APPLICATION NOTE

ANQ001 | Frequency Products – Basics of Quartz Crystals and Oscillators as Clock Generators

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1. INTRODUCTION

Frequency products are often described as the heartbeat of electronic circuits. In numerous applications, they provide the clock signal that drives ICs (integrated circuits) or microcontrollers, thus enabling smooth operation. Without these clock generators, many modern technologies and systems would not be possible. A large proportion of these frequency-determining clock generators are based on quartz-controlled circuits – the following section therefore examines the basics of these quartz-based components.

Following an overview of various frequency-determining products, the piezoelectric effect – the physical origin of quartz oscillation – is introduced. The quartz crystal itself is then examined as a component, including its manufacture and key parameters. A separate section is devoted to the watch crystal and its special characteristics. Building on this, quartz oscillators, their key parameters, and various types of quartz-based oscillators are explained. Finally, an overview of typical clock-generator applications is presented, without going into technical detail.

2. FREQUENCY PRODUCTS

Various technologies are used to generate a clock signal – as frequency products. The most common of these are briefly described below. The remainder of this Application Note focuses exclusively on quartz-based clock generators, however.

2.1 Discrete resonant circuit

A discrete resonant circuit is made up of basic passive components such as capacitors (C), inductors (L), and, where applicable, resistors (R). For example, an LC resonant circuit can have a defined resonant frequency but can only generate a damped oscillation. Continuous signal generation always requires active feedback, as found in oscillator circuits.

The achievable frequency accuracy of such discrete oscillators depends very much on the tolerances of the components used. RC-based oscillators are susceptible to temperature and aging effects, which can lead to frequency deviations in the range of several thousand ppm (parts per million). Parasitic effects and external coupling can also impair frequency stability. In practice, the accuracy of RC oscillators often only achieves an accuracy of 1% to 5%. LC oscillators achieve better values but still fall significantly short of quartz-based solutions, making them unsuitable for many applications.

2.2 Ceramic resonators

Ceramic resonators operate in a very similar way to quartz crystals – they both use the piezoelectric effect to generate a stable frequency. However, they use different material and manufacturing process. Ceramic resonators are often mechanically designed such that the two series-connected capacitors required for quartz crystals are integrated into the component itself, eliminating the need for additional external capacitors. As a result, ceramic resonators have the advantage of being more compact.

In addition, ceramic resonators are cost-effective, typically enable lower-power oscillator circuits, offer shorter start-up times than quartz crystals, and are resistant to shock and vibration. In contrast, the frequency stability and tolerance of ceramic resonators are in the range of 0.2% (~ 2,000 ppm) to 0.5% (~ 5,000 ppm).

2.3 MEMS

MEMS stands for micro-electro-mechanical systems, meaning microscopic systems that incorporate both mechanical and electronic components. In frequency control technology, MEMS generally refer to tiny silicon resonators manufactured using processes similar to those used in semiconductor fabrication. Depending on the application, MEMS components can integrate mechanical structures, sensors, actuators, and integrated circuits on a single chip. MEMS can serve many different functions and applications, including that of a MEMS oscillator.

Thanks to the high level of electronic integration, very small, compact designs are possible, which are also highly resistant to shock and vibration. In addition, the resonator frequency can be programmed within a defined frequency range using a phase-locked loop (PLL). However, the frequency of MEMS oscillators exhibits strong temperature dependence, making internal temperature compensation essential. The resulting frequency stability of MEMS oscillators is in the same range as that of quartz oscillators. This range extends from approximately ±20 ppm for standard components down to just a few ppb (parts per billion) for high-precision 'oven-controlled' MEMS oscillators.

2.4 Quartz-based clock generators

Quartz is the crystalline form of silicon dioxide (SiO_2) and forms the basis of many frequency-determining components. The reason lies in its unique physical properties, which make it well suited for generating stable oscillations. The frequency at which a quartz crystal vibrates depends largely on the geometry of the quartz 'blank'. A major advantage of quartz lies in its high frequency stability: with the appropriate processing, the frequency remains extremely constant over a wide temperature range, typically within ±15 to ±30 ppm (-40 °C to 85 °C). As a result, only slight frequency deviations are to be expected, even over many years. However, a quartz crystal always requires an additional active circuit to generate a usable clock signal – only in combination with these electronic components does it form a functioning oscillator.

3. PIEZOELECTRIC EFFECT

The operation of an oscillating quartz crystal is based on the piezoelectric effect. This effect was discovered in 1880 by the brothers Jacques and Pierre Curie. They discovered that applying mechanical force to certain crystalline materials generates an electric charge on the surface.

As shown in Figure 1, this effect is caused by a shift in the position of charge carriers in the material caused by mechanical deformation.

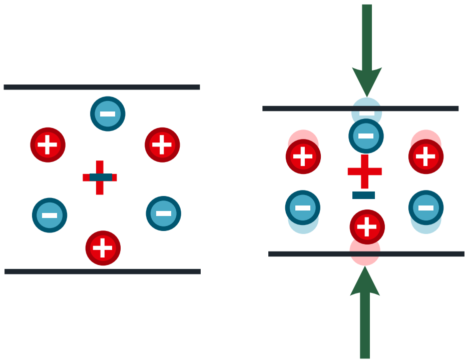

Figure 1: The principle of the piezoelectric effect in a quartz crystal.

