# Characterizing Intermodulation Distortion of High-Power Devices

**M. Ibrahim Khalil**

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), Gustav-Kirchhoff-Str. 4, D-12489 Berlin, Germany.

Email: ibrahim.khalil@fbh-berlin.de

*Modern wireless communication systems demand for high power and broadband devices. There are different technologies emerging offering more and more power density, with single devices delivering power levels above 100 Watts. These devices are targeted for broadband telecommunications like W-CDMA or Wi-Fi application. Intermodulation distortion is very critical in these applications because it generates crosstalk and requires costly linearization techniques. Therefore, it is necessary to characterize the devices for their linearity very accurately. A classical approach is to measure IP3. Because of the high power levels, however, this is not straightforward and requires a dedicated test setup. This is presented here, along with some tips and tricks to measure such devices.*

## I. INTERMODULATION DISTORTION

If an RF amplifier is used to amplify a pure sine wave then the output signal consists of the amplified signal and higher harmonics. The nearest harmonic product occurs at the double of the signal frequency and thus can be filtered out easily. For a modulated signal, however, this does not work anymore because mixing products are generated which fall in the signal band and it is impossible to filter them out. These mixing products are called intermodulation distortion products. The simplest signal having such characteristics is a two-tone signal, which is similar to an amplitude-modulated signal. A two-tone signal consists of two closely spaced sine waves. The following equations and Fig. 1 illustrate the intermodulation distortion mechanism.

If we consider an amplifier or any device that has a nonlinear transfer characteristic then the output of the device can be written as the function of input as a power series:

$$V_{out} = a_0 + a_1.V_{in} + a_2.V_{in}^{\ 2} + a_3.V_{in}^{\ 3} + .......a_n.V_{in}^{\ n} + ....... \tag{1}$$

A simple two-tone signal having the same amplitude A can be written as:

$$f_1 + f_2 = A(\sin\omega_1 t + \sin\omega_2 t) \tag{2}$$

The next step is to replace Vin in equation (1) by the two-tone signal as shown in equation (2) and to do some mathematical manipulations to have a spectral representation. Fig. 1 shows the resulting frequency components considering the terms up to third order in eqn. (1), Tab. 1 adds details on the respective spectral lines.

| **Frequency components** | **Magnitude** | **Phase** |
|---|---|---|
| dc | $a_0 + a_1 \ .A^2$ | … |
| $f_1, f_2$ | $a_1 A + \frac{9}{4} a_3 \ .A^3$ | *Sin* |
| $2f_1, 2f_2$ | $\frac{1}{2} a_2 \ .A^2$ | *-Cosine* |
| $3f_1, 3f_2$ | $\frac{1}{4} a_3 \ .A^3$ | *-Sin* |
| $(f_1 + f_2), (f_2 - f_1)$ | $a_2 \ .A^2$ | *-Cosine, Cosine* |
| $(2f_1 + f_2), (2f_2 + f_1)$ | $\frac{3}{4} a_3 \ .A^3$ | -Sin |
| $(2f_1 - f_2)$ | $\frac{3}{4} a_3 \ .A^3$ | *Sin* for $2f_1 \rangle f_2$<br>Otherwise –sin |
| $(f_1 + 2f_2), (f_1 - 2f_2)$ | $\frac{3}{4} a_3 \ .A^3$ | *Sin* for $2f_2 \rangle f_1$<br>Otherwise –sin |

Tab. 1: List of the output frequency components of a nonlinear system excited by a two-tone signal. The phase of a term is defined by its behavior at t=0.

