QUARTZ CRYSTALS IN THEORY AND PRACTICE

WHITEPAPER

QUARTZ CRYSTALS IN THEORY AND PRACTICE

Can you imagine a car without a steering wheel? A tower clock without a clock face? Hardly! Although both the steering wheel and the clock face are just one of many components, they are both absolutely indispensable for the product as a whole. The same applies to quartz crystals in electronic applications.

Quartz crystals can be found in almost every electronic device with integrated time measurement, as for example watches, smartphones or microwaves. In the field of digital data processing, quartz crystals can be found even more frequently. Wireless data transmission applications are particularly demanding, since the highest frequency accuracy is required for smooth communication between transmitter and receiver. Besides, quartz crystals set the “heartbeat” in numerous components in automotive electronics. So, putting all this together it’s safe to say that life in the modern digitalized world without quartz crystals is unthinkable.

Despite its central importance, the quartz crystal is often characterized as a C-component and thus only rarely catches the attention of most engineers. The majority see this as a standard component that will always work in its application. We are all the more pleased that you, dear reader, have decided to delve a little deeper into the subject of quartz theory!

On the following pages you can expect a detailed introduction to the world of quartz crystals. Together, we will first deal with the physical principles surrounding the piezoelectric effect and take a close look at quartz production. Then we will devote ourselves in detail to our core topic: the different electronic quartz parameters and the optimal design of an oscillator circuit based on a quartz crystal.

We wish you a good read!

Christian Büchler
Head of Technical Support

Mathias Laskus
Technical Support Engineer

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B.C.E. S.r.l. - Via Regina Pacis, 54/c - Sassuolo (MO) - I 41049 - Italy
Tel.: 0536 811616 - Fax: 0536 811500 - Web: www.bce.it - E-mail: bce@bce.it

1 THE PHYSICS

1.1 What is quartz – the raw material for crystals

The chemical formula of quartz is SiO_2 and it is composed of only two elements, silicon and oxygen.
In its amorphous form SiO_2 is the major constituent of many rocks and sand.
The crystalline form of SiO_2 or quartz is relatively abundant in nature, but in the highly pure form required for the manufacture of quartz crystal units, the supply tends to be small.
The limited supply and the high cost of pure natural quartz have resulted in the development of a synthetic quartz manufacturing industry.
Synthetic quartz crystals are produced in vertical autoclaves. The autoclave works on the principle of hydrothermal gradients with temperatures in excess of 400 °C and pressures exceeding 1,000 atmospheres.
Seed quartz crystals with the desired crystallographic structure are placed in the upper chamber of the autoclave.
The bottom of the autoclave is filled with crushed crystal material and an alkaline solution thus to serve the crystal growth onto the seeds placed at the top of the autoclave.

The autoclave is mainly heated from the bottom, so temperatures at the top are lower. The resulting temperature gradient causes thermal convection of the alkaline solution which dissolves the natural quartz at the bottom of the chamber and deposits it onto the seed crystals at the top.
So called “Alpha” crystals produced by this method can have masses up to some kilos and are grown in about 20 to 40 days. During this growth process the temperatures should not exceed 573°C to prevent a phase transition to a different lattice structure that would result in a loss of piezoelectric properties.

Nowadays quartz crystals are an indispensable component of modern electronic technology. They are used to generate precise clock frequencies to control and manage virtually all communication systems and all digital processing systems. They provide an isochronous reference clock in most electronic devices like watches, computers and microprocessors.

1.2 Why it works – the piezoelectric effect

The technical usage of modern quartz crystals is the result of the phenomenon of piezoelectricity discovered by the Curie brothers in France in 1880.

Piezoelectricity is a complex subject, involving the advanced concepts of both electricity and mechanics.
The word piezoelectricity takes its name from the Greek word “piezein” meaning “to press“, which literally means “pressure electricity”. In fact, a piezoelectric material shows an electrical charge caused by an external mechanical stress or strain. This effect is called “direct piezoelectric effect”.

The converse effect also exists, whereby a mechanical strain is caused in the piezoelectric material by a polarized electrical field. This deformation of the piezoelectric material caused by an electrical charge is called "inverse piezoelectric effect". Both effects are strongly linear and reversible.

1.3 The piezoelectric effect in a crystal

A quartz crystal resonator consists of a thin piece of piezoelectric material precisely dimensioned and orientated with respect to the crystallographic lattice. This so-called crystal blank has a pair of conductive electrodes, that are sputtered or evaporated onto the surfaces of that crystal blank in a vacuum.
When an alternating voltage is applied to the electrodes, the piezoelectric effect stimulates the mechanical vibration, whereby the resonant frequency is defined by the blank thickness. In simple words we can say that the inverse piezoelectric effect is used to stimulate the resonance of the crystal, and at the same time the direct piezoelectric effect is used to detect the mechanical movement, ideally at resonance.

1.4 Advantages of crystals over other resonators

Many different substances have been investigated as possible resonators, and for many years quartz has been the preferred material to satisfy the requirements for precise frequency generation. Compared to other resonators like LC circuits, mechanical resonators, ceramic resonators etc., the mechanical resonator made from quartz material has proven to be superior by having a unique combination of properties. These specific quartz crystal properties are both extreme stability over temperature and high repeatability.

1.5 What makes quartz crystals so important?

1.5.1 Key features – Q-factor and stability

The resonant loss of quartz is extremely low, resulting in an extremely high Q-factor. The intrinsic Q of quartz is 10^7 at 1 MHz. Mounted crystal resonators typically have Q-factors ranging from tens of thousands to several hundred thousand, orders of magnitude better than the best LC circuits. The other great key property of quartz crystals is its excellent frequency stability with respect to operating temperature variations.

1.5.2 Cutting angles

Various scientific investigations have been carried out to identify useful orientations of the cutting angle of crystal plates (blanks) for technical purposes, and to characterize the resonant properties of the crystal plates that have been cut under different certain angle versus the crystal lattice.

The so-called AT-cut angle is the most common cutting angle to manufacture quartz crystal resonators with a very stable frequency over temperature.

The figure below shows the orientation at which a crystal plate is cut from a crystal bar. The AT-cut reference angle is 35° 15'.

FIG. 1: Orientation of different cutting angles

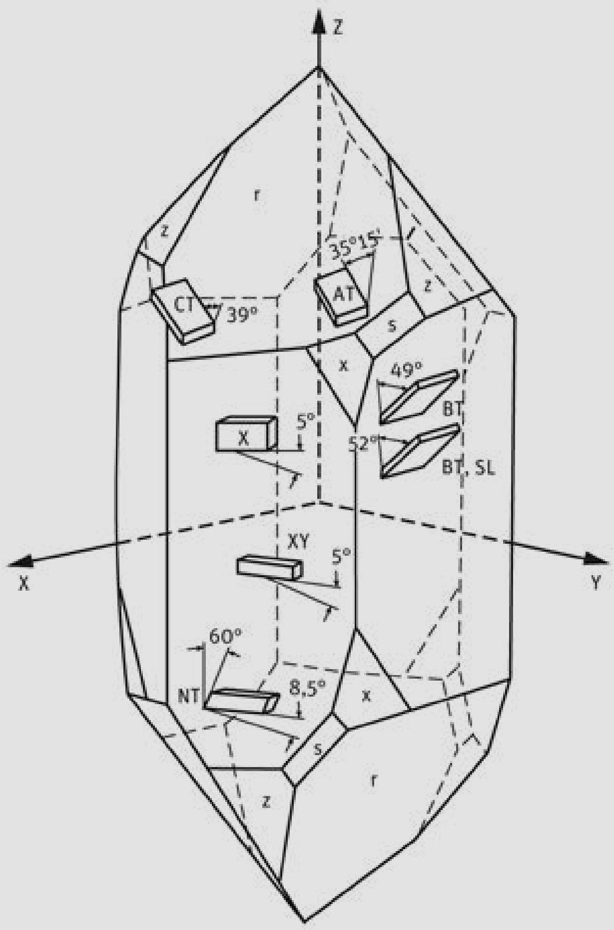

Image: Jauch Quartz GmbH

1.5.3 AT-cut characteristic

The frequency over temperature (F/T) characteristic resulting from the AT-cut (see figure below) has a frequency vs. temperature coefficient that can be approximated by a cubic function of the operating temperature.

FIG. 2: Typical F/T of an AT-cut crystal

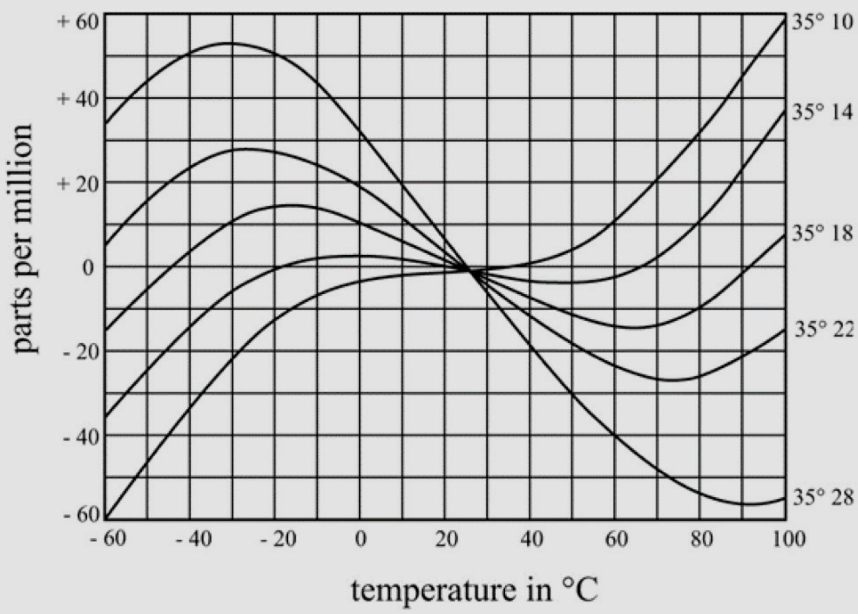

Image: Jauch Quartz GmbH

The individual F/T-characteristic can be precisely controlled, as small variations of the cutting angle can be used to find a F/T characteristic that is most suitable for specific applications or operating temperature ranges. However, once a suitable F/T characteristic and the corresponding cutting angle has been determined, the cutting angle of each crystal plate (blank) should be controlled carefully during production by keeping the variation of the cutting angle as small as possible.

