Motorola Inc.
Crystal Technology
Design Guidelines

by Ralph Marino

This chart has been developed by the Motorola Communications Sector Crystal Commodity Team and is intended to be an aid for engineering development. Its use should be used in conjunction with information provided by preferred Crystal Suppliers through early supplier involvement programs.

CRYSTAL UNITS

Technical Terms

The following technical terms are generally used for crystal units:

1. **Crystal water (blank):** A piece of quartz crystal cut as specified in terms of shape, dimensions and orientation.
2. **Electrode:** Conductive thin film vacuum-evaporated onto a crystal wafer to allow AC voltage to be applied.
3. **Holder:** A case housing a crystal wafer, electrode and support to prevent them mechanically and environmentally from being influenced by outside conditions, and also having terminals permitting the electrical connection of the electrode with an outside circuit.
4. **Crystal unit:** Mounted crystal wafer with electrode housed in a holder.
5. **Overtone:** Odd numbers assigned for frequencies in terms of specified oscillation mode (The first overtone is called fundamental mode, followed by 3rd, 5th and 7th overtones. The frequencies are not exactly three times, five times or seven times the fundamental mode.)
6. **Series resonance frequency:** Lower frequency of the two given when the electrical impedance of a crystal unit becomes resistant near resonance point.
7. **Load capacitance:** Effective series capacitance measured from the terminals of a crystal unit to the oscillation circuit and determined as a condition in the case of using a crystal unit in an oscillation circuit. Operating frequency is determined by the electrical characteristics of a crystal unit and the load capacitance.
8. **Nominal frequency:** Specific frequency at specific load capacitance.
9. **Series resonance:** Condition of resonance in the case of infinite load capacitance.
10. **Frequency tolerance:** Deviation from the nominal frequency expressed by ratio in reference to nominal frequency.
11. **Equivalent series resistance:** Equivalent resistance at series resonance frequency.
12. **On-load equivalent resistance:** Resistance for the lower frequency of the two given when the electrical impedance becomes resistant near the resonance point of a circuit, with the load capacitance connected with a crystal unit in series.
13. **Operating temperature range:** Temperature range wtihin which crystal units operate under specified conditions.
14. **Drive level:** Electric-power or current level under the specified conditions of a crystal unit.
15. **Main mode and spurious:** Main mode indicates the desired resonance frequency and spurious indicate other resonance frequencies when there are some resonance frequencies near the nominal frequency.

Cutting Angles

Cutting angles differ depending upon the applications (oscillation frequencies and electrical characteristics). The **Fig. 1** shows main cutting angles. And Table 1 shows vibration modes, frequency ranges and capacity ratios (typical values).

Taking the most popular AT-cut crystal wafer for example, it is in a plane which makes an angle of 35°15' to the Z axis and the wafer thickness is approximately 0.06mm in the case of 25MHz fundamental-wave thickness-shear vibration.

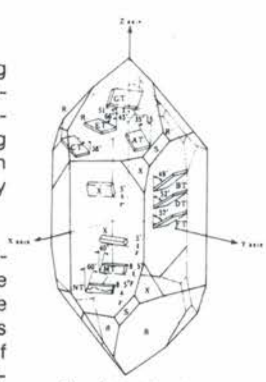
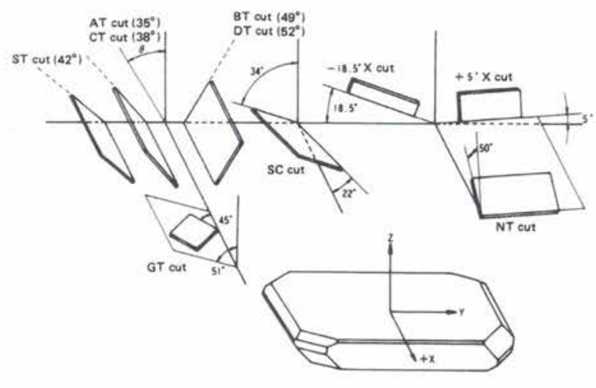


Fig. 1 Cut Angle

Orientation Angles



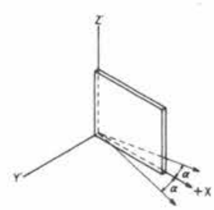
The specifications of the most common AT-cut wafers are as follows.

Accuracy

Directional angle (θ)
θ ± 15'
θ ± 30'
θ ± 1'
θ ± 2'
θ ± 3'

Primary Wafers

These are quartz crystal wafers polished with GC#1000 and can be selected freely from the table below according to the specifications of the quartz crystal unit to be manufactured.

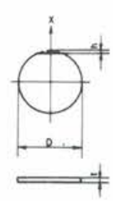


Inclinational angle (α = 0°00')
0°00' ± 5'
0°00' ± 10'
0°00' ± 20'
0°00' ± 30'

Finished Wafers

These are quartz crystal wafers on which the final precision polishing has been completed and on which immediate etching or electrode forming processes can be conducted.

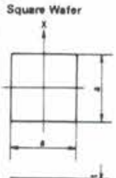
Round Wafer



Diameter D ±0.02	Axis Indication h ±0.02	Thickness t ±0.01
5	0.2	0.2~0.5
5.5	0.2	0.2~0.5
6.2	0.2	0.2~0.5
6.5	0.2	0.2~0.5
7.5	0.25	0.2~0.8
8.0	0.25	0.2~0.8
8.7	0.25	0.2~0.8
8.9	0.25	0.3~1.2
9.5	0.25	0.3~1.2
11	0.4	0.3~1.2
12.5	0.4	0.4~1.5
14	0.4	0.4~1.5
15	0.4	0.4~1.5

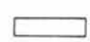
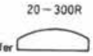
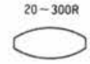
Unit (mm)

Square Wafer



Dimension a×a±0.02	Thickness t±0.01
8×8	0.25~1.2
9×9	0.25~1.2
10×10	0.3 ~1.5
11×11	0.3 ~1.5

Unit (mm)

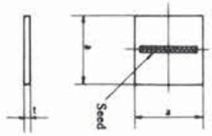
	Shape	Frequency in Fundament Mode	Surface Finish
Plane Wafer		5~35 MHz	WA #1000 WA #3000 Polish
Beveled Wafer		1~15 MHz	WA #1000 WA #3000
Plano-convex Wafer	20~300R 	1~12 MHz	WA #1000 WA #3000
Bi-convex Wafer	20~300R 	1~12 MHz	WA #1000 WA #3000

(1) Quartz crystal wafers other that the above will also be manufactured.

(2) Etching will also be conducted if desired.

ST Cut Wafers

Lapped GC# 1000 lapping or polished so it can be used as a SAW device.



Cut Angle Directional angle (θ)	Inclinational angle (α)
$\theta = 42°45' \pm 5'$ $\theta = 36°00' \pm 5'$	$\alpha = 0°00' \pm 15'$

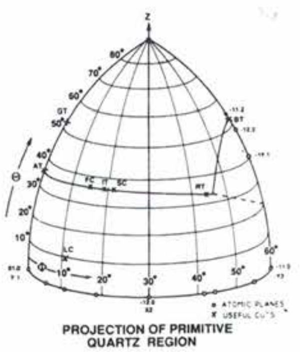
Dimension a × a ± 0.2	Thickness t ± 0.01
45 × 45 50.8 × 50.8	0.5

Unit (mm)

