Measuring the Nonlinearities of RF-Amplifiers using Signal Generators and a Spectrum Analyzer

Application Note

Products:

- R&S®FSC
- R&S®SMC100A

A typical application for signal generators and spectrum analyzers is measuring the nonlinearities of RF amplifiers.

This application note discusses the mechanisms of such nonlinearities and describes the nonlinearity measurements using the R&S Value Instruments RF Signal Generator R&S®SMC100A and Spectrum Analyzer R&S®FSC.

Application Note

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Table of Contents

1 Nonlinearities – Basics

1.1 Compression

The output power of an amplifier typically exhibits a linear correspondence to the input power as it changes (see Fig. 1-1): the gain, i.e. the output power/input power quotient remains constant (see Fig. 1-2). If you successively raise the power of the input signal, starting at a certain point the output power no longer corresponds exactly to the input power. There is an increasing deviation, the closer you come to the amplifier's maximum output power: the amplifier compresses.

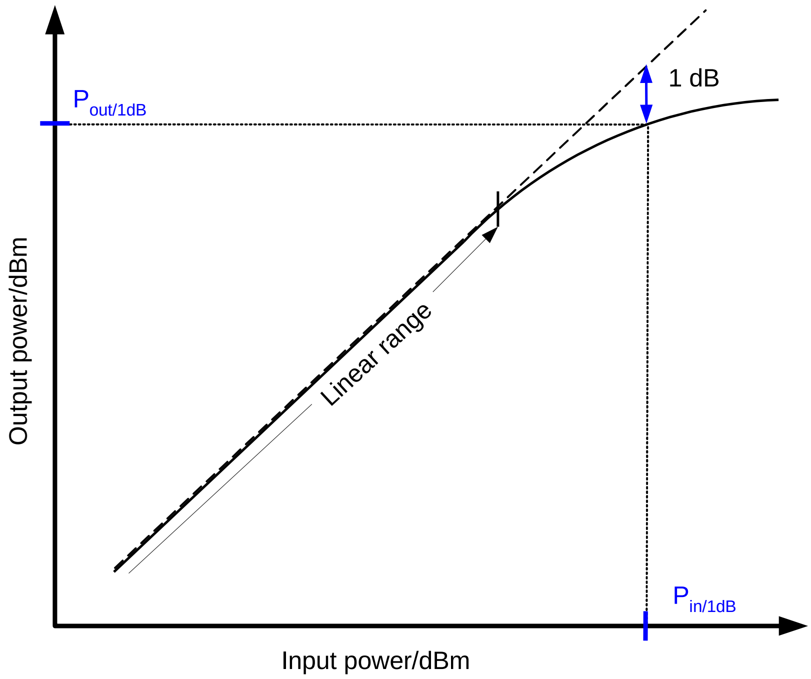


Fig. 1-1: Gain versus output power and definition of the 1 dB compression point at the amplifier output ($P_{out/1dB}$)

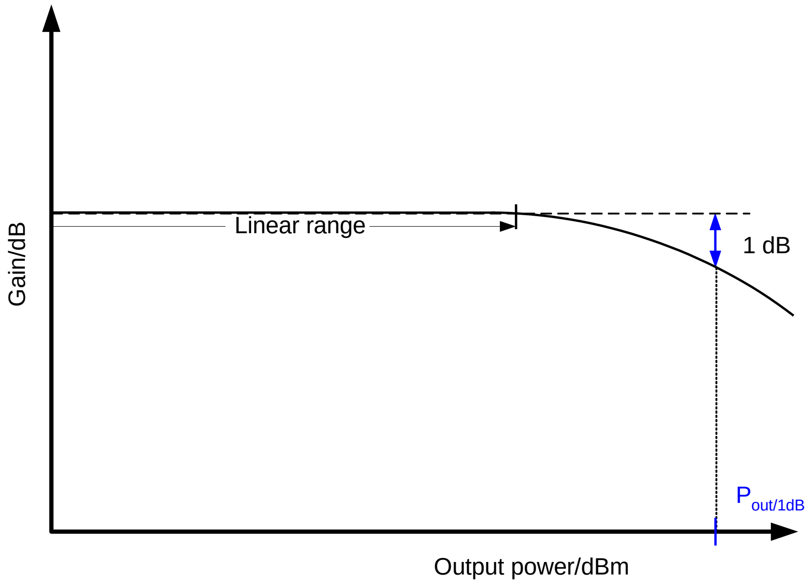


Fig. 1-2: Gain versus output power and definition of the 1 dB compression point at the amplifier output ($P_{out/1dB}$)

The 1 dB compression point specifies the output power of an amplifier at which the output signal lags behind the nominal output signal by 1 dB. A linear gain, i.e. a gain with a sufficiently low driving signal, would yield the nominal output signal. The difference in the level of the output signal to the nominal output signal can be at least qualitatively explained by the over-proportional in harmonics with a high driving signal.

To prevent the power of the harmonics from corrupting the measurement result, the output power must be selectively measured. The amplifier compression is best measured by using a setup with a signal generator and spectrum analyzer as subsequently described in chapter 2. If you want to use a power meter instead of the spectrum analyzer to measure the power, a suitable lowpass or bandpass must be connected ahead of the power meter to eliminate the effect of the harmonics on the result.

Compression measurements can also be performed with network analyzers using the power sweep function.

1.2 Nonlinearities

An ideal amplifier can be viewed as a linear two port and transfers signals from the input to the output without distorting them. The power transfer function of such a two-port is as follows:

$$P_{out}(t) = G_P \cdot P_{in}(t)$$ **(equation 1)**

where $P_{out(t)}$ power at output of two-port

$P_{in(t)}$ power at input of two-port

G_P power gain of two-port

The connection to the input and output voltage is as follows:

$$P_{in}(t) = \frac{1}{R_{in}} \cdot v_{in}^2(t)$$ **(equation 2)**

and

$$P_{out}(t) = \frac{1}{R_L} \cdot v_{out}^2(t)$$ **(equation 3)**

where R_{in} input resistance of two-port (for simplification, assumed real)

R_L load resistance of two-port (for simplification, assumed real)

$v_{in}(t)$ voltage at input of two-port

$v_{out}(t)$ voltage at output of two-port

The voltage transfer function of the linear two-port is as follows:

$$v_{out}(t) = G_v \cdot v_{in}(t)$$ **(equation 4)**

where G_v voltage gain of two-port

For the sake of clarity, the voltage gain is examined in the following.

In practice, ideal two-ports are only possible using passive components. For example, resistive attenuators are assumed to be ideal within wide limits. Two-ports that contain semiconductor components – such as amplifiers – exhibit nonlinearities. A nonlinear transfer function can be approached mathematically by a power series (Taylor series). The following formula is used:

$$v_{out}(t) = \sum_{n=0}^{\infty} a_n \cdot v_{in}^n(t) = a_0 + a_1 \cdot v_{in}(t) + a_2 \cdot v_{in}^2(t) + a_3 \cdot v_{in}^3(t) + \ldots$$ **(equation 5)**

where	$v_{out}(t)$	voltage at output of two-port
	$v_{in}(t)$	voltage at input of two-port
	a_0	DC component
	a_1	gain G_v
	a_n	coefficient of the nonlinear element of the voltage gain

In most cases, it suffices to take the square and cubic component into account, which means that equation 5 only has to be developed up to n = 3. The effects of the nonlinearities of a two-port on its output spectrum depend on the input signal.

1.2.1 Single-tone driving – harmonics

If a single sinusoidal signal $v_{in(t)}$ is applied to the input of the two-port

where

$$v_{in.}(t) = \hat{V}_{in}.\sin(2\pi f_{in,1} \cdot t) \qquad \text{(equation 6)}$$

and

$$v_{in.}(t) = \hat{V}_{in}.\sin(\omega_{in,1} \cdot t) \qquad \text{(equation 7)}$$

and $\hat{V}_{in}$:	peak value of $v_{in}(t)$
$f_{in,1}$:	frequency of $v_{in}(t)$,
$\omega_{in,1}(t) = 2\pi f_{in,1}$	(angular frequency)

this is referred to as single-tone driving. By inserting equation 7 into equation 5, it can be demonstrated that harmonics of the input signal having the frequencies $f_{n.H} = n \cdot f_{in,1}$ are produced by the nonlinearities (see also Fig. 1-3):

$$v_{out}(t) = a_0 + a_1 \cdot v_{in}(t) + a_2 \cdot v_{in}^2(t) + a_3 \cdot v_{in}^3(t) + \ldots .=$$

$$a_0 + a_1 \cdot \hat{V}_{in}(t)\sin\ (\omega_{in,1} \cdot t) + a_2 \cdot \hat{V}_{in}^2 \cdot \sin^2(\omega_{in,1} \cdot t) + a_3 \cdot \hat{V}_{in}^3 \cdot \sin^3(\omega_{in,1} \cdot t) + \ldots..$$

