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Second edition
2005-05

Surface acoustic wave (SAW) resonators –

Part 2: Guide to the use

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SURFACE ACOUSTIC WAVE (SAW) RESONATORS –

Part 2: Guide to the use

FOREWORD

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International Standard IEC 61019-2 has been prepared by IEC technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

This second edition cancels and replaces the first edition published in 1995. This edition constitutes a technical revision.

The main changes with respect to the previous editon are listed below:

- at the end of 5.1, the edge reflector has been added. Its reference literature has been inserted in the bibliography;
- in Table 1, the propagation properties of $LiNbO_3$ (64° Y) have been added;
- in Table 3, the clause and subclause numbers have been corrected in order to be consistent with IEC 61019-1 (2004) which has replaced IEC 61019-1-1 (1990) and IEC 61019-1-2 (1993).

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

FDIS	Report on voting
49/714/FDIS	49/723/RVD

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

IEC 61019 consists of the following parts, under the general title *Surface acoustic wave (SAW) resonators*

Part 1: Generic information

Part 2: Guide to the use

Part 3: Standard outlines and lead connections

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 maintenance result 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

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

This part of IEC 61019 gives practical guidance to the use of SAW resonators which are used in telecommunications, radio equipments and consumer products. IEC 61019-1 can be referred to for general information, standard values and test conditions.

The features of these SAW resonators are small size, light weight, adjustment-free and high stability. In addition, the operating frequency of SAW resonators extends to the VHF and UHF ranges.

This part has been compiled in response to a generally expressed desire on the part of both users and manufacturers for a guide to the use of SAW resonators, so that the resonators may be used to their best advantage. To this end, general and fundamental characteristics have been explained in this guide.

SURFACE ACOUSTIC WAVE (SAW) RESONATORS –

Part 2: Guide to the use

1 Scope

SAW resonators are now widely used in a variety of applications: VCR RF-converters, CATV local oscillators, measuring equipment, remote control and so on. While SAW resonators are also applied to narrow bandwidth filters, the scope of this part of IEC 61019 is limited to SAW resonators for oscillator applications

It is not the aim of this guide to explain theory, nor to attempt to cover all the eventualities which may arise in practical circumstances. This guide draws attention to some of the more fundamental questions, which should be considered by the user before he places an order for a SAW resonator for a new application. Such a procedure will be the user's insurance against unsatisfactory performance.

Standard specifications, such as those of the IEC of which this guide forms a part, and national specifications or detail specifications issued by manufacturers, will define the available combinations of resonance frequency, quality factor, motional resistance, parallel capacitance, etc. These specifications are compiled to include a wide range of SAW resonators with standardized performances. It cannot be over-emphasized that the user should, wherever possible, select his SAW resonators from these specifications, when available, even if it may lead to making small modifications to his circuit to enable the use of standard resonators. This applies particularly to the selection of the nominal frequency.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61019-1:2004, *Surface acoustic wave (SAW) resonators – Part 1: Generic specification*

IEC 61019-3:1991, *Surface acoustic wave (SAW) resonators – Part 3: Standard outlines and lead connections*

3 Technical considerations

It is of prime interest to a user that the resonator characteristics should satisfy particular specifications. The selection of oscillating circuits and SAW resonators to meet such specifications should be a matter of agreement between user and manufacturer.

Resonator characteristics are usually expressed in terms of resonance frequency, motional resistance, quality factor and parallel capacitance (for the one-port type) and centre frequency, insertion attenuation, loaded and unloaded quality factor, input capacitance and output capacitance (for the two-port type). A standard method for measuring resonator characteristics is described in 8.5 and 8.6 of IEC 61019-1. The specifications are to be satisfied between the lowest and highest temperatures of the specified operating temperature range and before and after environmental tests.

4 Fundamentals of SAW resonators

4.1 Basic structure

SAW resonators consist of interdigital transducers (IDT) and of grating reflectors, which are placed on the surface of a piezoelectric substrate. In most cases, the grating reflectors are made of thin metal (such as Al, Au) film while, in some cases, they are constructed with periodic grooves. The die is bonded by an adhesive agent into a sealed enclosure, and the IDT is electrically connected to the terminals with bonding wires. There are two SAW resonator configurations. One is a one-port SAW resonator. The other is a two-port SAW resonator. The former has a single IDT between two reflectors, as shown in Figure 1. The latter has two IDTs between two reflectors, as shown in Figure 2. In the figures, ℓ_{eff} is the resonator cavity length, as described in 5.2 c).

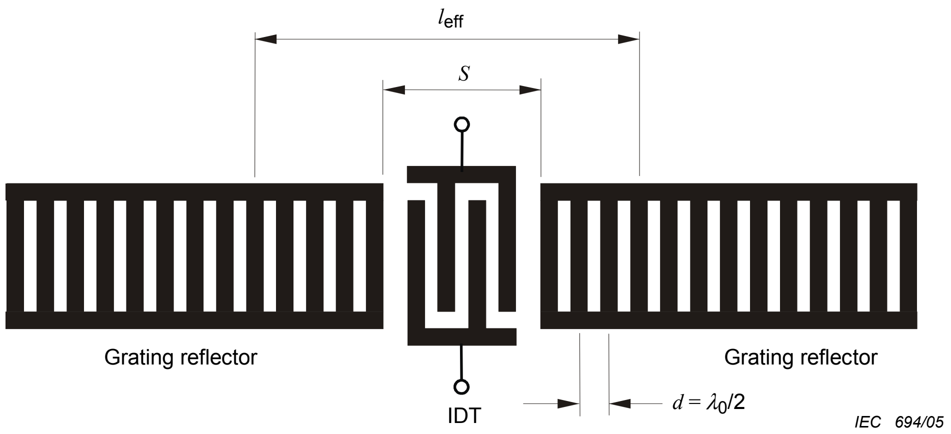


Figure 1 – One-port SAW resonator configuration

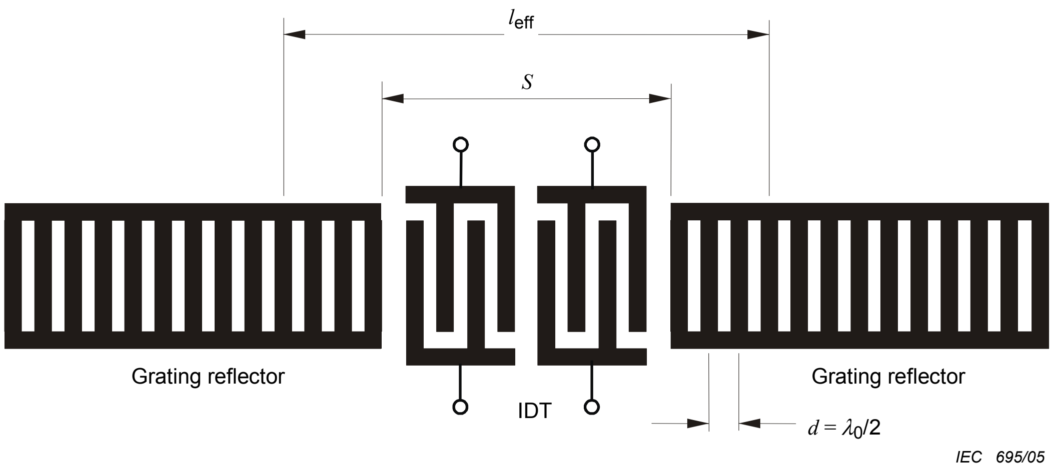


Figure 2 – Two-port SAW resonator configuration

4.2 Principle of operation

The resonance phenomenon for SAW resonators is achieved by confining the SAW vibration energy within grating reflectors. The SAW, excited by an alternating electrical field between IDT electrode fingers, propagates outside the IDT to be reflected by grating reflectors.