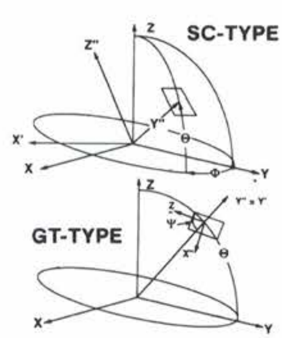
Table 1 Basic Characteristics

Mode of Vibration	Cut	Frequency Range	Frequency Formula	Capacitance Ratio (Typical)
Thickness-shear	AT Fundamental	800 ~ 5000 2000 ~ 30000	1670 × 1/t 1670 × 1/t	300 ~ 450 220
	AT 3rd Overtone AT 5th Overtone AT 7th Overtone AT 9th Overtone	20000 ~ 90000 40000 ~ 130000 100000 ~ 200000 150000 ~ 230000	$1670 \times \frac{n}{t}$	$n^2 \times 250$ n: Overtone Mode
	BT Fundamental	2000 ~ 35000	2560 × 1/t	650
Length-width-flexure	+ 2°X	16 ~ 100	$700 \times w / \ell^2$	450
Length-width-flexure	XY NT	1 ~ 35 4 ~ 100	$5700 \times t / \ell^2$ $5000 \times w / \ell^2$	600 900
Length-extensional	+ 5°X	40 ~ 200	$2730 \times 1 / \ell$	140
Face-shear	CT DT SL	250 ~ 1000 80 ~ 500 300 ~ 1100	$3080 \times 1 / \ell$ $2070 \times 1 / \ell$ $460 \times 1 / \ell$	400 450 450

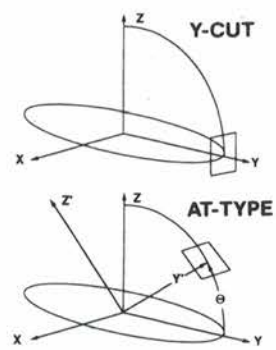
Note: With AT-cut 3rd overtone and 5th overtone, lower frequency are available.



Projection of Primitive Quartz Region



Doubly Rotated Y-CUTS



Singly Rotated Y-CUT

Internal Structure Of A Crystal Unit

Crystal wafer mechanically vibrates several modes as shown in **Table 1** To pick up desired vibration energy effectively, supporting system of crystal wafer is very important. **Fig. 2** shows typical example of internal construction for thickness shear mode crystal unit and face-shear unit. Crystal wafer is supported with thin metal wires etc. at the minimum displace point of mechanical vibration on the wafer. Therefore, if unnecessary shock or impact are given to the unit, the wire may be deformed and the wafer may attach to the inside surface of cover which affect quality performance.

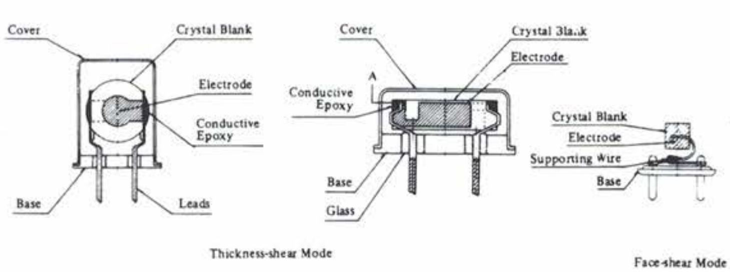
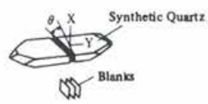
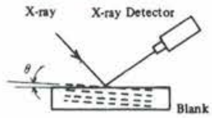
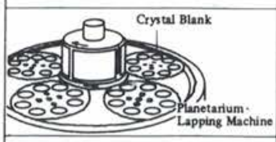
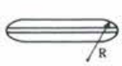
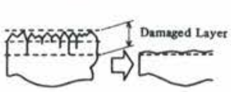
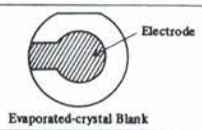
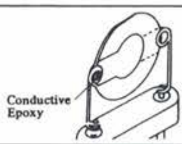
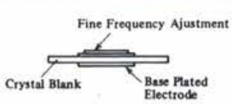
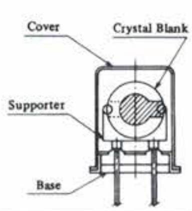


Fig. 2 Internal Construction

Production Processes

The following table shows the production process for the most popular AT-cut crystal unit.

OPERATION	PROCESS	PURPOSES and PROCEDURES
	Cutting	Cutting a lumbered crystal into thin crystal wafers (blanks) using a (multi-blade) cutting machine according to the specified cutting angle to the reference lattice plane.
	Cutting angle measurement	Measuring the angle to the reference lattice plane in terms of degree, minute and second by means of an X-ray angle measuring instrument for the purpose of guaranteeing proper frequency vs. temperature characteristics.
	Outside processing	To avoid the interference of face shear vibration, length-width flexture vibration and other types of vibrations, accurate outside processing in terms of μm is required.
	Lapping	A surface grinder simultaneously grinds wafer surfaces as specified using abrasives, making the surfaces evenly thick. With AT-cut crystal units, due to the fact that wafer thickness determines the frequency, accuracy in terms of 0.1μm or less is required.
	Beveling	With thick wafers (low frequencies), the centralization of vibrations requires curved surface processing along the circumference of each crystal wafer.
	Etching	Removing the layer having been produced by lapping and beveling.
	Evaporation	An evaporation machine forms electrode (Ag, Au, Al, etc.) on each crystal wafer. Evaporation patterns determine such constants as C_0, C_1 and L_1.

OPERATION	PROCESS	PURPOSES and PROCEDURES
	Support fixture	Supporting a crystal element (evaporated wafer) by fixing it with conductive epoxy which allows electrical continuity
	Frequency fine adjustment	For the frequency adjustment within the specified range, vacuum evaporation is conducted so as to add some electrode materials to the fundamental electrode while let the crystal element be oscillated.
	Sealing	The inside of a holder is evacuated or filled with inactive gases such as N_2 and Ar to protect crystal elements mechanically and prevent electrodes or others parts from being oxidized or influenced by ambient temperatures. A sealing method is cold-welded, resistance-welded or solder-sealed.
	Inspections	Crystal units are inspected in terms of airtightness, insulation, equivalent resistance, frequency vs. temperature characteristics and quivalent constants (C_0, C_1, L_1, Q).

Cutting Angles and Frequencies

Temperature changes cause oscillation frequencies to be changed, as shown by **Fig. 3,** cutting angles determine the rates of change. **Fig. 3** shows typical frequency vs. temperature characteristics for various cutting angles. **Fig. 4** shows how to make crystal units which have superlative temperature characteristics, taking the AT-cut crystal wafer (the most popular crystal wafer) for example.

Fig. 4 shows three different temperature characteristics for different cutting angles. You can easily find out that the curve ② provides the smallest rate of frequency change against temperature change near normal temperature and therefore, crystal units represented by this curve have excellent characteristics suited for most usual applications.

On the other hand, over a wider temperature range of -55 to 105°C, for example, the curve ① shows better characteristics.

So it is necessary to determine the most appropriate temperature characteristics taking into consideration applications and required operating temperature ranges.

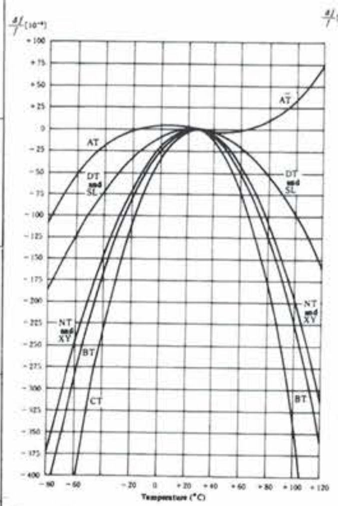


Fig. 3 Theoretical Frequency-temperature Curves of Various Cuts

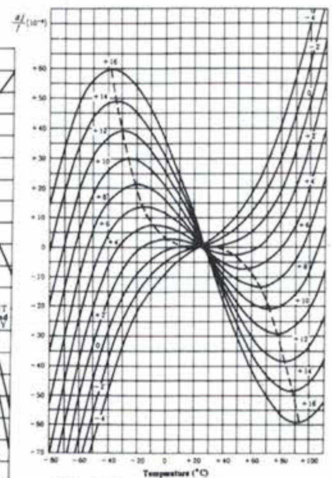


Fig. 5 Frequency-temperature (AT-cut)

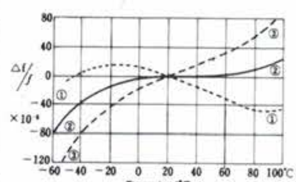


Fig. 4 Characteristics of Frequency-temperature (AT-cut)

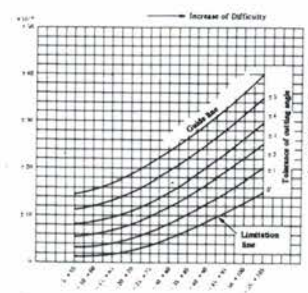


Fig. 6 Frequency Stability Guidance

Fig 5. shows frequency vs. temperature characteristics in the case of changing AT-cut angles with the increment of 2'. Cutting angle allowance is determined by operating temperature range and allowable frequency tolerance.