Applying the trigonometric conversion:

$$\sin^2(x) = \frac{1}{2}(1 - \cos 2x) \text{ and } \sin^3(x) = \frac{1}{4}(3 \cdot \sin x - \sin 3x)$$

to the square and cubic component yields:

$$= a_0 + a_1 \cdot \hat{V}_{in}(t) \cdot \sin\ (\omega_{in,1}t) + 0.5 \cdot a_2 \cdot \hat{V}_{in}^2 - 0.5 \cdot a_2 \cdot \hat{V}_{in}^2 \cdot \cos(2\omega_{in,1}t) +$$
$$+ 0.75 \cdot a_3 \cdot \hat{V}_{in}^3 \cdot \sin \omega_{in,1}t - 0.25 \cdot a_3 \cdot \hat{V}_{in}^3 \cdot \sin(3\omega_{in,1}t) ....$$

$$= a_0 + 0.5 \cdot a_2 \cdot \hat{V}_{in}^2 + (a_1 \cdot \hat{V}_{in} + 0.75 \cdot a_3 \cdot \hat{V}_{in}^3) \cdot \sin\ (\omega_{in,1}t) - 0.5 \cdot a_2 \cdot \hat{V}_{in}^2 \cdot \cos(2\omega_{in,1}t) -$$
$$- 0.25 \cdot a_3 \cdot \hat{V}_{in}^3 \cdot \sin(3\omega_{in,1}t) ....$$

(equation 8)

Note:

The 2nd harmonic ($2\omega_{in,1}$) is phase-shifted by 90° with respect to the fundamental, since the following trigonometric relationship applies: $\cos(x) = \sin(\pi / 2 - x)$

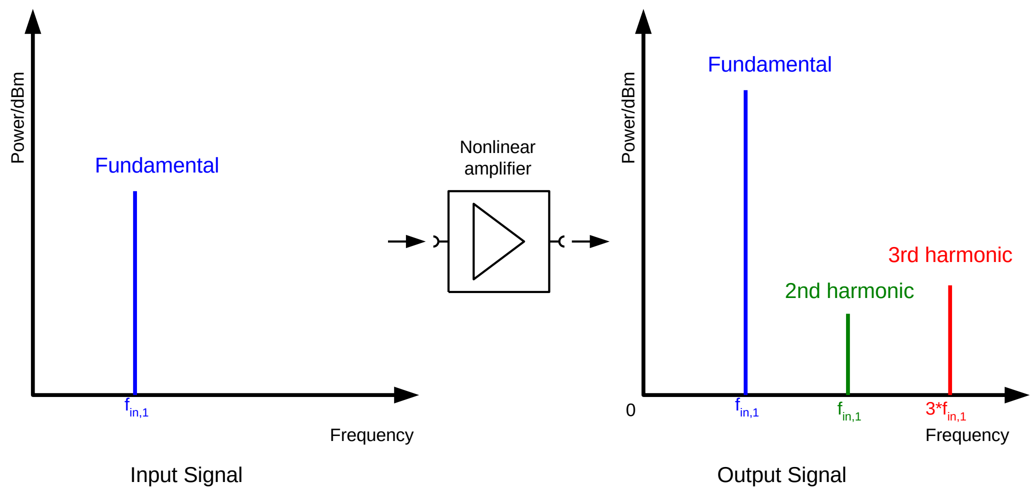


Fig. 1-3: Spectrum before and after a nonlinear two-port

The levels of these harmonics depend on the coefficients an in equation 2. But they also depend on the order n of the particular harmonic and on the input level. The levels of harmonics increase over-proportionally with their order as the input level increases, i.e. changing the input level by Δ dB changes the harmonic level by n · Δ dB.

Data sheet specifications of this type of signal distortion are usually limited to the 2nd and 3rd harmonic, for which the level difference a_{kN} to the fundamental at the output of the two-port is specified. Such specifications apply only to a particular input level P_{in} or output level P_{out} that must also always be specified.

A level-independent specification using the 2nd harmonic intercept (SHI) point is more favorable for comparisons.

Definition:

The SHI_{in} or SHI_{out} point corresponds to the fictitious input or output level at which the 2nd harmonic of the output signal would exhibit the same level as the fundamental at the output of the two-port. The fundamental is assumed to be linearly transferred (see Fig. 1-4).

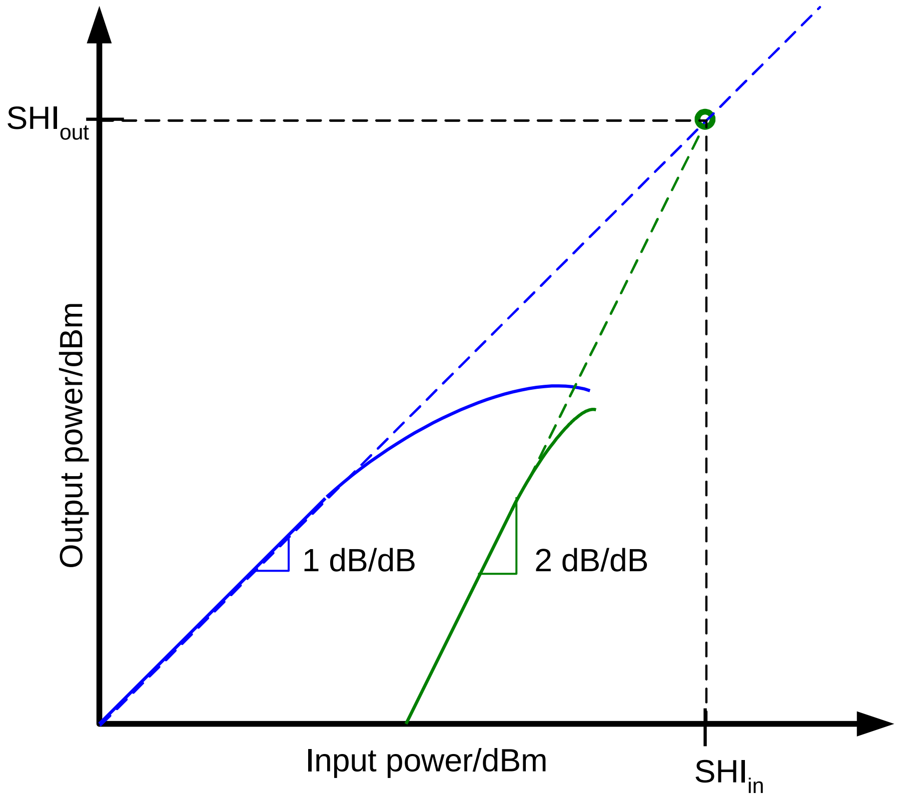


Fig. 1-4: Graphical definition of the 2nd harmonic intercept (SHI) point at the two-port input (SH_{Iin}) and at the two-port output (SHI_{out})

In practice, this point can hardly ever be reached, since the two-port, as shown in Fig. 1-4, compresses already at low input levels. The intercept point can be referenced to the input as well as the output level and is referred to as the input or output intercept point, respectively (called SHI_{in} or SHI_{out} here).

Assuming the input level P_{in} and the harmonic ratio a_{k2} of the 2nd harmonic are known, this point can be calculated as follows:

$$SHI_{in}/dBm = a_{k2}/dB + P_{in}/dBm \qquad \text{(equation 9)}$$

If SHI_{out} is referenced to the output, the following applies:

$$SHI_{out}/dBm = SHI_{in}/dBm + g \qquad \text{(equation 10)}$$

where g: power gain of two-port, in dB.

or also:

$$SHI_{out}/dBm = a_{k2}/db + P_{out}/dBm \qquad \text{(equation 11)}$$

if the output level is taken as the reference.

Example:

At 0 dBm input power and 30 dBm output power (gain g = 30 dB), an amplifier has a harmonic ratio of 30 dB (K2).

SHI_{in}= 30 dB + 0 dBm = + 30 dBm, referenced to the input

or

SHI_{out}= 30 dB + 30 dBm = + 60 dBm, referenced to the output.

1.2.2 Two-tone driving – intermodulation

Two-tone driving applies a signal $v_{in}(t)$ to the input of the two port. This signal consists of two sinusoidal signals of the same amplitude.

The following formula is valid for the input signal:

$$V_{in.}(t) = \hat{V}_{in,1} \cdot \sin(2\pi f_{in,1} \cdot t) + \hat{V}_{in,2} \cdot \sin(2\pi f_{in,2} \cdot t) \qquad \text{(equation 12)}$$

where $\hat{V}_{in,1,2}$ peak values of the two sinusoidal signals

$f_{in,1}$, $f_{in,2}$ signal frequencies

Inserting equation 12 into the nonlinear transfer function according to equation 5 yields at the output of the two-port, among other things, the intermodulation products listed in Table 1-1. The angular frequency ω is always specified, where $\omega_1 = 2\cdot\pi\cdot f_{in,1}$ and $\omega_2 = 2\cdot\pi\cdot f_{in,2}$.