The grating reflectors feed the perturbation to the SAW, owing to the discontinuity in electrical or mechanical impedance. When the SAW is incident on such grating reflectors, the incident wave is gradually converted into a reflected wave. Although the amount of perturbation per unit reflective element may be very small, a large number of such elements, arranged periodically, reflect the SAW in phase, and maximize coherent reflection.

These grating configurations can form effective reflecting boundary, creating a standing wave between the reflectors and make resonance with a very high Q. Figure 3 shows the displacement distribution for this standing wave for a one-port SAW resonator. As shown in the figure, the SAW energy is maximum near the centre of the IDT, and gradually decays towards the edges of the grating reflectors. The resonance frequency, f_r, is approximately determined by

$$f_r \approx v_s/(2d) = v_s/\lambda_0$$

where

v_s is the SAW propagation velocity;

d is the distance between electrode centres;

λ_0 is the SAW wavelength at the stop band centre frequency.

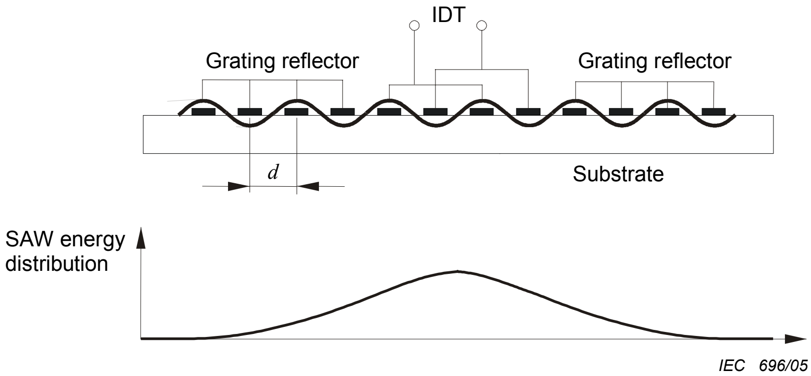


Figure 3 – Standing wave pattern and SAW energy distribution

5 SAW resonator characteristics

5.1 Reflector characteristics

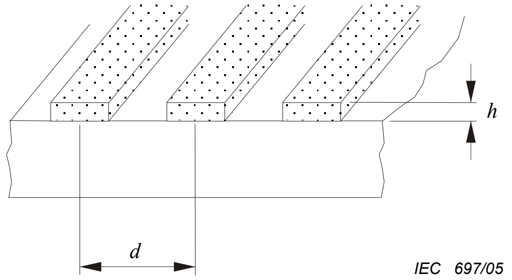
The reflector for SAW resonators consists of a periodically arranged array of reflective elements, called a grating reflector. As cross-sections show in Figure 4, possible array elements are:

a) metal strips or dielectric ridges;

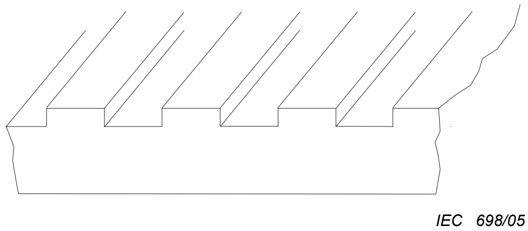
b) grooves;

c) ion-implanted or metal-diffused strips.

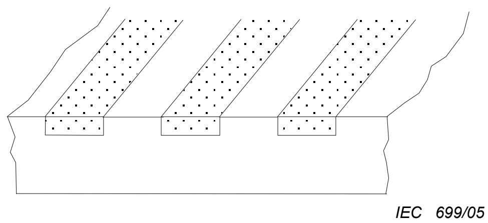
For example, an aluminum strip on ST-cut quartz, whose thickness h is 1 % of wave length $\lambda(h/\lambda_0)$ and whose width w is half the spatial period ($w = d/2 = \lambda_0/4$), has a small reflection coefficient ε of approximately 0,5 %. A groove with 1 % depth has almost the same ε. This periodic perturbation causes efficient reflection of SAW energy, if its wavelength equals twice its periodicity.



4a – Metal strips or dielectric ridges



4b – Grooves



4c – Ion-implanted or metal diffused strips

Figure 4 – Grating reflector configurations

A grating reflector without loss with a finite number of array elements has a frequency range of nearly total reflection called the stop band. The fractional stop bandwidth to centre frequency is $2\varepsilon/\pi$, where ε is the reflection coefficient for one element. Figure 5 indicates the frequency dependency on the total reflectivity $|\Gamma|$ for the grating reflector with a finite number N_R of array elements. Theoretically, the reflectivity maximum value is derived as:

$$|\Gamma|_{max} = \tanh(N_R \times \varepsilon)$$

at the centre frequency f_0 of the stop band. A greater reflectivity makes SAW resonator Q value higher, due to decreasing the leakage of SAW energy stored in the cavity between two grating reflectors.

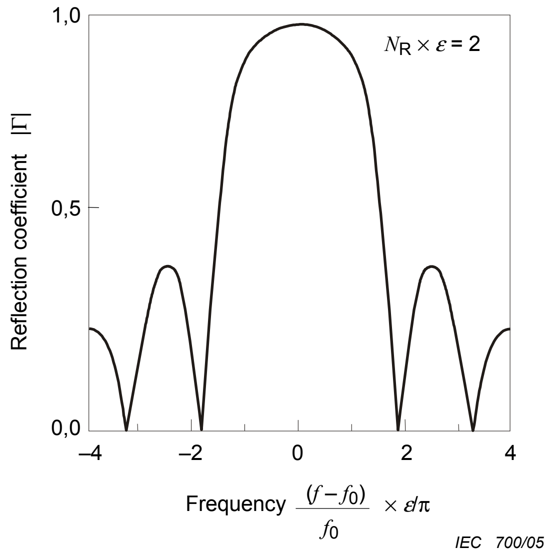


Figure 5 – Reflectivity response for grating reflection

For obtaining a greater reflectivity, it is clear, from the preceding equation, that $N_R \times \varepsilon$ should be larger. Increasing reflector element number N_R is the easiest way to obtain a higher reflectivity. However, in practice, a greater element number, i.e. longer reflector size, requires a larger SAW chip size and means an expensive SAW resonator. Generally, $N_R \times \varepsilon = 4$ is adequate for practical SAW resonators.

For obtaining greater reflectivity, increasing the reflection from one element is also effective. To accomplish this, strips should be thicker or grooves should be deeper. For the most part, ε is proportional to the thickness or the depth h/λ_0. Thicker strips or deeper grooves require less element number N_R for the same reflection coefficient and realize greater stop bandwidth. However, a reflector with a large h/λ_0 has the following disadvantages:

a) the mode conversion loss from SAW to bulk wave tends to increase, which may degrade the quality factor;
b) stopband centre frequency deviation from the frequency $v_s/(2d)$ increases, because the centre frequency is a function of the square of h/λ_0. This may cause mass production difficulties.