Fig. 6 shows cutting angle allowances (impracticality) corresponding to frequency vs. temperature characteristics. This figure reveals impractical zone.

Equivalent Circuit of a Crystal Unit

A crystal unit is equivalent to the following circuit **(Fig. 7)** where inductance (L_1), capacitance (C_1) and resistance (R_1) are connected in series and capacitance (C_0) is connected in parallel.

C_0 is called parallel capacitance resulting from the addition of stray capacitance between terminals to capacitance between electrodes.

L_1 and C_1 are equivalent constants of a crystal unit as an electromechanical vibration system and are determined by cut type, cutting angle, outside dimensions, electrode structure and other factors. And they feature reproductibility, thus allowing high precision manufacturing.

R_1 shows oscillation loss and is under the control of processing method, holding method, shape, dimensions and other factors.

L_1C_1 and R_1 are called motional inductance, motional capacitance and equivalent series resistance, respectively.

FIG. 8 and **FIG. 9** show practical L_1, C_1, R_1 values for main cut types.

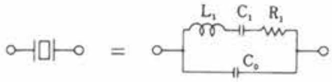


Fig. 7. Electric Equivalent Circuit of a Crystal Units

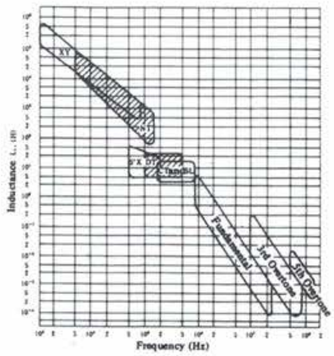


Fig. 8 Inductance Range foir Various Common Cuts

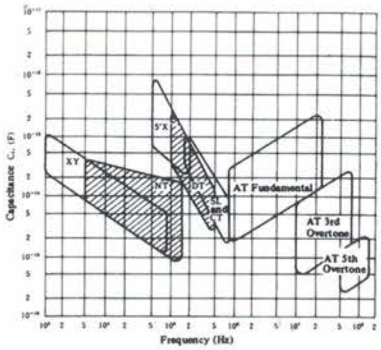


Fig. 11 shows the impedance and frequency characteristics. Resonance frequency and antiresonance frequency are calculated by the following equations, respectively:

$$f_0 = \frac{1}{2\pi\sqrt{L_1C_1}} \qquad f_a \doteqdot f_0\left(1+\frac{C_1}{2C_0}\right)$$

The following equations are also used to calculate other characteristics.

$$r = \frac{C_0}{C_1} \qquad Q = \frac{2\pi f_0 L_1}{R_1} = \frac{1}{2\pi f_0 C_1 R_1}$$

$$M = \frac{Q}{r} = \frac{1}{2\pi f_0 C_0 R_1}$$

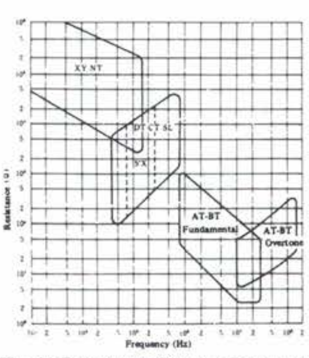


Fig. 10 Frequency Cut and Resistance Range of Hermetically Sealed Crystal Units (1 atmospnere)

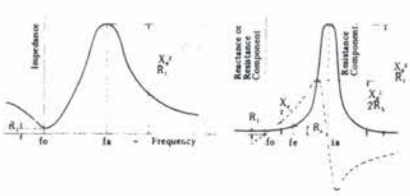


Fig. 11 Impedance-frequency Characteristics

Characteristics of Frequency vs. Load Capacitance

In the oscillation circuit allowing a crystal unit to be operated in terms of inductive impedance, negative resistance and impedance are equivalently given as shown by **Fig. 12.**

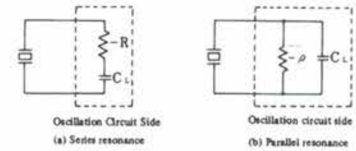


Fig. 12 Relationship between a Crystal Unit and the Oscillation Circuit

In the case of (a), a crystal unit and an oscillation circuit are connected in series and in the case of (b) in parallel.

The capacitance CL is an effective value measured from both terminals of a crystal unit to the oscillation circuit. It is generally called load capacitance and indicates the negative resistance on the —R or —ρ circuit.

In such a circuit, a crystal unit operates in such a way that inductive reactance Xe and resistance Re are connected in series as shown in **Fig. 13.** The oscillation frequency is given by the following equation:

$$X_e = \frac{1}{2\pi f_e C_L}$$

Circuit oscillation conditions in the case of **Fig. (a)** and **(b)** are $|Re|<|R|$ and $|R\rho|>|\rho|$, respectively. Re is the series resonance resistance (equivalent series resistance) of the series circuit consisting of a crystal unit and load capacitance, and Rρ is the parallel resonance resistance (equivalent parallel resistance).

You are requested to make the circuit load resistance (—R) large enough against Re so as to assure oscillation taking into consideration the increase in equivalent resistance at low drive level.

Due to the fact that oscillation frequencies are determined by electrical equivalent constants of a crystal unit and oscillation-circuit load capacitance (Operating temperature and drive level are to be specified.) irrespective of the composition of an oscillation circuit, please specify the load capacitace of the oscillation circuit prior to the production or use of a crystal unit.

Fig. 14 shows an equivalent circuit in the case of connecting C_L (load capacitance with a crystal unit in series. The equivalent constants are calculated as follows:

$$L_1' = L_1\left(1+\frac{C_0}{C_L}\right)^2 \qquad R_1' = R_1\left(1+\frac{C_0}{C_L}\right)^2$$

$$C_1' = \frac{C_1C_L^2}{(C_0+C_1+C_L)(C_0+C_L)} \qquad C_0' = \frac{C_0C_L}{C_0+C_L}$$

The oscillation frequency increases by **Δ**f: denoting the difference between the series resonance frequency F_0 and the oscillation frequency by **Δ**f, we obtain the following equation.

$$\frac{\Delta f}{f_0} = \frac{C_1}{2(C_0+C_L)}$$ change

If we rearrange the right side, it becomes the following equation.

$$\frac{\Delta f}{f} = \frac{1}{2\frac{C_0}{C_1}\left(1+\frac{C_L}{C_0}\right)}$$ change

C_0/C_1 is called capacitance ratio which is the barometer of the change in oscillation frequency caused by the change in load capacitance. **Fig. 15** shows load capacitance vs. frequency-change rate characteristics for AT-cut fundamental crystal wafers and 3rd overtone crystal wafers.

As shown by **Fig. 15,** the use of a fundamental-mode crystal wafer at lower load capacitance is required to get wider rate of change with the change of load capacitance.