The new frequencies produced are a result of the following trigonometric conversions:

$$\sin^2(x) = \frac{1}{2}(1-\cos 2x)$$ 2nd harmonic

$$\sin^3(x) = \frac{1}{4}(3\cdot\sin x - \sin 3x)$$ 3rd harmonic

$$\sin(x)\cdot\sin(y)=\frac{1}{2}\cos(x-y)-\frac{1}{2}\cos(x+y)$$ 2nd order intermodulation products

as well as:

$$\sin^2(x)\cdot\sin(y)=\frac{1}{2}(1-\cos 2x)\cdot\sin(y)$$ and

$$\cos(2x)\cdot\sin(y)=\frac{1}{2}\sin(2x-y)+\frac{1}{2}\sin(2x+y)$$ 3rd order intermodulation products

Description	Formulas	Comment
DC component	$a_2\cdot 0.5\cdot\left(\hat{V}^2_{in,1}+\hat{V}^2_{in,2}\right)$	
Fundamentals	$a_1\cdot\hat{V}_{in,1}\cdot\sin(\omega_1 t)$ $a_1\cdot\hat{V}_{in,2}\cdot\sin(\omega_2 t)$	
2nd order harmonics	$a_2\cdot 0.5\cdot\hat{V}^2_{in,1}\cdot\cos(2\omega_1 t)$ $a_2\cdot 0.5\cdot\hat{V}^2_{in,2}\cdot\cos(2\omega_2 t)$	-6 dB in comparison with 2nd order intermodulation products
2nd order intermodulation products	$a_2\cdot\hat{V}_{in,1}\cdot\hat{V}_{in,2}\cdot\cos(\omega_1+\omega_2)t$ $a_2\cdot\hat{V}_{in,1}\cdot\hat{V}_{in,2}\cdot\cos(\omega_2-\omega_1)t$	
3rd order harmonics	$a_3\cdot 0.25\cdot\hat{V}^3_{in,1}\cdot\cos(3\omega_1 t)$ $a_3\cdot 0.25\cdot\hat{V}^3_{in,2}\cdot\cos(3\omega_2 t)$	-9.54 dB in comparison with 3rd order intermodulation products $(20\log(0.25/0.75)=-9.54dB)$
3rd order intermodulation products	$a_3\cdot\hat{V}^2_{in,1}\cdot\hat{V}_{in,2}\cdot 0.75\cdot\cos(2\omega_1+\omega_2)t$ $a_3\cdot\hat{V}_{in,1}\cdot\hat{V}^2_{in,2}\cdot 0.75\cdot\cos(2\omega_2+\omega_1)t$ $a_3\cdot\hat{V}^2_{in,1}\cdot\hat{V}_{in,2}\cdot 0.75\cdot\cos(2\omega_1-\omega_2)t$ $a_3\cdot\hat{V}_{in,1}\cdot\hat{V}^2_{in,2}\cdot 0.75\cdot\cos(2\omega_2-\omega_1)t$	

Table 1-1:Intermodulation products up to max. 3rd order with two-tone driving

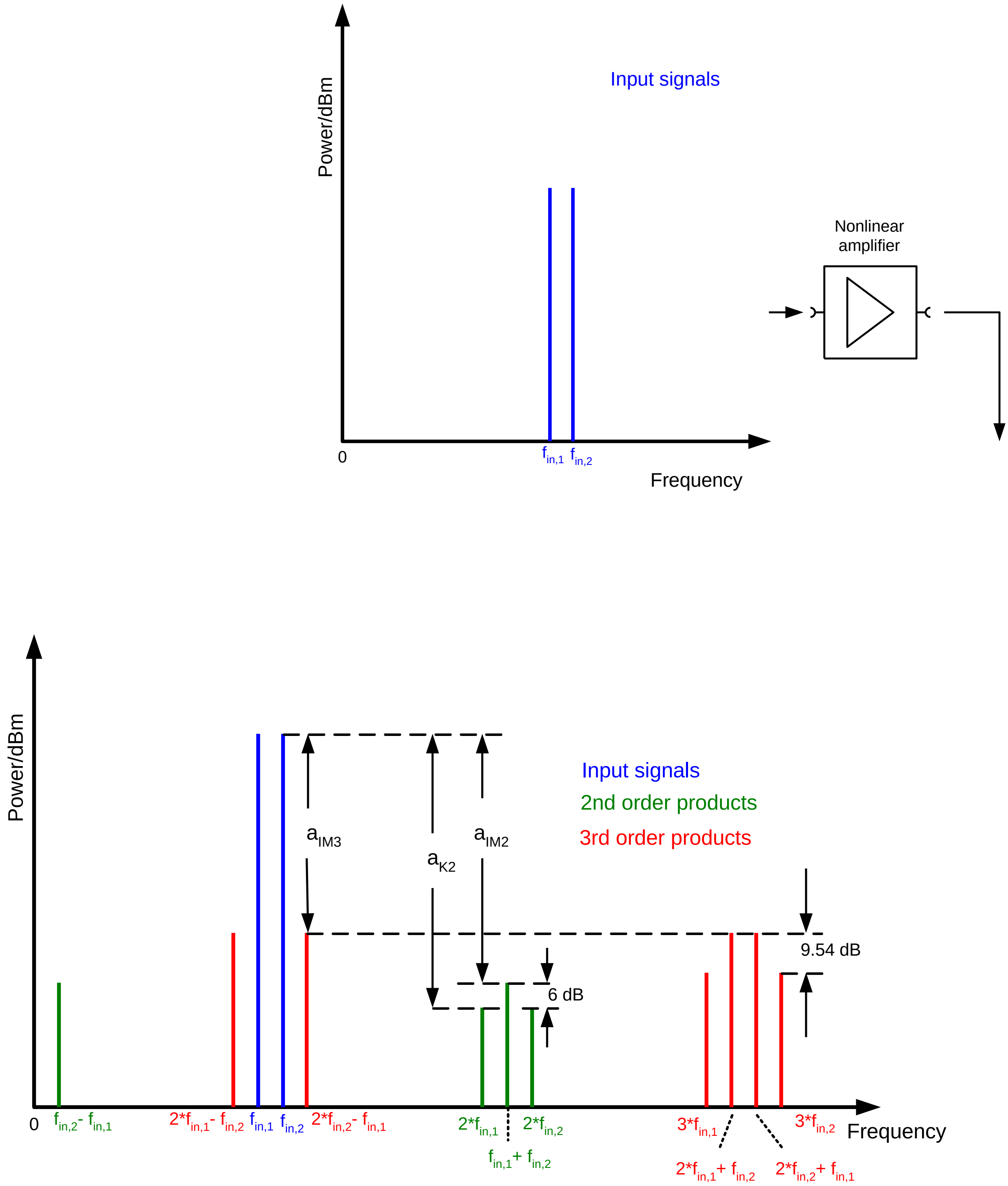


Fig. 1-5: Output spectrum of a nonlinear two-port with two-tone driving for intermodulation products up to max. 3rd order

Besides generating harmonics, two-tone driving also produces intermodulation products (also referred to as difference frequencies). The order of the intermodulation products corresponds to the sum of the order numbers of the components involved. For example, for the product with $2 \cdot f_{in,1} + 1 \cdot f_{in,2}$ the order is 2 + 1 = 3. Table 1-1 takes into account intermodulation products only up to the 3rd order.

The frequencies of even-numbered intermodulation products (e.g. 2nd order) are far away from the two input signals, namely at the sum frequency and at the difference frequency. They are in general easy to suppress by filtering.

Some of the odd-numbered intermodulation products (the difference products) always occur in the immediate vicinity of the input signals and are therefore difficult to suppress by filtering.

Depending on the application, products of both even- and odd-numbered order can cause interference. In the case of measurements on cable TV (CATV) amplifiers where a frequency range of more than one octave is to be tested, harmonics as well as intermodulation products of an even-numbered order occur in the range of interest.

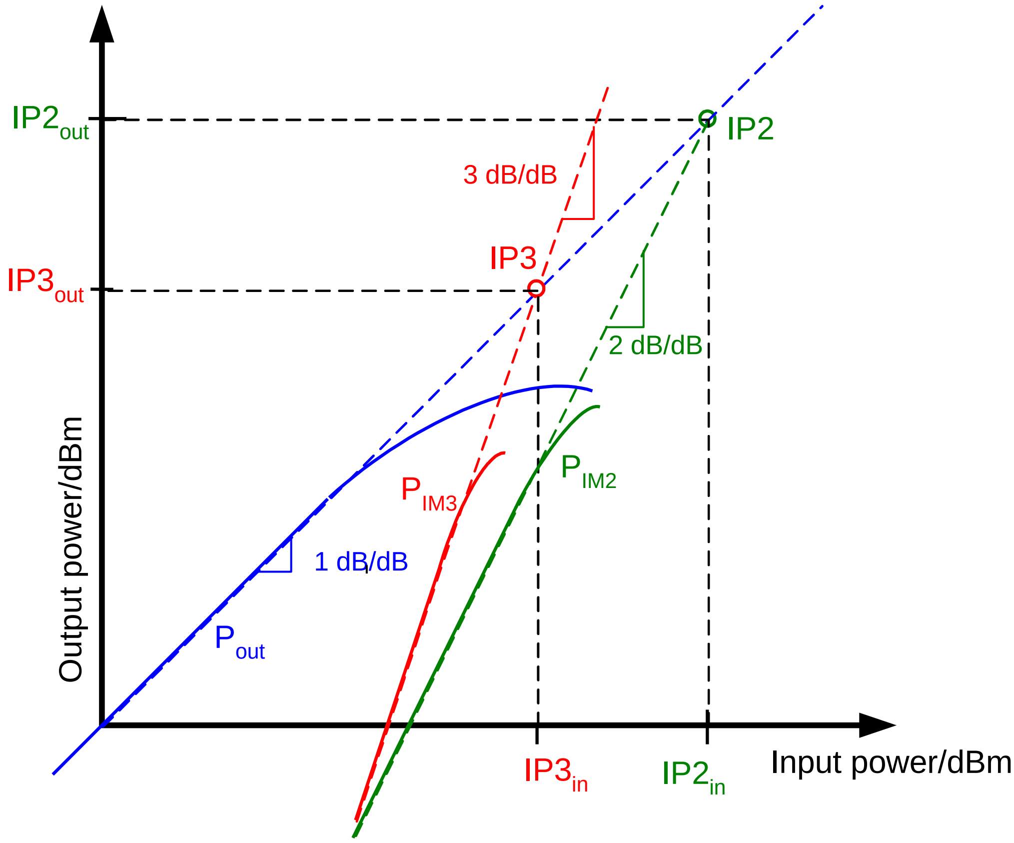


Fig. 1-6: Graphical definition of 2nd and 3rd order intercept points at the input ($IP2_{in}$, $IP3_{in}$) and at the output ($IP2_{out}$, $IP3_{out}$) of an amplifier

As with higher-order harmonics, a level change of the two sinusoidal carriers at the input by Δ dB causes the level of the associated intermodulation product to change by n · Δ dB. Specifications regarding the level differences between intermodulation products and the fundamentals of the sinusoidal carriers thus always require that the output level of the amplifier be specified, for otherwise no statement can be made about its linearity.