It should be noted that due to the cubic function that is associated with the AT-cut angle, the resulting F/T characteristic is more stable than most of the other cutting angles, which often show a parabolic temperature characteristic. Due to this property crystals that make use of the AT-cut angle are well suitable to applications requiring a high degree of frequency stability over wide temperature ranges. In addition, the AT-cut angle ensures a low aging and a high-quality factor Q.

B.C.E. S.r.l. - Via Regina Pacis, 54/c - Sassuolo (MO) - I 41049 - Italy
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1.5.4 Low long-term frequency changes

The long-term drift of the resonant frequency of a crystal is called aging. The aging of the crystal resonator is related to the stability of its mechanical components, and to a well-controlled manufacturing process. Resulting from that, mid and long-term stability manifests in frequency drifts of only a few parts per million per year at room operating temperature. Even low-cost commercial crystals show an aging of less than +/-5ppm first year. By special manufacturing process steps, low aging rates like +/-1ppm or less first year can be achieved.

1.6 Modes of vibration, cuts and frequency ranges

1.6.1 Resonant modes

The AT-cut crystal resonator uses the thickness shear mode of vibration (see figure below).

FIG. 3: Thickness shear mode of an AT-cut crystal

Image: Jauch Quartz GmbH

A standing wave builds up inside the crystal blank by reflection at both major surfaces, when traverse acoustic waves are travelling in the thickness direction. The major mechanical displacement is in the plane of the crystal at a right angle to the direction of wave propagation. At resonance, an odd number of acoustic half wave lengths fit into in the thickness plane of the crystal blank. Therefore, the thickness is the primary frequency determining dimension in AT-cut crystals. More details can be found in 1.6.2

Another important resonant mode is the flexure resonant mode (see figure below).
It is used in the so-called tuning fork crystals. See 1.6.3 for more information.

FIG. 4: Flexural mode

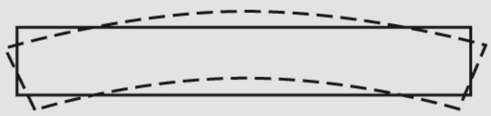


Image: Jauch Quartz GmbH

There are other resonant modes like the length extensional mode or the Lamé mode that might be used for specialized timing and sensor applications. For each of these vibration modes an optimal cutting angle is used, which controls the frequency characteristics of the quartz crystal resonator over the temperature range.

1.6.2 AT-cut crystals

AT-cut crystals are commonly manufactured in these frequency ranges:
1 MHz ~ 60 MHz, operating in fundamental mode
30 MHz ~ 250 MHz, operating in overtone mode (3rd; 5th; 7th; 9th)

As stated before, the required thickness d of a blank can be estimated, as an odd number of half wave lengths of the acoustic wave should fit into the thickness plane of the crystal blank.
In addition to the thickness of the crystal blank, the propagation velocity v of the acoustic wave inside the crystal material is needed to estimate the resonant frequency f. In AT-cut crystals, the propagation velocity is about 3320m/sec.

The required thickness d at a given frequency can be estimated as follows:

$$d \approx n \times \tfrac{1}{2} \times v/f \quad \text{with } n = 1, 3, 5, \ldots$$

In fundamental mode, the resulting thickness at the frequencies 10.0MHz and 40.0MHz are:

10,0 MHz ⇢ d = 166,0µm
40,0 MHz ⇢ d = 41,5µm

See below two figures depicting the fundamental mode and the 3rd overtone mode:

FIG. 5: Fundamental thickness shear mode (AT-cut) (left) and 3rd overtone thickness shear mode (AT-cut) (right)

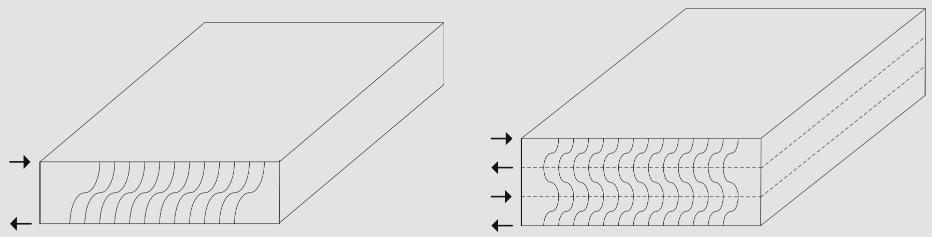


Image: Jauch Quartz GmbH

1.6.3 Tuning fork crystals for low frequencies

At low frequencies below about 1 MHz the AT-cut thickness shear mode resonators become too cumbersome and ineffective. Therefore, other modes of vibration are used. The most important resonant mode to create low frequencies like 32.768kHz is the flexural mode. Typically, a double flexural resonator is used – due to the shape with two arms this resonator is called tuning fork resonator.

FIG. 6: De-capped tuning fork crystal

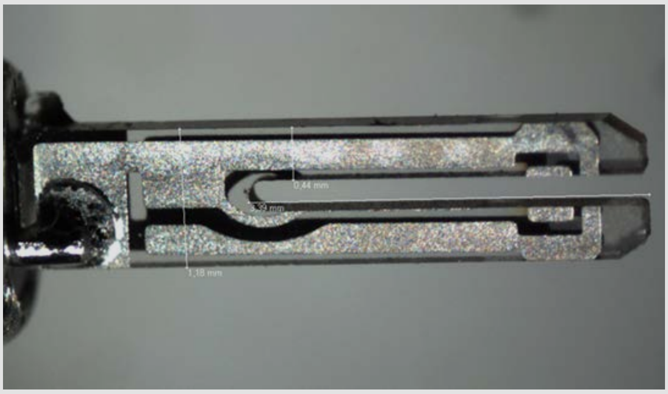


Image: Jauch Quartz GmbH

To stimulate the flexural resonant mode by the piezoelectric effect, the tuning fork resonator must be cut from the crystal bar at a different cutting angle.
The resulting characteristics of the resonant frequency over temperature (F/T) of this special cutting angle being used for tuning fork crystals shows the shape of an inverted parabola.

The frequency stability over temperature can be calculated by the following formula:

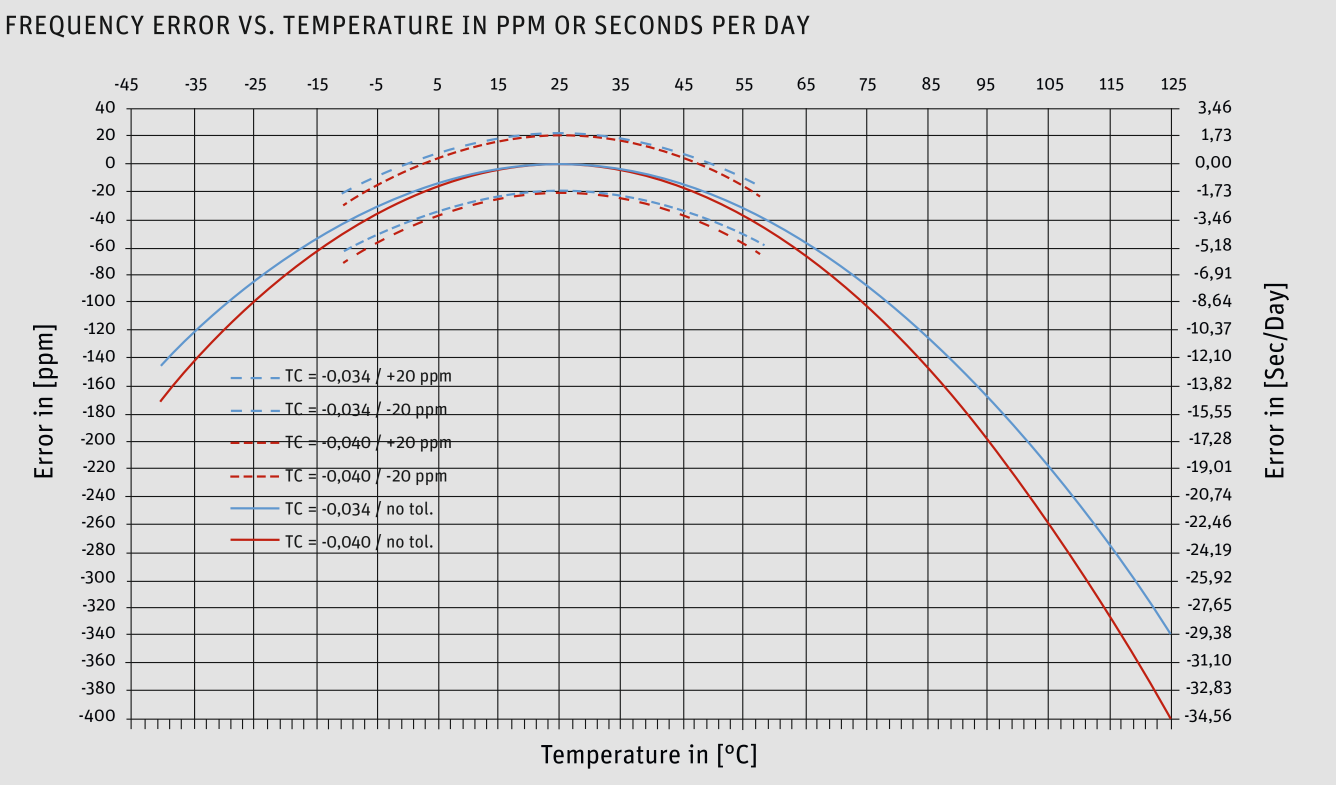
$$\Delta f = T_C \, (T_A - T_{TP})^2$$

Δf = delta of the resonant frequency, referred to the frequency at the temperature T_{TP}
T_C = temperature coefficient (- 0,034 ppm/°C² typical / - 0,040 ppm/°C² maximal)
T_A = operating or ambient temperature
T_{TP} = turning point temperature (+25 °C ±5 °C)

B.C.E. S.r.l. - Via Regina Pacis, 54/c - Sassuolo (MO) - I 41049 - Italy
Tel.: 0536 811616 - Fax: 0536 811500 - Web: www.bce.it - E-mail: bce@bce.it

Based on the formula, the frequency stability over temperature is shown below:

FIG. 7: F/T characteristics of a tuning fork crystal



Note that the graph shows F/T with a typical coefficient T_{Ctyp} of -0,034 and the max. coefficient T_{Cmax} of -0,04.

