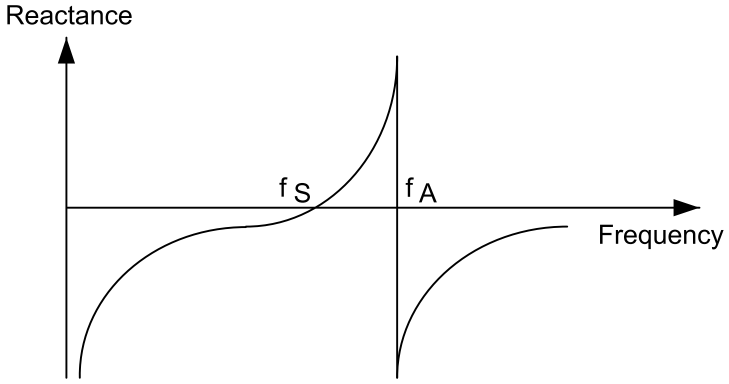
AN0016.3: Oscillator Design Considerations

This application note provides an introduction to the crystal oscillators on SiXG3xx devices and guidance on selecting the correct components for these circuits.

SiXG3xx devices contain two crystal oscillators: one low frequency (32.768 kHz) and one high frequency (38.4 MHz). Topics covered include oscillator theory and example crystal recommendations for these devices.

KEY POINTS

- Learn which parameters are important when selecting an oscillator.
- Learn how to properly configure a crystal oscillator for use with SiXG3xx devices.



1. Device Compatibility

This application note supports multiple device families, and some functionality is different depending on the device.

SiXG3xx consists of:

- SiBG301
- SiMG301

2. Oscillator Theory

2.1 What is an Oscillator?

An oscillator is an electronic circuit which generates a repetitive, or periodic, time-varying signal. In the context of SiXG3xx devices, this oscillator signal is used to clock execution of instructions and peripherals in the device. For radio communication the oscillator also provides an accurate and low noise frequency reference to the transceiver. There are multiple ways of generating such a signal, each with different properties that influence project cost, board size, and stability of the clock signal.

RC Oscillators

RC oscillators are built from resistors, capacitors, and an inverting amplifier. They come at a low cost and have a shorter start-up time than the crystal oscillator, but are generally less accurate and produce more noise. The SiXG3xx devices provide multiple internal RC oscillators including at least one High-Frequency RC Oscillator (HFRCO) and one Low-Frequency RC Oscillator (LFRCO). While the internal RC oscillators ensure proper operation of the SiXG3xx device, they are inadequate for applications such as radio communication.

Crystal Oscillators

Crystal oscillators use the mechanical vibration of a crystal to generate the clock signal. Due to the molecular composition of the crystal matter and the angle of which the crystal is cut, this type of oscillator is very precise and stable over a wide temperature range. The most commonly used crystal is the quartz crystal. Producing quartz crystals requires very stable temperature and pressure conditions over a few weeks. This makes crystal oscillators more expensive than RC oscillators.

2.1.1 Piezoelectricity

Quartz crystals hold the direct piezoelectric property. This means an applied electric field will cause the crystal to deform. Conversely, a deformation of the crystal will cause a voltage across the terminals. Once the oscillator has started, the changing voltage on the terminals of the vibrating crystal is used as the clock signal.

2.2 Basic Principle of Oscillators

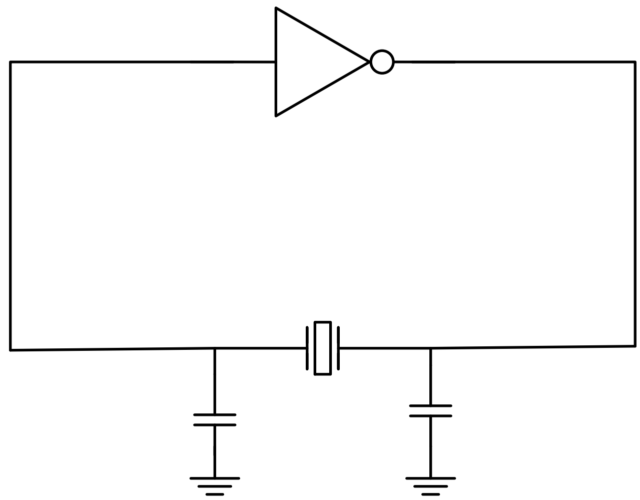


Figure 2.1. Simplified Oscillator Feedback Loop

The principle behind the oscillator is a positive feedback loop satisfying the Barkhausen condition: If the closed-loop gain is larger than unity and the total phase lag is 360°, the resulting closed-loop system is unstable and will self-reinforce. This is a necessary, but not sufficient, condition for oscillations to be present. When the necessary conditions are met, any disturbance (noise) in the oscillator will cause oscillations to start. The frequency that fulfills the Barkhausen condition is amplified the most, because it is in phase with the original signal.