Therefore, here too it is advantageous to calculate the nth-order intercept point. The following formula applies to the nth-order intercept point referenced to the input:

$$IPn_{in} = \frac{a_{IMn}}{n-1} + P_{in} \qquad \textbf{(equation 13)}$$

where IPn_{in} nth-order input intercept point, in dBm

a_{IMn} level difference between intermodulation product of nth order and fundamental of input signal, in dB

P_{in} level of one of the two input signals, in dBm

In most cases, the intercept points of the 2nd and 3rd order are specified (see also Fig. 1-6). They are abbreviated as IP2 or SOI (2nd order intercept) and IP3 or TOI (third order intercept), respectively.

Definition:

The 2nd order intercept point $IP2_{in}$ or $IP2_{out}$ corresponds to the fictitious input or output level at which the 2nd order intermodulation product would exhibit the same level as the fundamental at the output of the two-port.

The 3rd order intercept point $IP3_{in}$ or $IP3_{out}$ corresponds to the fictitious input or output level at which the third order intermodulation product would exhibit the same level as the fundamental at the output of the two-port.

In both cases, the fundamental is assumed to be linearly transferred (see Fig. 1-6).

The following formulas apply, respectively, to the 2nd and 3rd order input intercept points:

$$IP2_{in} / dBm = a_{IM2} / dB + P_{in} / dBm \qquad \textbf{(equation 14)}$$

and

$$IP3_{in} / dBm = \frac{a_{IM3}}{2} / dB + P_{in} / dBm \qquad \textbf{(equation 15)}$$

The output intercept points can be calculated from the input intercept points (or, vice versa, the input intercept points from the output intercept points) by adding the gain (g) of the two-port (in dB).

The following formulas apply, respectively, to the 2nd and 3rd order output intercept points:

$$IP2_{out}/dBm = a_{IM2}/dB + P_{in}/dBm + g/dB$$ **(equation 16)**

or

$$IP2_{out}/dBm = a_{IM2}/dB + P_{out}/dBm$$ **(equation 17)**

and

$$IP3_{out}/dBm = \frac{a_{IM3}}{2}/dB + P_{in}/dBm + g/dB$$ **(equation 18)**

or

$$IP3_{out}/dBm = \frac{a_{IM3}}{2}/dB + P_{out}/dBm$$ **(equation 19)**

2nd order intermodulation products with two-tone driving as well as the second harmonic with single-tone driving are the result of the square component of the nonlinear transfer function.

Between SHI and IP2 exists a fixed correlation that is derived from the coefficients from Table 1 (factor of 0.5 of the 2nd order harmonics vis-à-vis the 2nd order intermodulation products):

Second harmonic intercept (SHI) point :

$$SHI/dBm = IP2/dBm + 6dB$$ **(equation 20)**

Data sheets therefore mostly only specify IP2 or SHI, rarely are both values published simultaneously. Intercept points are almost always specified in dBm.

2 Brief Presentation of the Measuring Instruments Used

Whether you work in a major electronics R & D -facility or a small service lab, you are not always performing complex measurements and do not always need the -ultimate in high-end T & M equipment. What you need are precise, -reliable, universal measuring instruments. That is exactly what you get with value instruments from -Rohde & Schwarz: instruments that combine practical features with excellent measurement characteristics, -instruments that are easy to use and easy on the budget.

The practical implementation of different linearity measurements is described on the basis of the value instruments RF Signal Generator R&S®SMC100A and Spectrum Analyzer R&S®FSC briefly presented in the following.

2.1 RF Signal Generator R&S®SMC100A

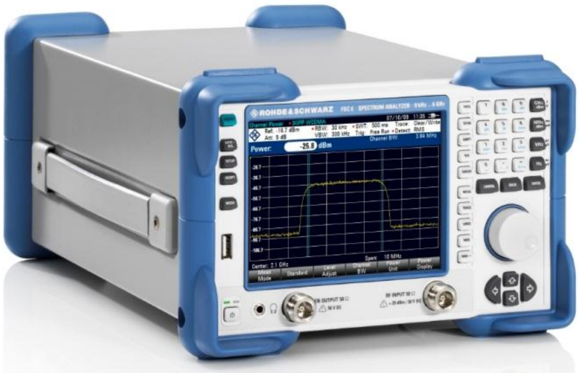
The R&S®SMC100A offers outstanding signal quality at an attractive price. It covers the frequency range from 9 kHz to 1.1 GHz or 3.2 GHz. All important functions like AM/FM/φM/pulse modulation are already integrated in the instrument. This makes the R&S®SMC100A signal generator a flexible and versatile instrument. These outstanding features make the R&S®SMC100A ideally suited for use in service and maintenance labs. Due to its small dimensions and lightweight design, the R&S®SMC100A is also the perfect choice for field applications or training and education environments.

Condensed data of the RF Signal Generator R&S®SMC100A [3]

- Frequency range 9 kHz to 1.1 GHz or 3.2 GHz
- Level range: -   +17 dBm (typ.)
- Modulation mode : AM/FM/φM/pulse
- SSB phase noise: -111 dBc (f=1GHz, 20 kHz carrier offset, 1Hz measurement bandwidth)
- Level uncertainty < 0.9dB
- Harmonics: < -30 dBc
- Remote control via GPIB/IEEE488 interface (option)

2.2 Spectrum Analyzer R&S®FSC

The R&S®FSC is a compact, cost-efficient solution that offers all essential features of a professional spectrum analyzer. It covers a wide range of applications from simple development tasks to production, or can be used for training RF professionals. Moreover, it is ideal for applications in service or maintenance. Its good RF characteristics and its high measurement accuracy help to ensure reliable and reproducible measurement results. The R&S®FSC features a wealth of functions for simplifying and speeding up the development and testing of RF products. Four different R&S®FSC models are available in the frequency range from 9 kHz to 3 GHz or 6 GHz. Owing to its compact design, the R&S®FSC takes up only a minimum of space on a lab bench. When installed in a rack, two R&S®FSC or one R&S®FSC and one R&S®SMC signal generator situated next to each other fit into the 19" space.



Condensed data of the Spectrum Analyzer R&S®FSC [2]

- Frequency range 9kHz to 3 GHz
- Resolution bandwidths 10 Hz to 3 MHz
- Measurement uncertainty : < 1 dB
- SSB phase noise: <-95 dBc (1Hz) (30 kHz carrier offset, f=500 MHz)
- Sensitivity: < -141 dBm (1Hz), <-161 dBm (1Hz) with optional preamplifier
- Third order intercept: >10 dBm, typ. 15 dBm
- Internal tracking generator (model.13/.16)
- Remote control vial USB or LAN

3 Practical Implementation of Linearity Measurements

3.1 Compression Measurement

3.1.1 Test setup:

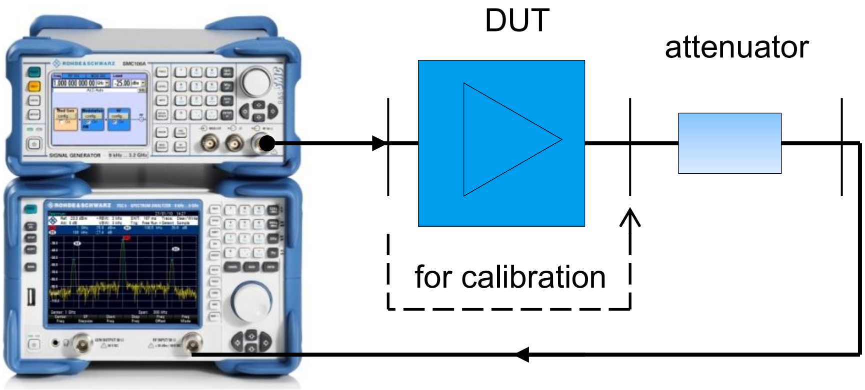


Fig. 3-1: Test setup for compression measurement on amplifiers. For calibration, the DUT is bypassed.

Fig. 3-1 shows the test setup for compression measurements on amplifiers using a signal generator and a spectrum analyzer. The signal generator feeds the amplifier input. To protect the spectrum analyzer input against overloading, the amplifier output is connected with the spectrum analyzer input via a suitable attenuator (depending on the amplifier's power).

To calibrate the test setup, disconnect the DUT and connect the generator output directly to the attenuator. On the spectrum analyzer, enter the deviation of the analyzer's level display from the level set on the generator as the Ref Level Offset.

If you now connect the DUT in between, the correct output power of the amplifier is displayed on the analyzer, and the difference in the levels displayed on the generator and the analyzer is equal to the DUT's gain. The effect of the cable attenuation from the power attenuator to the analyzer is eliminated.

3.1.2 Example:

The 1 dB compression point on an amplifier is to be verified at 824 MHz. The gain is 25 dB, the 1 dB compression point +15 dBm. A 20 dB attenuator is inserted ahead of the analyzer input.