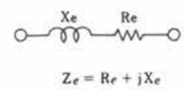


Fig. 13 Operating State of Crystal Units

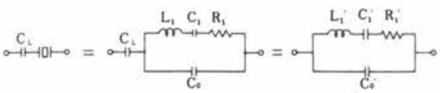


Fig. 14 Electrical Equipment Circuit with Load Capacitance

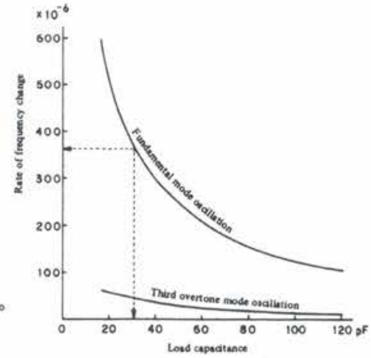


Fig. 15 Load Capacitance vs. Frequency Change

Frequency Aging Characteristics

Resonance frequencies of crystal units change just a little with the passage of time. Aging rates differ depending upon oscillation mode and shape of each wafer used.

The following factors exert influences upon aging rates:

1. Distortion caused by the wafer holder
2. Wafer-surface processing distortion
3. Gas and moisture absorption into electrode

Fig. 16 compares the aging characteristics of a coldwelded crystal unit with those of a solder-sealed crystal unit. This figure shows that the former is superior to the latter in terms of frequency stability.

With the increase in ambient temperature, aging rates become higher. **Fig. 17** compares the aging characteristics of a crystal unit, which is used at 60°C, with those of a crystal unit which is used at 85°C. Due to the fact that a crystal unit oscillates mechanically, the exciting current exerts influences upon aging characteristics.

Fig. 18 shows the relation between exciting current and aging rate. This figure demonstrates that frequency stability requires the operation of a crystal unit with the lowest exciting current.

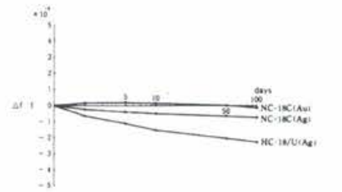


Fig. 16 Aging Characteristics (Holder)

Fig. 17 Aging Characteristics (Temp.)

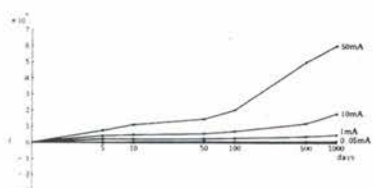


Fig. 18 Aging Characteristics (Drive Level)

CRYSTAL OSCILLATORS

Technical Terms

The following technical terms are generally used for crystal oscillators:

Nominal frequency: Specified output frequency of a crystal oscillator

Frequency tolerance: Deviation from the nominal frequency expressed in terms of % or PPM.

Operating temperature range: Temperature range within which output frequencies and other output signal characteristics meet the specifications

Operable temperature range: Temperature range within which crystal oscillators are still operable despite the failure to meet the specifications

Frequency vs. temperature characteristics (Frequency Stability): Change from frequency at normal temperature (25°C) given when only temperature is changed, with the other conditions kept constant.

Frequency vs. power source variation characteristics: Frequency change given when only power source voltage is changed, with the other conditions unchanged

Short-term frequency stability: Average of irregular output frequency fluctuations. There are several measurement methods which provide different points of view regarding irregularity. For crystal oscillators, either the definition in the frequency domain or the definition in the time domain shall be selected.

Harmonic distortion: Distortion due to unwanted harmonic spectrum component related with target signal frequencies. Each harmonic component is the ratio of electric power against desired signal output electric power and is expressed in terms of dB.
Ext.: 2nd harmonics ... —30dB or less

Crystal Oscillators

Crystal oscillators are classified into the following four types.

1. **Simple packaged crystal oscillators (SPXO)**

   There are two kinds of SPSO's the former is used for general applications and the latter is used as a clock. The frequency range is wide (1Hz to 1GHz). The former type of SPXOs are used in microwave communications equipment, broadcasting equipment, measuring instruments etc. while the latter type of SPXOs are used in frequency counters, facsimiles, etc. as a clock.

   Frequency vs. temperature characteristics result from the addition of the temperature characteristics of crystal units used to those of the oscillation circuit. The use of AT-cut crystal units in most cases causes the former characteristics to be expressed by cubic curves, and the latter characteristics are expressed by nearly straight lines. The addition of these two kinds of curves results in cubic curves. In some cases, a temperature compensating capacitor is used to compensate the slope of the temperature characteristic curve and to better the overall frequency vs. temperature characteristics.

   Frequency vs. temperature characteristics vary to a great extent depending upon applications: within a narrow temperature range the frequency vs. temperature characteristics are $\pm 50 \times 10^{-6}$(42)

2. **Temperature compensated crystal oscillators (TXCO)**
   The temperature characteristics of crystal oscillators are, for the most part, dependent upon those of crystal units used which are generally expressed by cubic curves (AT-CUT). Obtaining superlative temperature characteristics requires the operating temperature ranges to be limited or the ambient temperatures to be kept constant by means of a constant temperature oven.

   With TCSOs, temperature compensating circuits are built-in to get excellent temperature characteristics over a wide temperature range.

   The temperature compensating circuit performs the function of compensating the temperature characteristics of crystal units by temperature segmented circuits. That is why the resultant temperature characteristics differ depending upon the combination of compensating circuits or the specified temperature range, in general, temperature characteristics are expressed by 3rd to 5th order curves. (See **Fig. 2**)

   TCXOx feature excellent temperature characteristics, low power consumption, light weight, compactness and fast warm-up, and are ideally suited for various communications equipment (car telephones, walkie-talkies, MCAs, cordless telephones, microwave communications equipment and satellite communication system) and measuring instruments (frequency counters, frequency synthesizers, etc.) as standard oscillators.

3. **Voltage controlled crystal oscillators (VCXO)**
   With VCXOs, the connection of a variable capacitance diode with a crystal unit in series causes the diode capacitance to be changed in accordance with the voltage applied for frequency control, thus pulling frequency corresponding to the load capacitance characteristics of crystal units. VCXOs feature superlative linearity realized by the proper combination of the applied voltage and capacitance characteristics of a variable capacitance diode with the load capacitance and oscillation frequency characteristics of crystal units.

   The temperature characteristics of VCXOs are the same as those of SPXOs and are ideally suited for PLL, AFC, circuit servo system, FM modulator, sweep generator, etc.

4. **Oven controlled crystal oscillators (OCXO)**

The temperature characteristics of OCSOs are much superior to those of other crystal oscillators, because the ambient temperatures of crystal units are kept constant by means of a constant temperature oven.

In general, the temperature inside the oven is set at the value corresponding to the turnover point on the high temperature side of the cubic curve, for AT crystals and the low side for SC crystals. Decisive factor is stability of temperature inside the oven.

The lower limit of the operating temperature range is determined by the maximum value of power consumption and the upper limit by the set temperature of the oven and the thermal effect of the circuit-side power consumption.

Conventional high-stability crystal oscillators, for the mopart, use 1 to 5MHz overtone crystal units for high frequency stability.

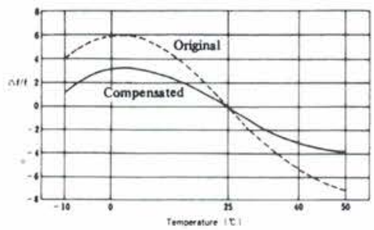


Fig. 1 Frequency Stability vs Temperature Range

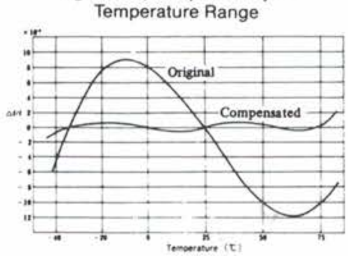


Fig. 2 Frequency Stability vs Temperature Range

CRYSTAL FILTERS

Technical Terms

The principal terminology to be used for crystal filters is as follows.