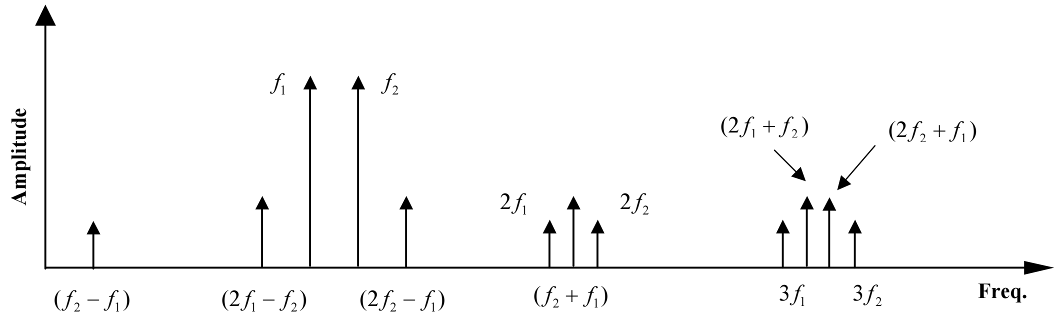

Fig. 1: The output spectrum of a device excited with a two-tone signal

The components at $(2f_1 - f_2)$, $(2f_2 - f_1)$ are of special interest because they fall inside the signal band. They are commonly referred to as third-order intermodulation products (IM3). $(2f_1 - f_2)$ is called "IM3L" and $(2f_2 - f_1)$ is called "IM3U" where "L" and "U" stand for Lower and Upper sideband. If the input signal is increased by a factor x then IM3 products will increase by $x^3$. That means in a flat gain operation, if the input and output fundamental signal amplitude is increased by 1 dB, the third-order components grow by 3 dB. If we imagine that we could increase the input signal amplitude further and further while maintaining this slope, at some point the IM3 will meet the Pout curve. This point is defined as third-order intercept point, often abbreviated as IP3 or TOI. This point is normally a point derived by extrapolation. A real amplifier will reach saturation far below this power level. The IP3 has been the most widely used measure for defining device linearity. Intercept points of any order can be calculated by a single RF measurement when applying the following formulas,

$$IP_n = Pout_{(fundamental)} + \frac{(Suppression)_n}{(n-1)} \quad (2)$$

where, $(Suppression)_n = Pout_{(fundamental)} - Pout_{(IM\,n)}$

For IP3, one obtains the specific result

$$IP_3 = Pout_{(fundamental)} + \frac{Pout_{(fundamental)} - Pout_{(IM3)}}{2} \quad (3)$$

This calculation is valid only if the measurement is performed carefully within the linear operation regime ensuring that the distortion products are well above the noise level.

## II. TEST SETUP

Usually the two-tone test signal is generated combining the output signals of two signal-generators. This method has a few drawbacks and difficulties:

i. It is very difficult to maintain equal amplitude of both tones due to the individual control of each tone. Especially if the signals are amplified by individual external amplifiers to obtain higher driving power problems arise due to gain differences in these amplifiers.

ii. In order to achieve stable and reproducible results the phases of the two signals must be controlled, which is maintained only if phase-locking the two generators externally.

iii. If the signal is first combined and then amplified by a single amplifier this amplifier itself generates distortion products, which result in an incorrect measurement. In this case, the amplifier must be operated at a large power backoff, which leads often to a very expensive solution and sometimes may be even impossible.

To avoid these problem modern multi-tone generators were developed. These generators have a built-in wide-band I-Q modulator. Controlling quadrature I-Q signals at the base-band it is possible to generate arbitrary multi-tone signals. If we generate a two-tone signal by this kind of generator the two-tone signal is available from a single channel, which eliminates the first two problems mentioned above. However, the output power of the generator is not very high and therefore we encounter the same problem like before in amplifying the signal without distortion, which is particular important for high-power devices. But, as we can control the base-band I-Q signal there is a possibility to compensate the distortion of the amplifier by a proper predistortion of the I-Q modulation. This, of course, requires an option at the generator to control the I-Q signal externally.

Therefore, it is necessary to set up a combined system with a connection between the analyzer and the generator. One has to measure the distortion products of the amplifier and, based on this information, produce a predistorted base-band signal at the input of this amplifier so that the resulting distortion components at the output vanish. This process can be called linearization. In our case, we use an Agilent PSG (Performance Signal Generator) and PSA

(Performance Spectrum Analyzer)[1] connected by GPIB to a computer. Such a measurement system using a multi-tone generator is shown in Fig. 2