☞ For calibration, connect the generator output to the analyzer input via the 20 dB attenuator

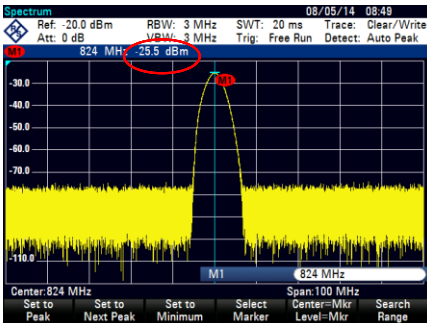
Calibration:

R&S®SMC100A:

- *PRESET*
- *FREQ 824 MHz*
- *LEVEL -5 dBm*
- *RF on*

R&S®FSC:

- *PRESET*
- *FEQ:Center 824 MHz*
- *SPAN 100 MHz*
- ⇨ *AMPT: Ref Level -20 dBm (default state)*
- ⇨ *MKR→: Set to Peak*



The marker (P_{M1}) reads now the attenuated input level of -25.5 dBm

Now enter the difference of the power set on the generator (PG) to the power measured with marker 1 (P_{M1}) as the Ref Level Offset.

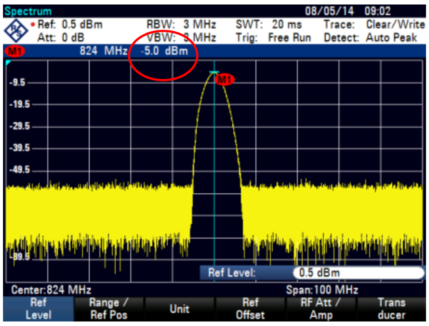
Ref Level Offset x = $P_G - P_{M1}$

Example:

P_G = -5 dBm, P_{M1} = -25.5 dBm → Ref Level Offset = -5 – (-25.5) = 20.5 dB

R&S®FSC:

- ⇨ *AMPT: Ref Offset -20,5 dBm*



The marker display now reads -5 dBm, i.e. the power set on the generator. Before looping in the amplifier, reduce the generator power and set the reference level on the analyzer to +25 dBm.

R&S®SMC100A:

- *LEVEL -20 dBm*

R&S®FSC:

- *AMPT: Ref Level 25 dBm*
- *MKR→: Set to Peak*

☞ Now connect the amplifier output with the attenuator and the amplifier input with the generator output. Increase the generator in steps of 1 dB, and read off the MKR1 level on the analyzer each time.

Generator level/dBm	Analyzer MKR1/dBm	Generator level/dBm	Analyzer MKR1/dBm
-20	5.3	-12	12.7
-19	6.3	-11	13.6
-18	7.2	-10	14.3
-17	8.15	-9	14.9
-16	9.0	-8	15.4
-15	10.0	-7	15.8
-14	10.8	-6	16.2
-13	11.8	-5	16.4

Table 3-1: Example of the measured values for the output power versus the input power of the amplifier. The generator level was increased at 1 dB increments and the marker 1 level was read off with each increment.

Using a spreadsheet analysis program you can now easily display the output versus the input power, or the gain versus the input power, and read off the 1 dB compression point (+14.3 dBm at the output, -10 dBm at the input); see Fig. 3-2 and Fig. 3-3

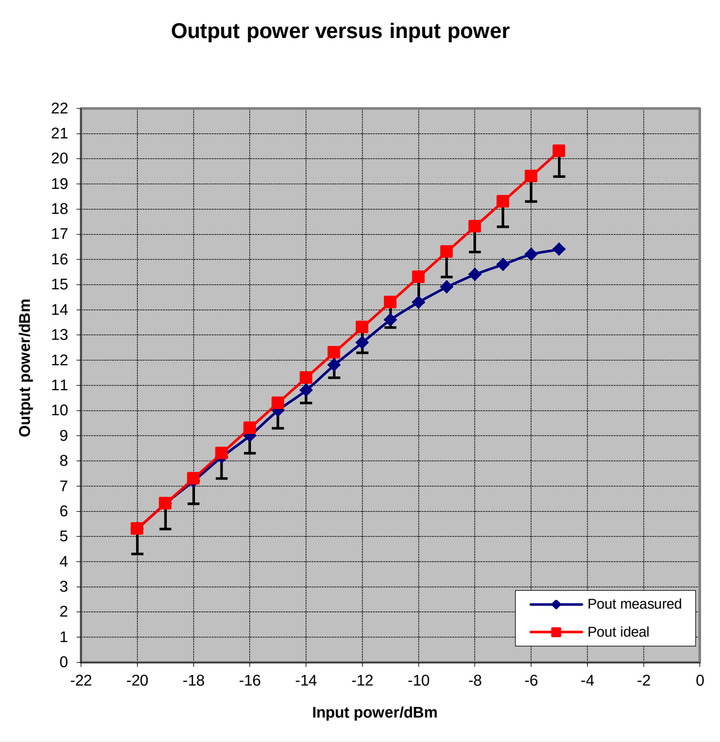


Fig. 3-2: Graphical display of the measured values (Table 3-1). The 1 dB compression point is the intersection point of the 1 dB error indicator of the ideal trace with the measured trace (P_{in}/1dB = approx. -10 dBm, P_{out}/1dB = approx. +14.3 dBm

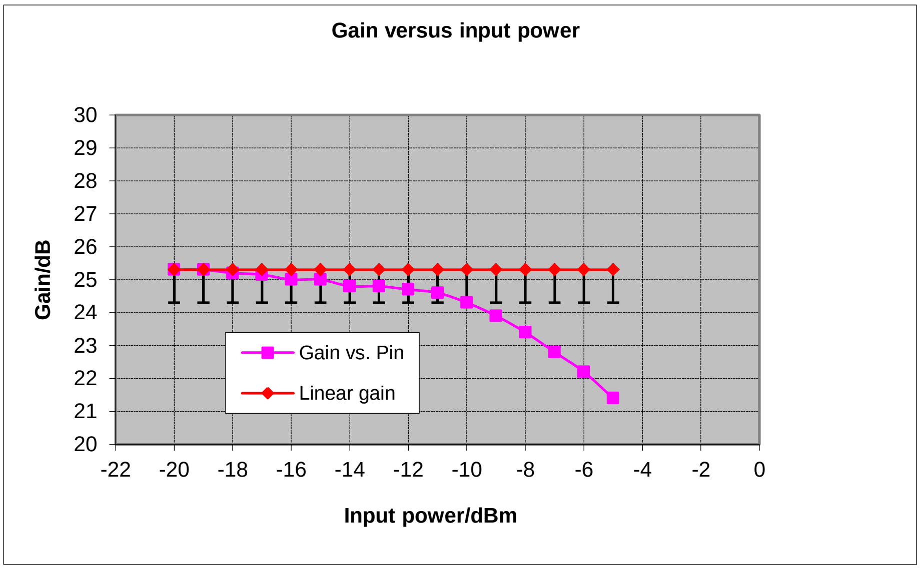


Fig. 3-3: Evaluation of the measured values (Table 3-1), gain versus input power. The 1 dB compression point (Pin/1dB) is the intersection of the 1 dB error indicator of the ideal trace with the measured trace (approx. -10 dBm).

3.2 Harmonic measurement K2, K3, ... Kn

3.3 Test setup:

Fig. 3-4 depicts the typical test setup for a harmonic measurement on amplifiers. An additional lowpass filter at the generator output is used to suppress the harmonics that are generated on the generator itself and corrupt the measurement result.

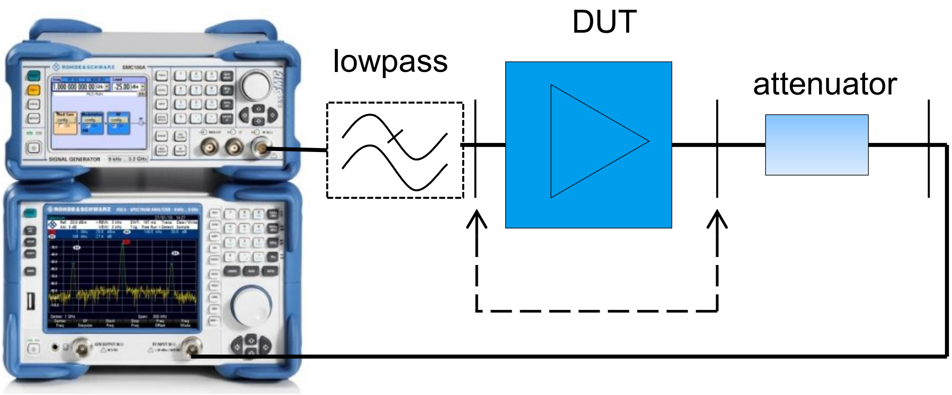


Fig. 3-4: Test setup for harmonic measurement on amplifiers. A lowpass filter at the generator output suppresses the generator's own harmonics.

3.3.1 Lowpass filter:

The cutoff frequency and the slope of the filter are selected such that the fundamental is within the filter's passband but the harmonics are sufficiently attenuated. The harmonics of <-30 dB specified for the signal generator are then further suppressed by the filter attenuation (the 2nd harmonic to approx. -60 dB in Fig. 3-5; the filter attenuates about 30 dB in this example) and the measurement range is accordingly expanded.

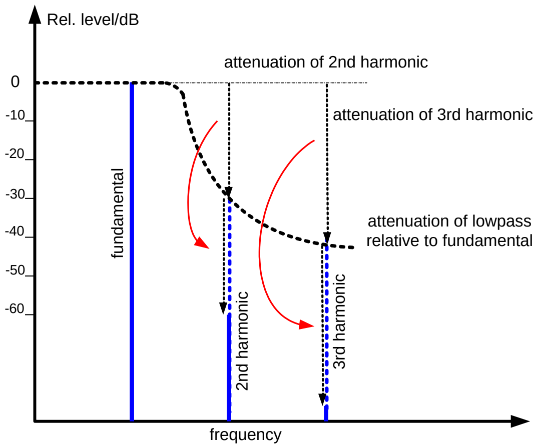


Fig. 3-5: Lowpass for suppressing the harmonics of the signal generator. The harmonics are suppressed by the attenuation of the lowpass.