This causes dipoles to form and results in an electrical voltage. To use a quartz crystal as a frequency-generating component, the reverse or inverse piezoelectric effect is utilized. Applying an electrical voltage deforms the quartz crystal. The deformation is typically in the range of around 1 to 10 picometers per volt. Even at 10 V, the deformation is only 10 to 100 picometers – significantly less than the diameter of a single atom (approx. 200 pm). Nevertheless, this minimal movement is sufficient to excite stable oscillations in the quartz crystal. This mechanical deformation generates an electrical voltage. When incorporated into a suitable electronic circuit, the quartz crystal begins to oscillate continuously. The quartz crystal is incorporated into a feedback circuit with active amplifying elements that continuously sustain its natural oscillation – typically as a 'quartz oscillator'. The frequency of this oscillation corresponds to the quartz crystal's natural resonant frequency and is determined primarily by the geometry of the quartz crystal and its electrode.

4. OSCILLATING QUARTZ CRYSTAL

Although the piezoelectric effect was discovered in 1880, quartz crystals did not begin to emerge as frequency-determining components until 1920, when physicist Walter Guyton Cady played a key role in their development. He used quartz in an oscillator and filed the first patent for a quartz oscillator just one year later.

The following section explains the electrical basics of quartz crystals and provides insight into their manufacturing process.

4.1 Circuit symbol

In circuits, the quartz crystal is represented as shown in Figure 2.

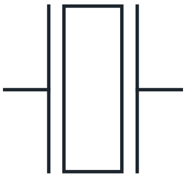

Figure 2: Circuit symbol of an oscillating quartz crystal.

There is no standardized symbol for active quartz oscillators, so the same symbol as for passive quartz crystals is often used, with the addition of a label or type designation for differentiation.

4.2 Equivalent circuit diagram

The equivalent circuit of a quartz crystal (Figure 3) consists of a series connection of R_1, C_1 and L_1 as well as the capacitor C_0.

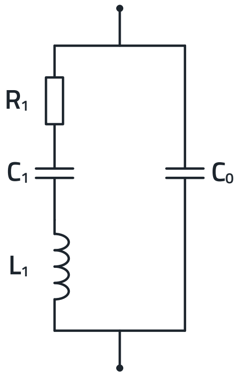

Figure 3: Equivalent circuit diagram of an oscillating quartz crystal.

Here, R_1 represents the resonance resistance, i.e., the damping of the mechanical oscillation, while L_1 represents the vibrating mass of the quartz crystal. C_1 represents the dynamic capacitance and thus corresponds to the piezoelectric effect. C_0 represents the parasitic coupling capacitance of the quartz crystal, which can also be measured directly.

4.3 Manufacturing

In the early years and for several decades thereafter, naturally grown raw quartz material was used for oscillator circuits. A groundbreaking development in the 1960s was the ability to manufacture synthetically grown quartz material. This development paved the way for improved control, accuracy and repeatability, and, above all, higher manufacturing output.

Synthetic quartz material is manufactured in autoclaves under high temperature and pressure. It takes an average of one to three months to produce quartz bars, which are further processed into wafers at a specific cutting angle in the next step. These wafers are then used to cut quartz blanks. The blanks differ in their shape and size depending on the frequency, package type, and their intended applications.

After cutting the wafers and blanks, the next step is to process the surface of the quartz blanks. Once the desired surface quality has been achieved, electrodes are applied to both sides of the blank. These electrodes later transmit the electrical pulse into the quartz material via the mounts and, conversely, the electrical oscillation signal out at the desired quartz frequency.

To establish contact with the electrodes, the quartz blank is attached to the package mounts. This is achieved with a special adhesive that provides a reliable mechanical, thermal, and electrical connection without impairing the vibration properties of the blank. Both the electrodes and the connection to the package mount can be seen in Figure 4.

For final frequency tuning, the quartz crystal is made to vibrate in this state (without the package lid), and final adjustments to the electrode are made during frequency measurement. The quartz crystal is then hermetically sealed, labeled, and subjected to final inspection.

4.4 The cutting angle

The cutting angle for slicing the blank from the quartz bar determines key properties of the quartz crystal. Depending on the angle and orientation at which the crystal structure is cut, different vibration modes, frequency ranges, and performance characteristics are obtained.

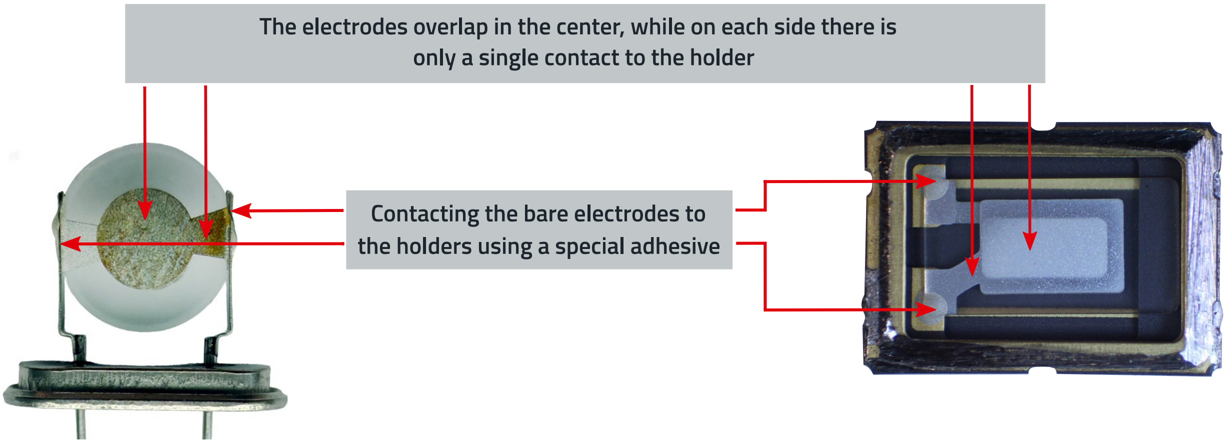

Figure 4: Electrode and structure of an HC49 quartz crystal and a quartz crystal in an SMT package.

