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BSI Standards Publication

Guidelines for the measurement method of nonlinearity for surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices in radio frequency (RF)

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National foreword

This British Standard is the UK implementation of EN 62761:2014. It is identical to IEC 62761:2014.

The UK participation in its preparation was entrusted to Technical Committee EPL/49, Piezoelectric devices for frequency control and selection.

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English Version

Guidelines for the measurement method of nonlinearity for surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices in radio frequency (RF) (IEC 62761:2014)

Lignes directrices pour la méthode de mesure des non-linéarités pour les dispositifs à ondes acoustiques de surface (OAS) et à ondes acoustiques de volume (OAV) pour fréquences radioélectriques (RF)
(CEI 62761:2014)

Leitfaden zum Messverfahren für die Nichtlinearität von Oberflächenwellen-(OFW-) und Volumenwellen-(BAW-)Bauelementen für Hochfrequenzanwendungen
(IEC 62761:2014)

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Foreword

The text of document 49/1091/FDIS, future edition 1 of IEC 62761, prepared by IEC/TC 49 "Piezoelectric, dielectric and electrostatic devices and associated materials for frequency control, selection and detection" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62761:2014.

The following dates are fixed:

– latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-12-26
– latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-03-26

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The text of the International Standard IEC 62761:2014 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60862-1:2003	NOTE	Harmonized as EN 60862-1:2003 (not modified).
IEC 62047-7:2011	NOTE	Harmonized as EN 62047-7:2011 (not modified).
IEC 62575-2:2012	NOTE	Harmonized as EN 62575-2:2012 (not modified).

CONTENTS

INTRODUCTION

Radio frequency (RF) surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices such as filters and duplexers are now widely used in various communication systems. Due to their small physical size, energy concentration causes generation of nonlinear signals even when relatively small electric power is applied, and they may interfere with the communications.

The features of these RF SAW/BAW devices are their small size, light weight, omission of impedance and/or frequency tuning, high stability and high reliability. Nowadays, RF SAW/BAW devices with low insertion attenuation are widely used in various applications in the RF range.

In such applications, suppression of transmission and generation of unnecessary signals is highly demanded. Since nonlinearity in the RF SAW/BAW devices will generate such signals, its ultimate suppression is always crucial. In the same time, measurement method of nonlinear signals should be well established from industrial points of view.

In passive filters like RF SAW/BAW ones, frequency selectivity is realized by impedance matching/mismatching with peripheral circuitry. Thus impedance of peripheral circuitry shall be set as specified for reliable and reproducible filter characterization. This is also true for non-linear characteristics. It should be noted that even-order non-linearity, which is not common in general passive electronic components, may occur in RF SAW/BAW devices employing piezoelectric materials for electrical excitation and detection of SAWs/BAWs. This is because crystallographic asymmetry is necessary for existence of piezoelectricity. Therefore, measurement methods should be specifically established for non-linear behavior of RF SAW/BAW devices.

This standard has been compiled in response to a generally expressed desire on the part of both users and manufacturers for general Information on test condition guidance of RF SAW/BAW filters, so that the filters may be used to their best advantage. To this end, general and fundamental characteristics have been explained in this standard.

GUIDELINES FOR THE MEASUREMENT METHOD OF NONLINEARITY FOR SURFACE ACOUSTIC WAVE (SAW) AND BULK ACOUSTIC WAVE (BAW) DEVICES IN RADIO FREQUENCY (RF)

1 Scope

This International Standard gives the measurement method for nonlinear signals generated in the radio frequency (RF) surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices such as filters and duplexers, which are used in telecommunications, measuring equipment, radar systems and consumer products.

The IEC 62761 includes basic properties of non-linearity, and guidelines to setup the measurement system and to establish the measurement procedure of nonlinear signals generated in SAW/BAW devices.

It is not the aim of this standard to explain theory, nor to attempt to cover all the eventualities which may arise in practical circumstances. This standard draws attention to some of the more fundamental questions, which the user has to consider before he/she places an order for an RF SAW/BAW device for a new application. Such a procedure will be the user's insurance against unsatisfactory performance.

2 Normative references

None

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 General terms

3.1.1
BAW duplexer
antenna duplexer composed of RF BAW resonators

3.1.2
BAW filter
filter characterised by a bulk acoustic wave which is usually generated by a pair of electrodes and propagates along a thin film thickness direction

3.1.3
bulk acoustic wave
BAW
acoustic wave, propagating between the top and bottom surface of a piezoelectric structure and traversing the entire thickness of the piezoelectric bulk

Note 1 to entry: The wave is excited by metal electrodes attached to both sides of the piezoelectric layer.

3.1.4
cut-off frequency
frequency of the pass-band at which the relative attenuation reaches a specified value

3.1.5
duplexer
device used in the frequency division duplex system, which enables the system to receive and transmit signal through a common antenna simultaneously

3.1.6
film bulk acoustic resonator
FBAR
thin film BAW resonator consisting of a piezoelectric layer sandwiched between two electrode layers with stress free top and bottom surface supported mechanically at the edge on a substrate with cavity structure as shown in Figure 1 or membrane structure as an example

Note 1 to entry: This note applies to the French language only.

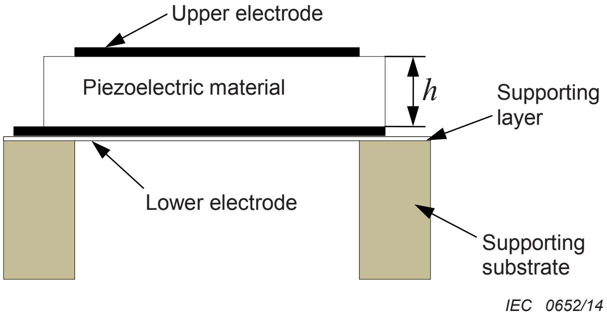


Figure 1 – FBAR configuration

3.1.7
Receiver (Rx) band
frequency band used in a receiver part to detect signals from an antenna

3.1.8
Rx filter
filter used in a receiver part to eliminate unnecessary signals

Note 1 to entry: The Rx filter is a basic part of a duplexer.