The initial oscillations are very weak, and it takes time to amplify the signal to the desired magnitude. When oscillations are established, only a small amount of energy is needed to compensate for losses in the circuit. Mathematically, a closed-loop gain of one is required to maintain steady state oscillations. The SiXG3xx relies on an adjustable current source controlled by automatic gain controller to achieve and maintain the desired amplitude.

Figure 2.1 Simplified Oscillator Feedback Loop on page 4 shows that the oscillator circuitry consists of two parts: an amplification stage and a filter that decides which frequency experiences a 360° phase lag. In the case of a crystal oscillator, the filter consists of the crystal and external load capacitors.

2.2.1 Start-up Time

The magnitude of the closed-loop gain has great influence on the start-up time. Low gain can cause excessively long start-up time or failure while start-up can fail altogether when gain is too high. The ideal gain is dependent on the negative resistance of the oscillator circuit, which is defined in Negative Resistance.

For the same reason, the oscillation frequency influences the start-up time. A crystal in the kHz range would have a considerably longer start-up time than a crystal in the MHz range because the time it takes to circulate the loop is longer. Typical start-up times for the SiXG3xx are 34 - 42 ms for the low frequency oscillator and 166 µs for the high frequency oscillator.

2.3 Modeling the Crystal

The crystal can be described by the electrical equivalent circuit in Figure 2.2 The Electrical Equivalent Circuit of a Crystal on page 5.

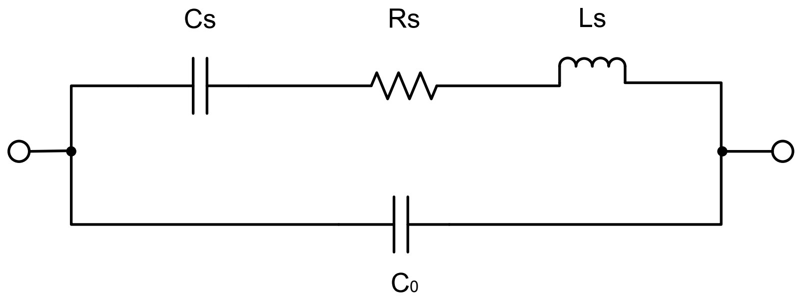


Figure 2.2. The Electrical Equivalent Circuit of a Crystal

- C_S is the motional capacitance. It represents the piezoelectric charge gained from a displacement in the crystal.
- R_S is the motional resistance. It represents the mechanical losses in the crystal.
- L_S is the motional inductance. It represents the moving mass in the crystal.
- C_0 is the shunt capacitance between the electrodes and stray capacitance from the casing.

For low frequencies, the electrical equivalent circuit will exhibit capacitive behavior as depicted in Figure 2.3 Reactance vs. Frequency on page 5. The presence of the inductor becomes more noticeable as the frequency, and thus the reactance, increases.

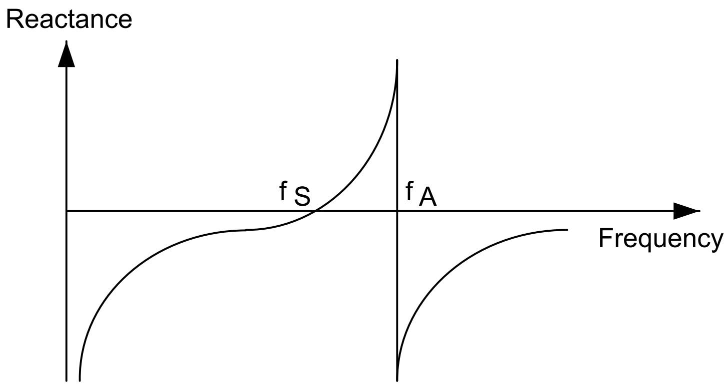


Figure 2.3. Reactance vs. Frequency

Ignoring the shunt capacitance C_0, the series resonant frequency is defined where the reactance of the inductor and capacitor cancels. At this frequency the crystal appears only resistive with no shift in phase. The series resonance frequency, f_S, therefore determines the relationship between C_S and L_S. This can be calculated with the equation below. The series resonance frequency is the natural resonance frequency where the energy transformation between mechanical and electrical energy is most effective.

$$f_S = \frac{1}{2 \times \pi \times (L_S \times C_S)^{\frac{1}{2}}}$$

At higher frequencies, the equivalent circuit will appear inductive, which implies higher impedance. When the inductive reactance from the crystal cancels the capacitive reactance from shunt capacitance C_0, another resonance frequency with zero phase shift exists. This frequency is called the anti-resonant frequency, f_A. At this frequency, the impedance is 0.

$$f_A = \frac{1}{2 \times \pi \times \left(L_S \times \frac{C_S \times C_0}{C_S + C_0}\right)^{\frac{1}{2}}}$$

The range of frequencies between f_S and f_A is called the area of parallel resonance and is where the crystal will normally oscillate. At the resonant frequency, the phase lag in the feedback loop is provided by an amplifier with 180° phase lag and two capacitors with a combined 180° phase lag. In practice, the amplifier provides a little more than 180° phase shift, which means the crystal must appear slightly inductive to fulfill the Barkhausen criterion.