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1.6.4 Inverted MESA blanks for high frequencies

To generate very high frequencies up to 300MHz in fundamental mode, crystal blanks are produced by inverted MESA crystal technology.

Inverted MESA is a technology that uses photolithographic techniques to create a cavity with very small thickness into a thicker crystal blank base. By this small thickness, resonance at very high frequencies in the fundamental mode becomes possible, that would not be available using standard AT-cut blanks.

Consequently, high clock frequencies can be generated without the need of a PLL multiplier, resulting in lower phase noise than PLL multiplier solutions.

FIG. 8: Inverted MESA blank

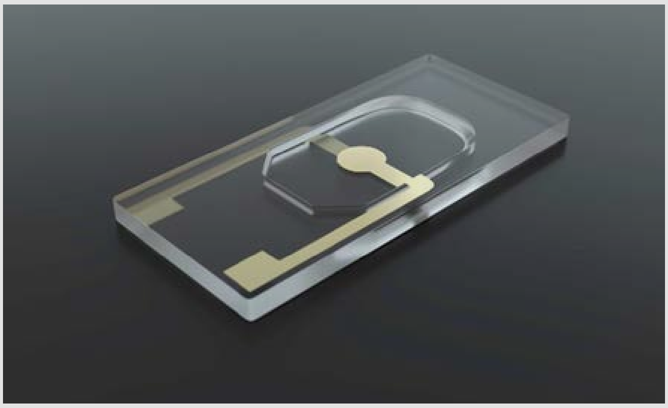

Image: Jauch Quartz GmbH

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2 MANUFACTURING OF AT-CUT QUARTZ CRYSTALS

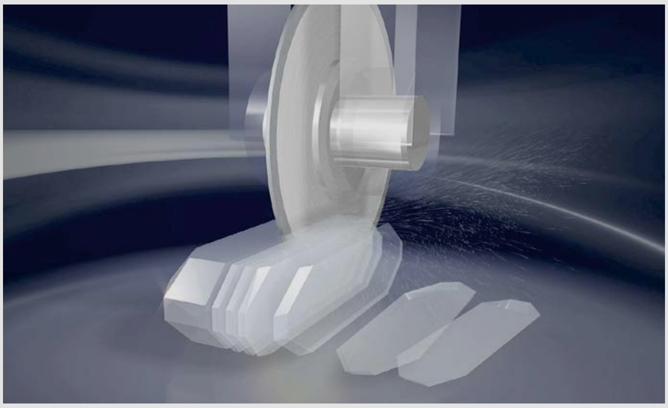
2.1 Careful design and production ensures quality

The process to create a reliable crystal requires both a careful crystal blank design as well as a proper setup and control of the production process.
The production process includes many steps that should be carried out very carefully. Most of the production steps require well-controlled clean room conditions.

Here are some key production steps to produce a reliable crystal:
- Correct selection and sorting of cutting angle to ensure the desired F/T stability
- Careful crystal blank design that avoids undesired resonant modes
- Appropriate blank polishing for lowest resonant losses
- Cleaning of blank surface for best electrode fixation
- Hermetic encapsulation in a dry nitrogen atmosphere for long operating life

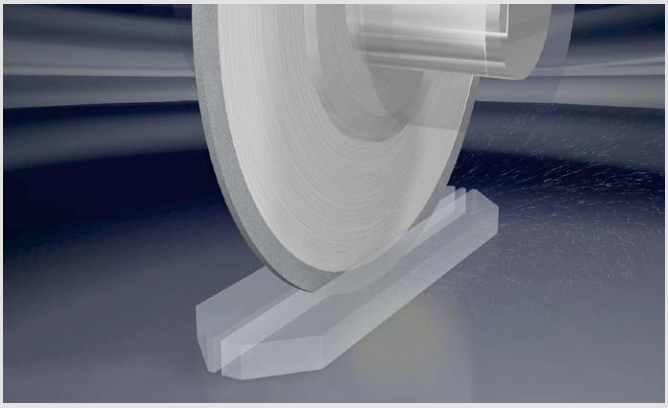
2.2 Production steps in more detail (excluding autoclave)

1. SAWING OF THE CRYSTAL BAR:



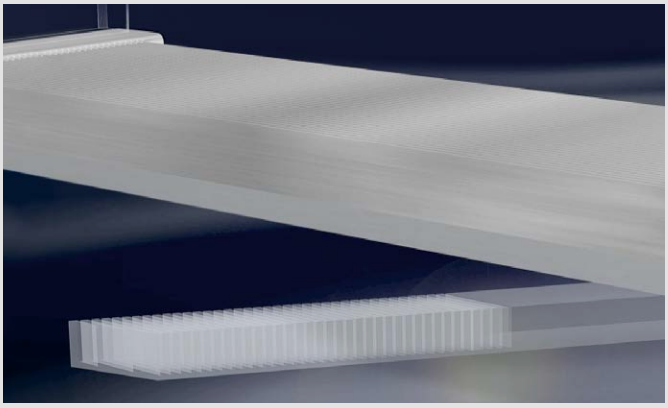
- Quartz crystal bars will be cut into lumbers.
- Sawing orientation is along the X- axis.
- The quartz seedling is still part of the lumbers.

2. REMOVING OF THE SEEDLING:



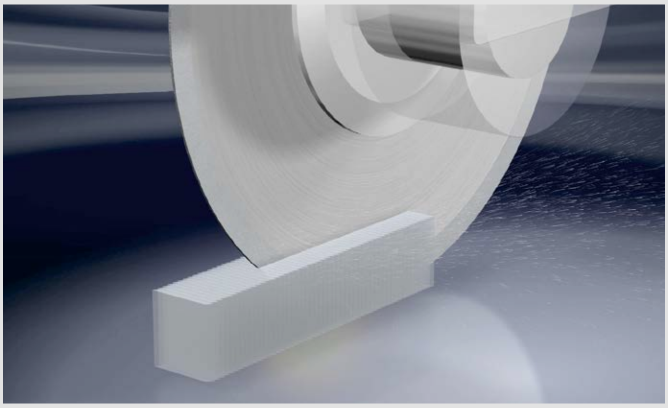
- The quartz seedling cannot be used to produce quartz crystal blanks and is cut out.

3. SAWING THE QUARTZ LUMBERS INTO WAFERS:



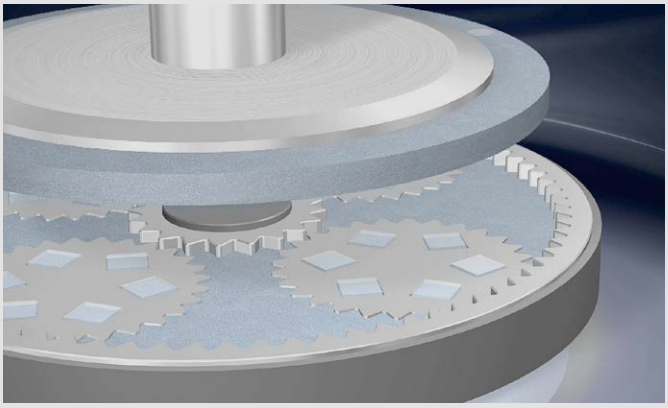
- Sawing the lumbers into wafers by wire saw or frame saw.
- The lumbers are sawn in predefined angles.
- The cutting angle is selected according to specification for temperature range and required frequency stability.
- The dedicated angle is the so-called AT-cut.

4. SAWING THE WAFERS TO RAW BLANKS:



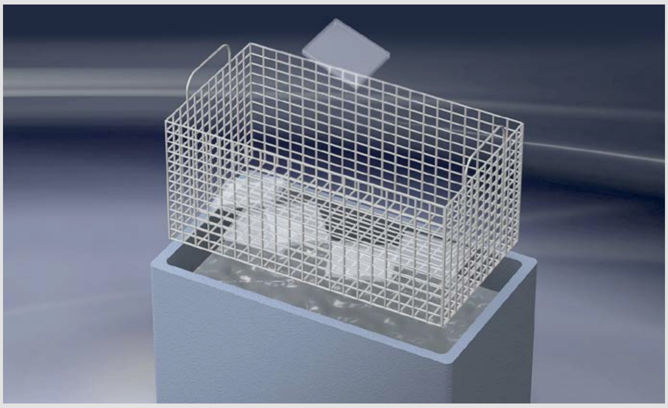
- The wafers are glued to stacked piles, which are sawn into quartz blanks.
  The size of the crystal blanks corresponds to the dimensions of the ceramics packages in which they are mounted later.