For a substrate material supporting shear wave, reflection at the edge of a substrate can be utilized as a substitute for a grating reflector. This gives the advantage of size reduction corresponding to the size of array elements.

5.2 SAW resonator characteristics

a) *One-port SAW resonators*

A one-port SAW resonator has the transmission characteristics shown in Figure 6.

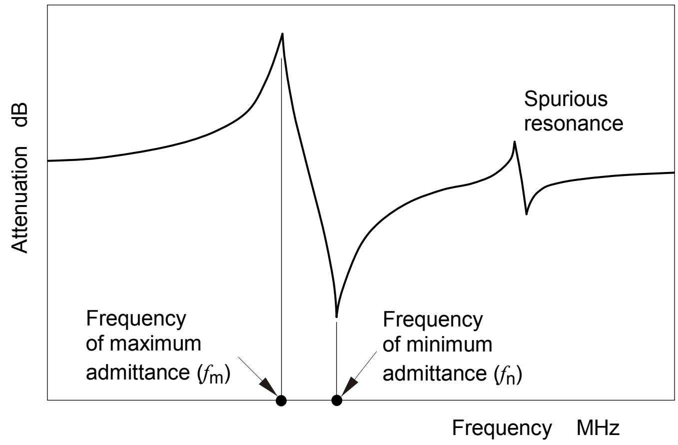
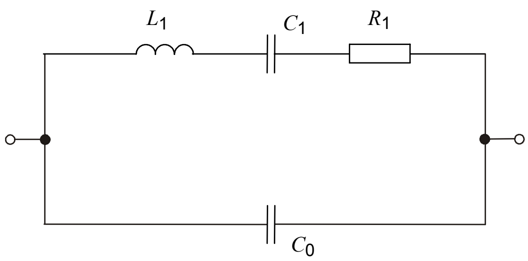


Figure 6 – Typical frequency characteristics for a one-port SAW resonator, inserted into a transmission line in series

The equivalent circuit in Figure 7 represents this one-port SAW resonator resonance. Comparing SAW resonators made from different piezoelectric materials, the figure of merit $M = Q/r$ derived from the equivalent circuit can be used. For example, SAW resonators on a quartz substrate have a high Q factor and a large r, while the values on X-cut $LiTaO_3$ are both smaller. Both resonators have similar figure of merit values. Considering only Q or the capacitance ratio r is insufficient for comparison purposes.

The equivalent circuit in Figure 7 can be replaced by a reactance with a series resistance: $R_e(f) + jX_e(f)$, where X_e and R_e are an equivalent series reactance and an equivalent series resistance, respectively. The frequency dependencies for these values are shown in Figure 8, where the value X_e/R_e reaches the maximum at the arithmetic mean of resonance and anti-resonance frequencies of zero susceptance.



$f_s = \dfrac{1}{2\pi\sqrt{L_1 \times C_1}}$	is the motional (series) resonance frequency;
$Q = 2\pi f_s \times L_1/R_1$	is the quality factor;
$r = C_0/C_1$	is the capacitance ratio;
$M = Q/r$	is the figure of merit;
L_1, C_1, R_1	are the motional inductance, motional capacitance and motional resistance respectively;
C_0	is the static capacitance.

Figure 7 – Equivalent circuit for a one-port resonator

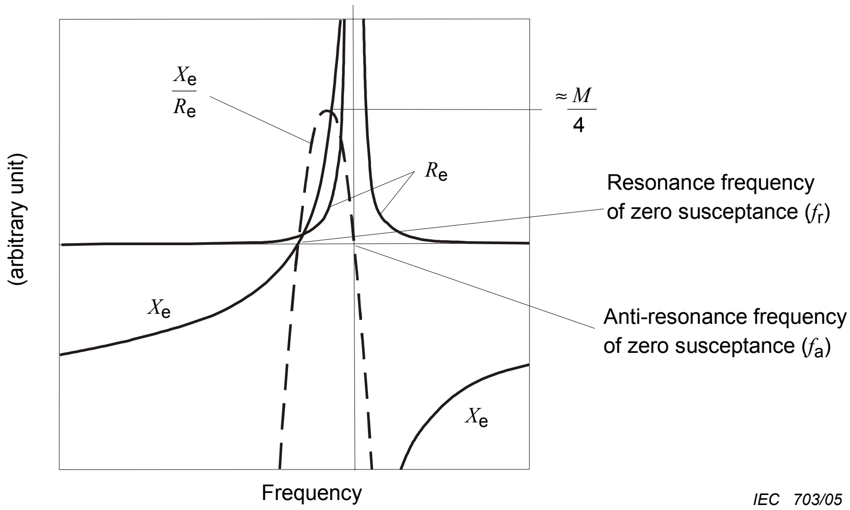


Figure 8 – Frequency response for series equivalent resistance (R_e), reactance (X_e) and X_e/R_e

The maximum value can be derived from the equivalent circuit as:

$$(X_e/R_e)_{max} \approx (Q/r)\ /4$$

In order to achieve oscillation more easily, resonators should show high Q reactance. Consequently, the figure of merit is adequate to compare SAW resonators.

Resonator impedance is inversely proportional to the aperture design. However, an over-narrow aperture resonator tends to increase r, due to the stray capacitance, and to degrade Q, due to the diffraction loss. On the other hand, an over-wide aperture resonator has a relatively low Q, due to electrode resistance.

b) *Two-port SAW resonators*

Two-port resonator transmission characteristics are shown in Figure 9.

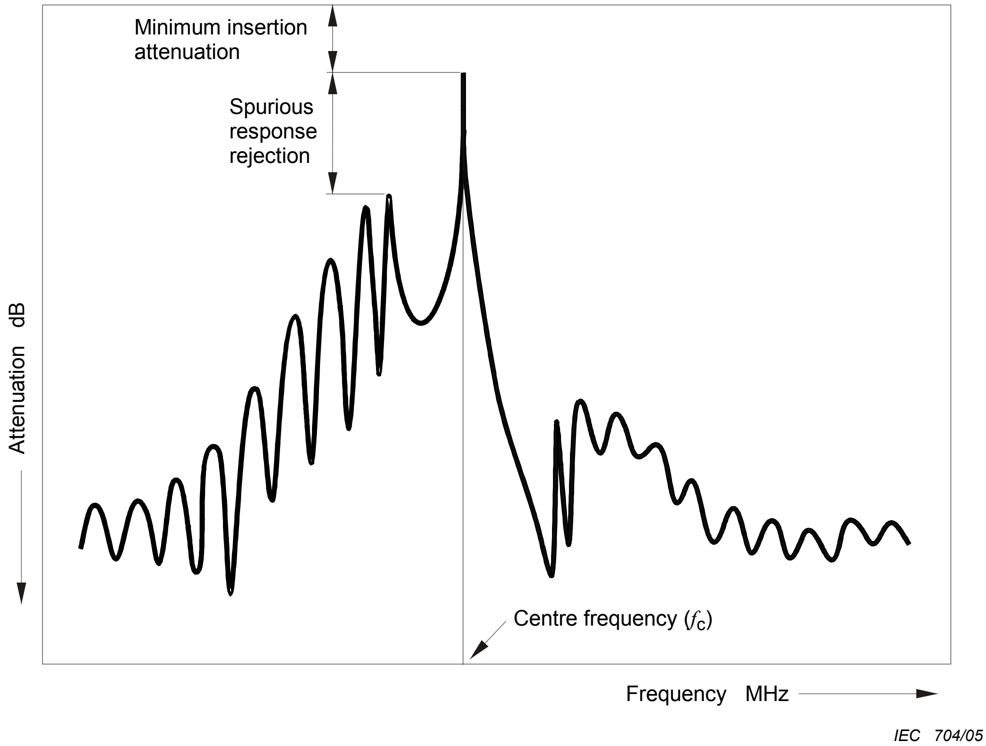
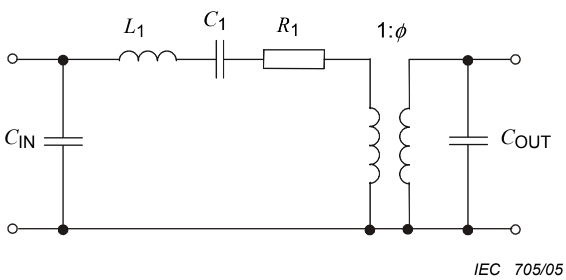