The most common cutting angles are shown in Figure 5.

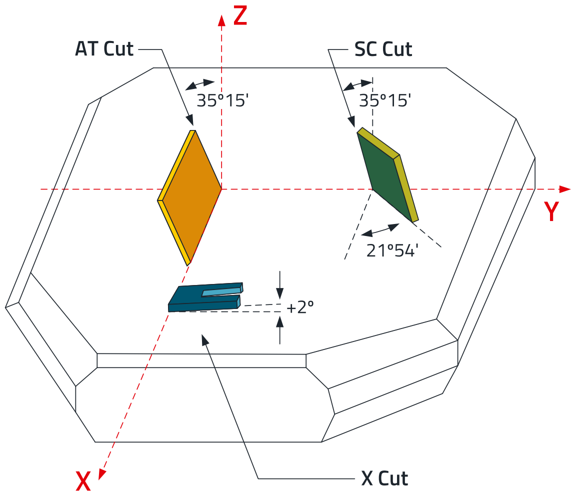

Figure 5: Various cutting angles on a quartz bar.

The most commonly used cutting angle is the AT-Cut, which is ideally at an angle of 35° 15' to the Z-axis – as shown in orange in Figure 5. This cut is used for the majority of quartz crystals in the MHz frequency range. At approximately 35° 15', the AT-Cut of an oscillating quartz crystal has a minimal temperature-frequency dependency, meaning that the frequency remains relatively stable over a wide temperature range. Figure 6 illustrates the frequency response over the temperature range.

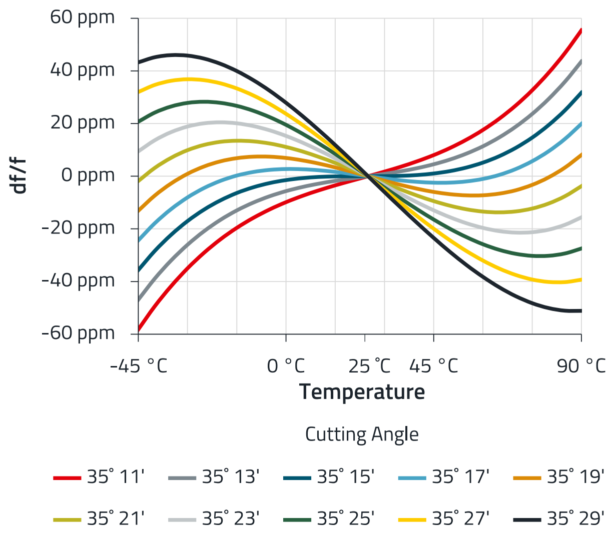

Figure 6: Frequency response of an AT-Cut oscillating quartz crystal over temperature.

Each colored line represents a deviation in the cut angle measured in arc-minutes. The graph shows that even slight deviations influence the temperature response of the quartz crystal. Further information on this can be found in the Section 5.4 'Temperature stability'.

Depending on the way the crystal structure is cut from the quartz bar, a specific vibration mode results. An AT-Cut quartz crystal is known as a thickness-shear resonator. Accordingly, as shown in Figure 7, the vibration passes through the thickness of the blank, that is, between the two electrodes on the top and bottom.

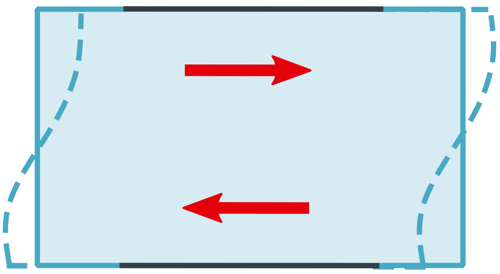

Figure 7: Thickness-shear vibration of the fundamental mode in an AT-Cut quartz crystal.

5. KEY PARAMETERS OF THE OSCILLATING QUARTZ CRYSTAL

There are several key parameters used to specify an oscillating quartz crystal. These parameters are particularly important for the specific circuit used in an application. The circuit must be designed and matched to the quartz crystal accordingly. The most important parameters are described below.

5.1 Frequency

The vibration frequency of a quartz crystal is probably its most important parameter. For example, the quartz crystal frequency serves as the clock for the microcontroller's synthesizer and must therefore be selected in accordance with the controller datasheet.

Depending on its size, the quartz crystal frequency is given in kilohertz (kHz) or megahertz (MHz).

The frequency is determined by various factors:

- The cutting angle previously mentioned defines a rough frequency range.
- During further processing, the frequency is determined by the thickness and geometry of the blank.
- Applying the electrodes to the quartz crystal also affects its geometry and mass, and therefore its frequency.

5.2 Fundamental mode and overtones

As described at the outset, in most applications a quartz crystal is excited at its resonant frequency (see Section 3 'piezoelectric effect'). This is also known as the fundamental mode. In this fundamental mode, the quartz crystal mechanically vibrates as shown in Figure 7. However, the frequency of the fundamental mode is physically limited, as the blank becomes progressively thinner as the frequency increases.

To achieve higher frequencies, the quartz crystal can be excited up to one of its overtones. These each provide an odd multiple of the fundamental frequency. Figure 8 shows a schematic example of thickness-shear vibration in the third overtone.