5. LAPPING THE BLANKS:



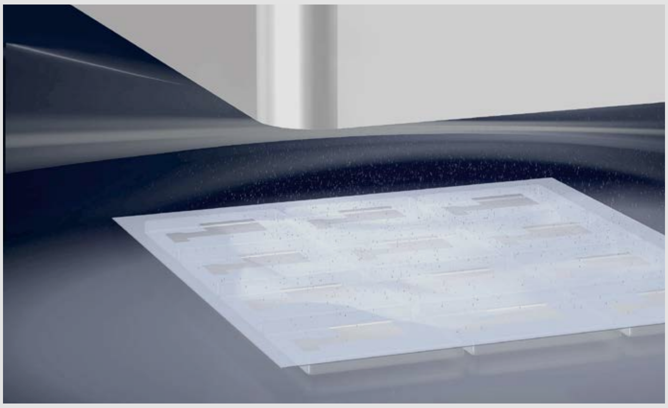
- Plane-parallel lapping of the blanks until the target frequency is reached.
- The thickness of the blank is defined by the specified target frequency. In this process, the frequency is kept slightly below the final resonant frequency.
- The thinner the quartz blank is lapped, the higher its frequency.

6. CLEANING THE BLANKS:



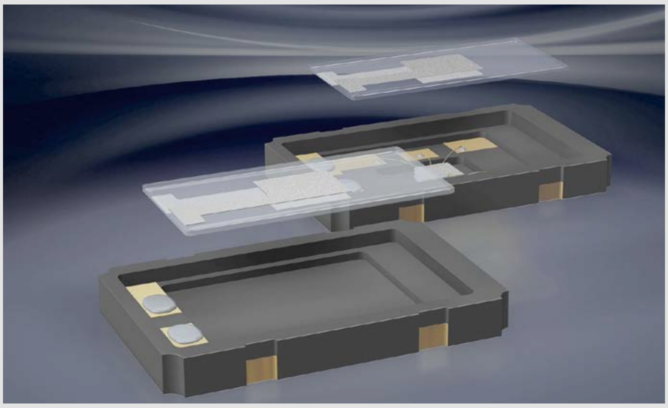
- Cleaning and etching processes to remove abrasive particles and impurities from the lapping process.
- The cleaning determines the roughness of the crystal blank surface, keeps the resonance resistance low and ensures a firm adhesion of the electrode to the blank surface.

7. EVAPORATION OF THE ELECTRODE:



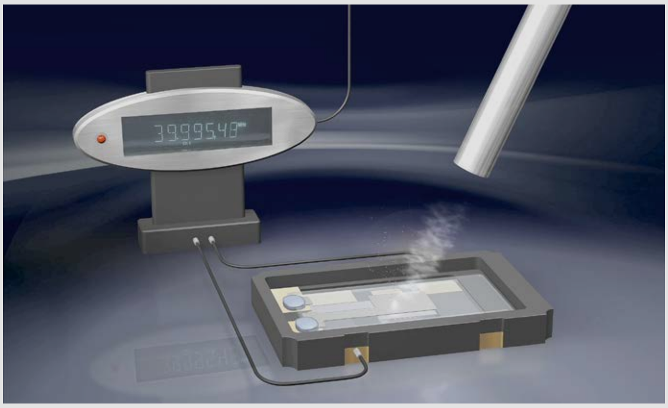
- Vapor deposition or sputtering of the silver electrode onto the blanks in a high vacuum.
- The electrode dimensions vary with the frequency.
- The electrode area defines the oscillation area of the mechanical resonance within the quartz blank.
- The deposition of the electrode increases the vibrating mass, the frequency decreases slightly.

8. MOUNTING THE QUARTZ BLANK:



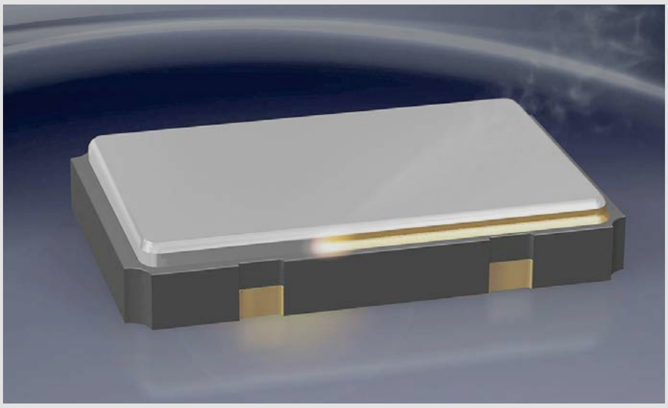
- Contacting the quartz blanks with an electrically conductive adhesive containing silver particles
- In oscillators, a wire-bonded semiconductor chip is located under the crystal blank. Depending on the dimension, flip-chipping might also be applied.

9. FINE ADJUSTMENT OF THE END FREQUENCY:



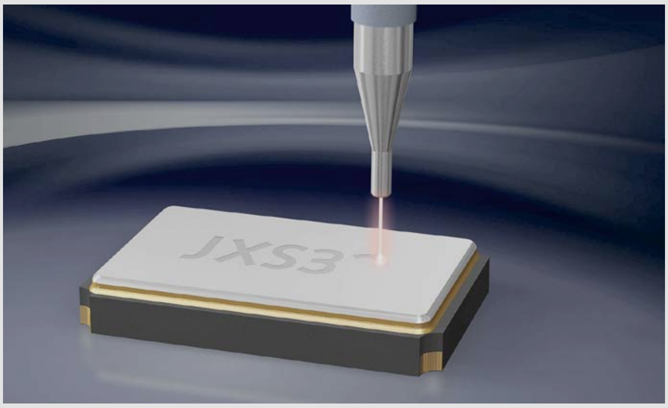
- 2 methods for frequency adjustment are possible:
  a) post-vaporization of the electrode – the frequency decreases
  b) removal of electrode material by plasma ion gun – the frequency increases
- In both cases, the final frequency adjustment is carried out by connecting the specified load capacitance C_L.

10. HERMETIC ENCAPSULATION:



- Practically, 2 methods are applied:
  a) resistance welding of the metal lid to the ceramic base (Seam Seal Method)
  b) Re-melting of a glass frit between ceramic lid and ceramic base (Glass Seal Method)
- Both methods are carried out in a dry nitrogen atmosphere to protect the electrodes from corrosion.

11. MARKING THE COMPONENTS:



- The marking is done by laser or ink method.
- Depending on the size of the component, the following information can be marked:
  Manufacturer
  Frequency with C_L Code
  Production code
  Date code

12. FINAL TEST AND PACKING:

- All components are checked in a 100% final test for the specified parameters.
- After testing, the insertion in tapes (for automatic PCB assembly) and reels is done.
- Finally shipment to the customer.

3 THE CRYSTAL AS AN ELECTRONIC COMPONENT

3.1 Equivalent circuit

The figure 9 shows the equivalent circuit of a crystal at a frequency near its main mode of vibration.

FIG. 9: Equivalent circuit of a crystal

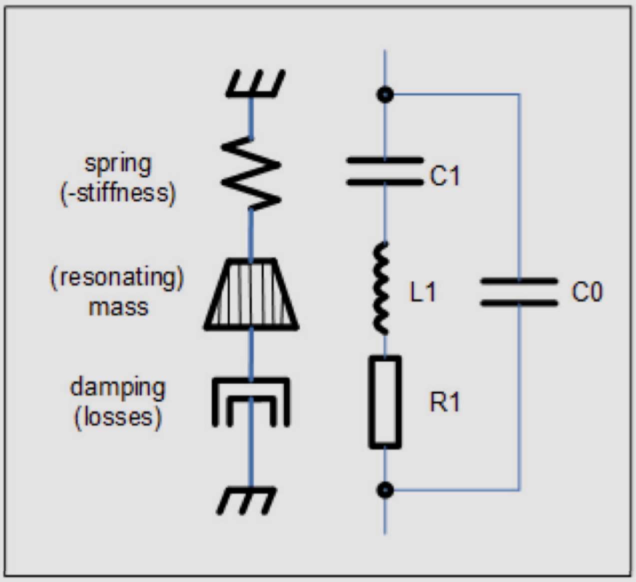


Image: Jauch Quartz GmbH

The parameters L_1, C_1, R_1 are known as the motional parameters of the crystal. L_1, C_1, R_1 are the electrical equivalents to the inertia, stiffness and internal losses of the crystal plate (blank) being a mechanical vibrating system. Compared to a conventional LC-based resonant circuit, the Q value of the motional arm defined by L_1, C_1 and R_1 of a crystal blank is extremely high (50.000 ~ 500.000).

The so-called static capacitance C0 represents the shunt capacitance resulting from stray capacitance between the terminals, and the capacitance between the electrodes which are situated at either surface side of the crystal blank. The static capacitance C0 can be determined by a precise capacitance tester if the test frequency is far from the series resonant frequency defined by L_1, C_1 and R_1.

The analysis of the equivalent circuit reveals several characteristic frequencies. Due to the very high resonator quality factor Q, two characteristic frequencies of the crystal are most interesting – the series resonant and anti-resonant frequencies f_s and f_a.

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$f_a = \frac{1}{2\pi\sqrt{\frac{C_0 C_1}{C_0 + C_1} L_1}}$$

The frequency f_S characterizes the series resonant frequency of the motional arm built by L_1, C_1 and R_1. At the resonant frequency fa, a parallel resonance occurs as the capacitors C_1 and C_0 are in parallel to the (almost lossless) motional inductance L_1. This frequency is often called anti-resonance.