Figure 9 – Insertion attenuation and spurious response characteristics for a two-port resonator

An equivalent circuit for a two-port SAW resonator, in the vicinity of the centre frequency, is shown in Figure 10. It is constructed with a motional arm with motional inductance (L_1), capacitance (C_1), and resistance (R_1) in series, two parallel capacitances (C_{IN} and C_{OUT}) shunting the input and output ports and an ideal transformer. The turns ratio ϕ for the ideal transformer is derived from the input and output transducer structures. When both structures are the same, the ϕ value is unity; a 0° phase shift type is expressed as $\phi = 1$ and a 180° type is expressed as $\phi = -1$. Two-port SAW resonators, with different input and output impedances, have a $|\phi|$ value, which is not equal to unity.



Key

L_1 motional inductance	C_{IN} input capacitance
C_1 motional capacitance	C_{OUT} output capacitance
R_1 motional resistance	ϕ turns ratio

Figure 10 – Equivalent circuit for a two-port resonator

For two-port resonators, there is no evident index as figure of merit as for one-port resonators. Easy-to-oscillate resonators are devices with low loss in the specific circuit and with the appropriate phase transition of 0° or 180°. Small motional resistance R_1 is essential for low loss. A lower impedance resonator (larger C_{IN} and C_{OUT}) has lower loss, in most cases.

c) *Equivalent circuit parameters*

Equivalent circuit parameters for a one-port SAW resonator can be represented as follows, when SAW reflection at IDT fingers is neglected:

$$L_1 = \frac{l_{eff}/\lambda_0}{4f_0|\Gamma|} \times R_a$$

$$R_1 = \frac{1-|\Gamma|}{2|\Gamma|} \times R_a$$

$$C_1 = \frac{1}{(2\pi f_0)^2 L_1}$$

$$C_0 = N \times w(1+\varepsilon_r) \times \varepsilon_0$$

where

$R_a = \frac{1}{8k_s^2 f_0 N C_0}$ is the IDT radiation resistance at f_0;

f_0 = $v_s/(2d)$;

N is the IDT finger pair number;

w is the aperture;

k_s^2 is the SAW coupling coefficient;

ε_r is the relative permittivity of a piezoelectric substrate;

ε_0 is the permittivity of vacuum;

Γ is the reflection coefficient of a reflector;

λ_0 is the SAW wavelength at the centre frequency;

l_{eff} is the resonator cavity length shown in Figures 1 and 2 ($l_{eff} \approx S + \lambda_0/(2\varepsilon)$), where S is a separation of grating reflectors.

For two-port SAW resonators, C_0 shall be replaced by C_{IN} or C_{OUT} respectively. Other equations are the same as the above equations.

5.3 Spurious modes

SAW resonators have many kinds of spurious modes. One is higher-order SAW resonance modes, called longitudinal and transverse modes. Other types of SAW modes, such as leaky SAW, SSBW, Love waves, may be excited by the IDT. Another mode is bulk wave modes. Figures 6 and 9 show the typical spurious characteristics for one-port and two-port resonators, respectively. These spurious modes can be reduced by applying several techniques to the resonators.

When used in an oscillator circuit, these spurious modes rarely cause problems. However, should there be spurious responses near the main mode or responses with relatively large amplitude, oscillation problems at those spurious frequencies could occur.

These spurious responses could result in anomalous frequency-temperature, resistance-temperature and frequency pulling characteristics. Even very small perturbations of this type can have very deleterious effects for VCO (voltage controlled oscillator) applications. It is more difficult to eliminate these spurious responses from the resonators. However, these resonators seldom give trouble, because the spurious resonance resistance is in general larger than that for the main mode. Manufacturers' standard products involve design measures which minimize these effects when coupled with reasonable oscillator design.

In any application, where there are spurious responses, it should be considered that there is a possibility of the oscillator starting at the spurious responses. In a frequency range around the main response, one of the following ratios can be specified:

$$\frac{\text{spurious resonance motional resistance}}{\text{main resonance motional resistance}}$$ for a one-port resonator

$$\frac{\text{spurious resonance response level}}{\text{main resonance response level}}$$ for a two-port resonator

For two-port resonators, only spurious resonances which fulfil the phase condition of the oscillator feedback loop have to be considered.

5.4 Substrate materials and their characteristics

Various kinds of piezoelectric substrates are available for use in SAW resonators. Piezoelectric substrates for SAW resonators are selected, in consideration of the following items:

1) propagation velocity (v_s);
2) coupling coefficient (k_s^2);
3) temperature coefficient of frequency (TCF);
4) relative permittivity (ε_r);
5) material propagation loss;
6) reproducibility and reliability;
7) price.

Items 1) to 5) are constants concerned mainly with materials. Items 6) and 7) are conditions depending on both materials and substrate fabrication techniques. Several kinds of substrates have been developed and put into practical use.

Ideally, a high coupling coefficient and a zero temperature coefficient are desired. At present, this is not possible. Thus, a design trade-off is required. It is necessary to select a substrate according to the required specifications. Relationships between material constants and resonator characteristics are descried below.

a) *Propagation velocity*

   The propagation velocity v_s (m/s) is an important factor, which determines the frequency range. Resonance frequency f_r (MHz) is given approximately by:

   $$f_r = v_s/(2d)$$

   where d (μm) is the spatial period of the grating. For a specified resonance frequency, slower velocities require a shorter finger period and, consequently, a smaller chip size. Faster velocity is desirable for high frequency resonators, in order to make the IDT fabrication easier. Propagation velocity for a practical substrate is usually in the 2 000 m/s to 5 000 m/s range.

b) *Coupling coefficient*

   SAW coupling coefficient k_s^2 is the transformation ratio between the electric energy and the mechanical (SAW) energy. The coupling coefficient is the principal factor that determines capacitance ratio r. When the coupling coefficient of the substrate is large enough, it is easy to design a low capacitance ratio SAW resonator. An achievable minimum capacitance ratio is represented as:

   $$r_{min} \approx \pi^2/(8k_s^2)$$

c) *Temperature coefficient*

This characteristic is determined mainly by the piezoelectric material and crystal orientations. Rotated Y-cut (around ST-cut) quartz and $Li_2B_4O_7$ materials have parabolic frequency-temperature characteristics, but with other piezoelectric materials they are nearly linear. Figure 11 shows frequency-temperature characteristics for various common substrate materials.