Nominal Frequency

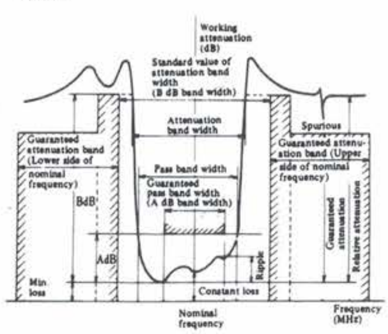
This normally refers to the nominal value of the center frequency in **Fig. 1** and is used as the reference frequency of related standards.

Pass Band Width

This is a frequency interval at a value assuring that the relative attenuation is equal or lower than the specified attenuation.

Ripple

This denotes the largest value of the difference between the maximum and minimum loss when there is an extremely high attenuation in the pass band.



Notes (1) A dB: Attenuation which specifies the pass band width
(2) B dB: Attenuation which specifies the

Insertion Loss

This is the difference in attenuation when a filter is and is not inserted and is classified into minimum loss and constant loss. Minimum loss is the minimum value of insertion loss and constant loss is the insertion loss at the nominal frequency and each is handled as the reference level of attenuation. Minimum loss is generally used as the references.

Attenuation Band Width

Frequency width at the value that assures that the relative attenuation is of the same value or higher than the specified attenuation.

Guaranteed Attenuation and Guaranteed Attenuation Band Width

These are the relative attenuation and frequency band guaranteed in the attenuation band.

Terminal Impedance

This is the power supply impedance or load impedance as viewed from the filter side and is generally indicated by resistance and parallel capacitance.

Balanced Type and Unbalanced Type

A balanced type is one in which a pair of terminals is not connected to the case, and an unbalanced type is one of a pair of terminals is connected to the case.

General Characteristics

A quartz crystal filter displays its outstanding features as a bandpass filter and band blocking filter depending on the properties of the crystal resonator use. The general characteristics of bandpass filters used most often as crystal filters are explained here.

Available Range

Bandpass filters are classified into three general types from the aspect of basic structure.

One is the **"narrow band filter"** in which the elements consist of a crystal resonator and capacitors only and is designed with a bandpass width of 0.005% —0.6% of the center frequency. Maximum bandwidth is decided by the capacitance ratio (C0/C1) of the crystal resonator and the narrow limit is decided principally by the Q of the crystal resonator and the stability of the frequency.

The second is constructed along the lines of a **"wide band filter"** and is designed with a bandpass width of about 1% to 6% of the center frequency. Construction wise, a coil and capacitors are connected in series or in parallel to the crystal resonator of the element section and the lower limit of the bandwidth is decided by the stability and Q of the coil. On one hand the capacitance ratio and spurious characteristics of the crystal resonator become a problem at the upper limit and is decided by the stability and Q of the coil and transformer.

Medium band filters are manufactured in considerable quantities in the intermediate range and in a part of the aforementioned narrow band. Coils are required in these filters to cancel out the capacity of the crystal resonator and the capacitance of the circuit. The upper limit of the bandpass width is related to capacitance ratio of the crystal and the Q of the coil. The lower limit is determined by the same condition as that of the narrow band .

Fig. 2 shows the general structural range of a bandpass crystal filter by the relation between the pass band width and the nominal frequency. Strictly speaking, the realizable range will differ according to several conditions such as required selectivity, ultimate attenuation, ripple, dimension and price.

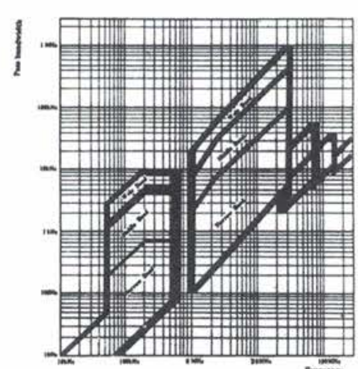


Fig. 2 Relation between pass bandwith and nominal frequency in Bandpass Filter

Attenuation curve

Although there are various attenuation curves depending on filter designing factors such as characteristic functions and position and degree of the attenuation poles, the basic attenuation characteristics when the pass band is of Tchebycheff (uniform ripple) characteristic and Butterworth (flat) characteristic with the attenuation pole of infinite characteristic are shown in **Fig. 3** as typical examples. Q here is standardized with a 3dB pass band width and is obtained by the following equation. The right and left attenuation characteristics become symmetrical when Q = 0 (center frequency)

= ((f-fo)(/BW/2)

fo:	Centre frequency of the filter
f:	Attenuation characteristics frequency
BW:	3 dB point pass band width

Phase linearity

Similar to attenuation characteristics, phase characteristics will also differ depending on the characteristics function and degree at which the filter is designed. **Fig. 4** shows the phase of the aforementioned Tchebycheff and Butterworth characteristics. Linear phase response filters can also be designed upon request. However, the manufacturing range will be limited as shown in **Fig. 2.**

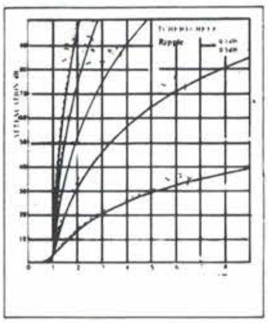


Fig. 3 (a) Attenuation Characteristics (Tchebycheff)

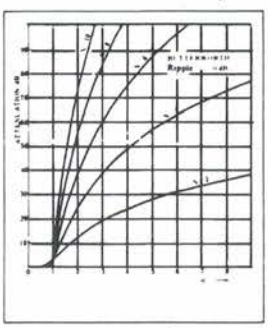


Fig. 3 (b) Attenuation Characteristics (Butterworth)

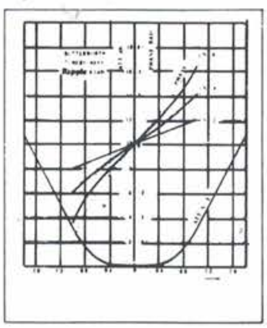
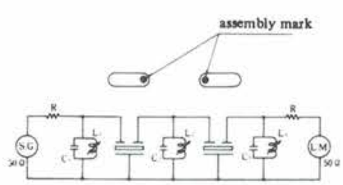


Fig. 4 Phase Characteristics

Application Note

Method of Adjusting the MCF Coupling Transformer

A circuit diagram such as of the overtone MCF in which the coupling of the input and output section is inductive is shown in the diagram below.



The change in filter characteristics (within the pass band) when the inductance of the coil in peach LC tuning circuit of the circuit diagram is shown in **Figures 4a ≃ b.** Pass band characteristics (ripple, loss, bandwidth) will also be affected to a certain extent if the inductance of coils L_1 and L_3 in the input and output section is varied. Moreover, band characteristics will also change greatly if the inductance of coil L_2 in the coupling section is varied. The positive side of the pass band width will become especially narrow and will become less than half if the inductance drops below the prescribed value. Therefore, adjust the respective coils to the correct inductance with a network analyzer while confirming the characteristics of the filter.

