

# A Simple Technique for IIP3 prediction from the Gain Compression Curve

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## Abstract

*This paper presents techniques using 1dB gain compression point measurements to estimate third-order intercept point in RF circuits. Classical analysis of transistor amplifier performance shows 9.6dB as the difference between the IIP3 and the 1dB gain compression point. An analysis and simulation of amplifier gain compression shows that this is not the case, that at least 5<sup>th</sup> order harmonics play a role in the gain compression curve and that the classical analysis is incorrect for submicron RF transistor amplifiers. Another approach that estimates the values of IIP3 from single-tone RF power gain data is presented. This approach is successfully applied to simulations of a common-source amplifier. Measurements of commercial amplifiers show that IIP3 can be estimated from their gain compression curves. This modeling approach uses a Taylor series expansion of the compression curves and relates the nonlinear coefficients of the compression curve to the IIP3 two-tone test data. This IIP3 estimation can simplify test protocol, shorten test time and lower cost of IC production test.*

## 1. Introduction

Gain compression and third-order intercept point (IP3) are important nonlinear parameters of RF/mixed-signal circuits and provide good verification of a circuit or device's linearity and dynamic range. The parameters can be correlated to adjacent channel power ratio (ACPR) and error vector magnitude (EVM) in amplifiers and must be kept under control. Gain compression is a relatively simple microwave measurement since it requires a variable power single tone source and an output power detector. IIP3

characterization is more complicated and more costly since two separate tones closely spaced in frequency must be generated and applied to the circuit under test (CUT) and the CUT's fundamental and third-order distortion term power must be measured. Thus, measurement of IIP3 requires high Q filters to select first- and third-order distortion frequencies in the detector circuit.

The published difference between 1dB gain compression and IIP3 is roughly 10dB. This relation is derived using first-order and third-order nonlinear coefficients of transistor amplifier circuits [1][2]. This calculation assumes that higher-order nonlinear coefficients do not affect the 1dB gain compression. This is not the case, at least 5<sup>th</sup> order harmonics play a role in the gain compression curve and that the classical analysis is incorrect for submicron RF transistor amplifiers [3].

By predicting IIP3 from one-tone gain compression measurements, the production testing of the manufactured IC can be greatly simplified. Although the accuracy of this approach may not be as great as direct IIP3 measurement, it has great appeal in test cost reduction and may be sufficient for production IC test.

## 2. Analysis on Gain Compression Curve

Intermodulation distortion (IMD) behavior is studied using a two-tone test. At low input power, a Volterra series analysis may be used for calculation of the IMD terms. If the frequency is low, the Volterra series analysis turns into a power series analysis of the transfer function around the quiescent voltage [4]. IMD can be predicted using a large-signal model [5].

In order to illustrate a one-tone gain compression curve, it is necessary to look at the large-signal behavior of a transconductance amplifier. For a nonlinear conductance, the current through the element is a nonlinear function of the controlling voltage. This

function can be expanded into a power series around the quiescent point [6].

The expression of the AC current through the conductance

$$i_{out}(t) = \alpha_1 v_{contr}(t) + \alpha_2 v_{contr}^2(t) + \alpha_3 v_{contr}^3(t) + \dots \quad (1)$$

Here,  $\alpha_1$  is the first nonlinear coefficient and  $\alpha_2$  is the second-order nonlinear coefficient, and so on. In the case of a memoryless nonlinear system, the output of this system can be represented by

$$v_{out}(t) = K_1 v_{in}(t) + K_2 v_{in}^2(t) + K_3 v_{in}^3(t) + \dots \quad (2)$$

in which  $K_1$  to  $K_n$  are real number coefficients.