The quality factor Q can be calculated based on the crystal series resistance R1 and the motional capacitance C_1

$$Q = \frac{1}{2\pi f_S R_1 C_1}$$

Practically, the ratio r is important:

$$\mathrm{r} = \frac{C_0}{C_1}$$

The ratio r effectively determines the sensitivity of the crystal resonant frequency to changes of external circuit parameters. Depending on the dimensions and shape of the crystal blanks the value r can have a range of 220 ~ 350.

It is approximately 250 for fundamental mode AT-crystals above 10 MHz (HC49/U) and 250 to 280 for low frequency fundamentals where the crystal blank is partially or fully contoured.

Small size SMD crystals can show ratios r between 280 to 350.

The ratio r for overtone crystals increases roughly in proportion to the square of the overtone order, where n is the order of overtone (n = 1, 3, 5,...).

$$\mathrm{r}_n \approx rn^2$$

The motional capacitance C_1 of an overtone resonant mode can be estimated based on the ratio r and the order of the overtone mode.

$$\mathrm{C}_1 = \frac{C_0}{rn^2}$$

3.2 C_L – the load capacitance is an important parameter

As explained in the previous paragraph, the electrical properties of a crystal can be described by the so-called crystal equivalent parameters L_1, C_1 and R_1 and the additional shunt capacitance C_0. As there are many crystal suppliers, each of them has their own “recipe” to design the individual crystal blank properties and electrode dimensions. So even at the same frequency and package these crystal equivalent parameters will differ from supplier to supplier. Consequently, infinite combinations of C_1, L_1 etc. exist that result in the same resonant frequency.

Just by taking the different crystal equivalent parameters of the different suppliers into account, crystals made from two different suppliers don’t necessarily show the same frequency in a customer circuit. For example, different values of C_0 due to different electrode dimensions can cause a frequency shift between different suppliers.

To overcome that problem, the so-called load capacitance C_L was introduced. By specifying a nominal load capacitance C_L to crystal suppliers, the different crystals made by different suppliers should show an accurate frequency if the crystal “sees” an effective load capacitance in the customer circuit that has the same value as the nominal C_L which has originally been specified to the crystal supplier.

3.3 The load capacitance C_L and its impact on frequency

The load capacitor C_L can be connected to the crystal either in series or in parallel. In both cases, slight variations of C_L can be used to fine tune the oscillator output frequency f_L. As shown in figure 10, the output frequency can be pulled up from f_r (series resonant frequency of the crystal) by a series load capacitor or downward from f_a (anti-resonant frequency of the crystal) by a parallel load capacitor.

Theoretically, the frequency f_L is forced to stay between f_r and f_a, no matter if the oscillation utilizes series resonance or anti-series resonance. In the most popular oscillation circuit, the crystal behaves like a high-Q inductance. This essential property of a crystal will only apply to the specific frequency band f_r to f_a.

Please refer to chapter 3.4 for more details.

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FIG. 10: Relationship between f_r, f_L and f_a at different load conditions

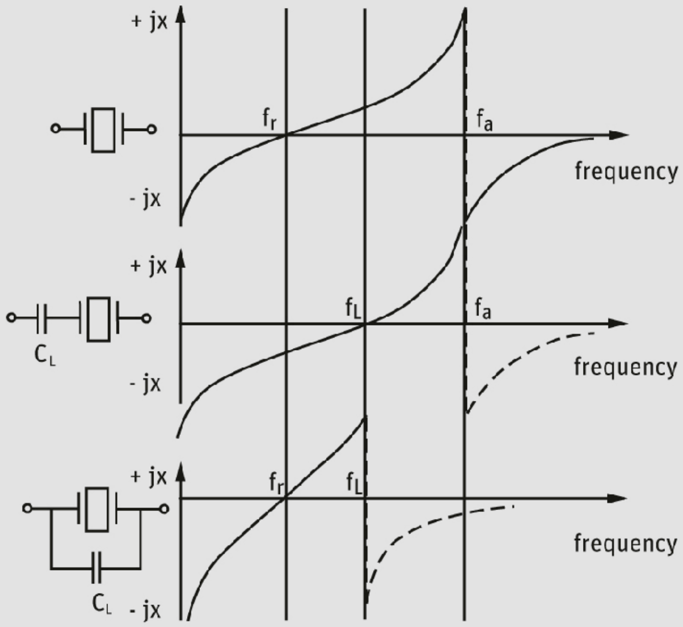

Image: Jauch Quartz GmbH

The amount of frequency pulling due to a variation of the load capacitance C_L is determined by C_L itself and the capacitance ratio (C_0/C_1) of the crystal. The term being used is the so-called tuning sensitivity TS.

It should be noted that the tuning sensitivity TS will be different from supplier to supplier, and also different from frequency to frequency. More information can be found in chapter 3.5.

3.4 Most often used – the Pierce oscillator configuration

An oscillator circuit topology that can be found very often is the so-called Pierce configuration, that is shown in figure 11.

FIG. 11: Pierce oscillator configuration

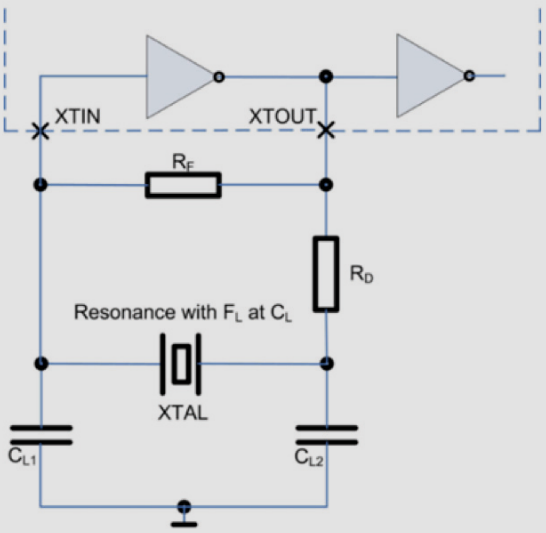

Image: Jauch Quartz GmbH

Most modern µControllers and other ASICs provide an inverting amplifier (ideally with a specified transconductance) which allows the connection of the crystal and two external load capacitors, as depicted above. Note that in some semiconductor datasheets, this amplifier is called "on-chip oscillator", though it requires an external crystal to generate a reference frequency.
The DC biasing of the amplifier might be provided internally, alternatively an external feedback resistor R_F is needed to stabilize the DC operating point.

We could also call the Pierce oscillator a positive reactance oscillator, as the crystal is operated in parallel resonance with the load capacitance C_L, where C_L is built by the two load capacitors C_{L1} and C_{L2} which are effectively connected in series. At that operating condition, the crystal is not resonating at its series resonant frequency f_r, but at a slightly higher frequency f_L where the crystal shows an inductive behavior.

To understand this, the reactance vs. frequency plots helps. As explained before, the crystal and the load capacitance C_L (built by the two load capacitors C_{L1} and C_{L2} in a series connection) lie in parallel if the oscillator operates in a Pierce configuration. To fulfill the oscillation criteria, at the resonant frequency the crystal combined with the load capacitors should cause a phase shift of 180°, whereas the amplifier adds

another 180°. The overall phase shift is 360°, which is one condition for positive feedback. A self-excitation of the resonance will occur if (in addition to the correct phase shift) the overall loop gain is greater than 1.
Due to the non-linear characteristic of the active device (for example due to output amplitude saturation of the amplifier), the overall loop will eventually limit itself to unity gain.

Theoretically, the load capacitance C_L (built by the series combination of C_{L1} and C_{L2}) can be considered as being coupled in parallel to C_0 of the crystal. Therefore, the so-called load resonant frequency f_L can be calculated as follows, and will lie above f_r:

$$f_L = \frac{1}{2\pi\sqrt{\frac{C_1(C_0 + C_L)}{C_1 + C_0 + C_L} L_1}}$$

More details of practical oscillator design and the Pierce topology can be found in chapter 4.

3.5 Tuning sensitivity TS

As explained before, a frequency shift occurs if the effective load capacitance C_{Leff} for the crystal is not equal to the nominal load capacitance C_{Lnom} that has been specified. The frequency error of the resonant frequency at two load capacitances C_{Lnom} and C_{Leff} is given by:

$$\Delta f_L = \left[\frac{C_1}{2} * \left(\frac{1}{C_0 + C_{Leff}} - \frac{1}{C_0 + C_{Lnom}}\right)\right] * 1 * 10^6 \ in\ [ppm]$$

The sensitivity of the resonant frequency versus small changes of C_L is given by the derivative of the above formula:

$$\mathrm{TS} = -\frac{C_1}{2\,(C_0 + C_L)^2} = \frac{d\left(\frac{\Delta f}{f_r}\right)}{dC_L}$$

Note that TS isn't constant, as it depends on the individual properties C_0 and C_1 of the crystal, as well as on the specified C_L.

The graph figure 12 shows the direct dependency of the tuning sensitivity TS from the specified C_L. It can be seen that the tuning sensitivity TS strongly depends on the crystal equivalent parameters C_0 and C_1.