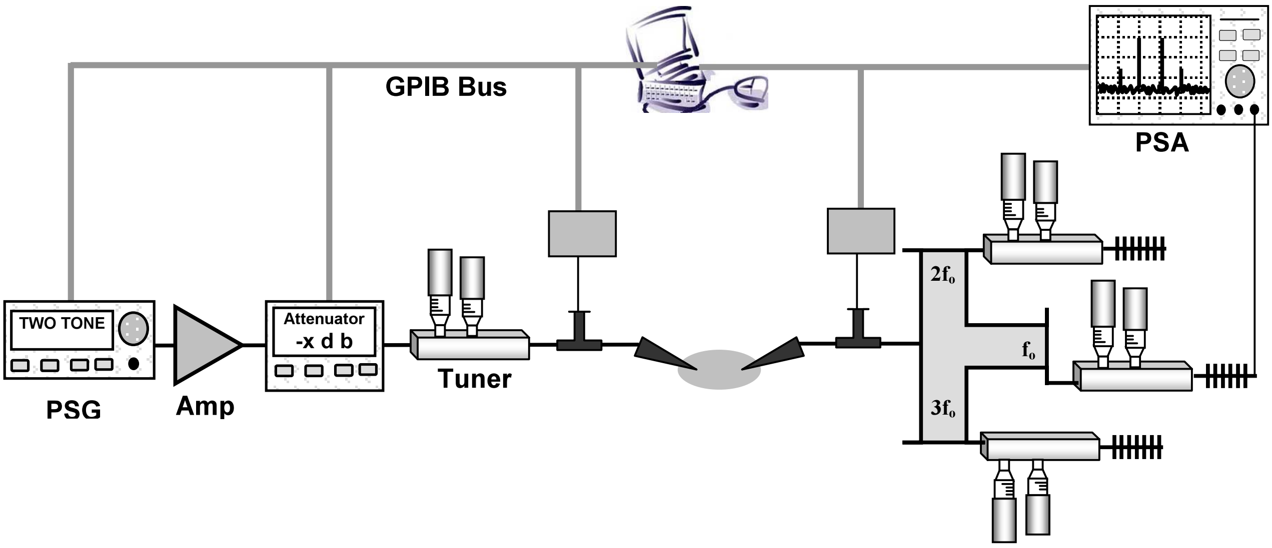

Fig. 2: IP3 measurement setup

As shown in Fig 2, a two-tone signal is generated using a PSG. Next to the generator, there is an amplifier followed by an automatic attenuator. Such an automatic attenuator, also remotely controlled by the computer, is required to realize the power sweep. This is necessary because the distortion of the input amplifier is suppressed by predistortion as stated earlier. But this linearization holds only at a particular power level. Thus, if the power level is swept at the generator the linearization will not be valid for the entire sweep and it is necessary to perform this linearization for each power value, which is impractical because of several reasons: First, linearization is very sensitive and not well reproducible. Thus, when using predertermined I-Q data from a look-up table, this may not yield the desired low distortion levels at the amplifier output. This is because the linearization depends on many factors like amplifier gain, phase, temperature etc. Second, the correction is achieved by an adaptive optimization algorithm and therefore time consuming. Moreover, the DUT (Device Under Test) must be replaced by a through. Therefore, the best idea is to perform the correction of the input amplifier at the highest possible output power and realizing the power sweep by using the step attenuator.

In Fig 3, the test signal is shown before and after linearization. To do the linearization we used Agilent Signal Studio[1] software but one can do the correction also manually by rotating the I-Q offset in the generator or applying an optimization program. The Signal Studio software works with Agilent PSA and PSG. The software gets the distortion data from the PSA and calculates an approximate distortion parameter according to the gain of the path (PSG output to PSA input) and rotates the I-Q offset at the generator. Then the output is measured again and compared with the previous setting. In this way, a continuous iteration is done to find the optimum pre-distortion parameter.

However, one must take care of selecting the appropriate amplifier and bias Tees.

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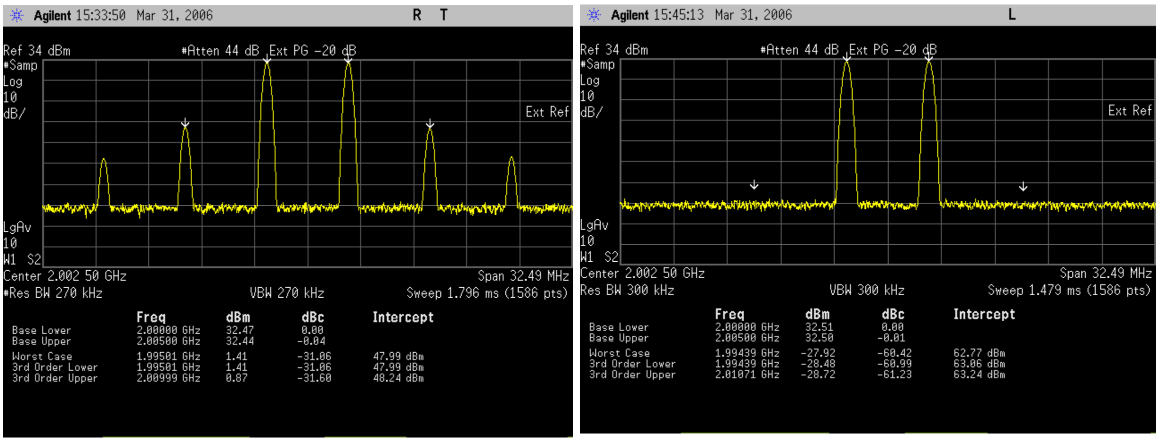
[1] PSA and PSG are the trademarks of Agilent Technologies.

