# AN0016.1: Oscillator Design Considerations

This application note provides an introduction to the oscillators in MCU Series 1 or Wireless SoC Series 1 devices and provides guidelines in selecting correct components for their oscillator circuits.

The MCU Series 1 or Wireless SoC Series 1 devices contain two crystal oscillators: one low frequency (32.768 kHz) and one high frequency (4-50 MHz depending on the device, see datasheet for more information). Topics covered include oscillator theory and some recommended crystals 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 MCU Series 1 or Wireless SoC Series 1 devices.
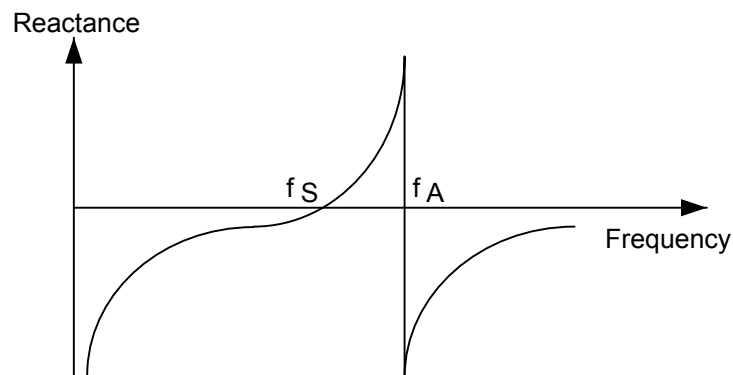
1. Device Compatibility

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

MCU Series 1 consists of:
- EFM32 Jade Gecko (EFM32JG1/EFM32JG12)
- EFM32 Pearl Gecko (EFM32PG1/EFM32PG12)
- EFM32 Giant Gecko (EFM32GG11)

Wireless SoC Series 1 consists of:
- EFR32 Blue Gecko (EFR32BG1/EFR32BG12/EFR32BG13/EFR32BG14)
- EFR32 Flex Gecko (EFR32FG1/EFR32FG12/EFR32FG13/EFR32FG14)
- EFR32 Mighty Gecko (EFR32MG1/EFR32MG12/EFR32MG13/EFR32MG14)

Z-Wave Modem SoC Series 1 consists of:
- EFR32 Zen Gecko (EFR32ZG13L/EFR32ZG13S/EFR32ZG14)

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 MCU Series 1 or Wireless SoC Series 1 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 transciever. 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 startup time than the crystal oscillator, but are generally less accurate and produce more noise. The MCU Series 1 or Wireless SoC Series 1 devices provide multiple internal RC-oscillators including one high frequency RC oscillator (HFRCO) and one low frequency RC oscillator (LFRCO). While the internal RC-oscillators will ensure proper operation of the MCU Series 1 or Wireless SoC Series 1 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.
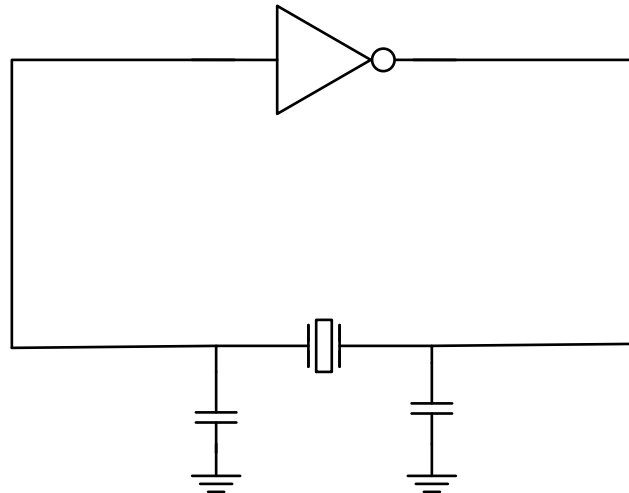
2.2 Basic Principle of Oscillators

Figure 2.1. Simplified Feedback Oscillator 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 MCU Series 1 or Wireless SoC Series 1 relies on an adjustable current source controlled by automatic gain controller to achieve and maintain the desired amplitude.