2.3.1 Series and Parallel Resonant Crystals

Physically there is no difference between series and parallel resonant crystals. Series resonant crystals are specified to oscillate at the series resonant frequency where the crystal appears with no reactance. Because of this, no external capacitance should be present as this would lower the oscillating frequency to below the natural resonance frequency. These crystals are intended for use in circuits with no external capacitors where the oscillator circuit provides 360° phase shift.

Parallel resonant crystals require a capacitive load to oscillate at the specified frequency. This is the resonance mode required for SiXG3xx devices, which have on-chip load capacitors that can be tuned under firmware control, thus reducing BOM cost and saving PCB space.

Note: SiXG3xx devices do not require external load capacitors and PCB designs for these devices must not include them.

The exact oscillation frequency for a parallel resonant crystal can be calculated with the equation below, where C_L is the load capacitance seen by the crystal. C_L is therefore an important design parameter and is given in the data sheet for parallel resonant crystals.

$$f_P = f_S \times \left(1 + \frac{C_S}{2 \times C_L}\right)$$

3. SiXG3xx Crystal Oscillators

SiXG3xx devices include a Low Frequency Crystal Oscillator (LFXO) and a High Frequency Crystal Oscillator (HFXO) that require a crystal connected to the specific oscillator's pins on the device. As noted previously, no external load capacitors are required and none should be included in any board design because each oscillator has on-chip tunable load capacitors.

The LFXO is intended for crystals with a nominal frequency of 32.768 kHz while the HFXO supports 38.4 MHz. External oscillators with sine wave output are also supported. Both the high and low frequency clock sources can be used simultaneously.

Pierce oscillator designs, which have low current consumption and are stable over a wide range of frequencies, are the foundation for both the LFXO and HFXO circuits as shown below:

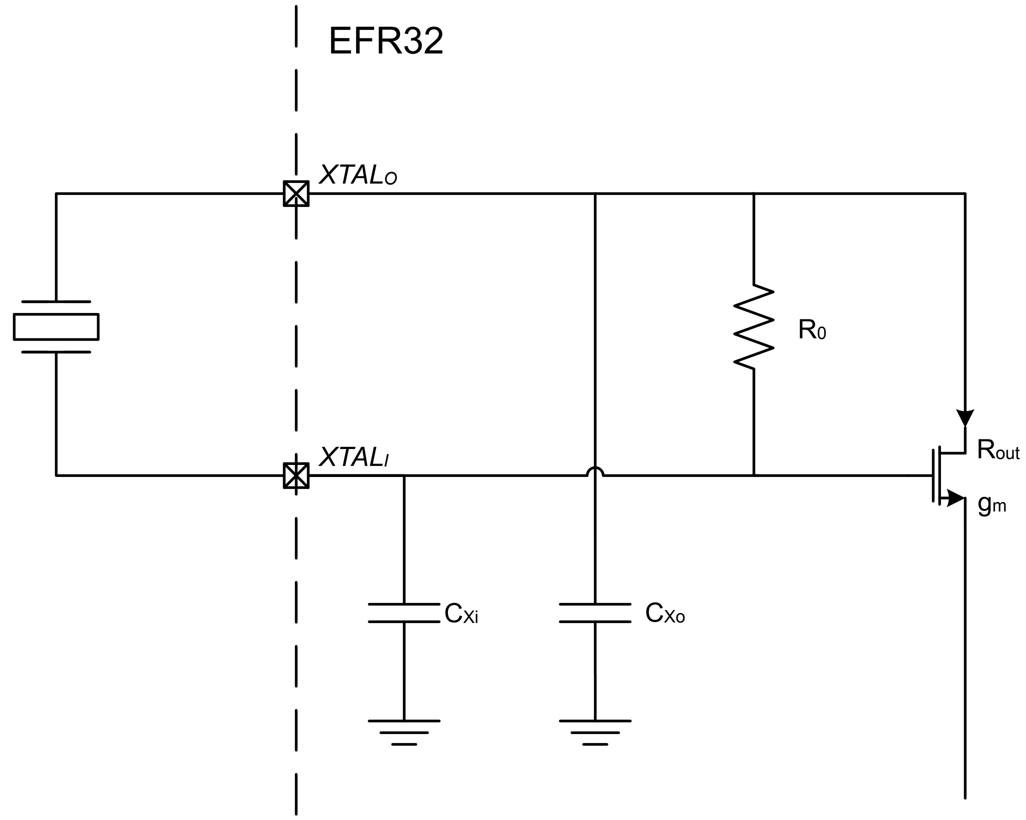


Figure 3.1. SiXG3xx Pierce Oscillator

The SiXG3xx crystal oscillators use a relatively low oscillation amplitude, which can lead to a lower oscillation frequency than the stated nominal value in a crystal's data sheet. More information on this effect is given in 6.4 Frequency Pulling.