*The Input Amplifier:*

If the Amplifier produces too high distortions then the software may not find a solution to linearize (and it might even be impossible on principle because the linearization concepts are limited in terms of the distortion level they can compensate). One should use an amplifier having low-noise, high-IP3 and broadband characteristics. If the amplifier is narrow-band (for ex. LDMOS amplifiers) it may be very difficult or impossible to linearize it according to the above-mentioned technique. In our case, we use GaAs-HBT and GaN-HEMT amplifiers. We tried Si LDMOS and TWT amplifiers as well but were not able to achieve satisfactory linearization even after a number of iterations.

Also, it is always better to have a single amplifier with large enough output power and gain margin. If more than one amplifiers are connected in series to achieve higher gain and power, it becomes difficult to linearize them due to interstage distortions.

The test signals before and after correction are shown in Fig 3. Here the tones have 5 MHz spacing and a linearization was done on a bandwidth of 25 MHz to suppress 3rd and 5th order distortion components.



| | Freq | dBm | dBc | Intercept |
|---|---|---|---|---|
| Base Lower | 2.00000 GHz | 32.47 | 0.00 | |
| Base Upper | 2.00500 GHz | 32.44 | -0.04 | |
| Worst Case | 1.99501 GHz | 1.41 | -31.06 | 47.99 dBm |
| 3rd Order Lower | 1.99501 GHz | 1.41 | -31.06 | 47.99 dBm |
| 3rd Order Upper | 2.00999 GHz | 0.87 | -31.60 | 48.24 dBm |

| | Freq | dBm | dBc | Intercept |
|---|---|---|---|---|
| Base Lower | 2.00000 GHz | 32.51 | 0.00 | |
| Base Upper | 2.00500 GHz | 32.50 | -0.01 | |
| Worst Case | 1.99439 GHz | -27.92 | -60.42 | 62.77 dBm |
| 3rd Order Lower | 1.99439 GHz | -28.48 | -60.99 | 63.06 dBm |
| 3rd Order Upper | 2.01071 GHz | -28.72 | -61.23 | 63.24 dBm |

Fig. 3: Test signal before and after linearization

*Bias Tee:*

It is very important to select proper bias-Ts for an IP3 measurement. The bias-T must cover the frequency range of the envelope, or the tone spacing i.e., $(f_2 - f_1)$. If the bias T does not pass this frequency component properly the envelope will be distorted and the measurement can be incorrect. This shows up as unsymmetry between the lower (IM3L) and upper (IM3U) distortion products, which may be misinterpreted as memory effect of the device.

We have also added tuners at the input and output for device characterization at different source and load impedances. A very high quality triplexer is used at the output to separate higher harmonics and tune them independently so that higher harmonic effects on linearity can be studied.

## III. CALIBRATION

A power calibration is necessary to perform accurate measurements. Loss at the output network must be determined using a network analyzer or a power meter. For this purpose, output and input are connected by a through and a power sweep is done using the attenuator. For each position of the attenuator, the power is measured taking into account the losses in the output network i.e., in the prober, the connectors, and the cable, and, if applicable, any attenuator in the input of the spectrum analyzer. The measured power is later used as the input power at the DUT for different attenuator positions.

## IV. MEASUREMENTS

The PSA provides a TOI measurement option, which is based on the suppression formula stated earlier in equation (3). This measurement has the following disadvantages:

i. The whole bandwidth from $(2f_1 - f_2) to\ (2f_2 - f_1)$ must be selected at once. Therefore, the noise level of the analyzer increases and it is not possible to measure small distortion values.

ii. Without performing a power sweep one does not know whether the measurements are reliable. If the device is operated at low input power the distortion components may not be high enough compared to system noise (i.e., close to or lower than MDS, the Minimum Detectable Signal). In this case, the analyzer takes the noise level as distortion component amplitude, which provides a totally wrong result. On the other hand, if the input level is too high the device enters the saturation region, it will show huge distortion and the results do not satisfy the IP3 definition. In Fig. 4, these two phenomenons can be observed at low and high input levels.

iii. Under some special conditions, that is at some particular bias-point and RF level, the device may operate in an extremely linear way, which is called sweet spot. One may take advantage of such conditions but it cannot be defined as the IP3 of the device. These points are very sensitive to all parameters and sometimes even not reproducible. Therefore, performing a single-point measurement one may incidentally meet this condition, which leads to a drastical overestimation of the device linearity.

Hence a complete power sweep is necessary. In our case, the measurement system is totally automated and computer controlled by in-house software developed using Lab View[2]. The frequency components of interest are measured individually with a very narrow bandwidth. Therefore, it is possible to detect also very low amplitudes. There is the possibility of hardware averaging and peak search to avoid possible uncertainties. DC-Sweep, RF-sweep and security measures are implemented in the program.