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

2.2.1 Startup time

The magnitude of the closed-loop gain has great influence on the startup time. Low gain can cause excessively long startup time or failure, and too high gain can startup to fail altogether. 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 startup time. A crystal in the kHz range would have a considerably longer startup time than a crystal in the MHz range because the time it takes to circulate the loop is longer. Typical startup times for the MCU Series 1 or Wireless SoC Series 1 are 200-400 ms for the low frequency oscillator and 200-400 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.
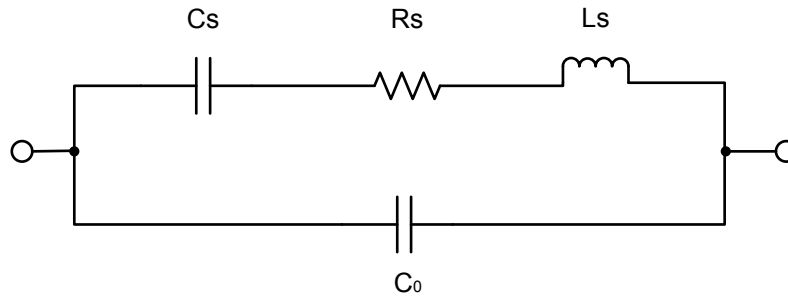

Figure 2.2. The Electrical Equivalent Circuit of a Crystal

- 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. 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.
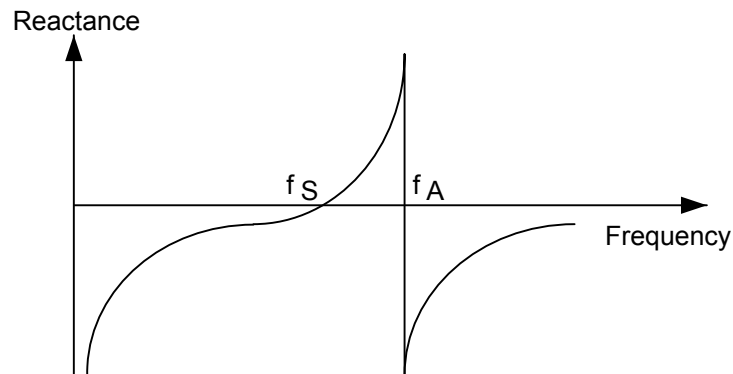

Figure 2.3. Reactance vs. Frequency

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

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.

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

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 has to 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 and this is the resonance mode required for MCU Series 1 or Wireless SoC Series 1 devices. On MCU Series 1 or Wireless SoC Series 1 devices, the load capacitors are located on-chip, and their values can be controlled by firmware. Thus, MCU Series 1 or Wireless SoC Series 1 devices do not require external load capacitors, reducing BOM cost and saving PCB space. 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 datasheet for parallel resonant crystals.

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

3. MCU Series 1 or Wireless SoC Series 1 Crystal Oscillators

The MCU Series 1 or Wireless SoC Series 1 devices include two crystal oscillators, the Low Frequency Crystal Oscillator (LFXO) and the High Frequency Crystal Oscillator (HFXO). These oscillators require an external clock or crystal connected to the crystal oscillator pins of the device, however, no external crystal load capacitors are required as they contain on-chip tunable load capacitors. The LFXO supports crystals with a nominal frequency of 32.768 kHz, while the HFXO supports 4-50 MHz depending on the device, see datasheet for more information. External oscillators which provide sine waves are also supported. Both the high and low frequency clock sources can be used simultaneously.