FIG. 12: Example for tuning sensitivity

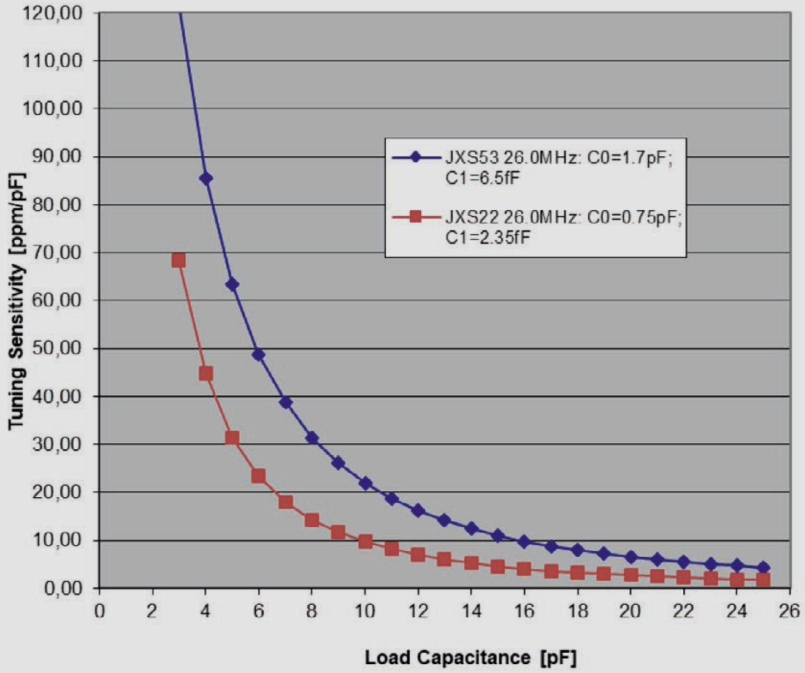

Image: Jauch Quartz GmbH

Tuning Sensitivity based on 2 examples:

- JXS22 26.0MHz 2520 crystal: C_0 = 0.75pF / C_1 = 2.35fF / C_0/C_1 = 320
- JXS53 26.0MHz 5032 crystal: C_0 = 1.70pF / C_1 = 6.5fF / C_0/C_1 = 260

The graph shows that crystals operating in fundamental resonant mode can have a tuning sensitivity TS of more than 40 ppm/pF if C_L values are low and C_1 is high. Consequently, too low nominal C_{Ls} should be avoided, as unwanted frequency shifts can occur even at small inaccuracies or tolerances of the load capacitors.

As explained in chapter 3.1, the tuning sensitivity of overtone crystals is lower, as the motional capacitance C_1 of overtone crystals is much lower than C_1 of crystals operating in fundamental resonant mode.

3.6 Intentional frequency tuning – the VCXO application

In certain applications, frequency tuning is a desired option. To make use of a crystal in a VCXO (Voltage Controlled Crystal Oscillator), the load capacitors are variable rather than constant.

In a VCXO application, the difference between the largest and the smallest variable C_L value will determine the tunable frequency range.

The upper tunable frequency can be calculated for a load capacitance C_{Lmin} that is lower than the nominal C_{Lnom} of the crystal in use.

$$\Delta f_{Lhigh} = \left[\frac{C_1}{2} * \left(\frac{1}{C_0 + C_{Lmin}} - \frac{1}{C_0 + C_{Lnom}}\right)\right] * 1 * 10^6 \; in \; [ppm]$$

The lower tunable frequency can be calculated for a load capacitance C_{Lmax} that is higher than the nominal C_{Lnom} of the crystal in use.

$$\Delta f_{Llow} = \left[\frac{C_1}{2} * \left(\frac{1}{C_0 + C_{Lmax}} - \frac{1}{C_0 + C_{Lnom}}\right)\right] * 1 * 10^6 \; in \; [ppm]$$

The total tunable frequency range can be calculated based on the maximal load capacitance C_{Lmax} and the minimal C_{Lmin}. The maximal load capacitance C_{Lmax} should be higher, and the minimal load capacitance C_{Lmin} should be lower than the nominal load capacitance C_{Lnom} of the crystal in use.

$$\Delta f_{Ltotal} = \left[\frac{C_1}{2} * \left(\frac{1}{C_0 + C_{Lmax}} - \frac{1}{C_0 + C_{Lmin}}\right)\right] * 1 * 10^6 \; in \; [ppm]$$

It should be noted that the crystal equivalent parameters can't be freely selected, as the electrical properties like C_0 and C_1 will be determined by the mechanical properties of the crystal blank being a mechanical resonator.

See chapter 3.1. for more information.

3.7 Crystal drive level

Before selecting a crystal with a very small dimension, a customer should be aware of the fact that small crystals can be overdriven, or even be destroyed by excessive drive levels. If possible, when ordering crystals, the customer should specify a typical and a maximal operating drive level. According to the drive level information provided by the customer, an appropriate crystal package can be recommended.

Another important aspect is that during oscillation startup, the drive level begins at very low levels and increases to a final level at a stable oscillation amplitude. Due to careful design and production, start-up problems at lowest drive levels can be eliminated.

A typical drive level of 50µW ~ 100µW is recommended for all oscillator circuits if larger crystals are used.

For a small crystal like JXS32 ~ JXS11 (3225 ~ 1612) in precision applications like IoT we recommend a typical drive level in the range of 10µW ~ 20µW, as at higher drive levels there's a risk of a drive level dependent frequency shift and a slightly increased long-term aging.

In a positive (i.e. inductive) reactance oscillator the crystal power can be approximated as:

$$P_{Crystal} = \left(I_{CLeff}\right)^2 * R_L$$

As the crystal is operated at positive reactance (see 3.4), the loaded resistance RL should be calculated by the following formula:

$$R_L = R_1 * \left(1 + \frac{C_0}{C_L}\right)^2$$

For the drive level calculation please make sure to use the individual crystal equivalent parameters. Real values for C_0, C_L and R_1 (ESR) should be used to calculate the drive level, as using the maximum values shown in the general datasheets might cause misleading drive level results.

In chapter 4 a practical method is described to determine the drive level.

3.8 Aging

Aging is defined as frequency changes over a defined period of time, like the first year or even over longer periods. The common aging rate for commercial crystals is +/-3ppm 1st year at +25°C, and +/-1ppm 1st year at +25°C for special types.

Note that the aging increases, if the crystal is operated at higher operating temperatures than +25°C.

It should also be noted that aging slows down over time, which means that the aging in the 2nd year is lower than the aging 1st year.

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3.9 Spurious responses

Spurious responses are unwanted resonant frequencies that may occur near the nominal resonant frequency. Undesired spurious resonances can occur quite close to the nominal resonant frequency. When designing a crystal, the blank design engineer takes special care to avoid spurious resonances, or keep the spurious responses as small as possible.

For special applications like wireless applications the ratio of the undesired spurious series resistance over the main mode series resistance is quite important, as spurious modes in the reference frequency of an RF-ASIC will cause problems in the resulting spectrum of the RF-frequency.

The success of spurious response prevention can be specified in two ways

$$a_{SP} = 20\ log_1 \left(\frac{R_N}{R_1}\right) \quad \text{or as a ratio} \left(\frac{R_N}{R_1}\right)$$

3.10 Crystal test methods

The electrical equivalent data of a crystal can be determined by a network analyzer and a so-called Pi-network, however unknown stray capacitances might cause inaccurate results.

Nowadays a typical test equipment for this method is integrated into a specialized PC-plug in card, which includes a crystal network analyzer for crystal testing, and uses a dedicated PC-based test software.

The required Pi-network is integrated into a benchtop test head supporting all common crystal types by special adapters.

The system requires a high precision frequency standard and should be re-calibrated after each adapter change.

FIG. 13: PC-based crystal analyzer setup with benchtop test jig (example Saunders & Associates, USA)

Image: Saunders & Associates, LLC, Info sheet '250B-2 Network Analyzer', p. 1

FIG. 14: Network analyzer card for PC-based crystal analyzer (example Kolinker, HK)

Image: Kolinker Industrial Equipments Limited, Info sheet 'KH1800 / KH 1820 – PI-network Crystal Measurement System', p. 1

4 CRYSTAL USAGE

4.1 Common crystal oscillation circuits

4.1.1 Pierce Oscillator

Pierce oscillators (see below) are most common in conjunction with quartz crystals. They require a small set of external components and therefore result in low series costs. This setup is known for its stable oscillation when combined with a quartz crystal resonator. For these reasons this oscillators setup is very common in conjunction with all types of controllers, RF-ASICs and other IC types.

Pierce Oscillator Circuit

FIG. 15: Pierce oscillator configuration with RF and RD

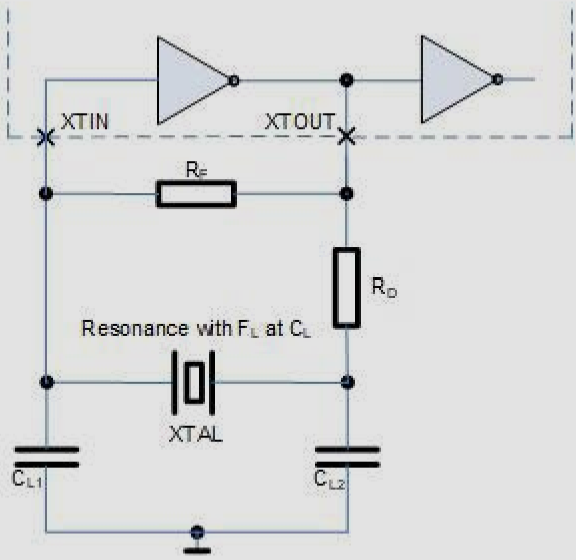

Image: Jauch Quartz GmbH

- The IC internal inverter works as an amplifier that's enabling the oscillation start-up and compensating energy losses in the oscillation circuit during operation.
- The biasing resistor RF adjusts the inverter to act as a linear amplifier and might be IC internal or external. Typical RF values range from 470kΩ to 25MΩ.
- XTAL: Quartz crystal works as the main resonator
- RD: Damping resistor, might be needed to limit the crystal drive level.
- C_{L1}, C_{L2}: Load capacitors. Together with the crystal they constitute the frequency determining resonant loop.