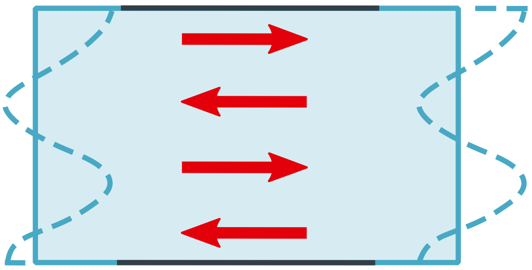

Figure 8: Thickness-shear vibration of the third overtone in an AT-Cut quartz crystal.

For operation at an overtone frequency, both the quartz crystal and the oscillator circuit must be designed accordingly, as the fundamental-mode resonance must be specifically suppressed. In many standard digital applications, however, this approach is only rarely used now – integrated oscillators are generally used instead.

5.3 Tolerance

The tolerance of a quartz crystal is based on its frequency accuracy at room temperature (25 °C). This is determined by manufacturing accuracy and is specified as a frequency deviation in ppm or ppb.

5.4 Temperature stability

The temperature stability of a quartz crystal, often referred to as just 'stability', indicates its frequency deviation within a specified operating temperature range.

Temperature stability is significantly influenced by the cutting angle, as shown in Figure 9.

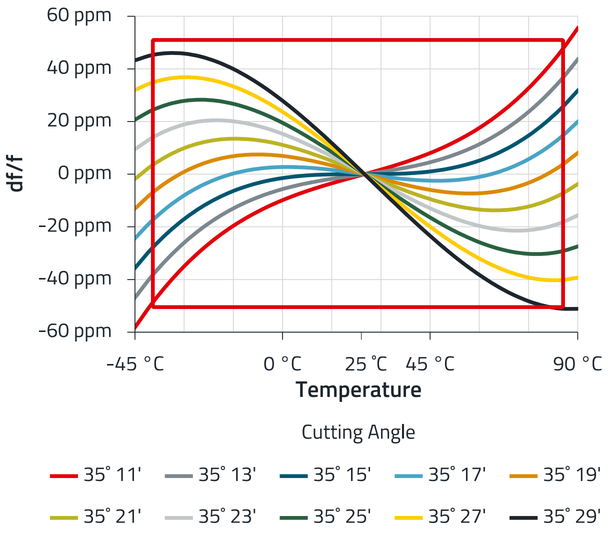

Figure 9: Quartz crystal frequency stability over temperature.

The most commonly used temperature range is from -40 °C to +85 °C. The wider the operating temperature range, the greater the frequency deviation. Temperature stability is also specified in ppm or ppb.

5.5 Load capacity

Load capacitance is one of the most important specification features of a quartz crystal and yet is often underestimated or incorrectly implemented. Specified in picofarads (pF), load capacitance indicates the load at which the quartz crystal was tuned during manufacturing – and compliance with the specification can only be guaranteed at this load. If the load is incorrectly designed when creating the oscillator circuit, this can lead to a shift in the quartz crystal frequency. Load capacitance in the oscillator circuit is determined by the two necessary capacitors (see Figure 13: Circuit diagram of a Pierce oscillator circuit), as well as by the stray capacitance of the traces and connections of the active circuit (e.g., microcontroller).

5.6 Equivalent Series Resistance (ESR)

The equivalent series resistance (ESR) corresponds to R_1 in the equivalent circuit and represents the damping of the mechanical vibration. This resistance results from the dimensions of the blank, but also, for example, from the resistance values of the blank mount. The ESR represents losses in the quartz crystal, so when designing the oscillator circuit, it must be ensured that the ESR is compensated by the gain of the electronic circuit for the quartz crystal to start oscillating.

5.7 Drive level

The drive level of a quartz crystal describes the power dissipated in the quartz crystal under steady-state oscillation. The drive level is a key parameter in designing the oscillator circuit. If the applied power exceeds the maximum permissible power of the quartz crystal, this can lead to changes in its properties or even to its destruction. However, if the applied power is too low, the quartz crystal may not start oscillating reliably, or its functionality may be impaired.

The drive level is specified in watts (W), but more commonly in milliwatts (mW) or microwatts (μW), and is largely determined by the geometry of the blank. As the probability and risks of an excessively high drive level are far greater, the datasheet of a quartz crystal typically specifies only the maximum permissible drive level.

6. WATCH CRYSTAL

The watch crystal is a special type of quartz crystal whose name obviously describes its main field of application – namely in watches or as a timekeeping reference. It differs from the quartz crystals previously described in a number of key features, which are explained in more detail below.

6.1 Frequency

Most quartz crystals referred to as watch crystals have a fixed frequency of 32.768 kHz. When divided by two 15 times in succession, this frequency is exactly 1 hertz (Hz), i.e., one oscillation per second, making it ideally suited for driving the stepper motor of a watch, for example. The frequency 32.768 kHz can still be produced easily, cost-effectively and in a small package, and has therefore become established as a clock frequency.

6.2 Blank shape

Another common term for the watch crystal is 'tuning-fork crystal', which refers directly to the shape of the blank. A different blank shape, cutting angle, and mode of vibration are used to achieve the low frequency of a watch crystal in a small package. If such a low frequency were to be realized in a blank with a conventional AT-Cut and a round or rectangular shape, it would already be very thick and therefore entirely unsuitable. For this reason, the blank of a watch crystal is cut in the shape of a tuning fork, as shown in Figure 10.

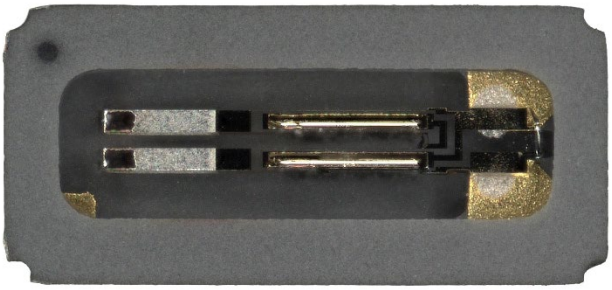

Figure 10: Tuning-fork shape of a watch crystal.