In the MCU Series 1 or Wireless SoC Series 1 oscillator circuits are designed as a Pierce oscillator as shown in Figure 3.1 The Pierce Oscillator in the MCU Series 1 or Wireless SoC Series 1 on page 7.
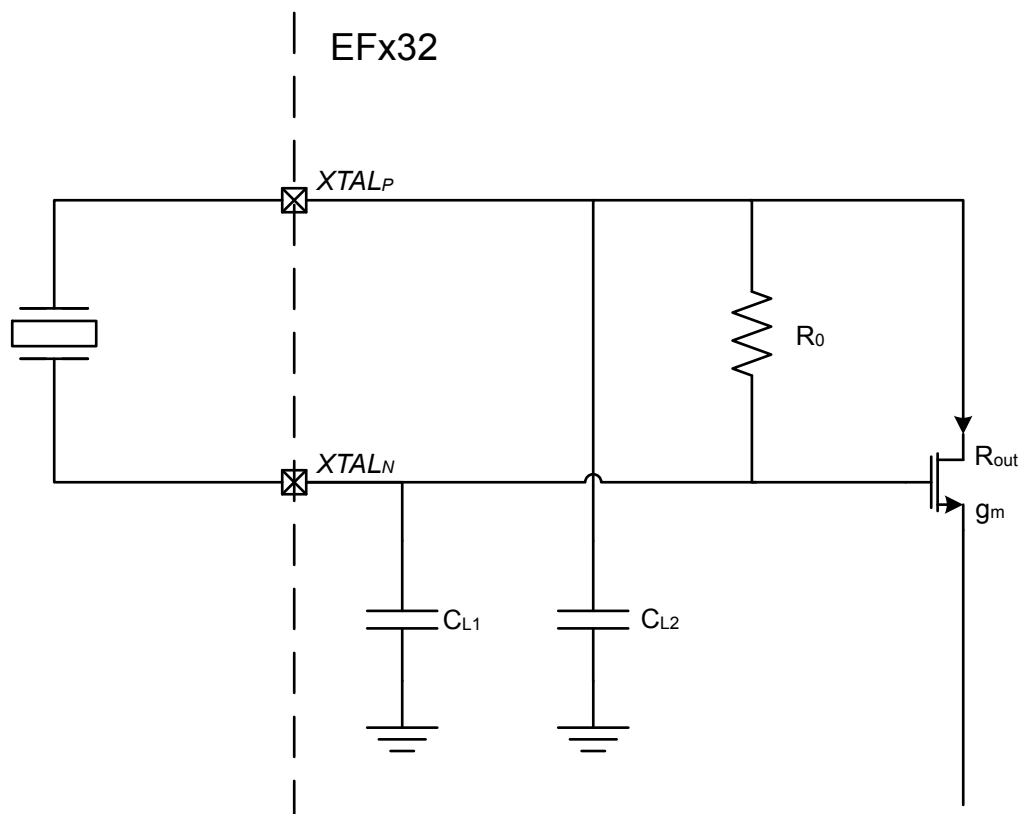

Figure 3.1. The Pierce Oscillator in the MCU Series 1 or Wireless SoC Series 1

The Pierce oscillator is known to be stable for a wide range of frequencies and for its low power consumption.

The MCU Series 1 or Wireless SoC Series 1 crystal oscillators use a relatively low oscillation amplitude, which can lead to a lower oscillation frequency than stated as the nominal value in the crystal's datasheet. More information on this effect is given in 5.4 Frequency Pulling.

3.1 Timeout

To ensure that the XO clock signals are not used internally in the MCU Series 1 or Wireless SoC Series 1 before they are stable, both the HFXO and the LFXO include a configurable timeout. When the XO 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 Oscillator Configuration

The LFXO/HFXO can be easily configured by leveraging the emlib library. The library contains oscillator initialization structures and functions which abstract the software options available for each oscillator.

At the register level, the HFXO and LFXO oscillation start-up on MCU Series 1 or Wireless SoC Series 1 devices are controlled by the CMU_HFXOCTRL, CMU_HFXOxxxCTRL, and CMU_LFXOCTRL registers. See the specific product reference manual for detailed register level desriptions of the configuration options available for the external oscillators.

For MCU Series 1 devices, there is an HFXO configuration spreadsheet available for download from https://www.silabs.com/community/mcu/32-bit/knowledge-base.entry.html/2018/09/20/hfxo_selection_andc-yqMU. The Knowledge Base article was written for EFM32GG11, but with the exception of the maximum frequency range, is relevant for the compatible MCU Series 1 devices mentioned in this Application Note. The article and spreadsheet highlight the required parameters needed from a potential crystal oscillator candidate, and provide optimal HFXO register settings to properly tune, optimize power consumption, and ensure reliable operation based on the oscillator manufacturer's specifications. The functions within emlib library assist in proper setup of these registers.

Wireless SoC Series 1 devices support a narrower range of HFXO frequencies, with 38.4 MHz recommended for most wireless applications to meet transceiver electrical specifications, and 39 MHz recommended for implementing Z-Wave devices. The default settings in the emlib library and Silicon Labs protocol stacks are recommended. [**Application Builder**] is a wireless project development tool in Simplicity Studio that will automatically configure the clock settings with the proper default values based on the selected wireless protocol.