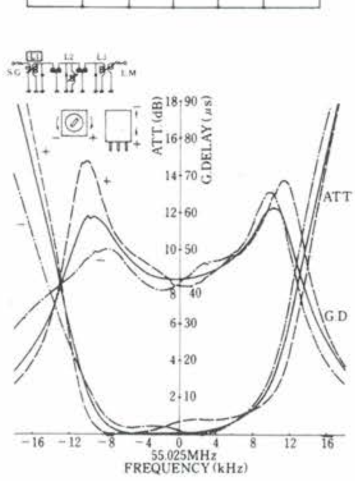


Fig. 4 (a) Characteristic change by inductance of coil L_1

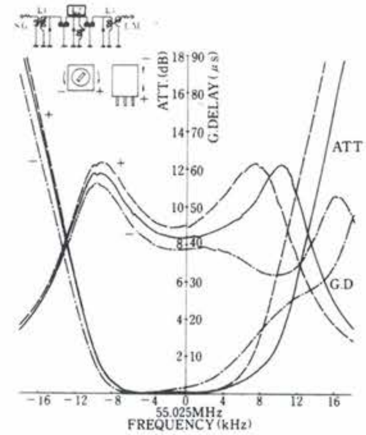


Fig. 4 (b) Characteristic change by inductance of coil L_2

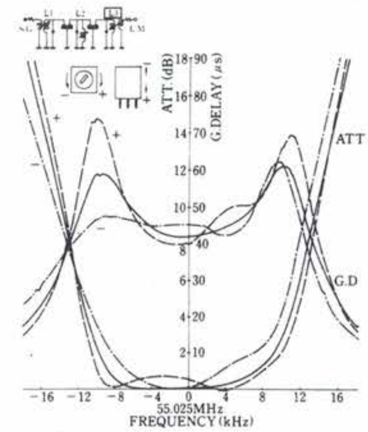


Fig. 4 (c) Characteristic change by inductance of coil L_3

Terminal Inpedance

Terminal impedance is the power supply impedance or load impedance as viewed from the filter side with the resistance and parallel capacitance specified separately. If this terminal impedance differs from the specified value, the pass band characteristics in particular will be greatly disturbed and it will not be possible to obtain the basic characteristics since the insertion loss, ripple and band width will change. The impedance on the circuit side must therefore be measured with an impedance analyzer and the impedance matched with terminal conditions. The pass band characteristics when an N = 2 (2 pole) terminal impedance is changed with a crystal filter a nominal frequency of 10.7 MHz and a pass band width of +/—7.5 kHz are shown in **Figures 5a — b.** Care is required especially when changing the resistance value since the pass band will shift greatly in relation to the prescribed band.

Input Level

It will be necessary to use an input level lower than the specified value. If an input exceeding the prescribed value is applied, the characteristics of the crystal resonator will deteriorate and it will not be possible to obtain the original characteristics of the crystal resonator. Care is required especially in the case of filters with a center frequency below 1 MHz since there will be danger of the crystal resonator being destroyed if the input level is raised above the prescribed value. The input level is as shown below.

Center frequency range	Input level
1MHz max	-20 dBm max
1MHz min	0 dBm max

Separation of Input and Output

Shield the input and output thoroughly to prevent electrostatic and magnetic coupling.

If there is coupling between the input and output, the guaranteed attenuation will drop and it will not be possible to obtain the inherent characteristics of the crystal filter since the input signal will enter the output side directly over at attenuation area. As an example. **Figure 6** shows the characteristics of a crystal filter with a nominal frequency of 10.7 MHz and a pass band width of +/—7.5 kHz, N = 6 (6 hole) when there is electrostatic coupling between the input and output. As may be discerned from **Figure 6,** even extremely small coupling will drastically lower the guaranteed attenuation.

Grounding the Filter

Crystal filters are provided with a mounting screw or grounding terminal so they can be grounded. Please use these and ground the filter.

Never attempt to solder directly to the casing as this may cause damage to the internal parts.

It will also be necessary to ground the entire bottom surface of the filter cases to prevent occurrence of potential difference between the circuit and ground. When using substrates printed on both sides, use through hold connections to eliminate potential difference between the top and bottom patterns. Do not use solder resist on the underside pattern of the filter.

DC Superimposed Current

When causing DC current to follow in a balanced filter, the prescribed current value must not be exceeded.

If currents exceeding the prescribed value are caused to flow, it will lead to troubles such as heating of the transformer windings, detective insulation or open circuits.

Mechanical Shocks.

The filter must never be subjected to strong shocks. When carrying or mounting on a device, care must be taken not to subject the filter to shocks by dropping or hitting with a hard object.

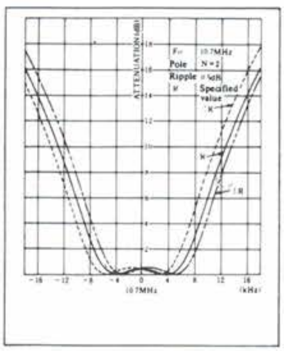


Fig. 5 (a) Characteristic Change Due to the Value of Resistance (N=2)

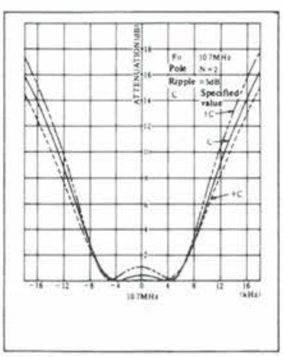


Fig. 5 (b) Characteristic Change Dut to the Value of Capacitance (N=2)

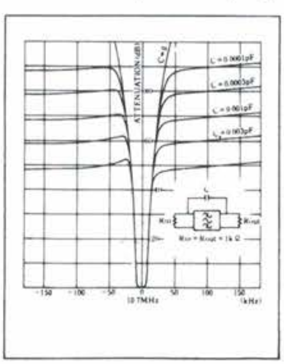


Fig. 6 Characteristic Change Due to Input-Output Coupling (Capacitance Coupling)

Oven Controlled Crystals (OCC)

A small oven or warmer is used to cotrol the temperature environment of an O.C.C. The oven temperature is normally at an elevated temperature 65, 75, 85 (degrees centigrade). The oven minimizes the effects of the external temperature variances. The reference temperature of the oven matches the temperature of the crystal frequency curve at a point where the frequency deviation is at a minimum (upper turning point). All ovens or warmers exhibit a warm-up characteristic and the frequency of the crystal may during this "warm-up" period exceed the maximum allowed tolerance. As the oven reaches its temperature set-point the frequency stabilizes within its specified tolerance. Oven temperature stabilities are critical and therefore proportional controlled ovens are recommended.

Load Capacity:

Standard C_L (12, 15, 20, 32pF)
C_L values between 12pF and Series resonance can be specified without additional cost.

Shunt Capacity:

Typical C_O = < 7pF.

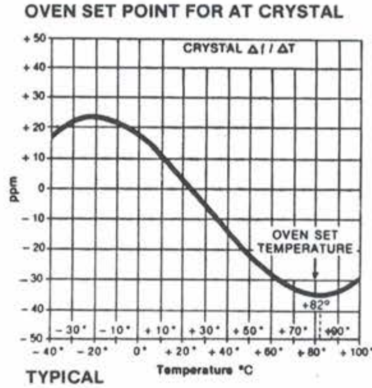
Drive level:

5 to 200 microwatts recommended.

Typical Aging

< 3ppm for Coldweld.
< 5ppm for Resistance Weld.
< 10ppm for Solder Seal.

OVEN SET POINT FOR AT CRYSTAL



Typical Part Dimensions and Mechanics

Refer to MIL STD H-10056 for mechanical industry standards, technical terms, and definitions.
Many suppliers have produced their own size versions so please refer to their reference information as well.

Surface Mount

Each supplier has their own style, so please refer to their information.

Packages are typically ceramic with glass, metal or ceramic lids having a solder seal which survives Motorola IR reflow and cleaning processes.

The terminals vary considerably in metalization shapes with options for gold or solder dip. In general the gold thickness should not be more than 85 micro inches to ensure gold embrittlement does not occur.

A cheap alternative surface mount consists of a plastic encapsulated IBP Tubular device mounted on a metal lead frame, these tend to be bulky.

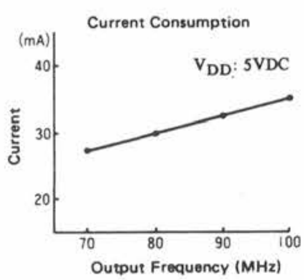
All surface mount devices can be packaged on tape and reel.