In the following we show an example of a complete measurement. The DUT is a packaged high-power GaN transistor. This device reaches an IP3 of about 50 dBm. To achieve good accuracy, one needs an adequate amount of linear input power. Therefore, an external amplifier was used to amplify the test signal and its distortion was suppressed as described above in order to obtain a distortion-free two-tone signal.

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[2] Lab View is a trademark of National Instruments.

Please notice that up to an input power of about 4 dBm the distortion components are below the MDS (Minimum detectable signal). This illustrates that to measure such a big device enough driving power is necessary to have a correct measurement. If the power of third-order distortion components does not grow according to a 3rd order rule, either there is no distortion by transfer mechanisms (this is the case for ideal linear devices such as a passive component, for instance) or the distortion components are out of measurement sensitivity. If the 3rd order distortion components show a 1st order characteristics, i.e., the curve is parallel to the fundamental power, this can be interpreted as input distortion, which might origin from the input amplifier or attenuator and is only amplified by the DUT.

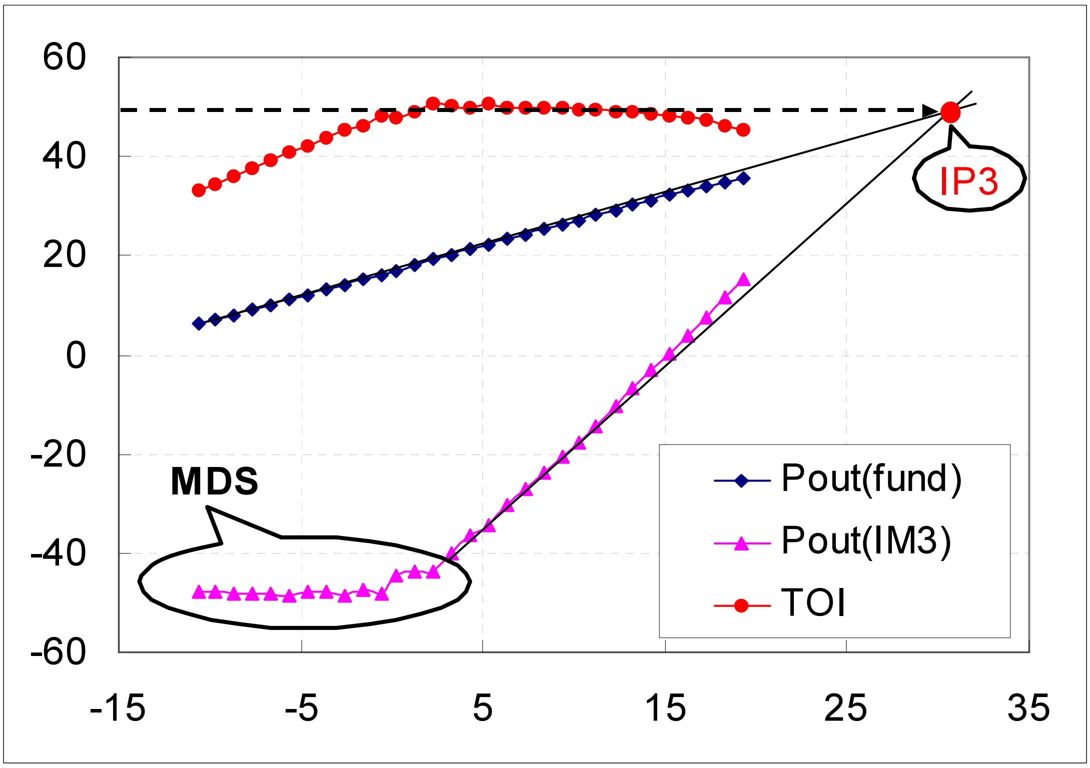

Fig. 4: Example of measurements: Output power, 3rd-order intermodulation power and the corresponding 3rd-order intercept point as a function of input power. The device is a packaged GaN-HEMT.

## V. CONCLUSION

The paper describes the basics of intermodulation distortion and presents a complete IP3 measurement setup for high-power device characterization. Details of the measurement system are described and critical issues and calibration methods are highlighted. The set-up has proven its usefulness in characterizing high-power GaN-HEMTs with IP3 in the 50 dBm range. Beyond the IP3 measurement described here, the system offers further capabilities in distortion analysis, such as ACPR (Adjacent channel power ration), AM-AM, AM-PM, Digital-Modulation analysis, Code-domain analysis for 3GPP, EVM (Error Vector Magnitude) and CCDF (Power Complementary Cumulative Distribution Function).

# VI. REFERENCES

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