3.1.9
SAW filter
filter characterised by one or more surface acoustic wave transmission line or resonant elements, where the surface acoustic wave is usually generated by an interdigital transducer and propagates along a substrate

3.1.10
solidly mounted resonator
SMR
BAW resonator, supporting the electrode/piezoelectric layer/electrode structure by a sequence of additional thin films of alternately low and high acoustic impedance Z_a with quarter wavelength layer, and these layers act as acoustic reflectors and decouple the resonator acoustically from the substrate as shown in Figure 2 for example

Note 1 to entry: This note applies to the French language only.

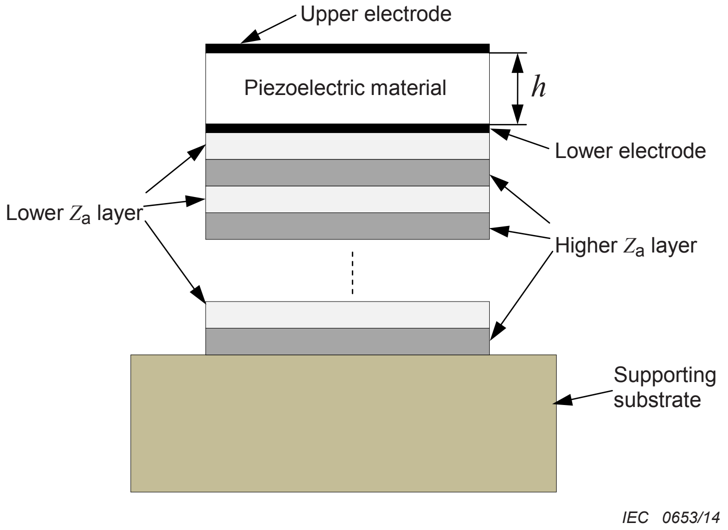


Figure 2 – SMR configuration

3.1.11
surface acoustic wave
SAW
acoustic wave, propagating along a surface of an elastic substrate, whose amplitude decays exponentially with substrate depth

[SOURCE: IEC 60862-1:2003, 2.2.1.1]

3.1.12
transmitter (Tx) band
frequency band used in a transmitter part to emit signals from an antenna

3.1.13
Tx filter
filter used in a transmitter part to eliminate unnecessary signals. It is a basic part of a duplexer

3.2 Response related terms

3.2.1
insertion attenuation
logarithmic ratio of the power delivered directly to the load impedance before insertion of the duplexer to the power delivered to the load impedance after insertion of the duplexer

3.2.2
pass band
band of frequencies in which the relative attenuation is equal to or less than a specified value

3.2.3
reflectivity
dimensionless measure of the degree of mismatch between two impedances Z_1 and Z_2 , i.e., $\frac{Z_1 - Z_2}{Z_1 + Z_2}$, where Z_1 and Z_2 represent respectively the input and source impedance or the output and load impedance

Note 1 to entry: The absolute value of reflectivity is called the reflection coefficient.

3.2.4
relative attenuation
difference between the attenuation at a given frequency and the attenuation at the reference frequency

3.2.5
stop band
band of frequencies in which the relative attenuation is equal to or greater than a specified value

3.2.6
transition band
band of frequencies between the cut-off frequency and the nearest point of the adjacent stop band

3.3 Nonlinearity related terms

3.3.1
harmonics
non-linear distortion of a device response characterized by the appearance of frequencies at the output equal to integral multiples of the original signal frequency

3.3.2
hysteresis
memory effect
phenomenon where the output is not determined only from the input and depends also on the internal state, in other words, the history of the input

3.3.3
intercept point
IP
power level where intensity of the non-linear signal generated by the intermodulation distortion (IMD) is equal to that of two input signals at the output

Note 1 to entry: This note applies to the French language only.

3.3.4
intermodulation distortion
IMD
non-linear distortion of a device response characterized by the appearance of frequencies at the output equal to the differences (or sums) of integral multiples of the two or more component frequencies present at the input

Note 1 to entry: This note applies to the French language only.

3.3.5
jammer signal
incoming unnecessary signal

3.3.6
nonlinear distortion
distortion of the signal waveform caused by nonlinearity of the system where the signal transmits

Note 1 to entry: When the distortion is originated to the frequency dependence of the system signal transfer function, it is called the linear distortion.

3.3.7
one decibel compression point
input power where gain, the ratio of the output to the input, decreases by 1 dB from the value when the input is very weak

3.3.8
saturation
phenomenon where gain, the ratio of the output to the input, decreases and approaches to zero when the input is large

3.3.9
three tone test
non-linearity measurement applying three sinusoidal signals with different frequencies simultaneously

3.3.10
triple beat test
same as the three tone test

3.3.11
two tone test
non-linearity measurement applying two sinusoidal signals with different frequencies simultaneously

4 Basic properties of nonlinear system

4.1 Behaviours of nonlinear system

Let us consider a response $y(x)$ of a circuit or a device when a signal x is applied. When the hysteresis (memory effect) is negligible or ignored, the Maclaurin expansion of y with respect to x gives

$$y(x) = c_1 x + \frac{1}{2} c_2 x^2 + \frac{1}{3} c_3 x^3 + \ldots \tag{1}$$

where c_m is the expansion coefficient. It should be noted that $c_m = 0$ for even m, when the circuit/device satisfies $y(-x) = -y(x)$.

Here we consider a case when two sinusoidal signals with frequencies f_a and f_b and amplitudes a_a and a_b are simultaneously applied, namely, $x = a_a\cos(2\pi f_a t) + a_b\cos(2\pi f_b t)$, and a_a is much greater than a_b. Then y is approximately given by

$$\begin{aligned} y \approx{} & c_1 a_a\left(1+\frac{c_3 a_a^2}{4c_1}\right)\cos(2\pi f_a t) + c_1 a_b\left(1+\frac{c_3 a_a^2}{2c_1}\right)\cos(2\pi f_b t) \\ & + \frac{c_2 a_a^2}{4} + \frac{c_2 a_a^2}{4}\cos(4\pi f_a t) + \frac{c_3 a_a^3}{4}\cos(6\pi f_a t) \\ & + \frac{c_2 a_a a_b}{2}\cos\{2\pi(f_a + f_b)t\} + \frac{c_2 a_a a_b}{2}\cos\{2\pi(f_a - f_b)t\} \\ & + \frac{c_3 a_a^2 a_b}{4}\cos\{2\pi(2f_a + f_b)t\} + \frac{c_3 a_a^2 a_b}{4}\cos\{2\pi(2f_a - f_b)t\} \\ & + \ldots \end{aligned} \tag{2}$$

Equation (2) indicates how nonlinearity influences to the circuit/device output. Namely, the first two terms indicate change in the transmission coefficients for a_a and a_b, and express saturation due to large signal input (usually c_3/c_1 is negative). The three terms in the second line express generation of harmonics with $f = mf_a$ (m: integer). The two terms in the third line express generation of new signals with $f = f_a \pm f_b$ called the second-order intermodulation distortion (IMD2). The remaining two terms in the fourth line express those with $f = |2f_a \pm f_b|$ or $f = |2f_b \pm f_a|$ called the third-order intermodulation distortion (IMD3).