The dynamic range of the spectrum analyzer for the harmonic as well as the intermodulation measurement is limited by the analyzer's nonlinearity, which results in the generation of harmonics or, with two-tone driving, intermodulation products. It is also limited by the analyzer's display noise. The effect of the spectrum analyzer's nonlinearity is mainly determined by the level at its input mixer. This makes it necessary to keep the level at the mixer as low as possible, i.e. to switch on a high attenuation on the analyzer or to insert an external attenuator.

The display noise of the analyzer depends directly on the attenuation ahead of the analyzer's input mixer and is lowest when there is as little attenuation as possible – at best none at all – ahead of the mixer. The resolution filter used also has a quite significant effect on the display noise, but it also affects the required sweep time and thus the measurement speed. For detailed explanations and formulas, refer to [1] .

If you set higher requirements on the dynamic range, it is generally not advisable or not even possible to display the complete signal with harmonics in one sweep: either the dynamic range is not wide enough or the sweep time becomes unacceptably long if the resolution bandwidth (RBW) is reduced. For this reason, the fundamental and the harmonics are measured in separate sweeps. The following example uses a span of 10 MHz and an RBW of 10 kHz, which results in a sweep time of 483 ms with the R&S®FSC and represents a good compromise between the dual requirements of having a wide dynamic range and acceptable measurement speed.

3.3.2 Reference measurement:

For the harmonic measurement in separate sweeps, perform a reference measurement on the fundamental: place a marker on the fundamental and measure the level. Now you can change the frequency and level setting as desired and, using a marker, still display the level of the desired harmonic relative to the previously measured fundamental.

Some relevant characteristics of the Spectrum Analyzer R&S®FSC with regard to measuring harmonics:

Harmonics:

For the R&S®FSC the SHI_{IN} is specified at + 40 dBm (f_{in} = 20 MHz to 1.5 GHz and 0 dB input attenuation)

With the help of equation 9 it is possible to calculate the maximum input power that the harmonics generated by the R&S®FSC do not exceed a certain limit.

P_{in}/ dBm = SHI_{IN} / dBm - a_{k2} /dB

Thus, if you wish to ensure that the harmonics caused by the R&S®FSC do not exceed 60 dB, its level at the input mixer must not exceed P_{in} = 40 dBm - 60 dB = -20 dBm.

The RF attenuation setting at the input of the R&S FSH is directly coupled to the reference level so that the input mixer always remains in the linear range. In its default state, the internal attenuator of the R&S®FSC is set to Auto Low Distortion mode, and the analyzer sets the attenuation in increments of 5 dB according to the reference level and the reference level offset. The R&S®FSC offers two modes: one for the highest possible sensitivity (Low Noise) and one for the lowest possible intermodulation products (Low Distortion).

If the **Auto Low Distortion** mode is active, the R&S®FSC sets the RF attenuation 10 dB higher according to the Table 3-2 below, making the stress of the input mixer 10 dB less at the specified reference level. However, the inherent noise display of the R&S®FSC increases due to the increased attenuation in front of the input mixer.

If the **Auto Low Noise** mode is active, the R&S®FSC sets the RF attenuation 10 dB lower. This increases the sensitivity of the R&S®FSC, which means that the inherent noise display decreases due to the lower attenuation in front of the input mixer.

Reference Level	Preamplifier OFF RF Attenuation		Preamplifier ON RF Attenuation	
	Low Noise	Low Distortion	Low Noise	Low Distortion
≤-30 dBm	0 dB	0 dB	0 dB	0 dB
-29 to -25 dBm	0 dB	0 dB	0 dB	5 dB
-24 to -20 dBm	0 dB	0 dB	0 dB	10 dB
-19 to -15 dBm	0 dB	5 dB	5 dB	15 dB
-14 to -10 dBm	0 dB	10 dB	10 dB	20 dB
-9 to -5 dBm	5 dB	15 dB	15 dB	25 dB
-4 to 0 dBm	10 dB	20 dB	20 dB	30 dB
1 to 5 dBm	15 dB	25 dB	25 dB	35 dB
6 to 10 dBm	20 dB	30 dB	30 dB	40 dB
11 to 15 dBm	25 dB	35 dB	35 dB	40 dB
16 to 20 dBm	30 dB	40 dB	40 dB	40 dB
21 to 25 dBm	35 dB	40 dB	40 dB	40 dB
26 to 30 dBm	40 dB	40 dB	40 dB	40 dB

Table 3-2: Settings of the RF attenuation depending on the reference level, attenuator setting mode and preamplifier setting.

Display noise caused by wideband noise:

In the frequency range of 10 MHz to 2 GHz the displayed average noise level of the R&S®FSC is specified at –141 dBm, typ. –146 dBm, at 1 Hz resolution bandwidth, 0 dB input attenuation and Preamplifier off. Increasing the attenuation increases the noise level. Increasing the bandwidth increases the noise level according to the following formula:

$$10 \cdot \log\left(\frac{RBW / Hz}{1Hz}\right)$$

Example:

A measurement is made with 10 kHz bandwidth:

The noise level then increases nominally by $10 \cdot \log\left(\frac{10000Hz}{1Hz}\right) =$ 40 dB, from typ. -146 dBm to -106 dBm.

3.3.3 Example of harmonic measurement K2, K3:

The harmonic ratio (2nd and 3rd harmonic) of a mobile radio power amplifier is to be measured at 824 MHz and an output power of +27 dBm. The amplifier has a nominal gain of 30 dB. A power attenuator with 20 dB attenuation is used.

R&S®SMC100A:

- *PRESET*
- *FREQ 824 MHz*
- *LEVEL -5 dBm*
- *RF ON*

R&S®FSC:

- *RESET*
- *FREQ: Center: 1.5 GHz*
- *SPAN: 3 GHz*
- *AMPT: Ref Offset 20 dB**)*
- *Ref Level: +30 dBm*
- *BW: 1 MHz (reduces the noise floor in order to detect the 3rd harmonic)*

*) You obtain a more exact display of the output power by performing a calibration as described on p.18 under Calibration

☞ Increase the level of the signal generator using the step keys until the level at 824 MHz reaches the desired 27 dBm. To do this, first select the 1 dB position with the ⇨ key and then increase the level by pressing the ⇧ key. Subsequently press ⇦ ⇨ to select the 0.1 dB position and fine-tune the level using the ⇧⇩ keys.

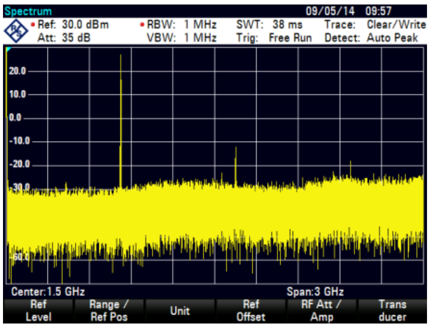


Fig. 3-6: Overview measurement of the harmonics in one sweep. The fundamental and the harmonics are displayed at the same time. The dynamic range is limited, since the resolution bandwidth (RBW) cannot be sufficiently reduced.

3.3.4 Reference measurement:

For the harmonic measurement in separate sweeps, perform a reference measurement on the fundamental: place marker 1 on the fundamental and write down the value of the Marker. Now you can change the frequency and level setting as desired and, using a marker, still display the level of the desired harmonic.

R&S®FSC:

- *FREQ 824 MHz*
- *SPAN 100 kHz*
- *⇨ BW: Manual RBW 1 kHz*
- *⇨ MKR→: Set to Peak*

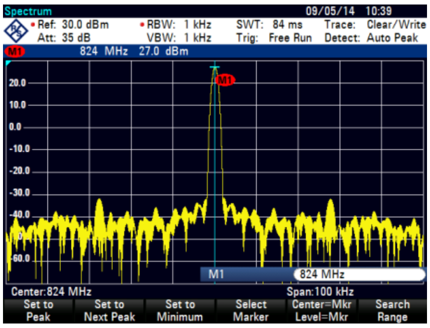


Fig. 3-7: Reference measurement for measuring the harmonics in separate sweeps. Due to the small span, the resolution bandwidth (RBW) can be reduced to e.g. 1 kHz to extend the dynamic range, without the sweep time becoming unreasonably long. The R&S®FSC is using faster sweep time with narrow resolution bandwidth due to use of FFT.

In this example the power of the fundamental P_F = 27 dBm. In order to calculate the ratio of the 2nd harmonic to the fundamental, place a marker on the 2nd harmonic.

R&S®FSC:

- *FREQ 1648 MHz*
- *MKR→: Set to Peak*

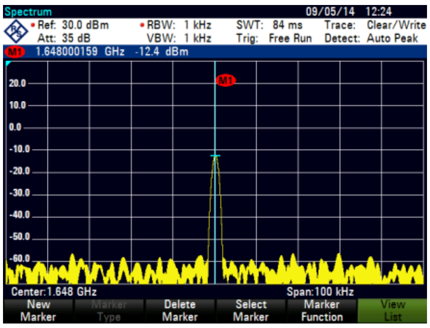


Fig. 3-8: Measurement of the 2nd harmonic level with -12.4 dBm at 1648 MHz. ⇨ 2nd harmonic= = -(27dBm- (-12.4 dBm)) = - 39.4 dBc. The reference is the level of the fundamental at 824 MHz.