4.2 Adjustment

Pierce Oscillator Circuit with C_{Stray}

FIG. 16: Pierce oscillator configuration with added C_{Stray}

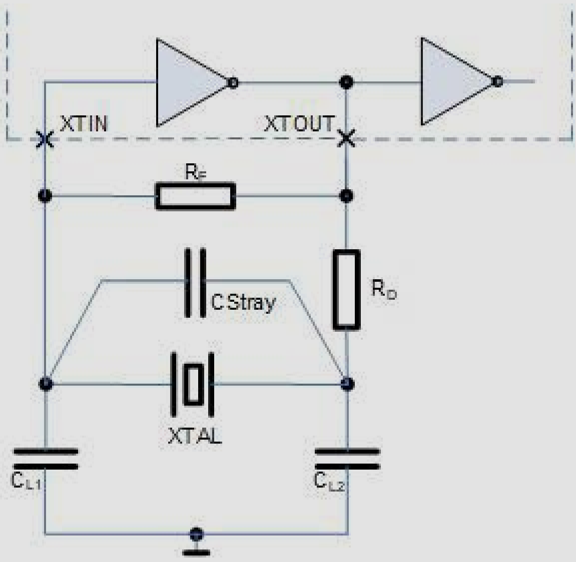

Image: Jauch Quartz GmbH

In real, existing circuits a stray capacitance C_{Stray} can always be found that lies in parallel with the crystal. This stray capacitance is the sum of microcontroller pin capacitances (XTIN and XTOUT) and the parasitic PCB capacitance caused by PCB traces and pads.
The overall stray capacitance may typically vary from 2.0pF to 5.0pF.
As a start value it might be a good idea to calculate with 3.0pF to 4.0pF.

C_L can be calculated by:

$$C_L = \frac{C_{L1} * C_{L2}}{C_{L1} + C_{L2}} + C_S$$

Example:

$$C_{L,nom} = 12pF \ , C_{stray} = 3pF \ (approximated)$$
$$\text{With } \ C_{L1} = C_{L2} \ \rightarrow \ C_{L1/2} = 2 * (C_L - C_S) = 18pF$$

By default the load capacitors are equal, but to find a better matching with the target C_L,nom of the crystal it might be appropriate to select load caps asymmetrically. In such cases it is recommended for most controllers to place the larger capacitor value connected to the inverter output (XTOUT).
The adjustment is typically done on the engineering workbench at approximately 25 °C.
Basically the design engineer adjusts the load capacitance C_L by observing the frequency of the oscillation circuit and adjusting the load caps if needed. If the frequency is high, the load capacitor values must be

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increased. If the frequency is low, the load capacitors should be decreased. During frequency measurement, a direct contact to the circuit should be avoided, as a contacting with a probe would always increase the effective C_L value, which results in shifting the frequency and therefor wrong results.

If no buffered output representing the resonant frequency is available, it is recommend to measure contactless using loose capacitive coupling. Precise frequency measurement equipment is recommended, that receives its reference clock from a highly stable OCXO or GPS-based clock.

If measurement is done without usage of well-known reference crystals, the average resonant frequency must be checked at least with a statistically significant number of circuits or modules. But even if the average resonant frequency is checked based on a high number of circuits and crystal samples, there's a certain risk of referring the test to a production lot of crystals that is systematically tolerated to one direction. Therefore, the adjustment method might be misleading as it includes a compensation for the shift brought in by the crystal production lot.

For very accurate adjustments, it's recommended to request a few sample crystals including a test report from the crystal supplier. If the deviation of the single crystals at 25°C is known, it can be eliminated by calculation. Be aware not to heat up those samples excessively when soldering because this may cause a residual frequency shift.

Another good option would be to ask the crystal supplier for a full adjustment service, as the supplier normally owns the required laboratory equipment to carry out such measurements with best experience.

4.3 How to keep your tolerance budget

Any application has its tolerance budget that must be kept even under worst case circumstances. In some cases, it might be difficult for design engineers to define the limits at which the application can safely be operated without showing failures due to an unprecise clock frequency.
Frequency deviations may occur caused by multiple reasons.
To eliminate (or at least reduce) the risk of failures caused by frequency deviation, the design engineer should check, if the sum of all worst-case contributions doesn't break the application's limits. It's in his responsibility to decide what design margins are needed, or what risk level of failure to accept or not.

Possible contributions for frequency deviation of a crystal resonant frequency are:

1. Frequency tolerance at 25°
2. Frequency stability over temperature
3. Long term aging (long term frequency drift over the application lifespan)
4. Frequency shift due to circuit C_L mismatch caused by the selected load cap values
5. Frequency variations due to circuit C_L tolerance caused by load cap tolerances
6. Frequency variations due to tolerance of pin / pad capacitances
7. Frequency variations due to tolerance of layer thicknesses (stray of pads and wires)

Basically, contributions 1. ~ 3. are under control of the crystal supplier.
Contributions 4. and 5. depend on an accurate C_L matching, and the choice of load capacitors with low tolerance.
Contributions 6. and 7. need to be mentioned here but are hard to determine for design engineers.
Therefore it is recommended to leave a margin of 1-2ppm in the budget to cover them.

Examples for tolerance calculations:
Example 1:
Overall tolerance budget: +/-100ppm
Crystal type: Q 16,0-JXS32-12-20/50-LF

Contribution:	**Value [ppm]**
Crystal tolerance at 25°C	+/-20
Crystal stability over temperature (-20°C ~ +70°C)	+/-50
Crystal max. long term aging over 7 years	+/-15
Circuit C_L mismatch (~ +/-0.5pF)	+/-7
Circuit C_L mismatch caused by load cap tolerance (+/-5% ~ +/-0.45pF))[1]	+/-6
SUM	**+/-98**
Judgement (<= +/-100ppm ?)	OK

Comments:
1) Only 2ppm reserved for other possible contributions!
2) C_L needs to be fine-tuned to 12pF +/- 0.5pF!
3) To properly calculate potential frequency shifts caused by C_L mismatch, the design engineer should request the crystal supplier to provide the TS (Tuning Sensitivity) value of the used crystal type at $C_{L,nom}$
In the example above, a tuning sensitivity TS of 14ppm/pF at a C_L of 12pF has been assumed. Attention: TS varies with C_L.

1 In this example the Cstray is considered to be ~3pF. Based on a target CL=12pF the load caps should contribute a capacitance of 9pF.

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Example 2:
Overall tolerance budget: +/-40ppm (i.e. Bluetooth)
First attempt: with Crystal type: Q 26,0-JXS32-8-10/15-T1-FU-LF

Contribution:	Value [ppm]
Crystal tolerance at 25°C	+/-10
Crystal stability over temperature (-40°C ~ +85°C)	+/-15
Crystal max. long term aging over 10 years	+/-20
Circuit C_L mismatch (~ +/-0.25pF)	+/-5
Circuit C_L mismatch caused by load cap tolerance (+/-2% = +/-0.16pF))[2]	+/-3
SUM	**+/-53**
Judgement (<= +/-40ppm ?)	Not OK !

Improvements needed:

- Change to crystal type with reduced long term aging
- Change load caps to a type with better tolerance +/-1% ; +/-0.1pF

Second attempt: with Q 26,0-JXS32-8-10/15-T1-FU-WA-LF

Contribution:	Value [ppm]
Crystal tolerance at 25°C	+/-10
Crystal stability over temperature (-40°C ~ +85°C)	+/-15
Crystal max. long term aging over 10 years	+/-7
Circuit C_L mismatch (~ +/- 0.25pF)	+/-5
Circuit C_L mismatch caused by load cap tolerance (+/-1% = +/-0.08pF))[2]	+/-1.5
SUM	**+/-38.5**
Judgement (<= +/-40ppm ?)	OK

Comments:
1) The Jauch JXS-WA crystal series has been optimized for low aging and low ESR. It is especially suitable for wireless applications.
2) Only 1.5ppm reserved for other contributions!
3) C_L needs to be adjusted with 8pF +/- 0.25pF!
4) To properly calculate potential frequency shifts caused by C_L mismatch, the design engineer should request the crystal supplier to provide the TS (Tuning Sensitivity) value of the used crystal type at its $C_{L,nom}$. Attention: TS is C_L dependent.

In the examples above, a tuning sensitivity TS of 20ppm/pF at a C_L of 8pF has been assumed.

2 In this example the Cstray is considered to be ~3pF. Based on a target CL=8pF the load caps should contribute a capacitance of 5pF. Consequently, 2 load caps of 10pF are appropriate.

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4.4 Oscillation Safety Factor (OSF)

The operating condition of the amplifier that is responsible for safe start-up and reliable operation depends on several environmental conditions such as temperature, humidity or supply voltage. Therefore its gain margin might be influenced by these variable environmental conditions. Furthermore, an important parameter of a quartz crystal resonator is the ESR (Equivalent Series Resistance or R_1). The value of R_1 varies slightly with temperature, but it should not exceed the specified value given by the crystal supplier.

The oscillation safety factor enables the design engineer to classify the safety of the oscillator to start-up properly and work under various operation conditions and during the application life.