To still ensure good properties, the blank is not cut from the quartz bar as an AT-Cut, but rather as an X-Cut (see Figure 5 in blue) or the XY-Cut (not shown). This change in cut is accompanied by a change in the vibration mode of the quartz crystal: as shown in Figure 11, the watch crystal undergoes a special form of flexural vibration.

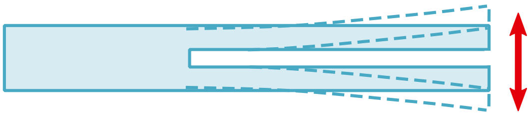

Figure 11: Schematics of the flexural vibration of a watch crystal.

Another consequence of the changed cutting angle is the changed temperature response of the frequency. Unlike AT-Cut quartz crystals (see Figure 6), the frequency curve is a downward-opening parabola (Figure 12).

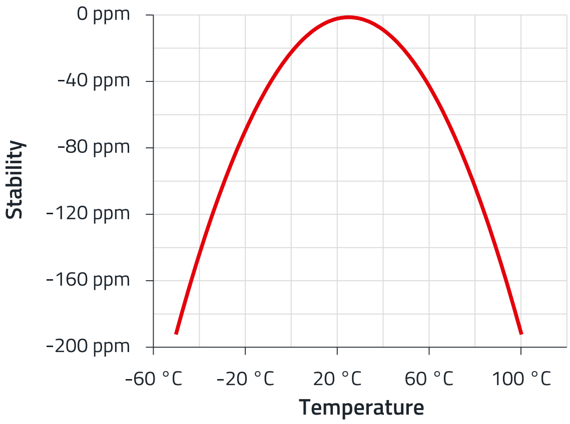

Figure 12: Watch crystal frequency stability over temperature.

Frequency accuracy is very high in the temperature range around 25 °C but decreases significantly as the temperature rises or falls. In addition, the temperature stability of a watch crystal cannot be improved by other production steps – if better temperature stability is required, this must be achieved by the oscillator itself. For this reason, most watch crystal datasheets do not specify temperature stability directly but instead provide the relevant coefficient from which the stability value for the respective temperature range can be calculated.

Due to its different geometry, the watch crystal also differs significantly from AT-Cut quartz crystals in having a much lower drive level and significantly higher ESR.

7. OSCILLATOR CIRCUIT

The oscillating quartz crystal is a passive component. To use it as a clock generator, an oscillator circuit is required that includes active electronic components such as transistors or operational amplifiers.

In most digital clock-oscillator applications, it is implemented with a Pierce oscillator circuit, as shown in Figure 13.

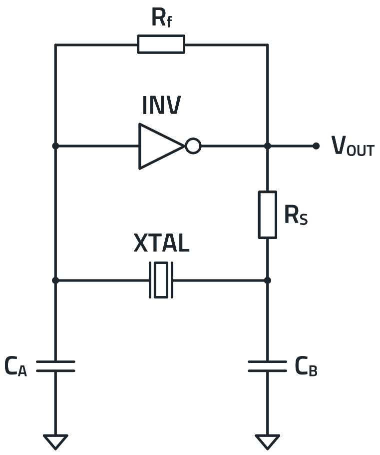

Figure 13: Circuit diagram of a Pierce oscillator circuit.

The oscillator generally consists of an inverting amplifier (e.g., an inverter or transistor) and a quartz crystal connected in a feedback loop. The quartz crystal determines the oscillator frequency through its resonance properties. Together with the quartz crystal, the two capacitors in the Pierce oscillator provide the necessary phase shift and feedback to maintain the oscillation. They also determine the effective load capacitance, which influences the exact oscillator frequency.

Two conditions (Barkhausen criteria) must be met for the circuit to function and generate self-sustaining oscillation:

- The total gain within the loop must be equal to or greater than one at the desired oscillation frequency.
- The phase shift in the loop must be zero or an integer multiple of $2 \cdot \pi$ (360 °).

If the inverter in Figure 13 now has a phase shift of -180 °, an additional -180 ° must be provided by the other external components to satisfy the phase-shift criterion.

The values of the external components must be selected such that both the amplitude and phase conditions of the resonance criterion described above are satisfied without the maximum quartz crystal load being exceeded. A good compromise can usually be found.

Choosing the same value for C_A and C_B is common practice and delivers good results in most cases. Different capacitance values can certainly be used to obtain the target load capacitance as closely as possible. Care should be taken, however, to ensure that the two values do not differ too greatly from one another. It is also important that the capacitor with the higher capacitance be used as C_B.

The typical value range for capacitors C_A and C_B is 3.3 to 47 pF.

The value used for R_f depends on the frequency. The lower the oscillator frequency, the higher the required value. The resistor should be dimensioned so that it is just above the value at which it begins to noticeably affect the oscillator frequency. Typical values for R_f are listed in Table 1.

Frequency	R_f [MΩ]
32.768 kHz	10 – 15 MΩ
1 MHz	5 – 10 MΩ
10 MHz	1 – 5 MΩ
20 MHz	470 kΩ – 5 MΩ
50 MHz	150 kΩ – 3 MΩ

Table 1: Typical values for the feedback resistor R_f.

Nowadays, the resistor R_f and the inverter are usually always integrated into the microcontroller / IC and therefore no longer need to be considered when designing the oscillator circuit.