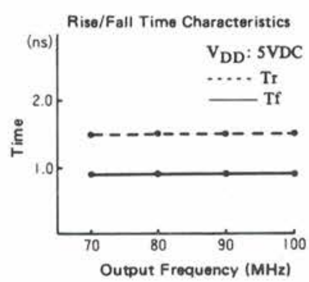
Frequency As A Cost Factor

All frequencies of crystals are not created with equal ease, some ranges present more difficulty than others. We have shown this in the table below by dividing the frequency range that we manufacture, (0.800 to 360.000 MHz) into 8 groups. The horizontal column along the bottom of the table indicates the relative cost factor to manufacture crystals in the frequency ranges shown in the vertical column above the factor. A factor of "1.0" indicates that this frequency range is the easiest to produce, all other parameters being equal.

CRYSTAL MODE CODE	FREQUENCY IN MHz									
A fundamental	0.800 to 0.999	1.000 to 1.599	1.600 to 4.999	5.000 to 8.999	9.000 to 19.999	20.000 to 22.999	23.000 to 25.999	26.000 to 27.999	28.000 to 29.999	30.000 to 33.000
	2.900 to 3.499	3.500 to 3.999	4.000 to 7.999	8.000 to 9.999	10.000 to 19.999	20.000 to 22.999	23.000 to 25.999	26.000 to 27.999	28.000 to 29.999	30.000 to 33.000
		6.500 to 8.499	8.500 to 12.999	13.000 to 19.999		20.000 to 22.999	23.000 to 25.999	26.000 to 27.999	28.000 to 29.999	30.000 to 33.000
	2.900 to 3.499	3.500 to 3.999	4.000 to 7.999	8.000 to 19.999		20.000 to 22.999	23.000 to 25.999	26.000 to 27.999	28.000 to 29.999	30.000 to 33.000
		10.000 to 10.999	11.000 to 14.999	15.000 to 19.999		20.000 to 22.999	23.000 to 25.999	26.000 to 27.999	28.000 to 29.999	30.000 to 33.000
B third overtone			9.900 to 14.999	15.000 to 19.999	20.000 to 59.999	60.000 to 65.999	66.000 to 77.999	78.000 to 83.999	84.000 to 89.999	90.000 to 100.000
		15.000 to 17.999	18.000 to 24.999	25.000 to 29.999	30.000 to 59.999	60.000 to 65.999	66.000 to 77.999	78.000 to 83.999	84.000 to 89.999	90.000 to 100.000
		25.000 to 32.999	33.000 to 34.999	35.000 to 59.999		60.000 to 65.999	66.000 to 77.999	78.000 to 83.999	84.000 to 89.999	90.000 to 100.000
		15.000 to 17.999	18.000 to 24.999	25.000 to 59.999		60.000 to 65.999	66.000 to 77.999	78.000 to 83.999	84.000 to 89.999	90.000 to 100.000
		30.000 to 32.999	33.000 to 44.999	45.000 to 59.999		60.000 to 65.999	66.000 to 77.999	78.000 to 83.999	84.000 to 89.999	90.000 to 100.000
C fifth overtone							45.000 to 129.999	130.000 to 139.999	140.00 to 149.999	150.000 to 165.000
D seventh overtone							80.000 to 129.999	130.000 to 195.999	196.000 to 209.999	210.000 to 230.000
E ninth overtone								162.000 to 251.999	252.000 to 269.999	270.000 to 300.000
F eleventh overtone								216.000 to 284.999 to	285.000 to 299.999 to	300.000 to 360.000 to
DIFFICULTY FACTOR	4.8	2.4	1.3	1.1	1.0	1.1	1.3	2.4	2.9	3.6

CRYSTAL CLOCK OSCILLATORS





Design Guide

1. Max Condition

Supply Voltage (V_{DD})	-0.5 ~ +7.0VDC
Storage Temperature Range	-55 ~125°C

2. Operation Condition

Supply Voltage (V_{DD})	+5VDC ± 0.5V
Operating Temperature Range	Selectable

3. Tr/Tf Measuring Condition

TTL Compatible

Value between V_{OL}MAX and V_{OH}MIN . . . **Fig. 1:** Load Condition
Fig. 3: Reference

TTL/C—MOS Compatible

Value between 0.1 x V_{DD} and 0.9 x V_{DD} . . . **Fig. 2:** Load Condition
Fig. 4: Reference

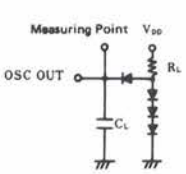


Fig. 1

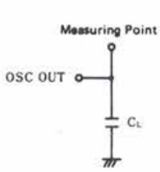


Fig. 2

1TTL=5LSTTL

TTL	C_L	R_L
1	15pF	4kΩ
2	15pF	2kΩ
5	15pF	800Ω
10	15pF	400Ω

(Note) C_L: Include capacitances of measuring system

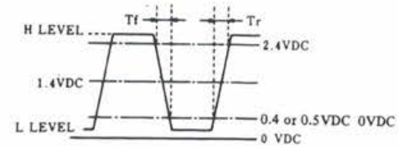


Fig. 3

Measuring Load Condition

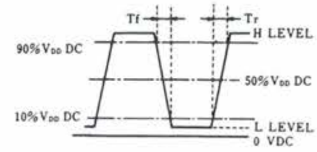


Fig. 4

Application Note

Crystal protects require different handling from other electric components. Special attention should be paid to the following:

1. **Crack caused by bending the lead**
The lead terminals are hermetically sealed by glass. If bent at the root of the terminals, a crack may occur and decrease quality due to insufficient air tightness.

2. **Resistance to dropping**
Crystals are designed to be impact proof so that no damage occurs when dropped from a height of 30 inches for desk top applications and 72 inches for portable products application. However, after any drop, it is advisable to check their performance.

3. **Electrostatic protection**
Crystal products which employ C-MOS ICs for the active element, should be used in static-free environment.

4. **High temperature**
Normal operation cannot be guaranteed for thse models at +125°C (for 24 hours). Be sure that the units are kept within the specified temperature range.

5. **Storage period for solderability**
For lead terminals which are solder plated, if stored for a long time, the solder may oxidize and reduce performance. It is advisable to avoid storing it for more than 6 months without assembling.

6. **EMI**
The crystal element is contained in a hermetic package and can be provided with a case earth to prevent electromagnetic interference. Careful attention should be paid to electromagnetic interference.

Oscillator Acronyms

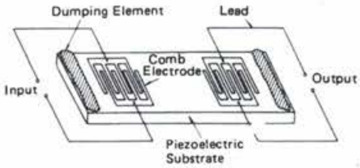
- **XO** .... Crystal Oscillator
- **VCXO** .... Voltage Controlled Crystal Oscillator
- **OCXO** .... Oven Controlled Crystal Oscillator
- **TCXO** .... Temperature Compensated Crystal Oscillator
- **TCVCXO** .... Temperature Compensated/Voltage Controlled Crystal Oscillator
- **OCVCXO** .... Oven Controlled/Voltage Controlled Crystal Oscillator
- **MCXO** .... Microcromputer Compensated Crystal Oscillator
- **RbXO** .... Rubidium-Crystal Oscillator

SAW DEVICES

Saw Filter

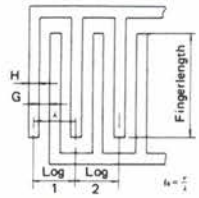
A surface acoustic wave (SAW) is a sound wave that propagates along the surface of an elastic body upon which its energy concentrates. Many electronic devices employ surface acoustic waves of different frequencies for practical applications.

Fig. 1 shows the basic construction of a SAW filter. Comb electrodes for exciting and receiving waves are composed of a metallic deposit on a piezoelectric substrate. When an AC voltage is applied at the input terminals of the electrodes, the piezoelectric action causes the portion of the substrate between the adjacent electrodes to be distorted to permit excitation of a SAW with a specific frequency.