Here we consider a wireless receiver tuned for a signal with $f = f_t$. Incident signals with $f = f_t/2$ and $f = f_t/3$ may be detected by the receiver after the harmonics generation, and may interfere the main signal detection. Similarly, when two signals with f_a and f_b satisfying either $f_t = |f_a \pm f_b|$, $|2f_a \pm f_b|$ or $|f_a \pm 2f_b|$ are incident to the receiver simultaneously, signals with $f = f_t$ generated by IMD2 or IMD3 may also interfere the main signal detection. For transceivers operating in the frequency division duplex (FDD) mode, transmitting signals with $f = f_a$ may cause IMD2 and/or IMD3 with an incident signal with $f = f_b$, and generated signals with $f = f_t$ may also interfere the main signal detection. For transmitters, nonlinearity causes emission of spurious signals, which may interfere with other wireless communications. These examples clearly reveal importance to characterise nonlinear behaviour of RF systems and components as well as the suppression.

For the characterisation of the transmission compression (saturation), we often use the input signal level where the transmission coefficient decreases by 1 dB, which is called the 1dB compression point (P_{1dB}). On the other hand, so called the intercept point is used for the IMD characterisation. That is, power $P_{a\pm b}$ of the IMD2 signal with $f = |f_a \pm f_b|$ is expressed as $P_{a\pm b} = P_{oa}P_{ob}/\text{OIP2}$ when signal levels are much lower than the saturation levels. In the expression, P_{oa} and P_{ob} are the output power with f_a and f_b and OIP2 is called the output second-order intercept point. In decibels, the relation is rewritten as

$$\text{OIP2} = P_{oa} + P_{ob} - P_{a\pm b} \tag{3}$$

In Equation (3), all variables are expressed in dBm.

Similarly, power $P_{2a\pm b}$ of the IMD3 signal with $f = |2f_a \pm f_b|$ is expressed as $P_{2a\pm b} = P_{oa}^2 P_{ob}/\text{OIP3}^2$ when signal levels are much lower than the saturation levels. In the equation, OIP3 is called the output third-order intercept point. In decibels, the relation is rewritten as

$$\text{OIP3} = P_{oa} + 1/2 \times P_{ob} - 1/2 \times P_{2a\pm b} \tag{4}$$

In Equation (4), all variables are expressed in dBm.

It should be noted that the intercept point is also defined by the input signal level P_{ia} $(= P_{ib})$ giving $P_{a\pm b} = \text{OIP2}$ and $P_{2a\pm b} = \text{OIP3}$. The input second- and third-order intercept points IIP2 and IIP3 are related to OIP2 and OIP3 as

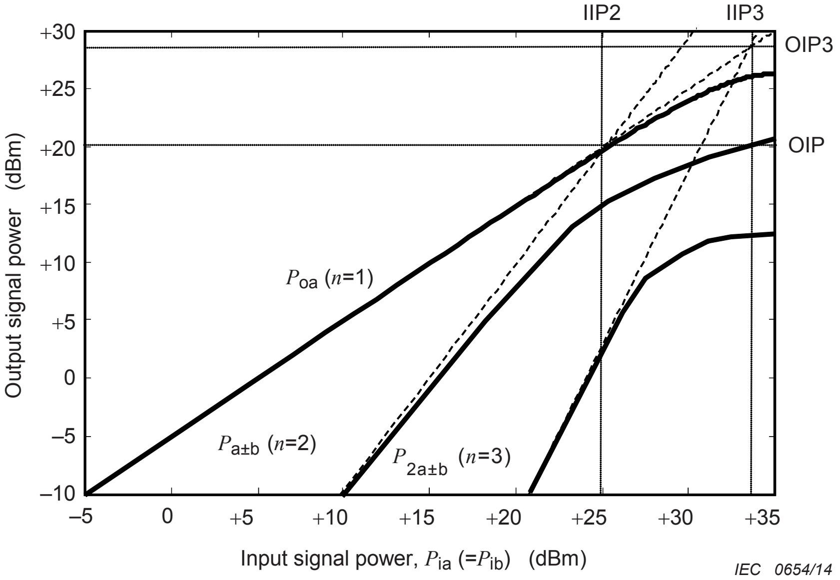
$$\text{IIP2} = \text{OIP2} + \text{IA} \tag{5}$$

and

$$\text{IIP3} = \text{OIP3} + \text{IA} \tag{6}$$

where IA is the insertion attenuation in dB of the device measured with very weak input signal level.

Figure 3 shows typical variation of P_{oa} $(n = 1)$, $P_{a\pm b}$ $(n = 2)$ and $P_{2a\pm b}$ $(n = 3)$ with P_{ia} $(= P_{ib})$. OIPn and IIPn can be estimated graphically from the intersection points between extrapolated two linear lines. In this case, IIP2 and IIP3 are about 25 dBm and 33 dBm while OIP2 and OIP3 are about 20 dBm and 28 dBm, respectively.



IEC 0654/14

Figure 3 – Fundamental and harmonics output as a function of input signal power

By the way, Equation (2) indicates that P_{1dB} and IIP3 are given by $10\log[4(1-0{,}89)c_1/c_3R_0]$ and $10\log[4c_1/c_3R_0]$, respectively, where R_0 is the circuit impedance. From these expressions, we obtain the following relation in decibels:

$$\mathrm{IIP3} = 9{,}6 + P_{\mathrm{1dB}} \qquad (7)$$

However, this relation does not hold in general, especially in RF filters. This is because all parameters appearing in Equation (2), namely c_1, c_2, and c_3 are frequency dependent. In addition, nonlinear parameters appeared in 4.1 such as IIPn and OIPn, are dependent on f_{a}, f_{b} and f_{t}. Thus they shall be specified at the measurement of nonlinear signals generated in RF SAW/BAW devices[1].