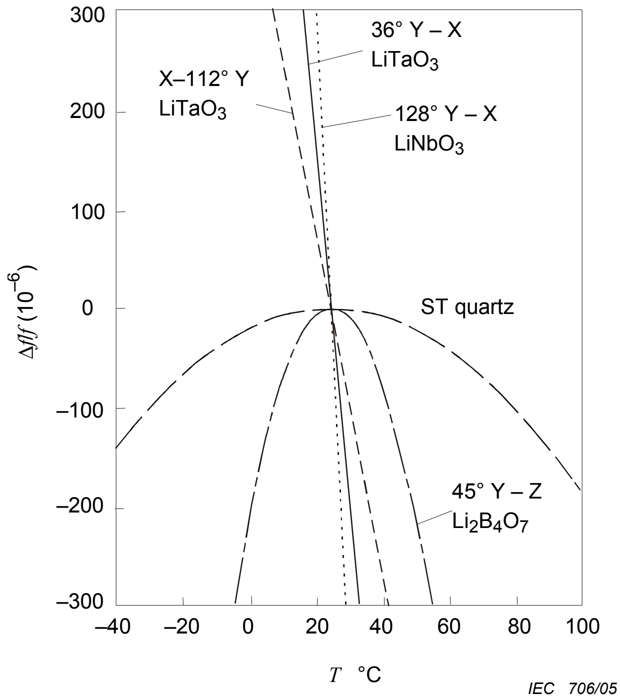


Figure 11 – Frequency-temperature characteristics for various common materials and their angles of cut

Typically the frequency-temperature dependence is:

$$\frac{\Delta f}{f} = a \times (T - T_0) + b \times (T - T_0)^2$$

where

$\frac{\Delta f}{f}$ is the fractional frequency change;

T_0 is the turnover temperature;

T is the operating temperature;

a is the first order temperature coefficient;

b is the second order temperature coefficient.

Typical temperature coefficient values are listed in Table 1.

d) *Relative permittivity*

The piezoelectric material permittivity is a second-order symmetric tensor. The static capacitance for the IDT, C_0, directly depends on the substrate permittivity.

e) *Material propagation loss*

The quality factor for the SAW resonator is a function of its various losses. The Q value depends on: material propagation loss (viscous damping and air loading), surface propagation loss (imperfect surface finish), bulk mode conversion loss, diffraction and other leakage losses from sides of reflectors and ohmic and frictional losses of electrodes. The material propagation loss determines the maximum Q limit, which is called material quality factor Q_m.

f) *Typical single-crystal materials*

Properties of single-crystal substrates are governed by the angle of cut and the SAW propagation direction, because of the crystal anisotropy. Single crystals have advantages concerning reproducibility, reliability, and low propagation loss.

However, it is still difficult to obtain a material which satisfies both large coupling coefficient and small temperature coefficient, simultaneously.

Typical crystals and their angles of cut recommended for SAW resonators are listed in Table 1 with their material constants.

Table 1 – Properties of single-crystal substrate materials

Material	Angle of cut	Propagation direction	Velocity V_s	Coupling coefficient k_s^2	Temperature coefficient		Relative permittivity ε_r
					a	b	
	Degrees	Degrees	m/s	%	10^{-6}/K	10^{-9}/K^2	
ST-quartz	42,75° Y	X	3 157	0,16	0	–34	4,5
LST-quartz	–75° Y	X	3 960	0,11	0	3rd order	4,5
$LiNbO_3$	Y	Z	3 488	4,82	–94	–	36,7
$LiNbO_3$	128° Y	X	4 000	5,56	–74	–	39,1
$LiNbO_3$	64° Y	X	4 742	11,3	–79	–	58,4
$LiTaO_3$	X	112°Y	3 295	0,64	–18	–	44,0
$LiTaO_3$	36° Y	X	4 178	4,8	–33	–	51,1
$Li_2B_4O_7$	45° Y	Z	3 401	1	0	–270	9,6

5.5 Available characteristics

a) *Frequency range*

The upper-limit frequency for SAW resonators is determined by fine pattern fabrication pitch is d (µm), the frequency is $v_s/(2d)$ (MHz), where v_s (m/s) means SAW velocity. The lower-limit frequency depends on chip size restriction. Available substrate wafer size and package dimensions are finite. In practice, demanded resonator cost also confines the allowable chip size. The typical frequency range for SAW resonators is from approximately 60 MHz to several GHz. However, this limitation is never strict.

b) *Quality factor*

The maximum possible quality factor for ideally designed and processed SAW resonator is limited to Q_m described in 5.4 e). Q_m depends on frequency and is approximately expressed as $Q_m = 10^7/f$ for typical substrate materials, where f is the frequency in megahertz. SAW resonators are reported to achieve Q_m at several frequencies. However, mass-produced SAW resonators using ST-cut quartz typically exhibit to have Q = 15 000 ∼ 20 000 at 100 MHz and Q = 10 000 at 600 MHz.

c) *Temperature coefficient of frequency*

Temperature-frequency characteristics of resonance frequency for SAW resonators are closely connected with the substrate material. However, mechanical stress to the substrate (such as adhesive agent), IDT and grating reflectors slightly affect the temperature dependency of the substrate itself.

Temperature-frequency characteristics for the quartz and $Li_2B_4O_7$ resonators have parabolic dependency. The temperature, where the parabolic curve locates its top position, is called turn-over temperature. It can be chosen by selecting an appropriate cut angle of the substrate. Generally, it is within the –20 °C to 75 °C range, and controlled within ±10 °C of a particular temperature.

SAW resonators with other materials provide a linear temperature-frequency relation. The temperature coefficient is also affected by the adhesive agent, IDT and grating reflectors, but is negligible compared with the material itself.

d) *Long-term stability*

Characteristic changes caused by ageing or long-term stability for SAW resonators are shown in resonance frequency changes and in quality factor degradation. These changes are influenced by

– contamination on the resonator chip surface;
– mechanical stress, for example by differences in thermal expansion between the resonator substrate and the package;
– too high drive level.

In the first two cases the cause exists in the SAW resonator device itself, and there may be many occasions where they arise. It is well-known that some of them occur during the manufacturing process. Examples are the bare-chip manufacturing process, the chip-bonding process using adhesive agent, the package sealing process and others.

In the third case, the characteristic changes occur in the over-excited condition and depend on oscillator circuit design. Excessive drive level damages electrodes in the SAW resonator and shortens its life. This is described in 5.5 e). Usually, with care applied to the drive level limitation, long-term stability is several parts per million/year or less.

e) *Power durability*

The excessive repeated mechanical stress may induce electrode deterioration, such as voids and hillocks. This brings about resonance frequency shifts and quality factor degradation. To make a resonator work for a long enough period in most applications, the drive level shall be less than several milliwatts.