Structure of SAW Filter (Transversal Type)

Fig. 1



Comb Electrode

Fig. 2

As illustrated in **Fig. 2,** the teeth of these electrodes are arranged with a certain pitch. A surface acoustic wave exits with the highest magnitude if its wavelength λ is equal to the pitch of the teeth of the electrodes. When the propagation velocity of a wave is v, the center frequency fo is given by fo $= v/\lambda$

SAW filters are available with electromechanical transducers (group-type unidirectional comb electrodes) and with bidirectional electromechanical transducers. The unidirectional models provide the advantage of lower loss characteristics while the bidirectional models provide an engineer with a considerably greater freedom of design.

SAW Resonator

Fig. 3 shows the basic construction of a SAW resonator. A resonator can be made by increasing the number of teeth of the comb electrodes.
As illutrated in **Fig. 4,** there are two types of resonators: (a) one-port resonators and (b) two-port resonators.

The frequency of these resonators depends upon the pitch between the teeth of their comb electrodes to allow basic waves with a higher frequency range to be oscillated. One-port resonators have high Q factors and are primarily used as oscillators. Two-port resonators are narrow-band filters and serve as filters and oscillators due to their passing characteristics. The bottom is flexed to make these resonators resistant to impact and shocks.

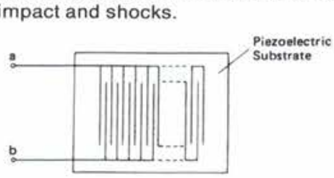
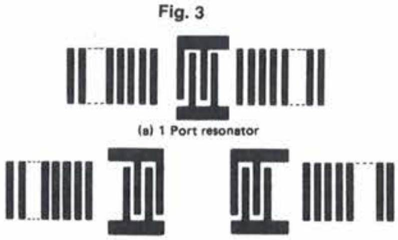


Fig. 3


(a) 1 Port resonator

(b) 2 Port resonator

Fig. 4

Characteristics of SAW devices

1. **Maximum Ratings**
   The standard operating conditions are listed below, although they are different from SAW device to device. These values represent "absolute maximum ratings" that are never allowed to be exceeded even for a moment. Any instantaneous excess over these values can reesult in a breakdown and deterioration, or reduced life of the SAW devices. In addition, these rations are closely related with each other and require simultaneous compliance.

DC.EP. Voltage	**Between each lead 3V max**
Maximum input	-10dBm max

2. **Reliability**
   Various reliability tests are carried out to maitain and ensure the quality and-reliability assurance level.

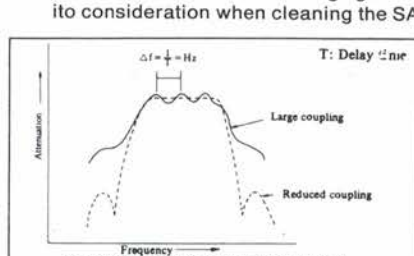
3. **Quality Assurance**
   After the last process, all of the finished products are inspected for design and appearance, electrical performance
   and other conditions to make sure that they conform to requirements for proper and strict quality assurance.

Furthermore, the quality assurance department then determine whether or not these inspected products satisfy the customer's specific needs as well as their reliability.

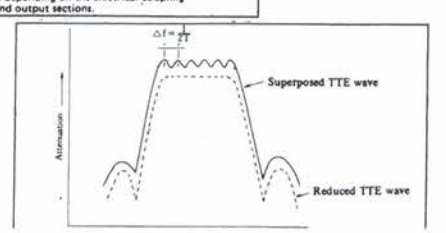
	Environmental Test
Vibration	10~55 Hz total amplitude 1.5mm 1~2 minutes 0.5H total 1.5H
Natural drop	Onto hard wooden board from 10cm height, 3 times
Shock	100G, 6ms
Solder heat	By solder dipping tools 180°C, 20s
Sealing	By Helium detector 1 x 10^{-7} ATM^{cc}/s
Temp. cycle	at -20°C, 80°C each 30 min, 5 cycle
Humidity	45°C 90%, 48 hours

Application Note

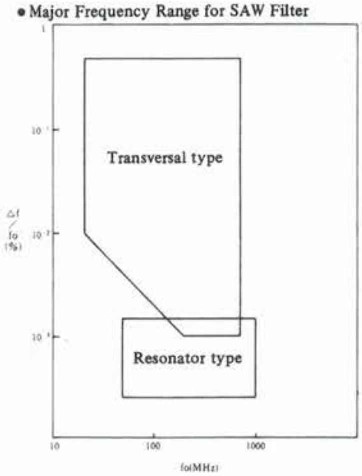
1. Use the SAW product within its maximum ratings.
2. Never apply a voltage higher than the maximum input rating, as a higher voltage will accelerate deterioration of the product's characteristics.
3. The shield grounding conditions should be determined so that electrical coupling between input and output may be minimized before using the SAW device. Otherwise, the coupling between input and output will cause ripples in the amplitude and group delay characteristics. Note that the ripple frequency is $\triangle f = 1/T$.
4. The SAW's TTE waves that have been multiply reflected between the input and output sections are superimposed over the main signal wave to produce ripples in the amplitude and group delay characteristics. These ripples may be reduced by mismatching the I/O terminating conditions. The SAW devices should be operated at the specified terminating conditions. Note that the ripple frequency is $\triangle f = 1/2$.
5. Be careful not to apply force to the pin terminals.
6. The specified ambient temperature conditions when storing and transporting the SAW device must be less than 85°C.
7. Be careful not to apply a power voltage to the SAW product when soldering it.
8. Avoid ultrasonic cleaning for the SAW device both as an independent unit and after it has been mounted on a PC board. The choice of a cleaning agent should also be taken ito consideration when cleaning the SAW product.



Filter characteristics depending on the electrical coupling between the input and output sections.



• Major Frequency Range for SAW Filter



Materials

The substrate materials used are listed below.

The 128° Y-X lithium niobate ($LiNbO_3$) substrate is suitable for broad-bandwith low-loss filters since it features both a large temperature coefficient and a high electromechanical coefficient of coupling, as well as minimal bulk spurious waves.

The ST cut quartz is suitable for device substrates to be used in communications equipment since the frequency-temperature characteristic is varied in the form of a secondary curve having a zero temperature coefficient around normal temperature, even though it has a small coefficient of coupling.

The X-112°Y lithium tantalate ($LiTaO_3$) substrates has intermediate coupling and temperature characteristics between those of $LiNbO_3$ and quartz substrates.

Material	Symbol	Section	Coupling Coefficient (k^2)	Temperature Coefficient ($\times 10^{-6}$/°C)
$LiNbO_3$	L	128°Y-X	0.055	-75
$LiTaO_3$	T	x-112°Y	0.0064	-20
Quartz	Q	ST	0.0016	-10~60°C 70x10-6

S.A.W. Filters, Delay Lines and Resonators
Practical Ranges and Limitations

Center Frequency 20 MHz to 1.0 GHz

- Lowest frequency limitations are due to bulk modes that cause spurious signals.
- Highest frequency limitations are due to line width resolution between inter-digital electrodes.

Amplitude Ripple

- Typically +/0.5 dB
- 0.3 to 0.4 dB can be achieved depending on bandwidth.
- 0.1 dB can be achieved with rounded passband response.

Group Delay Distortion

- Can achieve 10 nano second peak to peak with short time delays (1.0 micro-seconds or less) with standard insertion losses of 20-25 dB.

Shape Factor

- The steepest skirt that can be practically manufactured is 1.1:1. This means that the width of the band at the -40 dB point is 10% wider than the top of the band.

Insertion Loss

- Typically 20-25 dB.
- New low loss designs are being developed that will be in the 6-15 dB range.

Ultimate Rejection

- Typical close in rejection is 50-55 dB with 55-60 dB of ultimate rejection.

Oscillators (Resonators)

- For microwave applications considerable noise and parts count advantage can be obtained. Up to 26 dB noise reduction can be achieved by using S.A.W. oscillators rather than crystal oscillators.

The information in part has been supplied by:

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