases have been modeled. The model accurately represents high nonlinearities and rapid phase variations of a high power class AB amplifier. A WCDMA measurement and simulation have been conducted for verification. The measured and modeled ACPRs are in agreement. This nonlinear behavioral model of a high power amplifier is very useful for the design of various predistortion linearizers and for the simulation of the amplifier systems incorporating various digital and analog control circuits. *

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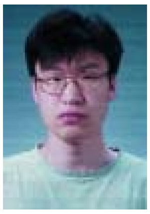

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