To improve high-power withstanding durability, doping a small amount of copper or titanium to the aluminium electrodes is used. Epitaxially-grown aluminium electrodes on quartz are also used. They are all designed to be effective to control the grain boundary in deposited, aluminium thin film. This limitation level depends on frequency, ambient temperatures, electrode constitutions and device design.

f) *Short-term stability for SAW oscillator*

Short-term stability is the spectrum purity of the oscillator and is defined as SSB (single side-band) noise, residual FM noise or C/N (carrier to noise ratio) for the oscillation signal. The performance depends on the quality factor of the SAW resonator and handling power level in an oscillation loop. In general, SAW oscillators can achieve higher, short-term stabilities compared with LC oscillators and dielectric resonator oscillators.

g) *Availability*

Typical properties of the available one-port SAW resonators for the various materials are shown in Table 2. For the two-port resonators, the quality factor is almost the same as for one-port resonators.

Table 2 – Typical properties of available one-port SAW resonators up to about 600 MHz

Substrate materials	ST-cut quartz	X-112° Y $LiTaO_3$	36° Y-X $LiTaO_3$
Quality factor Q	12 000 – 24 000	12 000 – 17 000	600
Capacitance ratio r	1 200 – 1 600	800	14
Figure of merit $M = Q/r$	9 – 17	18	40
TCF	$-0{,}034 \times 10^{-6}/K^2$	$-18 \times 10^{-6}/K$	$-33 \times 10^{-6}/K$

6 Application guide

6.1 Oscillator circuits and oscillation condition

Oscillators using SAW resonators provide stable oscillation in VHF and UHF frequency ranges without frequency multiplexing, and have good spectrum purity (i.e. short-term stability).

One-port SAW resonators are very similar to crystal resonators, from the electrical viewpoint, in spite of differences in mechanical vibration modes and frequency ranges used. Consequently, oscillators are constructed with the same type of crystal oscillator circuits.

On the other hand, two-port SAW resonators are electrically treated as narrow bandwidth filters. Oscillators are constructed with feedback amplifiers.

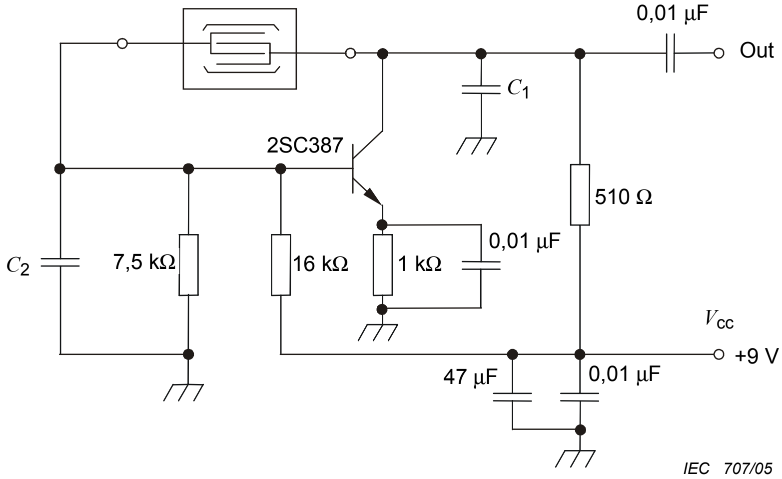
Figure 12a presents a typical one-port SAW resonator oscillator in the 100 MHz frequency range. This can be reduced to that shown in Figure 12b, considering the r.f. signal alone. The oscillation occurs in the frequency range, where the resonator is inductive.

In order to analyze the oscillation condition, the oscillator circuit is modelled by the equivalent circuit, consisting of a resonator element side and an active element side, as shown in Figure 12c.

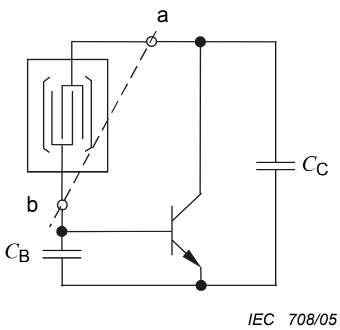
The resonator on the left-hand side can be re-written into the lumped element equivalent circuit, which is a reactance $X_e(f)$ in series with a resistance $R_e(f)$. The active element side can be replaced by a negative resistance R_L with a load capacitive reactance $X_L(= 1/(2\pi f \times C_L))$.

Oscillation occurs at the frequency f_{OSC} where the following equations are satisfied:

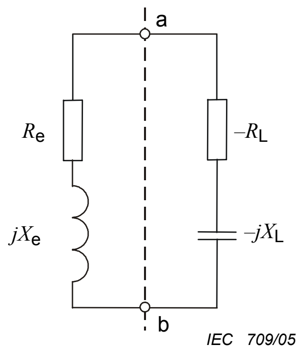
$$\begin{cases} X_e(f) = X_L \\ R_e(f) = R_L \end{cases}$$



a) – Oscillator circuit



b) – RF circuit of the oscillator



c) – Equivalent circuit

Figure 12 – 100 MHz one-port SAW resonator oscillator

The oscillation frequency can be approximately determined by the following equation:

$$f_{OSC} = f_r \times \left(1 + \frac{C_0}{2r(C_0 + C_L)}\right)$$

where

f_r is the resonance frequency;

r is the capacitance ratio (C_0/C_1) of the resonator;

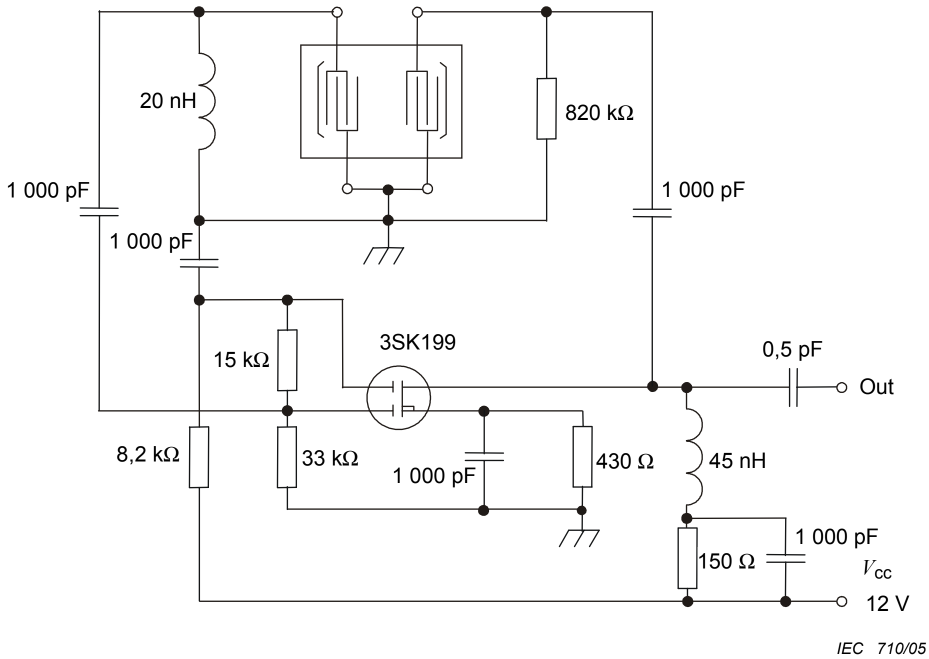
This means that the oscillation frequency can be changed slightly by varying the load reactance.