Prior analysis on the gain compression,  $IP_{1dB}$  and  $IIP3$  used nonlinear coefficients up to 3<sup>rd</sup> order, failed to explain the simulated and measured difference between gain compression and  $IIP3$ . More accurate modeling of gain compression requires at least 5<sup>th</sup> order coefficients, as is done here. The previous work shows that 1dB gain compression point satisfies the following equation, when including 5<sup>th</sup> order coefficient.

$$\frac{5}{8} \left( \frac{K_5}{K_1} \right) A_{1-dB}^4 + \frac{3}{4} \left( \frac{K_3}{K_1} \right) A_{1-dB}^2 + 0.109 = 0 \quad (3)$$

Here,  $A_{1-dB}$  is the input amplitude at the 1dB gain compression point. The smallest positive real number satisfying the above equation (3) is the input power amplitude at 1dB gain compression. This mathematical solution is the proper physical solution to this fourth order equation.

In a two-tone test, the third-order intercept point is defined as below,

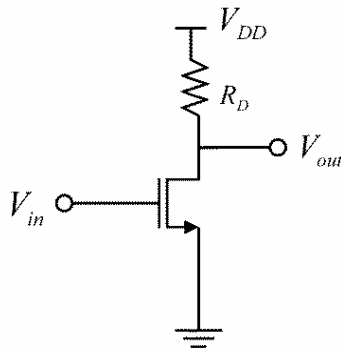


Fig. 1. The Schematic of Common-Source Amplifier with resistive load ( TSMC 0.25um MOSFET)

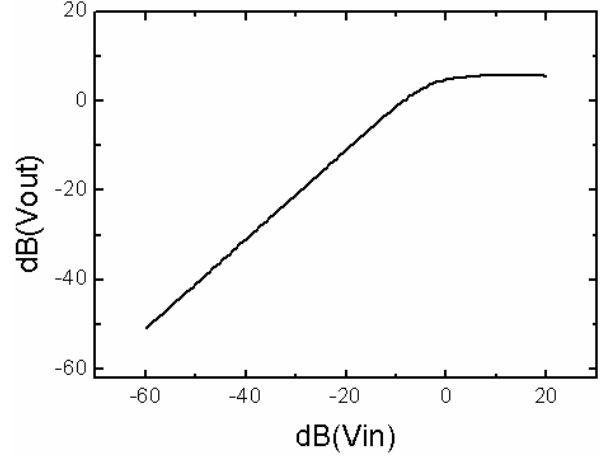


Fig. 2. The Voltage Gain Compression Curve using One-tone Harmonic Balance Simulation at Fundamental Frequency (100MHz)

$$A_{IP3} = \frac{2}{\sqrt{3}} \left( |K_1 / K_3| \right)^{1/2} \quad (4)$$

In a one-tone test, it is possible to obtain the nonlinear coefficients from the gain curve at the signal fundamental frequency, since the output amplitude is  $A_{out} = (K_1 A_{in} + (3/4)K_3 A_{in}^3 + (5/8)K_5 A_{in}^5)$ . Here  $A_{in}$  is the input amplitude.

To get the nonlinear coefficients from the gain compression curve, a linear regression analysis is used to fit the curve. A common-source single transistor amplifier design using TSMC 0.25um MOSFET is used. Fig.1 shows the schematic for one-tone simulation using the Agilent ADS2002 software. A voltage gain curve is made by the measurement of the output amplitude when sweeping the input amplitude at a fixed frequency. Fig.2 shows the result of a one-tone test. From this voltage gain compression curve, the input referred 1dB voltage compression point is -6.67dB. Through two-tone simulation at the same quiescent bias, the simulated third-order intercept point is 5.33dB. In this test, the difference between 1dB compression point and third-order intercept point is 12dB. The voltage gain curve at the fundamental