The series resistor R_S, which is located at the output of the inverter, decouples the output driver from the complex load formed by C_B, C_A and the quartz crystal. R_S is essential, especially for tuning-fork crystals (watch crystals), as these may only be operated at a very low power (typically < 1 µW). A resistor value that is too low can permanently damage the quartz crystal. Typical values for R_S are above 10 kΩ. In addition, R_S and C_B form a delay network that generates an additional phase shift, which is required for stable oscillator operation, especially at low frequencies below 10 MHz. This additional phase shift reduces jitter in the time domain and phase noise in the frequency domain. At frequencies above 16 MHz, R_S can often be omitted because the phase shift provided by the inverter and C_B is already sufficient. For standard crystals (MHz), the typical value of R_S is in the range of 10 to 1000 Ω.

8. OSCILLATOR

Instead of using a quartz crystal and a separately designed 'activation circuit', it is also possible to use a ready-to-operate integrated oscillator.

The following section explains the differences between a quartz crystal and an integrated oscillator and presents selection criteria for these oscillators. A brief overview of the most common oscillator types is also provided, along with a summary of the key parameters.

8.1 Difference between quartz crystal and crystal oscillator

A quartz crystal is a passive component and cannot generate oscillations on its own. Alternatively, oscillators are also available as ready-made components in which the quartz crystal and the necessary electronics are already integrated in a single package. An oscillator is therefore considered an active component. Figure 14 once again illustrates the difference between a quartz crystal, an oscillator circuit, and an integrated oscillator.

Whether a quartz crystal or an integrated oscillator is chosen depends on several factors:

- Development effort and know-how: designing a reliable and effective oscillator circuit requires both time and expertise. By contrast, using an integrated oscillator is usually simple and quick to implement.
- Price: as a passive component, the quartz crystal is generally much cheaper than the oscillator. However, it should be borne in mind that additional components are required to make the quartz crystal oscillate – these should also be considered when calculating the costs.
- Space: the integrated oscillator solution can save space on the PCB.
- Frequency:
  - In the case of integrated oscillators, low frequencies can be easily realized in small package sizes, whereas quartz crystals are subject to physical limitations in this respect. With quartz crystals, the lower the frequency, the thicker the blank becomes – however, in most cases, realizing a low frequency in a small package using a divider is considerably more complex than using a ready-made oscillator.
  - High frequencies are also easier to realize with an oscillator, as quartz crystals would need to use an overtone, which in turn entails a more complex circuit design.
- Stability: if higher frequency stability is required than can be achieved with a quartz crystal and a simple activation circuit, additional components and circuit elements are needed – in such cases, it is advisable to use a more sophisticated integrated oscillator, for example a TCXO (Temperature-Compensated Xtal Oscillator).

8.2 Types of oscillators

To improve the frequency stability of the basic circuit, such as the Pierce circuit shown in Figure 13, most oscillator topologies can be enhanced by additional circuitry. These are

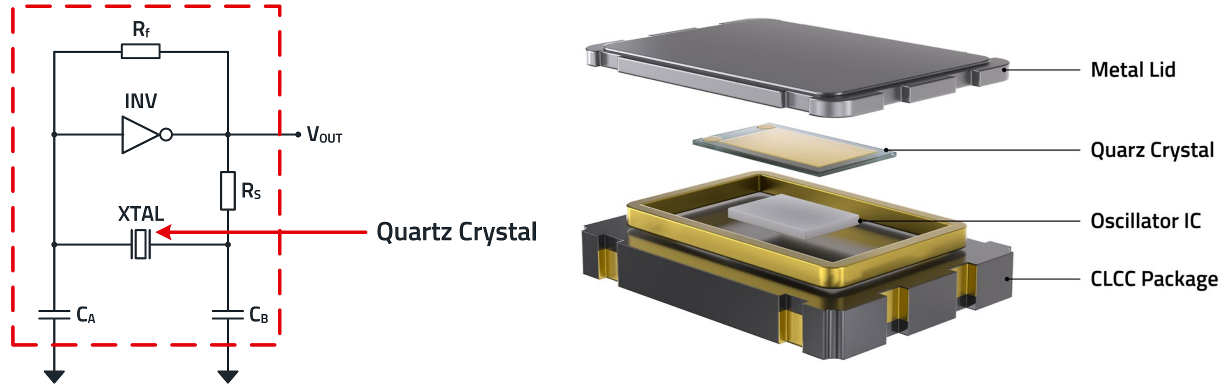

Figure 14: The difference between an analog oscillator circuit (left) and an integrated oscillator (right).

briefly explained below. In addition, Table 2 provides an overview of the types and their key parameters.

SPXO VCXO TCXO OCXO Disciplined OCXO Rubidium oscillator	Stability and phase noise are steadily improving	↓	Power consumption, price, package size and number of components are steadily going up

Table 2: Overview of the different oscillator types and the key parameters.

XO/SPXO

The simple oscillator, often referred to as an XO or SPXO (Simple Packaged Xtal Oscillator), corresponds in design to the basic quartz crystal activation circuit (e.g., the Pierce oscillator). The performance in terms of frequency stability corresponds to that of a quartz crystal and is accordingly in the range of ±15 ppm to ±50 ppm over a temperature range of -40°C to 85°C. SPXOs are nevertheless sufficient for many applications and, thanks to their simplicity, represent a good and cost-effective solution.

VCXO

A VCXO (Voltage Controlled Xtal Oscillator) presents the user with the option of using an additional voltage, the control voltage, to vary the oscillator frequency to a certain degree. This means that the effects of temperature, aging, and changes in supply voltage and load can be compensated by an electronic circuit. The VCXO is frequently used in a phase-locked loop (PLL) circuit, in which the output signal is compared with a reference signal and adjusted with the aid of the control voltage.