4.2 Measurement setup for nonlinearity

4.2.1 Harmonics measurement

Figure 4 shows a basic setup for the N-th harmonics measurement of RF components or systems. A sinusoidal signal with frequencies f_{a} and power P_{ia} is supplied to a device under test (DUT) by a signal generator (SG), and a target spectrum component P_{t} with frequency f_{t} (= Nf_{a}) is selectively detected by a spectrum analyser (SA). At the measurement, we shall examine following two issues: (a) nonlinearity of SG and SA is negligible, and (b) circuit impedance looking from the DUT ports shall be defined well not only for the fundamental frequency (f_{a}) but also for harmonics with f=nf_{a} ($n \le N$). The latter is extremely important for passive RF filters. This is because their frequency selectivity is owed to impedance mismatching with peripheral circuits, and the device characteristic is sensitive to the circuit impedance. Usually the circuit impedance is chosen to be equal to specific impedance R_0 of the measurement system.

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[1] RF BAW devices are often called the film bulk acoustic resonators (FBARs) or solidly mounted resonators (SMRs) depending their device configuration.

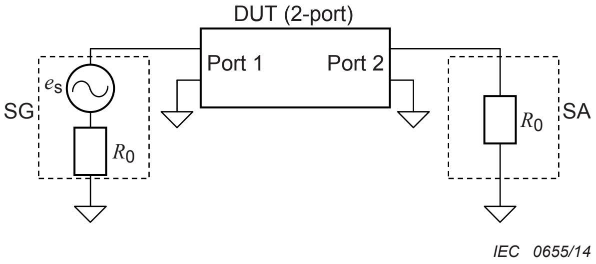

Figure 4 – Basic setup for the harmonics measurement

Use of an adequate filter is effective to reject nonlinear signals generated in the peripheral circuit as shown in Figure 5. However since inserted passive filters exhibit the circuit impedance of R_0 only in the filter pass band, we need to insert an attenuator (ATT) between the filter and DUT. When the nominal attenuation of the ATT is A dB, insertion of the ATT improves the return attenuation of the peripheral circuit looking from the port 1 by $2A$ dB. Insertion of the ATT also results in reduction of the input signal intensity by A dB, which causes reduction of the n-th harmonics intensity by nA dB. Reduction of the signal level may cause fluctuation (inaccuracy) in the SA read due to the thermal noise. Increasing the SG output seems to be a solution of this difficulty. However, we shall check (a) whether the harmonics generation in the SG is negligible for the measurement, and (b) whether heat up of the ATT does not cause variation of the attenuation level with time.

The ATT inserted between the DUT and SA is aimed at suppressing harmonics generation at SA and variation of the input admittance of SA. Of course this ATT is not necessary when these effects are negligible.

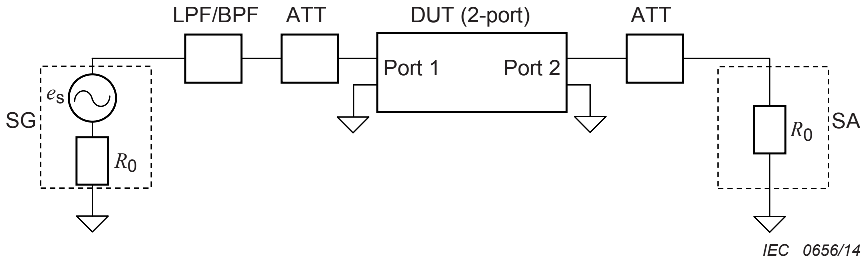

Figure 5 – Practical setup for the harmonics measurement

When SG output power is not sufficient, we need to add a power amplifier (PA). In that case, insertion of the filter may not be practical. This is because larger output power is necessary to compensate the attenuation of the inserted ATT, and may make nonlinearity of the PA more obvious. In that case, an isolator (or circulator) is often inserted instead of the filter to suppress influence of the input impedance of the DUT port 1 to the PA (see Figure 6). It shall be noted that since the circulator/isolator transmits spurious signals in some extent, their generation in the PA shall be suppressed sufficiently. In addition, since isolators/circulators usually exhibit their functionality in a narrow frequency range, insertion of an ATT might be necessary to improve the return attenuation looking from the DUT port.

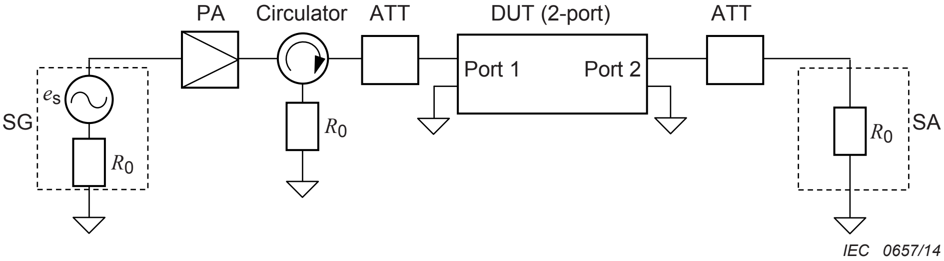

Figure 6 – Setup when the circulator/isolator is used

4.2.2 IMD Measurement

Figure 7 shows two configurations for the IMD measurement of RF components or systems. This set up is often called the two-tone test. Two sinusoidal signals with frequencies f_a and f_b are applied to the DUT by two SGs, and a target spectrum component P_t with frequency f_t is selectively measured by the SA. For two-port DUTs, a power combiner is necessary to apply two signals to the DUT simultaneously as shown in Figure 7(a). In both cases, an appropriate filter is given to each SG to reject generated nonlinear signals and avoid IMD generation in SGn. Since characteristics of the power combiner are usually frequency dependent, we may need to add ATT between the power combiner and the DUT port 1 so as to improve the return attenuation looking from the DUT port 1. For the three-port configuration shown in Figure 7(b), ATTs are inserted between the filter and DUT since passive filters exhibit the circuit impedance of R_0 only in the filter pass band (not for frequencies of IMD signals generated in the DUT).