TABLE I  
ANALYSIS OF VARIANCE

| Source               | df | SS                      | MS                       |
|----------------------|----|-------------------------|--------------------------|
| Regression           | 3  | 4.8282                  | 1.6094                   |
| Residual             | 74 | 6.40 x 10 <sup>-9</sup> | 8.65 x 10 <sup>-11</sup> |
| Total<br>(Corrected) | 77 | 4.8282                  |                          |

frequency is used to extract the nonlinear coefficients ( $K_1$ ,  $K_3$ , and  $K_5$ ) through a linear regression analysis. In the linear regression analysis, the polynomial model is below,

$$Y = B_0 + B_1X + B_3X^3 + B_5X^5 + Error \quad (5)$$

From the analysis of the standard errors of each the coefficients and the residual, the fitting region is at it's the lowest point near the 1dB compression point. Table.1 shows the analysis of variance about this fitting. From this analysis of variance the fitting model gives a good description of the voltage gain compression curve. The third-order intercept point calculated from extracted nonlinear coefficients is 5.47dB. The difference between the simulated value and calculated value is around 0.2dB. This result show that the proposed approach gives a good estimate of the third-order intercept point without a two-tone measurement using the nonlinear coefficient extracted in a one-tone test.

### 3. Analysis on real measurement data

The application of this technique to manufacturing test LNA measurements requires substantial modification. IIP3 extraction from LNA gain simulation data has the benefit of many decibel places of accuracy (high S/N) and an ideal (no loss) test system. Real measurements from spectrum analyzers can exhibit roughly 1% accuracy in the data and substantial power loss due to cables and fixtures in the test setup. Even after using power magnitude calibration techniques on spectrum analyzer data, significant uncertainty can exist due to phase errors. In addition, it was found that to properly extract IIP3 parameters the data has to be measured on one power range of a spectrum analyzer. Using multiple spectrum analyzer power ranges introduced offset errors in the measured data. In summary, the simulated LNA data had remarkably high S/N across the entire data set while the measured LNA gain data had a mediocre S/N at high-power which decreased as power decreased.

Given the situation, a global extraction of the LNA power series expansion coefficients (4) was not stable with small changes in the data set. Adding a few more data points at the high-power range creates large changes in the  $K_3$  and  $K_5$  extracted coefficients. To counteract this problem, which would be seen in ATE systems doing manufacturing test, a new parameter extraction methodology had to be created. After experimenting with many ways of performing this

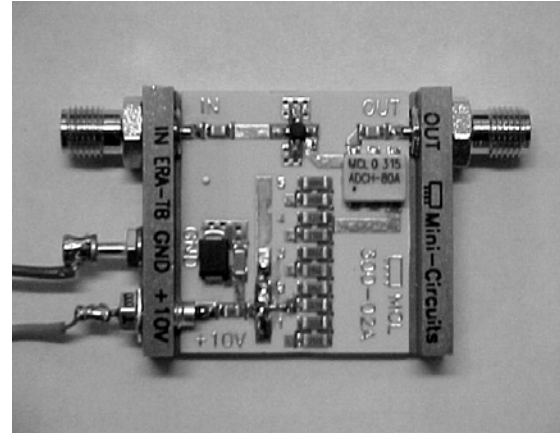


Fig. 3. The Commercial Amplifier (ERA series in Mini-Circuits)

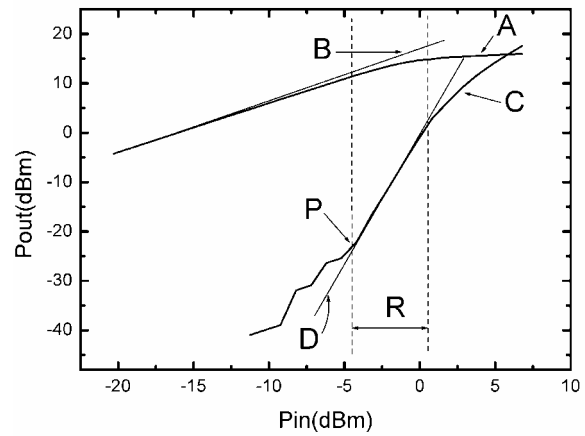


Fig. 4. One-tone data from ERA2 device

parameter extraction, a regional parameter extraction methodology was devised.