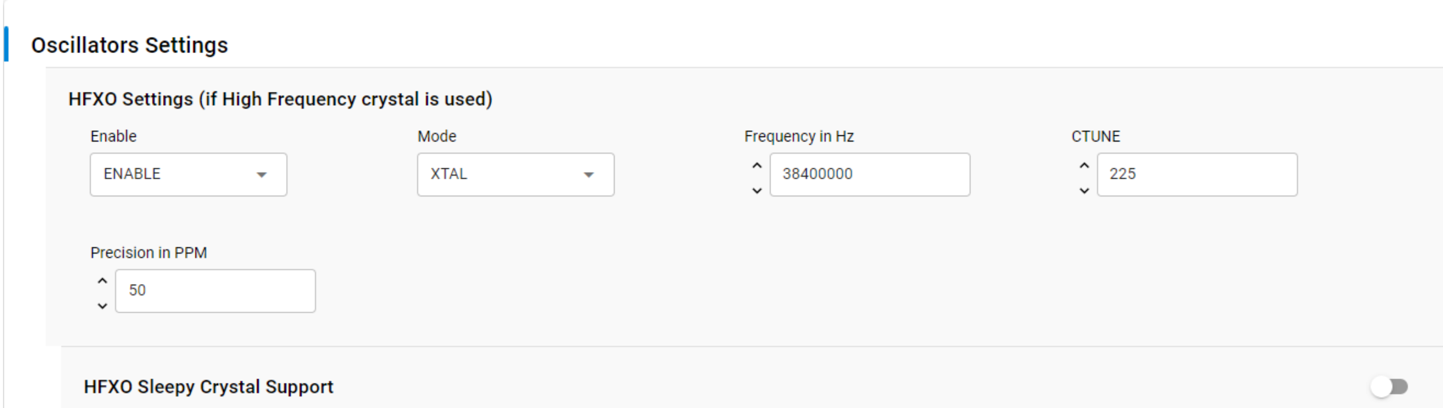
3.1 Timeout

To ensure that the crystal oscillator outputs are not used internally on SiXG3xx devices before they are stable, both the HFXO and the LFXO include a configurable timeout. When the oscillator starts up, the timeout counter will count to the configured number of cycles before the clock signal propagates to the internal clock trees and the digital logic.

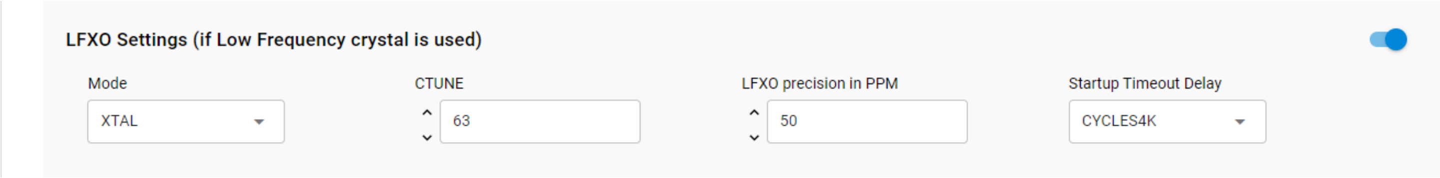
3.2 Software Configuration

Crystal oscillator initialization on SiXG3xx devices is supported exclusively by the Clock Manager service in Simplicity SDK. This differs from Series 2 EFM32/EFR32 devices where emlib CMU APIs are used in Gecko SDK and can also be used in Simplicity SDK in place of or alongside Clock Manager. Oscillators must be configured using the Clock Manager component and are initialized during system setup when `sl_clock_manager_init()` is called.

Settings that were previously applied by passing a pointer to a structure of type `CMU_HFXOInit_TypeDef` when calling `CMU_HFXOInit()` in Gecko SDK are now specified using the Clock Manager HFXO Settings panel as shown below:



Likewise, to configure the LFXO, settings that were previously applied by passing a pointer to a structure of type `CMU_LFXOInit_TypeDef` when calling `CMU_LFXOInit()` in Gecko SDK are now specified by enabling the LFXO Settings panel in Clock Manager as shown below:



Collectively, these settings, along with those for the different RC oscillators and PLLs, are written to the `sl_clock_manager_oscillator_config.h` file in the project's `config` directory. It is possible to edit these settings directly, such as for build configurations in which Simplicity Studio is not used. However, use of Clock Manager's configuration panels in Simplicity Studio is strongly recommended because parameter checking prevents settings from being entered that are not legal.

3.3 PCB Layout

To minimize noise sensitivity caused by parasitic antenna and spurious coupling phenomena, the distance between the crystal, and the SiXG3xx oscillator pins should be as short as possible. If it is not possible to place the external oscillator components close to the oscillator pins, care should be taken when routing these signals. Avoid long traces underneath the SiXG3xx package and other circuitry that could create spurious coupling with logic activity. Also avoid routing any other signals through the crystal area.