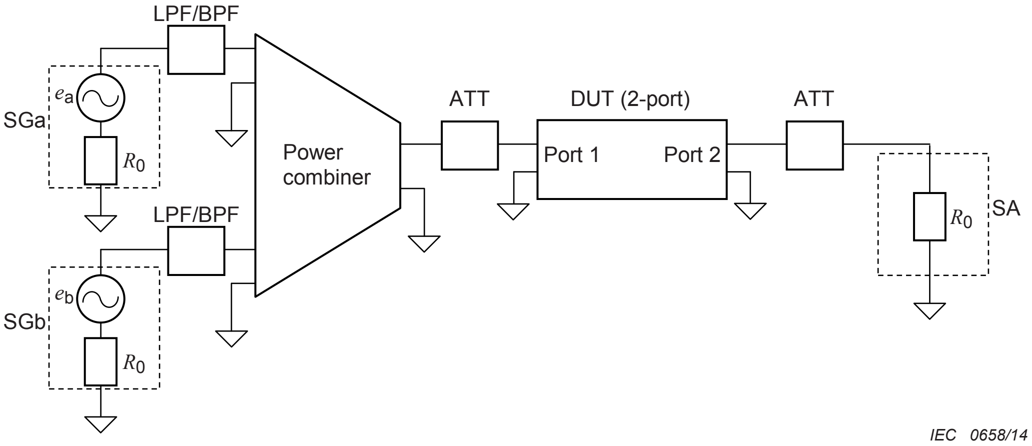

Figure 7 a) – Two-port DUT

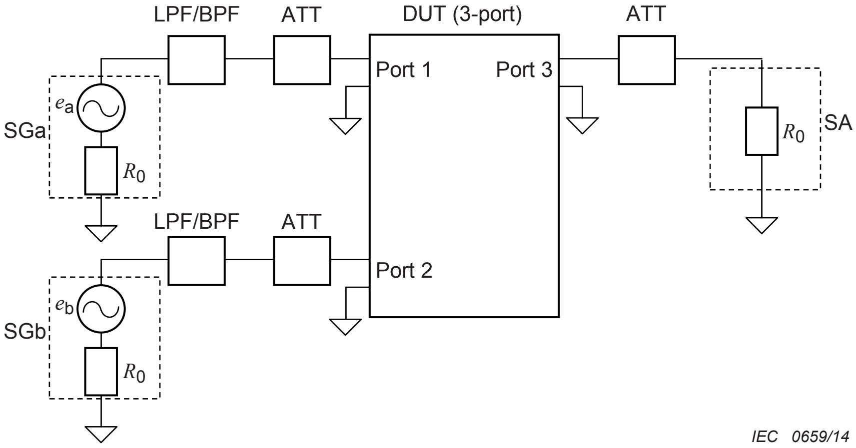

Figure 7 b) – Three-port DUT

Figure 7 – Practical setup for the IMD measurement (two-tone test)

Figure 8 shows another configuration for the IMD3 measurement using three SGs. This set up is often called the three-tone (triple-beat) test. Three sinusoidal signals with frequencies f_a, f_b and f_c are applied simultaneously to the DUT, and a target spectrum component P_t with frequency f_t $(= f_c \pm (f_a - f_b))$ is selectively measured by the SA. Filters and ATT are arranged with the power combiner to reject generated nonlinear signals and avoid IMD generation in SGa and SGb and to improve the return attenuation looking from the DUT port also for frequencies of IMD signals generated in the DUT.

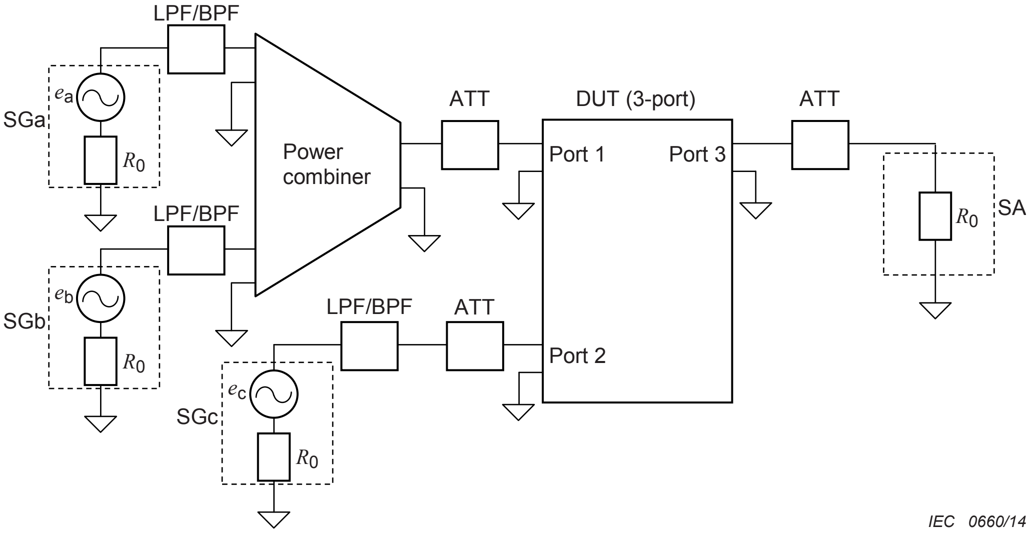

Figure 8 – Practical setup for three-tone measurement

4.3 Influence of circuit impedance for nonlinearity measurement

Here we discuss influence of the circuit impedance quantitatively. As an example, let us consider the IMD2 measurement for a SAW/BAW antenna duplexer shown in Figure 9. The antenna duplexer is composed of two filters:

a) a transmit (Tx) filter connected between ports 1 and 2 that transmits signals in the Tx band, and

b) a receive (Rx) filter connected between ports 2 and 3 that transmits signals in the Rx band. Ports 1, 2 and 3 are often called the Tx, antenna (ANT) and Rx ports, respectively.