Simplicity Studio also contains a tool, [**Hardware Configurator**], to assist users when configuring both load capacitance and software settings for using the LFXO and the HFXO. Once the correct hardware configuration has been found [**Hardware Configurator**] generates C-code which can be used within an application to implement variances from default configurations.

3.2.1 LFXO Gain Setting Recommendations

When setting the GAIN value in the CMU_LFXOCTRL register, the following guidelines should be observed:

- C_0 must be ≤ 2pF
- For 12.5 pF ≤ C_L ≤ 18 pF, set GAIN = 3
- For 8 pF ≤ C_L ≤ 12.5 pF, set GAIN = 2
- For 6 pF ≤ C_L ≤ 8 pF, set GAIN = 1
- For C_L ≤ 6 pF, set GAIN = 0

The GAIN setting affects oscillator bias current during the startup phase only. Following these guidelines will allow for maximum transconductance gain (g_m) during the LFXO startup phase, ensuring a fast and robust startup.

3.3 External Clock and Buffered Sine Input

The HFXO and LFXO oscillators can be used as inputs for an externally generated digital clock signal. When using the oscillators in this way, connect the clock input to HFXTAL_N or LFXTAL_N. The max frequency of these inputs are limited by the max clock frequency of the device (see the device data sheet for more information). An externally buffered sine signal can also be applied to the HFXTAL_N or LFXTAL_N pin. The recommended amplitude of this signal is between 0.8 and 1.2 V_{pk-pk}, and the frequency must be the same as required when using crystals with the HFXO and LFXO.

4. Z-Wave Modem SoC Series 1 Crystal Oscillators

The Z-Wave Modem SoC Series 1 devices include a High Frequency Crystal Oscillator (HFXO). The oscillator requires an external clock or crystal connected to the crystal oscillator pins of the device, however, no external crystal load capacitors are required as tunable load capacitors are contained on-chip.

The Z-Wave Modem SoC Series 1 devices share common oscillator design and theory with MCU Series 1 or Wireless SoC Series 1. However, due to the strict frequency requirements for Z-Wave, the supported HFXO frequency is limited to 39.0 MHz and the crystal specifications are more stringent. The oscillator settings for the devices are preconfigured for this frequency, with a limited subset of configurable options. The most pertinent portion of this document for designs with Z-Wave Modem SoC Series 1 is the recommended crystal section Table 8.4 39 MHz Crystals on page 17.

For more information regarding crystal specifications and configuration and calibration of the crystal oscillator for Z-Wave Modem SoC Series 1 devices please refer to the product datasheet, along with *INS14487: Z-Wave Integration Guide*, *INS14498: Mandatory Crystal Adjustment for EFR32ZG14 Based Products*, and *INS14283: Instruction for Bring-up/Test HW Development*.

5. Crystal Parameters

5.1 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.

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

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

5.2 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_N and HFXTAL_P pins on the MCU Series 1 or Wireless SoC Series 1 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 and any parasitic capacitance, and can often be assumed in the range 2-5 pF. Right choice of C_L is important for proper operating frequency. Crystals with small load capacitance would typically start faster than crystals requiring a large C_L. Large load capacitors also increase power consumption. It is recommended to use a crystal with C_L as specified in 8. Recommended Crystals. The MCU Series 1 or Wireless SoC Series 1 device datasheets also contain more information on the allowed load capacitance range.

Note: The MCU Series 1 or Wireless SoC Series 1 devices have internal loading capacitors and do not need external capacitors connected to the crystal. See the device data sheet or reference manual for more information.

5.3 Equivalent Series Resistance

The 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.

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

The HFXO/LFXO circuits of the MCU Series 1 or Wireless SoC Series 1 cannot guarantee startup of crystals with ESR larger than a certain limit. Please refer to the device datasheet for further details. The smaller the ESR, compared to this maximum value, the better gain margin for startup of the crystal which in turn reduces the startup time. Additionally, a small ESR value gives lower power consumption during oscillation.

Note that HF crystals have ESR of a few tens of Ohms as compared to the LF crystals which have ESR values normally measured in kOhm. Therefore a few Ohm of series resistance has more influence on the startup margin in the MHz range as compared to the kHz range.