Ensure that the ground plane underneath the oscillator is of good quality. Do not use a separate ground plane under the oscillator with a narrow connection to the reference ground as this can act as an antenna. To avoid coupling from surrounding signal traces, it is a good practice to place a grounded guard ring around the oscillator and its components. Figure 3.2 Reference HFXO Layout on page 9 shows the layout used for the crystal connected to the HFXO on Silicon Labs' SiXG3xx board designs.

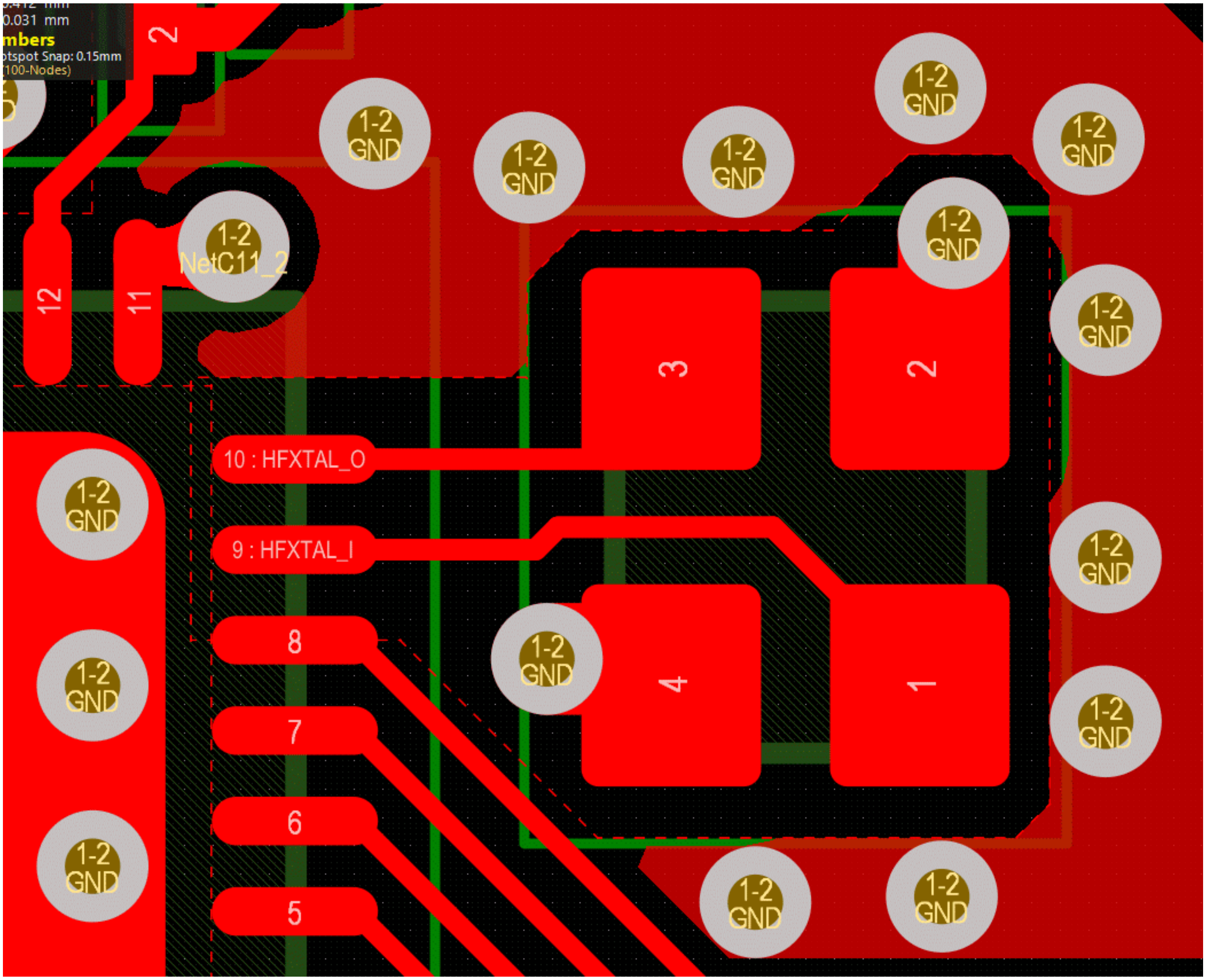


Figure 3.2. Reference HFXO Layout

4. Application-Level Considerations for SiXG3xx Devices

4.1 General Notes for Radio Applications

This section provides details about specific requirements related to wireless applications.

The standard HFXO crystal frequency for SiXG3xx devices is 38.4 MHz, but this can differ depending on the specific device and its supported radio protocol requirements. A given device's transceiver electrical specifications are based on its datasheet-specified crystal frequency.

The crystal frequency tolerance is determined by various aspects of the design:

Required frequency tolerance of the protocol

For example, 802.15.4 applications require ±40 ppm accuracy under all conditions.