Commercial amplifiers and test boards (ERA-series, MiniCircuit, Co.) shown in Fig. 3 were used for the development of this measurement algorithm. As stated above it was difficult to impossible to extract the nonlinear power coefficients for these ERA amplifiers due to noise sources in the measurement system. A new robust measurement extraction algorithm was developed for one-tone gain data as graphed in Fig.4 (ERA 2 amplifier). In this new algorithm, the nonlinear power coefficients are extracted regionally. First, the entire one-tone power compression curve is measured as shown by curve A in Fig. 4. Line B is a straight-line that can be fitted to the low-power amplifier data. A linear regression analysis is applied to this fitting. The fitting range for this straight line B is well defined through the analysis of variance and residuals. From this line B, the  $K_1$  factor is determined. The effects of the  $K_1$  factor are subtracted from the original gain

compression curve A (slope 1/1). Curve C shows the

TABLE II  
COMMERCIAL AMPLIFIERS (ERA SERIES IN MINI-CIRCUITS)

| Device Name | IP <sub>1-dB</sub> *<br>(dBm) | IIP <sub>3</sub> **<br>(dBm) | Estimated IIP <sub>3</sub><br>(dBm) |
|-------------|-------------------------------|------------------------------|-------------------------------------|
| ERA 1       | 1.7                           | 16.3                         | 16.82                               |
| ERA 2       | -0.2                          | 14.5                         | 12.81                               |
| ERA 3       | -8.1                          | 3.4                          | 3.71                                |

\*One-tone test : Source frequency = 100MHz

\*\*Two-tone test : frequencies = 100MHz, 110MHz

TABLE III  
COMMERCIAL AMPLIFIERS (ERA SERIES IN MINI-CIRCUITS)

| Device Name | IP <sub>1-dB</sub> *<br>(dBm) | IIP <sub>3</sub> **<br>(dBm) | Estimated IIP <sub>3</sub><br>(dBm) |
|-------------|-------------------------------|------------------------------|-------------------------------------|
| ERA 2       | -0.4                          | 12.1                         | 12.08                               |

\*One-tone test : Source frequency = 2.4GHz

\*\*Two-tone test : frequencies = 2.4Hz, 2.475GHz

remaining terms on the gain compression curve ( $3/4K_3A_{in}^3 + 5/8K_5A_{in}^5 + \dots$ ). From this curve C, it is easy to see that the  $K_3$  extraction region below point P of region R has very high noise. Instead of  $K_3$ , the  $K_5$  factor is extracted from the compression region R of Fig. 4. This is easily verified because the slope of line D is 5/1. Fortunately, it is not necessary to know the slope of the  $K_3$  factor, since it is 3/1. To determine the value  $K_3$ , one needs to know where it intercepts line D and that is at point P. Point P is at the intercept between the  $K_3$  line and the  $K_5$  line and is equivalent to IP<sub>35</sub> in Fig.3. Point P is also the highest S/N point in the measured  $K_3$  factor data.

Table II shows the measured characteristics and estimated IIP3 of the ERA devices (ERA1, ERA2 and ERA3). From this table, the difference between the measured IIP3 and the estimated IIP3 is less than 2dB in all cases and less than or equal to 0.41 dB for most cases. The ERA2 amplifier is retested at a relatively high frequency (2.4GHz) in Fig.8. The result in Table III shows that this algorithm is working in microwave

frequencies. Through these experiments a method for predicting IIP3 using a one-tone LNA gain measurement was developed.

## 4. Conclusion

In this paper, IIP3 estimation from the gain compression curve was demonstrated from a one-tone test for both simulated and measured data cases. The linear regression analysis on the simulation data gives the fitting range and nonlinear coefficients. The modification of the fitting algorithm on the real measurement data enables this technique. This method estimates the values for both gain compression and IIP3 without the need of a two-tone test. Practically, this approach means that the measurement of output power without any filter gives two important RF parameters when sweeping input power. This simplified the circuit and the measurement for both 1dB gain compression and IIP3 since only a one-tone test is needed. A typical RF/Mixed-signal test may use this approach to avoid the difficulty of the two-tone measurement. This simplified test can be very important for production test.

## 5. References

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