4.4.1 Determination of Oscillation Safety Factor

Fig. 1 shows a typical oscillation circuit in a Pierce configuration with an added resistor R_{Pot}

FIG. 17: Simplified Pierce oscillator configuration with added R_{Pot}

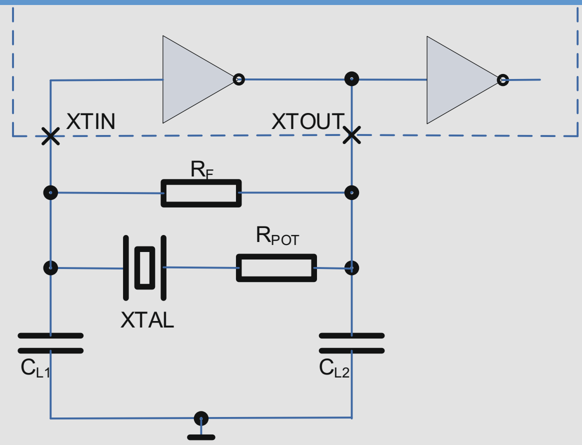

Image: Jauch Quartz GmbH

To verify the oscillation safety factor (OSF) of an oscillator circuit, the following steps should be investigated:

- calculate the individual loaded series resistance R_L at the original circuit conditions, using the parameters of the individual crystal* in the circuit using this formula:

$$R_L = R_1 * \left(1 + \frac{C_0}{C_L}\right)^2$$ [3]

3 To determine the equivalent data of the individual crystal which is used to determine the OSF (like C_0 and R_S) special crystal measurement equipment is required. Also, if the effective load capacitance C_L (including stray capacitances) is not exactly known, this can only be determined using special crystal test equipment. All measurements refer to the individual crystal parameters and amplifier parameters

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- calculate the worst case loaded series resistance R_{Lmax} using the max. specified series resistance of the selected crystal* series:

$$R_{Lmax.} = R_{1max.} * \left(1 + \frac{C_0}{C_L}\right)^2$$) 4

- insert a series resistor or miniature potentiometer R_{POT}

- increase R_{POT} and measure the maximum resistance of $R_{POTmax.}$ where the oscillation just securely restarts, starting from max. value for $R_{POTmax.}$ or from a value which stopped the oscillation

- determine the oscillation safety factor (OSF) using the following equation:

$$OSF = \frac{(R_L + R_{POT\,max.})}{R_{L\,max.}}$$

OSF judgement table

	Judgement	
OSF	**MHz-oscillators**	**kHz-oscillators**
OSF ≥ 10	Very Safe	Very Safe
5 ≤ OSF ≤ 10	Safe	Very Safe
3 ≤ OSF ≤ 5	Not Safe	Safe
OSF < 3	Risky	Not Safe

General Remark: All measurements and calculations according to this method are valid for the individual crystal and customer circuit. Any change or variation of the crystal driving circuit and load capacitance will change the resulting OSF.

4 As an estimation, the oscillation safety factor (OSF) can be calculated assuming an ideal crystal without any losses with: $OSF = \frac{R_{POTmax.}}{R_{Lmax.}}$

4.4.2 Methods to improve oscillation safety

There are several options to improve the oscillation safety factor. Unfortunately, the design engineer normally isn't free to select the driver circuit. That's why other ways of optimization must be identified.

Options for improvement:

a) **Switch to a crystal type with a reduced ESR max. value.**
   This will most easily improve the OSF, but may result in a higher crystal price, as a tighter sorting is required. Ask your supplier for available options.
   Be aware that some vendors provide a lower ESR,max. solution by enlarging the electrode on the crystal blank. This might lead to a lower Rpot max., but a higher tuning sensitivity TS (and therefor higher sensibility for C_L errors) might be a potential side effect.

b) **Reduction of C_L by decreasing load capacitor values.**
   The decrease of the circuit C_L normally results in an improvement of the OSF.
   The design engineer can stepwise decrease load capacitor values until the OSF measurement results in an acceptable value. However, reducing the load capacitors will cause a shift of the resonant frequency. If the introduced frequency shift still doesn't exceed the limit in the overall tolerance budget calculation, this might be a solution. If the overall frequency budget is exceeded, consider the next step.

c) **Reduction of the load capacitors, plus crystal change to a crystal version with lower nominal load capacitance $C_{L,nom}$.**
   On the one hand, the decrease of C_L will on one hand result in a better OSF.
   But on the other hand, the C_L mismatch might cause an inacceptable frequency deviation. To counteract this frequency shift, switching to a crystal type with a lower nominal C_{Lnom} and fine-tuning the entire circuit to that lower nominal C_{Lnom} will be the best option.

   It should be noted that with a lower C_L the crystal TS value will increase, so the circuit will become more sensitive against C_L mismatch or tolerances. Therefore it is recommended to reconsider the tolerance budget calculation, as the modification of the nominal C_L will have an impact on frequency accuracy parameters that depend on tuning sensitivity TS.

4.5 Keeping drive level limits

To ensure that the crystal is not overdriven in its circuit environment, it is necessary to measure the power that is applied to the crystal. By keeping the drive level limits of the crystal, an increased aging rate can be avoided, as well as an increased ESR and a certain shift of the resonant frequency (caused by a high drive level).

4.5.1 Drive level measurement

The most reliable way to determine the crystal drive level is to measure the crystal power by a miniature RF current probe. A typical configuration of a crystal circuit and the correct position to insert the current probe is shown in the next figure.

FIG. 18: Pierce oscillator configuration, current probe added to determine the drive level

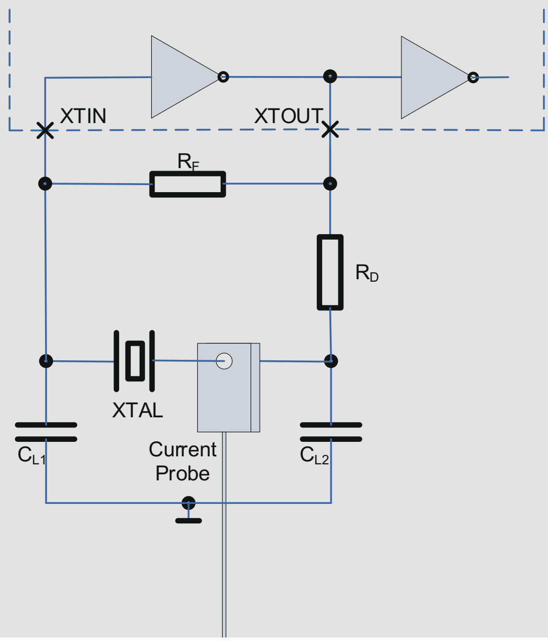

Image: Jauch Quartz GmbH

The crystal power (also called drive level) can be determined as follows:

- calculate the loaded series resistance R_L at the original circuit conditions, using the parameters R_1 and C_0 of the individual crystal* in the circuit using formula (1):

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

- the crystal current I_{CSpp} is measured with the current probe and an oscilloscope as a voltage U_{CSpp} being proportional to the measured current I_{CS}.
  The conversion factor K_{CS} of the current probe is only valid if it is terminated by a 50 Ohm load.
  The RMS current I_{CSRMS} must be calculated from the peak to peak current I_{CSpp} to calculate the crystal power correctly.

- The crystal power can be calculated based on the RMS current I_{CSRMS} and the resonance load R_L

$$I_{CSpp} = U_{CSpp} * K_{CS} \qquad (2)$$

$$I_{CSRMS} = \frac{I_{CSpp}}{2 * \sqrt{2}} \qquad (3)$$

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$$P_{Crystal} = R_L * (I_{CSRMS})^2 = R_L * \left(\frac{I_{CSpp}}{2 * \sqrt{2}} \right)^2 = R_L * \frac{(I_{CSpp})^2}{8} = R_L * \frac{(U_{CSpp} * K_{CS})^2}{8} \quad (4)$$

To determine the equivalent data of a crystal like C_0 and R_S, special crystal measurement equipment is required. Also, if the effective load capacitance C_L (including stray capacitances) is not exactly known, this can only be determined using special crystal test equipment. Customers can request typical data for C_0 and R_S from his crystal supplier.
Note that test results and calculations according to this method are valid for the individual crystal and individual oscillation circuit. Any change or variation of the crystal driving circuit and load capacitance will change the resulting OSF.

4.5.2 Options for drive level reduction

In the case that the drive level measurement results in a value that needs to be reduced, there are several options:

1. **Add a damping resistor**
   A damping resistor R_D can be introduced into the path from XOUT to Crystal and C_{L2}.
   This will improve the drive level, but with the disadvantage that most likely the OSF will be decreased. Furthermore, the effective load capacitance as seen by the crystal might be reduced slightly because the pad capacitance and PCB trace stray capacitance between R_D and XOUT will be decoupled from the capacitance C_{L2}.

2. **Reduce circuit load capacitance C_L**
   With reduced C_L, the amount of energy that's oscillating will be reduced, and therefore the drive level too. This assumes that a the current I_{CSRMS} keeps constant during a change of C_L.
   The load capacitor values can be reduced stepwise, and the resulting drive level should be observed. After this adjustment the crystal must be normally mounted and (after a rest period) the frequency has to be measured again. If the resulting frequency shift becomes unacceptable due to the reduction of load capacitors, a change to a crystal with lower $C_{L,nom}$ becomes inevitable. The C_L reduction can be continued until the drive level becomes acceptable, but in addition the new load capacitance should be determined, to decide which new $C_{L,nom}$ a new crystal should have.

3. **Reduce circuit load capacitance C_L plus damping resistor**
   In some cases it is mandatory to use a combination of options. It means that a damping resistor must be inserted into the circuit, and the circuit must be tuned to such a low C_L that the drive level becomes acceptable. If the resulting frequency deviation isn't acceptable, a modification of the nominal load capacitance $C_{L,nom}$ of the crystal might also become necessary.

4. **Choose a larger crystal type that is capable to handle a higher drive level.**
   This is most the most promising approach, but it requires a redesign of the PCB.

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B.C.E. s.r.l.
Via Regina Pacis, 54/c - 41049 SASSUOLO (MO) Italy
Tel. +39 0536 811.616 r.a. - Fax +39 0536 811.500
www.bce.it - E-mail: bce@bce.it