Temperature range

The S-shaped temperature characteristic of AT-cut crystals becomes steeply negative at low temperatures, steeply positive at high temperatures. A larger temperature range requires a specific cut angle of the crystal to bound the absolute accuracy. Most crystals are specified from -40 to +85 °C, but some applications may require operation up to 105 °C or 125 °C ambient temperature.

Manufacturing accuracy

Individual crystals have a frequency error at 25 °C. This is typically specified as ±10 ppm "manufacturing tolerance" or "make tolerance". This error adds to the temperature error.

Aging tolerance

Crystals drift over time, typically 1-2 ppm per year. Excessive heat during assembly or from hand soldering may also prematurely age a crystal.

The allowable frequency error of the crystal is the sum of temperature, board-to-board, and crystal-to-crystal variations.

4.2 Crystal Loading and Production Tuning

The load capacitance, C_L, is implemented on-chip by two tunable capacitors. External capacitors are neither required nor recommended.

The load capacitor tuning range in pF is given in the data sheet by C_{L_HFXO} with a resolution of SS_{HFXO} per step. The resulting frequency per step depends on the crystal's pulling sensitivity and the shunt capacitance of the oscillator circuit.

4.2.1 Tuning Strategies

The on-chip variable load capacitors may be used in one of two ways.

- A fixed value may be used for all units. During design, a number of units should be characterized and an average center CTUNE value determined. Some crystal vendors may provide characterized samples to help tune to the center of the crystal distribution. In corner cases the remaining error should be on the order of only a few ppm depending on manufacturing spread of things like PCB parasitics, component variation, etc.
- Each unit may also be calibrated in production. A unique value of CTUNE is determined per unit and stored in flash memory. This calibrates out the manufacturing error of the crystal, leaving only the temperature error and aging components. This may allow the system to operate across a wider temperature range or with a less accurate crystal at the expense of production calibration time.

The variable on-chip loading capacitors can theoretically be used to offset temperature-induced errors as well. While simple in concept, this is difficult in practice primarily due to temperature characteristic differences from crystal to crystal.

4.3 External Tuning Capacitance

All required crystal loading capacitance is on-chip. External load capacitors must not be used.

4.4 External Oscillator Operation

For narrowband applications the system reference frequency may be provided by an external oscillator such as a temperature-compensated crystal oscillator (TCXO). To use a TCXO, the output should be connected to the HFXTAL_I pin and the `Mode` selection on the Clock Manager HFXO Settings panel should be set to `EXTCLK` as shown below:

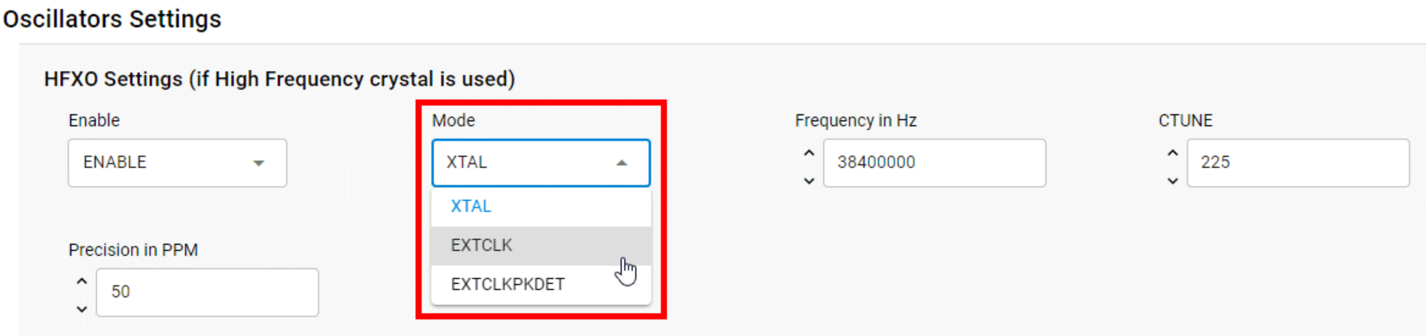


Figure 4.1. HFXO Mode Selection for External Oscillators

Sine and clipped sine waveforms are supported by the HFXO in this mode. The external waveform should adhere to the following limitations for ideal performance.

Parameter	Min (V)	Max (V)
Input Voltage	0.0	1.05
Peak-to-Peak Amplitude	0.55	1.05

The input signal can be directly connected to the HFXTAL_I pin (DC coupled) or connected through a series capacitor (AC coupled). The series capacitor can be used to limit current into the device and keep the input voltage within the recommended range. Lower capacitance results in higher impedance. A typical value for the series capacitor is 100 pF, although testing should be done to make sure the input voltage is within the recommended range.

When using an AC coupled input, the bit HFXO_CFG.ENXIDCBIASANA must be set. This enables an internal DC bias of 410 mV. This bit does not need to be set with a DC coupled input, but it will not cause any problems if it is. The advantage of AC coupling is that the DC bias is fixed, and the amplitude can be managed with the series capacitor. The input capacitance at the HFXTAL_I pin with CTUNEXIANA = 0 and CTUNEFIXANA = 0 is about 7 pF.