The stability of the VCXO without additional control is comparable to that of the quartz crystal or SPXO.

TCXO

A TCXO (Temperature-Compensated Xtal Oscillator) utilizes the fact that the frequency response of the quartz crystal over temperature is known and predictable. In the manufacture of a digital TCXO, its frequency response is recorded and stored for this purpose. Using an integrated temperature sensor, the temperature can be measured during operation, allowing the corresponding frequency deviation to be determined and compensated based on stored records. This allows a significantly higher frequency stability of ±2.5 ppm and better to be achieved.

OCXO

An OCXO (Oven Controlled Xtal Oscillator) contains a heater that keeps the quartz crystal and parts of the surrounding circuitry at a constant temperature. The temperature is usually around 80°C, as this represents a favorable point for both the AT-Cut and the SC-Cut frequently used here. In Figure 15, the frequency deviation curves over temperature are shown for the respective cuts, with a focus on 80°C. As can be seen, the curve of the SC-Cut is significantly flatter at this temperature point, so small temperature fluctuations have a far smaller influence on the stability of the SC-Cut.

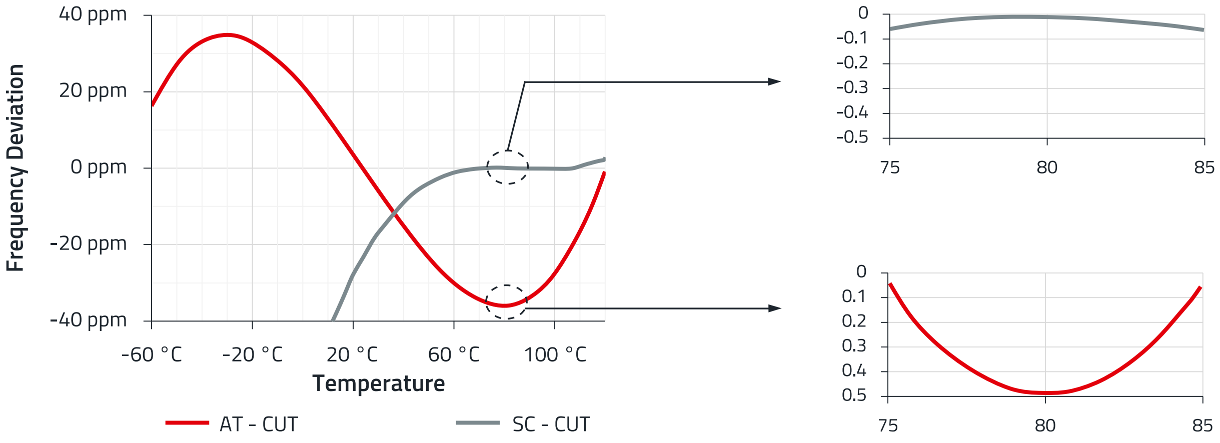

Figure 15: Difference in frequency vs. temperature characteristic curves of AT-Cut and SC-Cut crystals.

The permanently temperature-controlled quartz crystal almost eliminates external temperature influences, allowing for a very high stability in the range of 10 ppb and better to be realized. However, continuous heating also results in power consumption for an OCXO that is much higher than that of less accurate oscillator types.

Disciplined OCXOs

Disciplined OCXOs offer the possibility of additional synchronization using a signal from a high-precision source, such as a global navigation satellite system (GNSS). This further improves the stability, especially over a long period of time. In addition, many disciplined OCXOs offer excellent holdover – this means that if the reference signal fails, they continue to provide a very accurate signal for many hours.

Rubidium oscillators

Rubidium oscillators are atomic clocks and ensure absolute accuracy in both the short and long term. In a rubidium oscillator, the reference frequency is captured by the energy state transition of the rubidium atoms and compared with the frequency of an OCXO using a phase-locked loop (PLL). This ensures a very precise frequency, which is used, for example, as a time and frequency standard.

9. KEY OSCILLATOR PARAMETERS

An oscillator combines and incorporates many of the parameters already explained in Section 5 regarding quartz crystals, but there are also differences that are discussed in more detail here.

9.1 Frequency

The frequency of the oscillator is no different from that of a quartz crystal – it remains the most important feature.

9.2 Overall stability

While temperature stability and tolerance are considered separately for a quartz crystal, for an oscillator a single value is usually specified – the overall stability. In addition to temperature stability and tolerance, this value often includes the frequency deviation of the oscillator caused by supply voltage fluctuations and load variations. Overall stability is also specified in ppm (parts per million) or ppb (parts per billion).

9.3 Supply voltage

As an oscillator is an active component, a supply voltage must be applied to operate it. Integrated oscillators for PCB applications are available in all common supply voltages, such as 5 V, 3.3 V, or 1.8 V. There is also an increasing number of oscillators available that can be operated over a variable range of supply voltages.

9.4 Output signal

The output signal of a quartz crystal is always a sine wave at its resonance frequency. In the case of an oscillator, the output signal can also be a square wave voltage, e.g., depending on the application. Oscillators with a sinusoidal output voltage are used in applications where very low signal distortion is required: the proportion of overtones and the phase jitter must be as low as possible. Typical applications include signal mixers, test and signal generators, as well as transmitter units.

A more common application for oscillators is in the field of digital electronics, which involves a square-wave output voltage. The CMOS (Complementary Metal Oxide Semiconductor) oscillator is typically integrated as a chip, which outputs a square-wave signal. This allows the oscillator to be connected directly to the microcontroller or IC. The frequency range of these oscillators typically extends up to 200 MHz.

