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Edition 1.0 2014-02

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

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

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)

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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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The text of this standard is based on the following documents:

FDIS	Report on voting
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Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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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.

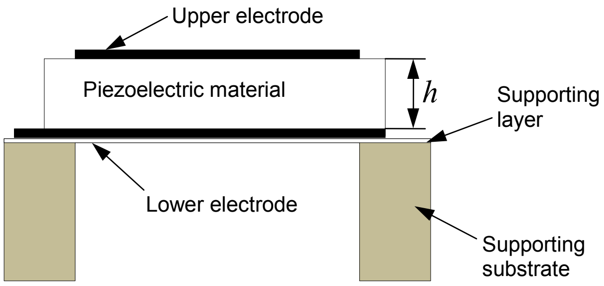

Figure 1 – FBAR configuration

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.

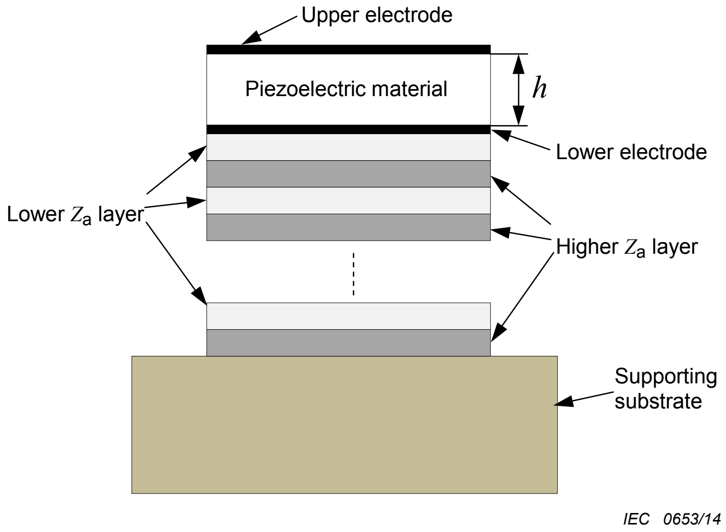

Figure 2 – SMR configuration

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

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

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 $P_{a\pm b} = P_{oa}P_{ob}/\mathrm{OIP2}$ 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

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

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 $P_{2a\pm b} = P_{oa}^2 P_{ob}/\mathrm{OIP3}^2$ 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

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

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 $P_{a \pm b}$ = OIP2 and $P_{2a \pm b}$ = OIP3. The input second- and third-order intercept points IIP2 and IIP3 are related to OIP2 and OIP3 as

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

and

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

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.

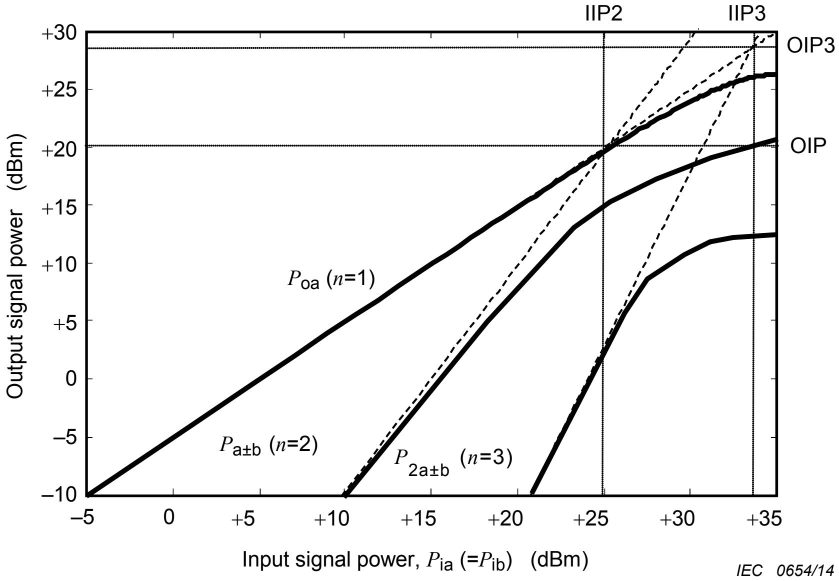

Figure 3 – Fundamental and harmonics output as a function of input signal power

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:

$$\text{IIP3} = 9{,}6 + P_{1dB} \tag{7}$$

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.

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

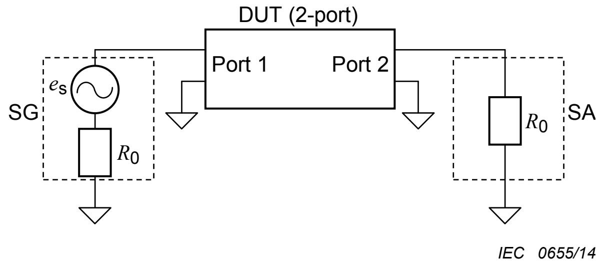

Figure 4 – Basic setup for the harmonics measurement

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.

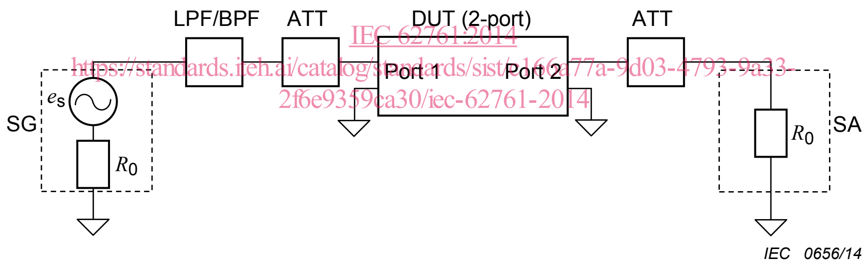

Figure 5 – Practical setup for the harmonics measurement

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.