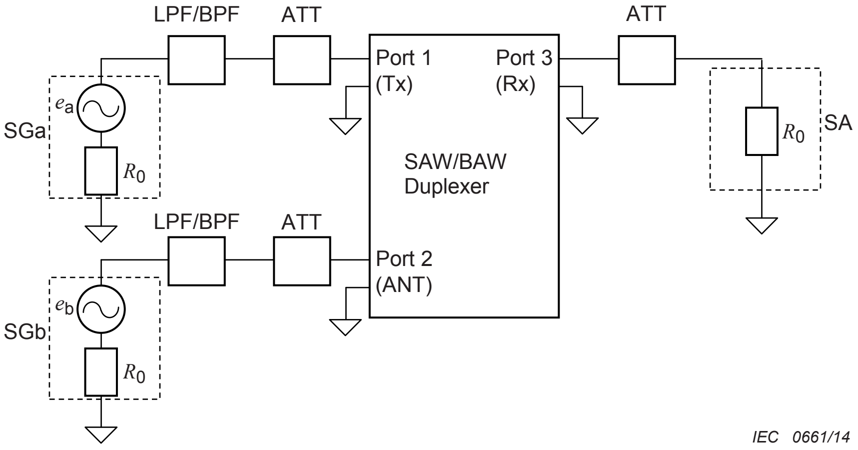

Figure 9 – Setup for IMD2 measurement of SAW/BAW antenna duplexers

For the IMD2 measurement, two RF signal generators “SGa” with f_a and “SGb” with f_b are connected to the ports 1 and 2, respectively, and they simulate the Tx and jammer signals, respectively. Thus f_a and f_b are specified so that:

- f_a is in the Tx band, and
- $f_a + f_b$ or $f_a - f_b$ is in the Rx band. This means that
- f_b is far from the Tx and Rx bands.

Thus the signal “a” incident from the port 1 will transmit to the port 2 through the Tx filter while the signal “b” incident from the port 2 will be attenuated significantly at the transmission in the Tx and Rx filters. This implies that the IMD2 signal is mainly generated by SAW/BAW resonators close to the port 2, and appears to the port 3 after the transmission through the Rx filter.

Variation of IMD2 output is caused mainly by the following five mechanisms:

- variation of the Tx signal intensity due to impedance mismatching at the Tx port for $f = f_a$,
- re-entry of the Tx signal to the ANT port due to impedance mismatching at the ANT port for $f = f_a$,
- variation of the jammer signal intensity due to impedance mismatching at the ANT port for $f = f_b$,
- re-entry of the nonlinear signal to the ANT port due to impedance mismatching at the ANT port for $f = f_a + f_b$ or $f = f_a - f_b$, and
- variation of detector read due to impedance mismatching at the Rx port for $f = f_a + f_b$ or $f = f_a - f_b$.

When the IMD2 signal is assumed to be generated very close to the DUT port 2, fractional error δ of the SA read b due to these effects may be approximately given by

$$\delta = \frac{\delta b}{b} \approx S_{32}^{a\pm b}(S_{21}^{a} S_{11}^{a} \Gamma_1^{a} + S_{22}^{a} \Gamma_2^{a} + S_{22}^{b} \Gamma_2^{b} + S_{22}^{a\pm b} \Gamma_2^{a\pm b}) + S_{33}^{a\pm b} \Gamma_3^{a\pm b} \tag{8}$$

where S_{nn} is the reflectivity for the DUT port-n, and Γ_n is that of the peripheral circuit looking from the DUT port-n. In Equation (8), the superscript is added to indicate its frequency because S_{nn} and Γ_n are frequency dependent.

Figure 10 shows range of deviation of the SA read resulting from δ in dB, namely the range from $20\log(1-|\delta|)$ to $20\log(1+|\delta|)$. Since $|S_{32}^{a\pm b}| \approx 1$ and $|S_{21}^{a}| \approx 1$, this result indicates that $S_{11}^{a}\Gamma_1^{a}$, $S_{22}^{a}\Gamma_2^{a}$, $S_{22}^{b}\Gamma_2^{b}$, $S_{22}^{a\pm b}\Gamma_2^{a\pm b}$, and $S_{33}^{a\pm b}\Gamma_3^{a\pm b}$ shall be suppressed better than − 25 dB and − 31 dB to obtain measurement accuracy better than ± 0,5 dB and ± 0,25 dB, respectively. In commercial duplexers, $S_{11}^{a} \approx 0$, $S_{22}^{a} \approx 0$, $S_{22}^{a\pm b} \approx 0$, and $S_{33}^{a\pm b} \approx 0$ but $|S_{22}^{b}| \approx 1$. Thus we shall pay much attention to the suppression of Γ_2^{b}; it shall be better than -25 dB (or − 31 dB) to obtain measurement accuracy better than ± 0,5 dB (or ± 0,25 dB).

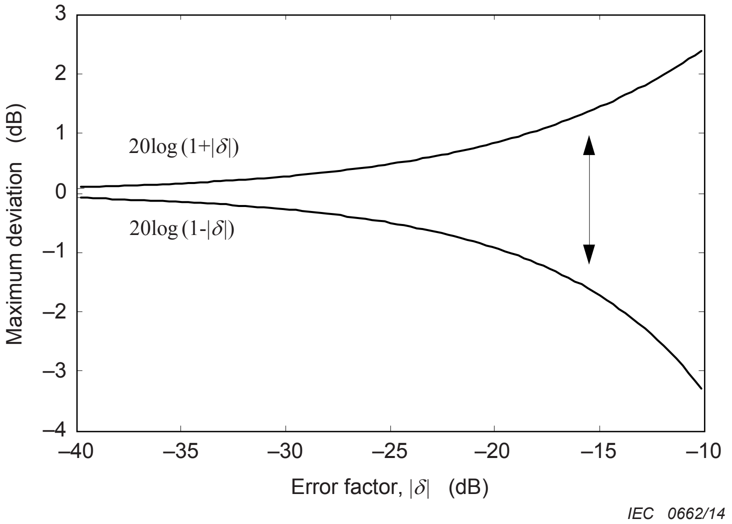

Figure 10 – Range of deviation resulting from δ in dB

4.4 Influence of circuit nonlinearity

Here we discuss influence of nonlinear signals generated by the peripheral circuits quantitatively. As an example, let us consider the IMD2 measurement for an RF SAW/BAW duplexer shown in Figure 9. In the case, fractional error δ of the SA read b due to the circuit nonlinearity may be given by

$$\delta = \frac{\delta b}{b} \approx \sqrt{\mathrm{IP2_{DUT}}}\left(S_{31}^{\mathrm{a}\pm\mathrm{b}} S_{12}^{\mathrm{b}} e^{i\phi_1} / \sqrt{\mathrm{IP2}_1} + S_{32}^{\mathrm{a}\pm\mathrm{b}} S_{21}^{\mathrm{a}} e^{i\phi_2} / \sqrt{\mathrm{IP2}_2} + S_{31}^{\mathrm{a}} S_{32}^{\mathrm{b}} e^{i\phi_3} / \sqrt{\mathrm{IP2}_3}\right) \qquad (9)$$