4.5 Reducing Power Dissipation and Energy Use

The power associated with the crystal oscillator is mostly determined by its drive level, which equals the power dissipated in the crystal as given by the following equation:

$$DL = \frac{1}{2} \times ESR \times (2 \times \pi \times f \times V_{pp} \times (C_0 + C_L))^2$$

V_{pp} is the peak-to-peak voltage across the crystal at the resonance frequency. The target V_{pp} for SiXG3xx devices can vary, but for a safe estimate to check the maximum drive level for a given crystal, calculate the above formula using 500 mV for the value of V_{pp}.

During start-up, current consumption is higher than after oscillations have stabilized. A short start-up time reduces the period during which current consumption is high and is therefore essential if an oscillator is frequently switched on and off. In general, total energy use is lowest the sooner the output from an oscillator becomes available, which favors making start-up times as short as possible. Crystals with low equivalent series resistance (ESR) and load capacitance typically have the shortest start-up times and consume the least amount of current.

SiXG3xx devices enable clock sources, which include the crystal oscillators, RC oscillators, and PLLs, on-demand. This means that a clock source is automatically enabled when requested by the Clock Management Unit (CMU) and then automatically disabled when it is no longer requested. Enabling a clock source on-demand reduces energy use at the expense of incurring a start-up delay, particularly for crystal oscillators, whenever the clock source is needed.

Alternatively, on-demand behavior for most oscillators, including the HFXO and LFXO, can be disabled by setting the DISONDEMAND bit in the module's CTRL register. Subsequently, firmware can enable or disable an oscillator when needed by setting or clearing the CTRL register FORCEEN bit. In such cases, recurring start-up delays are eliminated in exchange for continuous oscillator current consumption.

5. Recommended Crystals

5.1 General Notes for Crystal Selection

When selecting a crystal for a given design, proper functioning of the crystal oscillator can depend on the following factors:

Operating Environment

Temperature, humidity, and mechanical vibration affect stability properties. For crystals, define what crystal cut is most appropriate for the application. In most cases, AT cut is an excellent choice due to good stability over a wide temperature range. SC cut has good stability when exposed to mechanical vibrations but suffers from humidity and temperature changes. Many more cuts with different properties exist.

Package

Surface mount or through-hole. If size is critical, define maximum package dimensions.

Load Capacitance

Ensure that C_L is within the range specified by the SiXG3xx data sheet. Generally, lower load capacitance crystals have better startup and current consumption performance, see 4.5 Reducing Power Dissipation and Energy Use for details.

ESR

Ensure that ESR is within the range specified by the SiXG3xx data sheet. Generally, lower ESR crystals have better startup and current consumption performance, see 4.5 Reducing Power Dissipation and Energy Use for details.

The recommendations that follow are from a range of crystals with different ESR, cost, frequency stability, and tolerance. In addition to the considerations listed above, certain radio protocols may impose requirements that determine a suitable crystal selection.

All the recommended crystals are fundamental mode, as is required for SiXG3xx devices.

5.2 Crystal Specifications for SiXG3xx Devices

The following crystals have been tested for use with SiXG3xx devices. Suitability for a particular application should be verified. Different frequency tolerance / temperature ranges may be available. Contact the crystal vendor for details.

Table 5.1. 38.4 MHz Crystals

Mfg	Part	ESR (Ω)	Max C_0 (pF)	Temp (°C)	Temp Tolerance (ppm)	Mfg Tolerance (ppm)	C_L (pF)	Footprint (mm)
Kyocera	CX2016DB38400F0FSRC1	40	1	-40 to +125	±40	±10	10	1.6 x 2.0
NDK	NX2520SA-38.4M-EXS00A-CS08361	40	1.05	-40 to +125	±32	±10	10	2.0 x 2.5
Tai-Saw	TZ3398B	40	3	-40 to +105	±20	±10	10	1.65 x 2.05
TXC	8Y38472006	35	1	-40 to +125	-11/+80	-5/+7	10	1.6 x 2.0

Table 5.2. 32768 Hz Crystals

Mfg	Part	Ordering Specification	ESR (kΩ)	Typ C_0 (pF)	Temp (°C)	Tolerance (ppm)	C_L (pF)	Footprint (mm)
Abracon	ABS07	32.768KHZ-7-T	70	1.5	-40 to +85	20	7.0	1.5 x 3.2

6. Crystal Parameters

6.1 Quality Factor

The quality factor Q is a measure of the efficiency or the relative storage of energy to dissipation of energy in the crystal. For the electrical-equivalent circuit, the equation below states the relation between R, C and Q. In practice, crystals with higher Q-values are more accurate, but have a smaller bandwidth for which they oscillate. Therefore, high Q-factor crystals will start slower than crystals with higher frequency tolerance.

$$Q = \frac{X_{LS}}{R_S} = \frac{1}{(X_{CS} \times R_S)} = \frac{1}{(2 \times \pi \times f \times C_S \times R_S)} = \frac{2 \times \pi \times f \times L_S}{R_S}$$

X_{LS} and X_{CS} are the reactance of L_S and C_S, respectively, at the operating frequency of the crystal.