Proceed analogously to measure the 3rd harmonic:

R&S®FSC:

- *FREQ: Center 2472 MHz*
- *⇨ MKR→: Set to Peak*

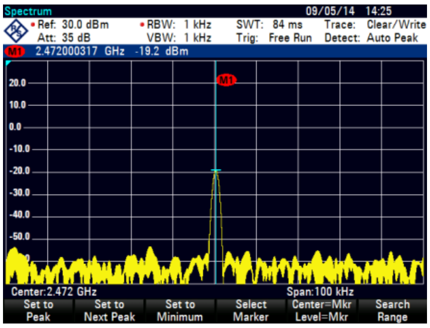


Fig. 3-9: Measurement of the 3rd harmonic level with - 19.2 dBm. ⇨ 3nd harmonic= = -(27dBm- (-19.2 dBm)) = - 46.2 dBc. The reference is the level of the fundamental at 824 MHz.

Tip:

To test whether the measured values for the 2nd and 3rd harmonic are not generated or affected by the analyzer, increase the attenuation of the input attenuator by 10 dB.

If the measurement results remain unchanged or deteriorate (due to the increasing noise contribution), any significant influence from the analyzer can be ruled out.

However, if the measured ratios improve considerably (by approx. <1 dB), the nonlinearity of the analyzer has already had a significant effect on the measurement results.

3.3.5 Calculating the intercept point K2 (SHI):

The measured values for the output power (27 dBm) and the 2nd harmonic ratio (39.4 dBm) are used to calculate the output intercept point of the amplifier according to equation 11:

SHI = 39.4 dB + 27 dBm = 66.4 dBm

3.4 Intermodulation measurements

3.4.1 Test setup:

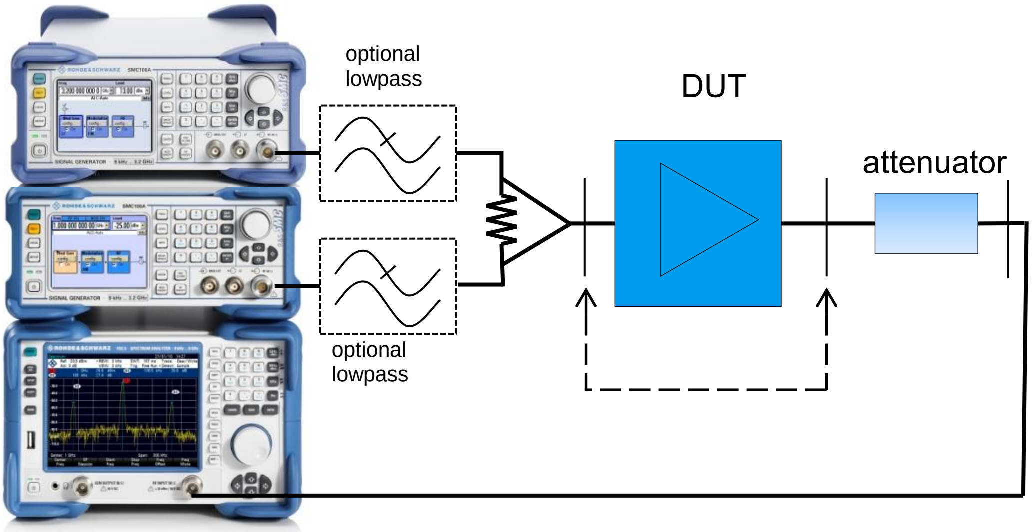


Fig. 3-10: Test setup for intermodulation measurement on amplifiers. The two generators are interconnected via a power combiner. The optional lowpass filters are used to eliminate the effect of the generator harmonics.

The test setup for the intermodulation measurement on amplifiers is depicted in Fig. 3-10. The test setup for the intermodulation measurement on amplifiers is depicted in Figure 16. Two generators that each generate a single-tone signal with the desired offset (e.g. 1 MHz) are interconnected by means of a power combiner. There are basically two kinds of power splitters: purely resistive power splitters and hybrid power splitters. Hybrid models (e.g. from Mini-Circuits, type ZFSC 2-2500) have the advantage of lower attenuation (nominally 3 dB compared with nominally 6 dB of a resistive power splitter) and better isolation of the two inputs (typically 20 dB compared with 6 dB of a resistive power splitter). A disadvantage, however, is the limited frequency range – therefore a suitable type must be selected for the particular application.

The optional lowpass filters are used to suppress generator harmonics, which may otherwise corrupt the measurement results (by mixture products from the harmonics occurring at the d2 and d3 intermodulation products to be measured).

3.4.2 Dynamic range

(see also p. 22)

The dynamic range of the intermodulation measurement is limited by the intermodulation generated by the test setup itself and by noise.

Intermodulation:

- Intermodulation of the two generators due to insufficient decoupling of the two outputs. This occurs especially at high levels, when there is only little or no attenuation at the output. Using isolators can improve this. Isolators ensure further decoupling (typ. 20 dB per isolator), without significantly attenuating the output signal.

- Intermodulation in the spectrum analyzer depends on the driving signal: the higher the level at the input mixer of the spectrum analyzer, the higher the intermodulation products. The level of the d3 intermodulation products increases by three times the dB value of the level increase, the level of the d2 inter-modulation products by two times the dB value.

Noise:

- Besides the input noise of the spectrum analyzer, the measurement of d3 intermodulation products near the carrier is also affected by phase noise. The phase noise of the generator used combines with that of the analyzer at each measurement frequency. See also [1] p. 139 ff.

Some relevant characteristics of the Spectrum Analyzer R&S FSC with regard to measuring d3 intermodulation products:

d3 intermodulation products:

The intermodulation-free range of the R&S®FSC is specified at –60 dBc at a level of 2 x -20 dBm (30 MHz ≤ f ≤ 3.6 GHz). According to equation 15, this corresponds to an input intercept point IP3 of 10 dBm at the input mixer. If you wish to ensure that the IP3 intermodulation products generated by the R&S FSC do not exceed 50 dB, the level per signal must not exceed -15 dBm.

In its default state, the internal attenuator of the R&S®FSC set to Auto Low Distortion Mode, and the analyzer sets the attenuation in increments of 5 dB according to the reference level and the reference level offset such that the level on the input mixer is in the linear range.

The Low Distortion mode provides the lowest possible intermodulation products (see also P.22/23)

Display noise caused by phase noise:

The value specified for the R&S®FSC is -95 dBc (1 Hz) at 30 kHz from the carrier (f=500 MHz). The value for the R&S®SMC100A is -105 dBc1 Hz at 1 GHz and at 20 kHz from the carrier. With a carrier offset of 1 MHz as described in the following measurement examples, however, the phase noise at 1 MHz from the nearest signal is relevant. A typical measured value for this is -120 dBm/Hz as the sum of the combined R&S®FSC/R&S®SMC100A phase noise at 824 MHz in the following measurement example.

Display noise caused by wideband noise:

See also pp. 22/23. The displayed average noise level specified for the R&S®FSC is =–141 dBm, typ. –146 dBm, at 1 Hz resolution bandwidth and 0 dB input attenuation (10 MHz ≤ f ≤ 2 GHz). Increasing the attenuation increases the noise level. Increasing the bandwidth increases the noise level according to the following formula:

$$10 \cdot \log\left(\frac{RBW / Hz}{1Hz}\right)$$

Example:

A measurement is made with 10 kHz bandwidth:

The noise level increases nominally by $10 \cdot \log\left(\frac{10000Hz}{1Hz}\right) =$ 40 dB, from -141 dBm to -101 dBm.

In the following Excel spreadsheet (Figure 17; see also [1] p. 149), the different contributions of d3 intermodulation products, phase noise at 1 MHz, and wideband noise for the R&S®SMC100A and R&S®FSC combination were added up. You can see that the optimal dynamic range of approx. -63 dB is attained with a level of approx. –36 dBm at the R&S®FSC input mixer.

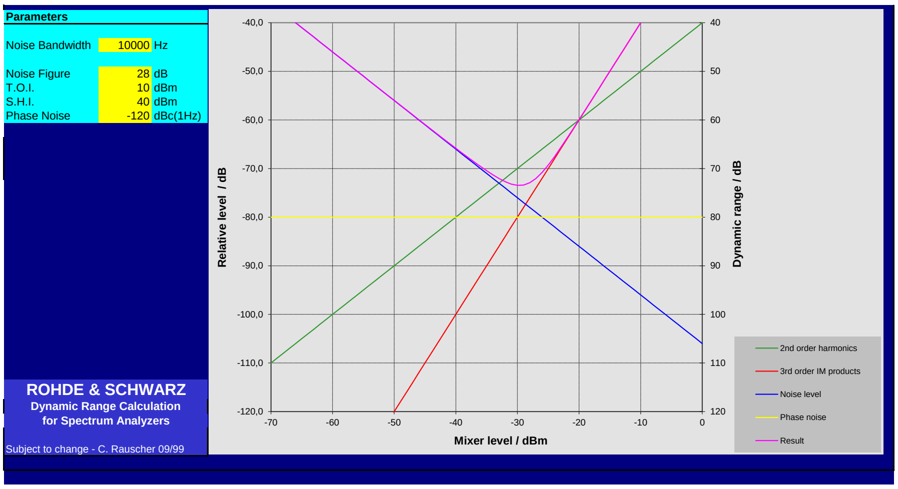


Fig. 3-11: Dynamic range of the R&S®FSC taking into account thermal noise, phase noise and 3rd order intermodulation products (noise figure = 28 dB, IP3 = +10 dBm, phase noise = -120 dBc/Hz, noise bandwidth = 10 kHz)

3.4.3 Example of d3 intermodulation measurement:

The 3rd order intermodulation ratio on a mobile radio power amplifier is to be measured with a two-tone signal of 824 MHz and 825 MHz (1 MHz frequency offset) and 27 dBm output power per signal. The amplifier has a nominal gain of 30 dB. A power attenuator with 20 dB attenuation is used.