where $\mathrm{IP2_{DUT}}$ is the IP2 of the DUT, $\mathrm{IP2}_n$ is the IP2 of the peripheral circuit connected to the DUT port n, and ϕ_n is relative phase of the IMD2 signal generated at the peripheral circuit connected to the DUT port n. Since $|S_{31}^{\mathrm{a}\pm\mathrm{b}} S_{12}^{\mathrm{b}}| << 1$, $|S_{31}^{\mathrm{a}} S_{32}^{\mathrm{b}}| << 1$ but $|S_{32}^{\mathrm{a}\pm\mathrm{b}} S_{21}^{\mathrm{a}}| \approx 1$, we shall pay much attention for the suppression of $\mathrm{IP2}_2$; Figure 10 indicates that $\mathrm{IP2}_2/\mathrm{IP2_{DUT}}$ shall be better than − 25 dB (or − 31 dB) to obtain measurement accuracy better than ± 0,5 dB (or ±0,25 dB).

5 Nonlinearity measurement

5.1 Measurement equipment

5.1.1 Signal generator and power amplifier

In the setups shown in Figures 4-9, SGs shall possess the following properties:

a) small nonlinearity,

b) good short term stability (small frequency fluctuation),

c) capability to synchronise with an external standard oscillation signal (usually 10 MHz).

Requirements b) and c) are imposed to reduce the thermal noise level in the SA read as will be discussed later.

When the use of Pas is needed, their choice is crucial. Namely, the output stage of the PA shall operate in the class A mode, and the nominal maximum output of PA shall be sufficiently larger than the value required for the measurement. For example, use of PAs with maximum output of 5 W seems appropriate for 500 mW output. Since thermal noise is also emitted from PAs, the use of PAs with too large maximum output power may result in an increase in the noise level in the SA read.

5.1.2 Spectrum analyser

In the nonlinearity measurement, various spectrum components are simultaneously incident to the SA, and some of them may be much stronger than the target frequency component. Thus the SA shall possess good linearity and wide dynamic range. Since minimum detection level is determined by the noise level, SAs with low noise level is preferable. One may think that the vector network analysers (VNAs) can be used for this purpose. Since VNAs possess smaller linearity and dynamic range than SAs in general, applicability of VNAs might be limited.

It should be noted that the thermal noise level in the SA read is inversely proportional to the resolution bandwidth (RBW), which is adjustable in conventional SAs. Namely, the noise level decreases in the form of $10\log(RBW)$ in dB. For the RBW reduction, fluctuation in the SG and/or SA frequencies shall be suppressed sufficiently. Or the fluctuation will result in decrease of the SA read.

A convenient technique to reduce the fluctuation is synchronisation of all SGs and the SA. Current RF instruments generate RF signals using frequency synthesisers, and their output frequencies are given by the standard signal frequency f_s (usually 10 MHz) times a digitally preset coefficient. Thus, provided that common f_s is used in all SGs and the SA, fluctuation in f_a, f_b and f_t caused by that of f_s can be cancelled out by taking out f_s from one of these instruments and supplying it to the others. Present commercial RF instruments equip functions to input and output the standard signal. This technique allows to reduce RBW to 1 Hz for the measurement in GHz range. If not, fluctuation more than 100 Hz might be observable on the SA display output. When the RBW is too narrow, the SA read decreases due to uncorrelated frequency fluctuation among f_a, f_b and f_t.

Attention should also be paid not to confuse RBW with another adjustable parameter of SAs called the video bandwidth (VBW). Reduction of VBW enables to smooth out the SA display output. This is sometimes effective to suppress fluctuation caused by the thermal noise, but it may also smooth out line spectra. This causes decrease of the SA read. Usually VBW is set automatically.

Some SAs offer the averaging function. It stores results of multiple measurements and outputs their average. This is also effective to suppress fluctuation caused by the thermal noise, but the output becomes inaccurate when the frequency fluctuation is not sufficiently smaller than the RBW. We shall check whether the SA read does not change when the use of the averaging function is desired.

Since reduction of RBW also causes increase in the response time (time constant) of the SA, the measurement data points and the frequency bandwidth shall be set minimal.

5.1.3 Network analyser (optional)

The network analyser is convenient to check whether the DUT works properly and whether the DUT has not been damaged during the measurement. Vector network analysers are preferable rather than the scalar ones because of higher dynamic range. Combination of the SA with the tracking generator is another choice.

5.1.4 Accessories

In the nonlinearity measurement, certain number of passive components such as LPF/HPF, ATT and terminator are used. They shall be durable for the applied power and shall not generate non-linear signals for the applied signal level. In general, bulky devices for higher power use exhibit lower nonlinearity for given applied power. In addition, the nominal frequency range of cables, adaptors for connector conversion, ATTs, and terminators shall be sufficiently higher than frequencies of input and nonlinearly generated signals.

A variable ATT is convenient to check the influence of circuit impedance as described in 5.3.2d). It shall be passive type, and variation from 0 dB to 10 dB with 1 dB step might be appropriate.

If possible, a reference device shall be prepared. It shall have the same pass-band location with the DUT but higher power durability and small nonlinearity. For example, bulky RF filters using dielectric resonators can be a good choice as a reference for the nonlinearity characterisation of RF SAW/BAW filters.

5.2 Measurement Specifications

For the nonlinearity measurement of RF SAW/BAW devices, the following shall be specified:

a) DUT type and connectors
b) Basic setup of the measurement system and connection with the DUT
c) Circuit impedance (usually 50 Ω)
d) Scanning range and intervals of frequencies of applied signals, and corresponding frequency to be measured by the SA

e) Intensity of applying signals. Indicate a particular DUT port where the input or output power is specified

EXAMPLE

Specification for the IMD2 measurement of US PCS duplexer

a) Device under the test (DUT)

US PCS Duplexer placed on a PCB with SMA connectors

b) Measurement setup

See Figure 11. It should be noted that in practice, supplemental components such as filters and attenuators are added so as to satisfy requirements.