6.2 Load Capacitance

As seen in the equation below, the two capacitors C_{L1} and C_{L2} provide capacitive load for the crystal. The effective load capacitance, C_L, as seen from the HFXTAL_I and HFXTAL_O pins on the SiXG3xx is the series combination of C_{L1} and C_{L2} through ground.

$$C_L = \frac{(C_{L1} \times C_{L2})}{(C_{L1} + C_{L2})} + C_{stray}$$

Where C_{stray} is the pin capacitance of the microcontroller plus any parasitic capacitance and can often be assumed in the range 2-5 pF. The correct choice of C_L is necessary for the crystal to operate at its expected frequency. Crystals that require a small load capacitance typically start faster than those requiring a large C_L. Large load capacitors also increase current consumption. Refer to 5. Recommended Crystals for C_L parameter guidance when selecting a crystal. Data sheets for SiXG3xx devices also contain more information on the allowed load capacitance range.

Note: SiXG3xx devices have internal load capacitors and do not need external capacitors connected to the crystal.

6.3 Equivalent Series Resistance

Equivalent series resistance is the resistance in the crystal during oscillation and varies with the resonance frequency. ESR, given by the equation below, will typically decrease with increasing oscillation frequency.

$$\text{ESR} = R_S \times \left(1 + \frac{C_0}{C_L}\right)^2$$

The HFXO and LFXO circuits on SiXG3xx devices cannot guarantee startup of crystals with ESR larger than a certain limit. Refer to the device data sheet for further details. The smaller the ESR is relative to this maximum value, the better the gain margin during start-up of the crystal, which in turn reduces the start-up time. Additionally, low ESR values correspond to lower current consumption during oscillation.

Note that high-frequency crystals have ESR on the order of tens of ohms versus low-frequency crystals, which have ESR values typically measured in kΩ. Therefore, a few ohms of series resistance has more influence on start-up margin in the MHz range as compared to the kHz range.

6.4 Frequency Pulling

SiXG3xx devices drive crystals with a relatively low oscillation amplitude. Because of this, the oscillation frequency can be lower than the nominal frequency stated in the crystal data sheet when using the suggested load capacitance. This offset is best found by measuring the resulting frequency when using the suggested load capacitance. The offset will be stable and not affected by temperature, voltage or aging. If it is desirable to achieve the nominal frequency given for the crystal, there are two options:

- Order a crystal from the crystal vendor that has a nominal frequency equal to the required frequency plus the measured offset frequency.
- It is possible to slightly alter the oscillation frequency of a crystal by adjusting the load capacitance (C_{L1} and C_{L2}). The pullability of the oscillation system refers to the extent it is possible to tune the resonance frequency of the crystal by changing these values. The crystal sees these capacitors in series through ground, parallel to the closed loop. They will therefore slightly alter the anti-resonance frequency of the crystal. The equation below shows the pullability in terms of frequency change in ppm as it relates to the combined load capacitance in pF.

$$\text{average pullability (ppm/pF)} = \frac{C_s \times 10^6}{2 \times \left(C_0 + C_L\right)^2}$$

6.5 Drive Level

Drive level is a measure of the power dissipated in the crystal. The manufacturer data sheet should specify the maximum power dissipation tolerated because exceeding this can damage the crystal.

$$\text{DL} = \text{ESR} \times I^2$$

Here, I is the RMS current flowing through the crystal.

6.6 Minimum Negative Resistance

A critical condition for oscillations to build up requires the energy supplied to exceed the energy dissipated in the circuit. In other words, the negative resistance of the amplifier has to exceed the equivalent series resistance in the crystal. An approximate formula for negative resistance is given in the equation below.

$$R_{\text{neg}} = \frac{-g_m}{(2 \times \pi \times f)^2 \times C_{L1} \times C_{L2}}$$

Here, g_m is the transconductance of the oscillator circuitry. To ensure safe operation over voltage and temperature, ensure that the ESR does not exceed the device data sheet maximum. This maximum value corresponds to the oscillator circuit's realizable negative resistance.

If the crystal ESR does not satisfy this criterion, another crystal with lower ESR should be chosen. The equation above shows an approximate formula for this calculation which excludes shunt capacitance and internal loss.

6.7 Frequency Stability

Frequency stability is the maximum frequency deviation from the specified oscillating frequency over the given operating temperature range.

6.8 Frequency Tolerance

Frequency tolerance is the maximum frequency deviation from the specified oscillating frequency at 25 °C. This parameter gives an indication of variations between individual crystals.

7. Revision History

Revision 0.1

September, 2025

- Initial revision.

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