3.4.4 Calibrating the test setup:

In order for the intermodulation ratio to be determined at the correct (input and output) power, the test setup must be calibrated. First the path attenuation from the generator outputs to the combiner output is determined and corrected using the generators' level offset function. Subsequently the path attenuation from the input of the power attenuator to the analyzer input is measured and corrected using the analyzer's level offset function.

☞ Connect both generators (SMC100A_1, SMC100A_2) to the combiner as shown in Fig. 3-10. Connect the analyzer directly to the combiner output using a cable that is as short as possible.

R&S®SMC100A_1:

- *PRESET*
- *FREQ:824 MHz*
- *LEVEL: -5 dBm*
- *RF ON*

R&S®FSC:

- *RESET*
- *FREQ: Center:824.5 MHz*
- *SPAN 10 MHz*
- *AMPT: Ref Level 0 dBm*
- *BW: Manual RBW: 10 kHz*
- *MKR→: Set to Peak (M1)*

R&S®SMC100A_2:

- *PRESET*
- *FREQ:825 MHz*
- *LEVEL: -5 dBm*
- *RF ON*

R&S®FSC:

- *MKR: New Marker: Marker Type (M2)*

Marker 1 now indicates the level at 824 MHz on the combiner output, marker 2 the level at 825 MHz. Enter the difference of the measured levels ($P_{M1,2}$) to the level displays on the generators ($P_{G1,2}$) as the level offset and then reset the generator level to -5 dBm.

Level offset SMC100A_1 = $P_{MKR1} - P_{SMC100A\_1}$

Level offset SMC100A_2 = $P_{MKR2} - P_{SMC100A\_2}$

Example: marker 1: -11.1 dBm, marker 2: -11.2 dBm

Level offset SMC100A_1: -11.1 dBm – (-5 dBm) = -6.1 dB

Level offset SMC100A_2: -11.2 dBm – (-5 dBm) = -6.3 dB

R&S®SMC100A_1:

- *DIAGR:* select *RF config* by using the arrow keys ⇦⇨ *ENTER*
- Select *Level/Attenuator…* by using the arrow keys ⇧⇩ *ENTER*
- Select *Offset…* by using the arrow keys ⇧⇩ *ENTER*
- *Offset -6.1 dB ESC/CLOSE*
- *LEVEL -5 dBm*

R&S®SMC100A_2:

- *DIAGR:* select *RF config* by using the arrow keys ⇦⇨ *ENTER*
- Select *Level/Attenuator…* by using the arrow keys ⇧⇩ *ENTER*
- Select *Offset…* by using the arrow keys ⇧⇩ *ENTER*
- *Offset -6.3 dB ESC/CLOSE*
- *LEVEL -5 dBm*

The powers set on the generators (-5 dBm) should now be applied to the combiner output and measured by the analyzer with markers 1 and 2.

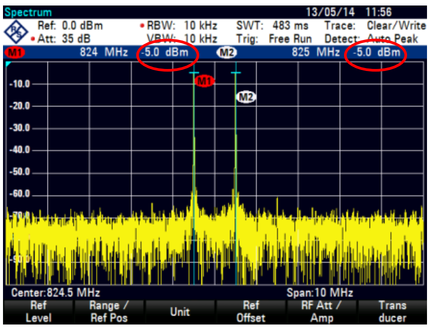


Fig. 3-12: Level on the combiner output after the correction of the generator output level by the path attenuation

Now connect the combiner output to the analyzer via the power attenuator and read off the measured value of marker 1 (P_{M1}).

Now enter the difference of the power set on generator SMC100A_1 ($P_{SMC100A\_1}$) to the power measured with marker 1 ($P_{MKR\ 1}$) as the Ref Level Offset.

Ref Level Offset x = $P_{SMC100A\_1}$ - $P_{MKR\ 1}$

Example:

P_G = -5 dBm, P_{M1} = -25.1 dBm → Ref Level Offset = -5 - (-25.1) = 20.1 dB

R&S®FSC:

- *AMPT: Ref Offset 20.1 dB*

The R&S R&S®FSC now displays the power at the combiner output and at the attenuator as depicted in

Fig. 3-12.

If the amplifier to be measured is subsequently connected between the combiner and the power attenuator, the level displays of the two generators show the input power of the signals at 824 MHz and 825 MHz. Markers 1 and 2 on the analyzer display indicate the amplifier's output power applied to the power attenuator. The level settings of the two generators are then changed such that markers 1 and 2 display the desired power (+27 dBm in this example) at which IP3 is to be measured:

☞ Loop in the amplifier to be measured between the combiner and the power attenuator. Increase the level of each of the signal generators using the step keys until the levels at 824 MHz and 825 MHz reach the desired +27 dBm. To do this, first select the 1 dB position with the ⇦ ⇨ keys and then increase the level by pressing the ⇧ key; if necessary, press the ⇦ key to select the 0.1 dB position and fine-tune the level.

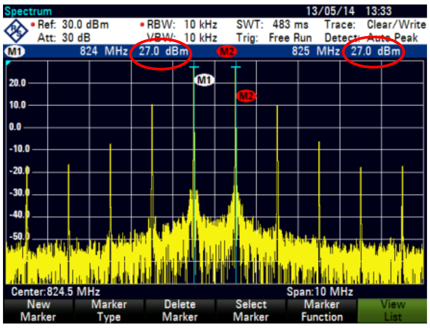


Fig. 3-13: The amplifier to be measured now supplies +27 dBm output power at 824 MHz and at 825 MHz

Now place marker 2 on e.g. the lower d3 product and switch to relative display.

R&S®FSC:

- *MKR*
- *Select Marker M2*
- Press *Marker Type* (Marker M2 becomes now a delta marker)
- *MKR* ➔ *press Set to Next peak* until the delta marker is located on the lower d3 product

Marker 2 now displays the level of the lower d3 intermodulation product relative to marker 1 (power at 824 MHz).

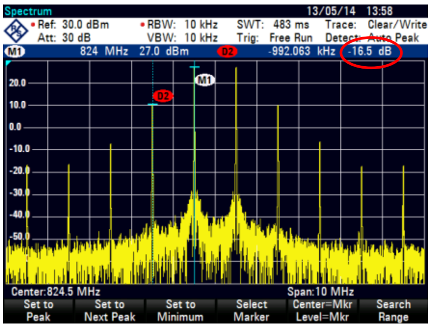


Fig. 3-14: Delta marker 2 (red) is used to determine the lower d3 intermodulation product relative to marker 1 (white) for –16.5 dB

To check whether the analyzer may already be corrupting the measured d3 intermodulation product, its input attenuation is increased by 10 dB. Subsequently the level display of marker 2 is compared with the previous display.

R&S®FSC:

- *AMPT: RF Att/Amp: Manual 40 dB*
- *Select Marker M2*

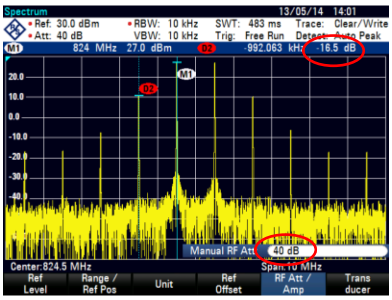


Fig. 3-15: After having increased the input attenuation by 10 dB, there is virtually no change to the level of the intermodulation product (-25 dB). The measurement is valid!

3.4.5 Calculating the d3 intercept point:

The d3 intercept point at the output of the amplifier is calculated using equation 19:

$$IP3_{out}/dBm = \frac{a_{IM3}}{2}/dB + P_{out}/dBm$$ = 8.3 dB + 27 dBm = +35.3 dBm

4 Literature

[1] Christoph Rauscher (Volker Jansen, Roland Minihold), Fundamentals of Spectrum Analysis

[2] R&S®FSC Spectrum Analyzer Specifications PD 5214.3330.22, Version 2.0

[3] R&S®SMC100A Signal Generator Specifications PD 5214.1143.22, Version 1.01

[4] Detlev Liebl, Measuring with Modern Spectrum Analyzers, R&S Application Note 1MA201

5 Ordering Information

Designation	Type	Order No.
Signal Generator	R&S®SMC100A	1411.4002.02
Options		
RF Path 9 kHz to 1.1 GHz	R&S®SMC-B101	1411.6505.02
RF Path 9 kHz to 3.2 GHz	R&S®SMC-B103	1411.6605.02
GPIB/IEEE488 Interface	R&S®SMC-K4	1411.3506.02
Spectrum Analyzer, 9 kHz to 3 GHz	R&S®FSC3	1314.3006.03
Spectrum Analyzer, 9 kHz to 3 GHz, with tracking generator	R&S®FSC3	1314.3006.13
Spectrum Analyzer, 9 kHz to 6 GHz	R&S®FSC6	1314.3006.06
Spectrum Analyzer, 9 kHz to 6 GHz, with tracking generator	R&S®FSC6	1314.3006.16
Options		
Preamplifier, 100 kHz to 3 GHz / 6 GHz (for the R&S®FSC3/6)	R&S®FSC-B22	1314.3535.02

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Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

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ISO 9001

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