Figure 13a presents a typical two-port SAW resonator oscillator, for the 600 MHz frequency range. This can be simplified as shown Figure 13b, where an active element works as a feedback amplifier. The feedback amplifier shall be designed to satisfy the following conditions:

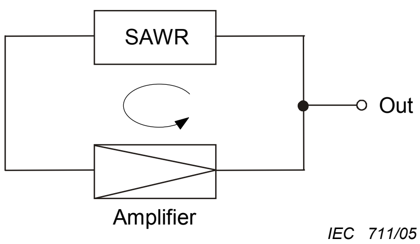
$$IA \leq G_E \quad \text{(dB)}$$
$$\phi + \phi_E = 2n\pi \quad \text{(radian)}$$

where n is an integer.

The former is an amplitude conditional equation for oscillation, where the amplifier gain G_E is required to exceed the SAW resonator insertion attenuation (IA). The latter is a phase conditional equation, where the loop phase shift across the amplifier ϕ_E and the SAW resonator ϕ is required to be an integral number of 2π at the oscillation frequency. This means that the oscillation does not occur at the exact resonance frequency of the SAW resonator, but mainly depends on the phase condition, influenced by the feedback amplifier phase shift.



a) Oscillator circuit



b) Equivalent circuit

Figure 13 – 600 MHz two-port SAW resonator oscillator

Also, attention should be paid to the fact that two-port SAW resonators could be designed to approximately 0° phase shift or 180° phase shift, by appropriately setting the IDT position and by lead connection.

6.2 Practical remarks for oscillator applications

As described previously, the oscillation frequency differs from the exact resonance frequency and the centre frequency of either one-port or two-port SAW resonators. The frequency difference depends on the oscillator circuit condition; load capacitance or feedback amplifier phase shift. Resonators should be ordered with due consideration to the frequency dependency on the designed oscillator circuit.

A check should also be made to determine whether or not an application accepts the degree of resonator characteristic changes, as descried in 5.5 d). For this purpose, the manufacturer shall continually carry out quality conformance tests, especially accelerated or continuous ageing tests, and then present the data.

High power excitation tends to degrade the SAW resonator characteristics and change the resonance frequency, as described in 5.5 e). This means degradation of long-term stability for the resonator. An oscillator circuit shall be designed so as not to exceed the maximum drive level for the resonator. It is recommended to carry out long-term ageing tests in the actual oscillator circuit, when a new SAW oscillator circuit is designed.

In general, accelerated ageing tests, which are much more severe than normal operating conditions with regard to excitation, temperature, or others, will be carried out for the power dissipation capability evaluation.

7 Checklist of SAW resonator parameters for drawing up specifications

The following checklist (Table 3) provides guidance for the manufacturer to complete specifications for a particular SAW resonator type, including parameters and operating environmental characteristics. It is also useful for ordering the resonator and should be considered in drawing up the specifications. The prospective user is then able to more accurately evaluate the applicability of the resonator to his intended use. The list also assists the user when he finds it necessary to specify a new SAW resonator for a particular application, by alerting him to the various operating conditions and performance characteristics which need definition.

When the requirements are met by a standard item, it is sufficient to specify the corresponding specifications. When the requirements cannot be wholly met by existing detail specifications, the specifications should be referred to, together with a list of known differences.

In rare cases, where the differences are such that it is not reasonable to quote existing detail specifications, new specifications should be prepared in a similar format to that already used for standard detail specifications.

Clearly, it is not necessary to specify all the parameters listed for every application; only those which are of importance in a particular case should be imposed. Specifications regarding non-critical parameters, as well as imposition of unnecessarily close tolerances, can result in excessive costs.

In Table 3, references are made to the relevant clauses and subclauses of IEC 61019-1. These references appear in column 2. In column 3, "one-port" and "two-port" mean "one-port SAW resonator only" and "two-port SAW resonator only", respectively.

Table 3 – Checklist

Parameters and characteristics	Clause and subclause of IEC	Comments
1	2	3
Application		
Description		
Operating conditions		
Operating temperature range	61019-1, 4.2.4	
Level of drive	61019-1, 4.2.7	
Absolute maximum level of drive		
Testing level of drive		
Frequency characteristics		
Nominal frequency	61019-1, 4.2.1	
Working frequency	61019-1, 4.2.2	
Temperature coefficient of frequency		
Frequency tolerances	61019-1, 4.2.3	
Overall tolerance	61019-1, 4.2.3.1	
Adjustment tolerance	61019-1, 4.2.3.2	
Ageing tolerance	61019-1, 4.2.3.3	
Frequency of maximum admittance	61019-1, 4.2.10.2.1	One-port
Motional resonance frequency	61019-1, 4.2.10.2.2	One-port
Anti-resonance frequency	61019-1, 4.2.10.3	One-port
Load resonance frequency	61019-1, 4.2.10.13	One-port
Spurious resonance	61019-1, Figure 4	One-port
Centre frequency	61019-1, 4.2.11.9	Two-port
Motional resonance frequency for two-port resonator	61019-1, 4.2.11.4	Two-port
Minimum insertion attenuation for two-port resonator	61019-1, 4.2.11.8	Two-port
Spurious resonance rejection	61019-1, 4.2.11.10	Two-port
Electrical characteristics		
Quality factor	61019-1, 4.2.10.8	One-port
Unloaded quality factor	61019-1, 4.2.11.5	Two-port
Loaded quality factor	61019-1, 4.2.11.6	Two-port
Motional resistance	61019-1, 4.2.10.4	One-port
Shunt capacitance	61019-1, 4.2.10.7	One-port
Load capacitance	61019-1, 4.2.10.11	One-port
Input capacitance	61019-1, 4.2.11.2	Two-port
Output capacitance	61019-1, 4.2.11.3	Two-port
Operating phase shift	61019-1, 4.2.11.11	Two-port
Tuning inductance	61019-1, 4.2.11.12	Two-port
Insulation resistance	61019-1, 8.6.3	
DC voltage overdrive		
Voltage proof	61019-1, 8.6.4	
Electromagnetic interference		
Electrostatic damage		
Other factors		

Table 3 *(continued)*

Parameters and characteristics	Clause and subclause of IEC	Comments
1	**2**	**3**
Environmental characteristics		
Temperature ranges		
Absolute maximum temperatures		
Storage temperature range		
Operable temperature range	61019-1, 4.2.4.1, 5.2	
Rapid temperature change (thermal shock in air)	61019-1, 8.7.4, 8.7.5	
Bump	61019-1, 8.7.6	
Vibration	61019-1, 8.7.7	
Shock	61019-1, 8.7.8	
Acceleration, steady state	61019-1, 8.7.10	
Low air pressure	61019-1, 8.7.11	
Climatic sequence	61019-1, 8.7.15	
Dry heat	61019-1, 8.7.12	
Damp heat, cyclic, first cycle	61019-1, 8.7.13	
Cold	61019-1, 8.7.14	
Damp heat, cyclic, remaining cycles	61019-1, 8.7.13	
Damp heat (long term exposure)	61019-1, 8.7.16	
Sealing test	61019-1, 8.7.2	
Gross leak test	61019-1, 8.7.2.1	
Fine leak test	61019-1, 8.7.2.2	
High temperature ageing	61019-1, 8.8.1	
Other factors		
Physical characteristics		
Outline dimensions	61019-3	
Electrical connections of terminals	61019-3	
Robustness of terminals	61019-1, 8.7.1	
Solderability	61019-1, 8.7.3	
Marking	61019-1, Clause 6	
Mounting arrangements		
Weight		
Other factors		
Inspection requirements		
Applicable documents (related specifications)		
Inspection authority		
Type test		
Type test procedure		
Acceptable quality level		
Other factors		

It should be clearly stated in the detail specification whether the SAW resonator is required to operate while under conditions of shock, vibration or acceleration.