Another option for an oscillator output signal is the clipped sine wave. This provides an analog, sine-wave-like output waveform whose peaks are slightly clipped by an internal limiter circuit. This signal has significantly fewer overtones and lower power consumption than a digital square-wave signal, making it well-suited for RF applications and TCXOs. If a clipped sine-wave signal is to be subsequently used in digital circuits, such as for the clock input of an MCU or a logic component, it is often passed through a Schmitt trigger. This converts the analog clipped sine-wave signal into a clean digital square-wave signal by using defined upper and lower switching thresholds. This creates hysteresis, which suppresses noise and generates a stable digital signal.

For circuits with symmetrical clock signals, usually associated with high clock frequencies, oscillators with differential output signals are used.

Differential signals also compensate for electromagnetic interference, as the interference affects both lines to the same extent and they cancel each other out. Their low jitter and minimal distortion improve signal quality and thus signal integrity, making them particularly well-suited for high-speed applications. Differential signals allow lower losses and phase shifts on account of their properties, making them more robust for longer transmission distances. Differential signals are also less susceptible to fluctuations in the power supply or ground (GND), as they use the differential voltages between the lines rather than absolute, ground-referenced voltages. The most used signals here are (LV) PECL (Low Voltage Positive Emitter Coupled Logic) and LVDS (Low Voltage Differential Signaling).

9.5 Phase noise / jitter

Phase noise and jitter are specific signal characteristics. For oscillators, these are used to describe short-term stability.

Phase noise describes random fluctuations in the phase of a signal over time. These fluctuations cause the spectrum of an ideal, narrow-band signal to broaden, creating sidebands around the central frequency. Analyses and measurements are performed in the frequency domain. Phase noise is the spectral density of the phase error, measured in dBc/Hz (decibels relative to the carrier per hertz) at a specific offset from the carrier frequency. Phase noise is measured by comparing the spectrum of a real oscillator with that of an ideal, noise-free oscillator.

Jitter refers to the temporal fluctuations of a signal, specifically in relation to the temporal position of the signal edges. It is thus a measure of instability in the time domain. Jitter is the temporal deviation from the ideal transition time of a signal, measured in seconds or as a ratio (e.g., ppm). In high-speed data communication systems, jitter can compromise the integrity of the data signal, leading to transmission errors and synchronization issues.

Phase noise and jitter depend on various factors, such as the quartz crystal used, the oscillator circuit, the power consumption, but also environmental influences like temperature, shock, and vibration.

10. APPLICATIONS

Quartz crystals and oscillators are required in a wide variety of applications. Some areas of application are explained in more detail below.

10.1 Timing devices

Watch crystals have been used for decades as clock generators for clocks and timekeeping systems. Thanks to their precise frequency at temperatures around 25 °C, their low cost, and their simplicity, they remain the first choice for time measurement in electronic circuits today.

10.2 Microcontrollers / processors

As previously mentioned, frequency products often serve as clock generators for microcontrollers. They are ideally suited for this purpose thanks to their accuracy, robustness, and generally favorable price.

As the clock source, the frequency of the quartz crystal or oscillator determines the timing of all processes within the microcontroller. This component ensures that processes run synchronously, the required processing speed is achieved, and, above all, high timing accuracy is guaranteed. While many microcontrollers feature an internal clock generator, they often lack the precision offered by external quartz crystal or oscillator circuits.

10.3 Communication

Quartz crystals and oscillators are used to ensure that electronic systems can communicate with one another. To ensure this, all components involved must ‘speak’ at the same frequency. Certain interfaces and technologies utilize internationally coordinated frequencies to achieve consistent global communication.

Typical clock frequencies are listed below (this list is not exhaustive, as other frequencies are also possible). These are also system clocks, not transmission frequencies.

Wired communication / interfaces

Applications in wired communication include, for example:

- CAN-Bus (Controller Area Network), usually with 12 MHz, 16 MHz, or 26 MHz
- UART (Universal Asynchronous Receiver Transmitter), for example with 1.8432 MHz, or multiples thereof
- USB 2.0/3.0 and High-Speed USB (Universal Serial Bus), often with 20 MHz, 24 MHz, or 25 MHz
- Ethernet and Gigabit Ethernet, including 10 MHz, 25 MHz, 50 MHz, 100 MHz, and 125 MHz
- PCI Express (Peripheral Component Interconnect) with 25 MHz, 50 MHz, and 100 MHz

Wireless communication

The entire infrastructure of wireless applications, such as the cell phone network, is built upon frequencies and therefore relies heavily on quartz crystals and oscillators. Several common technologies and frequencies are listed below.

- 3G/4G/5G/LTE (Long Term Evolution): 19.2 MHz, 25 MHz, and 38.4 MHz
- Bluetooth: 16 MHz, 24 MHz, and 26 MHz
- GPS (Global Positioning System): 16.384 MHz and 26 MHz
- ISM (Industrial, Scientific and Medical Band): 16 MHz, 27.12 MHz, and 32 MHz
- RFID (Radio Frequency Identification): 13.56 MHz and 27.12 MHz
- Wi-Fi: 20 MHz, 40 MHz, and 48 MHz

11. CONCLUSION

Frequency products are a fundamental prerequisite for the safe and precise operation of many modern electronic systems. Quartz-based clock generators have become established as the industry standard through their high level of frequency stability, reproducible temperature performance, and long-term reliability. Understanding the physical principles, the key quartz crystal parameters, and the oscillator circuit design is essential to ensure stable clock generation in line with specifications. Depending on the requirements for accuracy, package size, development workload, and cost, integrated oscillators represent a high-performance alternative, allowing for an optimal clock solution to be realized for every application.

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