1) Continuous signal source connected to the transmit (Tx) port (SGa)

Frequency f_a: See Table 1

Intensity A_a: +21 dBm at the ANT port

Source impedance: 50 Ω

2) Continuous signal source connected to the antenna (ANT) port (SGb)

Frequency f_b: See Table 1

Intensity A_b: -15 dBm at the ANT port

Source impedance: 50 Ω

3) Spectrum analyser connected to the receive (Rx) Port (SA)

Target frequency f_t: See Table 1

Source impedance 50 Ω

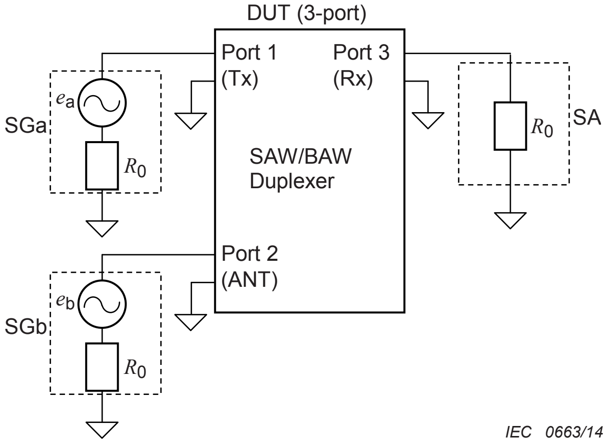

Figure 11 – Ideal IMD2 measurement setup for RF SAW/BAW duplexers

Table 1 – Frequencies f_a and f_b of input signals and target frequency f_t

f_a [MHz]	1 850	1 855	1 860	5 MHz step	1 905	1 910
f_b [MHz] (up-conv.)	80	80	80	80	80	80
f_b [MHz] (down-conv.)	3 780	3 790	3 800	10 MHz step	3 890	3 900
f_t [MHz]	1 930	1 935	1 940	5 MHz step	1 985	1 990

5.3 Measurement procedure

5.3.1 DUT check

Measure insertion and return attenuation of the DUT, and check whether the DUT works properly.

5.3.2 Setup and check

The measurement system shall be setup carefully so that sufficient measurement accuracy is achievable.

a) Prepare appropriate SGs (and PAs if necessary), SA and accessories following the suggestions given in 5.1, and set them up accordingly.

b) Connect the reference device to the setup instead of the DUT, and perform the nonlinearity measurement described in 5.3.3 to check whether the SA read for the reference device is at least 25 dB (or 31 dB) lower than the expected nonlinear output for the DUT to obtain measurement accuracy better than ±0,5 dB (or ± 0,25 dB). If not, return to step a).

c) If higher signal to noise ratio is required in the SA read, try to reduce the resolution bandwidth (RBW). Details are given in 5.1.2.

d) Connect the DUT to the setup, and add the variable ATT next to one of the fixed ATT from the DUT. Then perform the nonlinearity measurement described in 5.3.3 to check whether the SA read decreases according to the attenuation level. This check shall be performed for all DUT ports. If the result is not satisfactory, increase the value of the fixed ATT and return to step b) because the SG (or PA) output shall be increased to compensate the increased attenuation.

e) Perform the final measurement.

5.3.3 Data acquisition

The measurement shall be carried out according to the following procedure:

a) Measure ambient temperature.

b) Power on SGs (and PAs if necessary) and SA, and wait for a while till temperature of all the devices including DUT becomes almost constant.

c) Adjust the SG output so that the input signal intensity becomes a specified value at a specified frequency. It should be noted that it is sometimes defined by the output power from the DUT instead of the input power to the DUT. Figure 12a) shows the measurement setup when the intensity is specified by the power applied to the DUT port. Figure 12b) shows the measurement setup when the intensity is specified by output power from the DUT ANT port. Here the measurement setup for RF SAW/BAW antenna duplexers shown in Figure 9 is used as an example. At this measurement, open ports such as the DUT (Rx) port 3 in Figure 12b) shall be terminated by the specific impedance R_0.

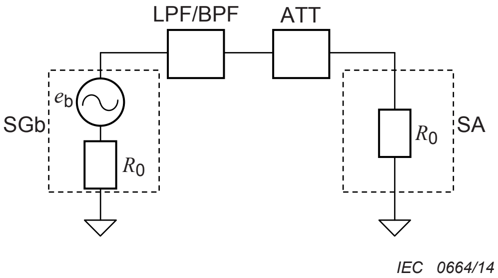

Figure 12a) – Setup with signal intensity specified by input power to the DUT ANT port

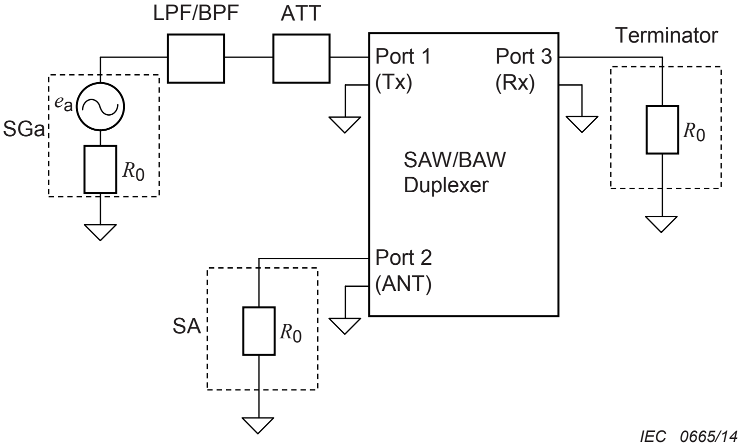

Figure 12b) – Setup with signal intensity specified by output power from the DUT ANT port

Figure 12 – Setup for the measurement of input signal intensity

d) Measure the nonlinear signal intensity using the setup.

e) Change the SG output frequency and repeat steps (b) and (c) until the measurement is completed for requested frequency points.

If the signal power is stable with time and reproducible with respect to the frequency setting, steps (c)-(e) can be modified as follows;

c') Measure the setting of SG(s) giving specified signal power for requested frequency points.

d') Measure the nonlinear signal intensity using the setup for requested frequency points. The signal power can be set using the setting data determined in step c') for each frequency point.

5.3.4 DUT final check

Measure insertion and return attenuation of the DUT, and check whether the DUT has not been damaged during the measurement.

5.4 Report

The measurement report shall include the following items:

a) Date
b) Device under the test (DUT)
c) Employed measurement setup
d) Measured signal power and circuit impedance
e) Measured ambient temperature
f) Insertion and return attenuation characteristics
g) Measured nonlinear characteristics (nonlinear output versus signal frequencies)

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