Bibliography

Books

[1] H. Matthews: *Surface Wave Filters*, John Wiley and Sons Inc., New York, 1977

[2] E.A. Gerber and A. Ballato: *Precision Frequency Control*, Academic Press, Orlando, FL 1985.

[3] D.P. Morgan: *Surface-Wave Devices for Signal Processing*, Elsevier Science Publishers B.V., 1985.

[4] M. Feldmann and J. Henaff: *Surface Acoustic Waves for Signal Processing*, Artech House, Boston, 1989.

Specialist articles

Materials

[1] A.J. Slobodnik, Jr.: *Surface Acoustic Waves and SAW Materials*, IEEE Proceedings. 64, 5, pp.581-595, 1976.

[2] M.B. Schulz, B.J. Matsinger and M.G. Holland: *Temperature Dependence of Surface Acoustic Wave Velocity on alpha Quartz*. J. of Applied Physics, 41, 7 , pp. 2755-2765, 1970.

[3] H. Hirano: $LiTaO_3$ *Single Crystals for SAW Device Applications*, Proc. 1st Meeting on Ferroelectric Materials and Their Applications, pp. 81 -86, 1977.

[4] N.M. Shorrocks, R.W. Whatmore, F.W. Ainger and I.M. Young: *Lithium Tetraborate – A New Temperature Compensated Piezoelectric Substrate Material for Surface Acoustic Wave Devices*, Proc. IEEE Ultrasonics Symp., pp. 337-340, 1981.

[5] Y. Shimizu, M. Tanaka, and T. Watanabe: *A New Cut of Quartz with Extremely Small Temperature Coefficient by Leaky Surface Wave*, Proc. IEEE Ultrasonics Symp., pp. 233-236. 1985.

Reflector structures

[1] R.C. Williamson and H.I. Smith: *The Use of Surface-Elastic-Wave Reflection Grating in Large Time-Bandwidth Pulse-Compression Filters*. IEEE Trans. Microwave Theory and Tech., MTT-21(4), pp.195-205, 1973.

[2] E.K. Sittig and G.A. Coquin: *Filters and Dispersive Delay Lines Using Repetitively Mismatched Ultrasonic Transmission Lines*, IEEE Trans. Sonics & Ultrason., SU-15, pp. 111-119, 1968.

[3] P.S. Cross; *Properties of Reflective Arrays for Surface Acoustic Resonators*, IEEE Trans. Sonics & Ultrason., SU-23(4), pp. 255-262. 1976.

[4] R.C.M. Li and J. Melngailis: *The Influence of Stored Energy at Step Discontinuities on the Behavior of Surface-Wave Gratings*, IEEE Trans. Sonics & Ultrason., SU-§§22(3), pp. 189-198, 1975.

[5] T. Kojima and J. Tominaga: *Split Open Metal Arrays and Their Application to Resonators*, Proc. IEEE Ultrasonics Symp., pp. 117-122, 1981.

[6] H. Shimizu and M. Takeuchi: *Theoretical Studies of the Energy Storage Effects and the Second Harmonic Responses of SAW Reflection Gratings*, Proc. IEEE Ultrasonics Symp., pp. 667-672, 1979.

[7] M. Koshiba, S. Mitobe and M. Suzuki: *Finite-Element Analysis of Periodic Waveguides for Acoustic Waves*, Japan J. Appl. Phys., vol. 23, Supplement 23-1, p. 139, 1984.

[8] Y.Suzuki, H.Shimizu, M.Takeuchi, K.Nakamura, and A.Yamada: *Some Studies on SAW Resonators and Multiple-mode Filters*, Proc. IEEE Ultrasonics Symp., pp.297-302, 1976

Resonator design and application

[1] E.A. Ash: *Surface Wave Grating Reflectors and Resonators*, Proc. IEEE Symp. Microwave Theory and Tech., 1970.

[2] E.J. Staples, J.S. Schoenwald, R.C. Rosenfeld and C.S. Hartmann: *UHF Surface Acoustic Wave Resonators*, Proc. IEEE Ultrasonics Symp., pp. 245-252, 1974.

[3] K.M. Lakin and T.R. Joseph: *Surface Wave Resonators*, Proc. IEEE Ultrasonics Symp., pp. 269-278, 1975.

[4] D.T. Bell Jr. and R.C.M. Li: *Surface-Acoustic-Wave Resonators*, Proc. IEEE, 64, 5, pp. 711-721, 1976.

[5] Y. Koyamada, S. Yoshikawa and F. Ishihara: *Analysis of SAW Resonators Using Long IDTs and Their Applications*, Trans. IECE Japan, J-60A(9), pp. 805-812, 1977.

[6] T. Uno, H. Jumonji: *Optimization of Quartz SAW Resonator Structure with Groove Gratings*, IEEE Trans. Sonics & Ultrason., pp. 299-310, 1982.

[7] F.G. Marshall: *Surface Acoustic Wave Resonators Constructed of Aluminum on ST Quartz for Use in High Stability Feed Back Oscillators*, Proc. IEEE Ultrasonics Symp., pp. 290-292, 1975.

[8] Y. Ebata, K. Sato and S. Morishita: *A* $LiTaO_3$ *SAW Resonator and its Application to Video Cassette Recorder*, Proc. IEEE Ultrasonics Symp., pp. 111-116, 1981.

[9] J.I. Latham, W.R. Shreve, N.J. Tolar and P.B. Ghate: *Improved Metallization for Surface Acoustic Wave Devices*, *Thin Solid Film*, 64, pp. 9-15, 1979.

[10] Y. Ebata and S. Morishita: *Metal-migration of Aluminum Film on SAW Resonator*, Trans. IECE Japan, Vol. J67-C, No.3, pp.278-285, 1984.

[11] J.A. Learn: *Electromigration Effects in Aluminum Alloy Metallization*, *J. of Elec. Mat.*, 3, 2, pp. 531-552, 1974.

[12] J. Yamada, N. Hosaka, A. Yuhara and A. Iwama: *Sputtered Al-Ti Electrodes for High Power Durable SAW Devices*, Proc. IEEE Ultrasonics Symp., pp. 285-290, 1988.

[13] M. Koshino, K. Yamashita, T. Kurokawa, Y. Ebata and M. Takase: *Driving Current Dependence of Aging Drift in 600 MHz Band SAW Resonators*, IEEE Trans. Consumer Elec., Ce-32(3), pp. 659-665, 1986.

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