5.4 Frequency Pulling

As the crystal oscillators in the MCU Series 1 or Wireless SoC Series 1 use a relatively low oscillation amplitude, the oscillation frequency can be lower than stated in the datasheet 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:

- Option A — Order a crystal from the crystal vendor that has a nominal frequency equal to the frequency you want to achieve plus the measured offset frequency.
- Option B — 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 which 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 per change in combined load capacitance in pF.

$$\text{Average pullability (ppm/pF)} = \frac{C_S \times 10^6}{2 \times (C_0 + C_L)^2}$$

5.5 Drive Level

Drive level is a measure of the power dissipated in the crystal. The crystal manufacturer should specify the maximum power dissipation value tolerated by the crystal in the crystal datasheet. Exceeding this value can damage the crystal.

$$DL = ESR \times I^2$$

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

5.6 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.

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

Where g_m is the transconductance of the oscillator circuitry. To ensure safe operation over all voltage and temperature variations, ensure that the ESR does not exceed the device datasheet 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.

5.7 Frequency Stability

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

5.8 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.

5.9 PCB Layout

To minimize noise sensitivity caused by parasitic antenna and spurious coupling phenomena, the distance between the crystal, and the MCU Series 1 or Wireless SoC Series 1 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 MCU Series 1 or Wireless SoC Series 1 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.

6. Reducing Power Consumption

The power consumption of the crystal oscillator is mostly determined by the drive level of the oscillator. This equals the power dissipated in the crystal as given in the equation below.

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

V_{pp} is the peak to peak voltage across the crystal at the resonance frequency.

Because the internal buffer draws some current regardless of clock frequency, the average power consumption per MHz is usually lower for high clock frequencies. In the energy conscious sense it is therefore favorable to alternate between short periods in run mode with HFXO enabled and lower energy modes where HFXO is not running.

During startup the current consumption is higher than after oscillations have stabilized. A short startup time reduces the period in which the current consumption of the oscillator is high and is therefore essential if the oscillator is frequently switched on and off. In general one would like the circuit to be operational as fast as possible and a fast startup time is therefore favorable. Crystals with low ESR and load capacitance typically have the shortest startup time and consume the least amount of power.

7. Considerations for Radio Applications with the MCU Series 1 or Wireless SoC Series 1 Portfolio

7.1 General Notes

This section adds a few details about specific requirements related to wireless applications.

While MCU Series 1 or Wireless SoC Series 1 devices support a range of 38 to 40 MHz for the HFXO, the recommended value is 38.4 MHz. For our Z-Wave products, the recommended value is 39.0 MHz. Transceiver electrical specifications are based on these frequencies, and Silicon Labs protocol stacks use these as the default.

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 °C 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.

7.2 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 datasheet by C_{HFXO_T} 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.

7.2.1 Tuning Strategies

The on-chip variable load capacitor 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 in the order of a few ppm only, depending on manufacturing spread (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 broader temperature range or with a less accurate crystal at the expense of production calibration time.

The variable on-chip loading capacitor 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.

Crystal ppm error can be measured by outputing a clock signal to a GPIO pin. This process, along with example code demonstrating oscillator calibration, is described in *AN0004.2: EFR32 Series 2 Wireless MCU Clock Management Unit (CMU)*

7.3 PCB Layout

The crystal section PCB layout should be kept compact and close to the IC. Longer traces increase possibility of spurious transmission and increase the fixed parasitic loading capacitance. The crystal's case ground pins should be grounded. Please refer to *AN928: "EFR32 Layout Design Guide"* for further notes on this subject. Application notes can be found on the Silicon Labs website (www.silabs.com) or in Simplicity Studio.

7.4 External Tuning Capacitance

All required crystal loading capacitance is on-chip, therefore, external loading capacitors are not recommended.

7.5 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). The TCXO output is connected to the HFXTAL_N pin and the `mode` field is set to `cmuHfxoOscMode_ExternalSine` in the `em_lib` HFXO initialization struct.

7.5.1 TCXO Phase Noise Recommendations

When using a 38.4 MHz TCXO in a radio application, designers must ensure that phase noise in the system meets or exceeds the performance measurements below (i.e. is less than these figures) in order to avoid phase noise related performance degradation.

Table 7.1. TCXO Phase Noise Referenced to 38.4 MHz Fundamental Frequency

Offset From 38.4 MHz Carrier	Phase Noise (dBc/Hz)
1 kHz Offset	-123
3 kHz Offset	-132
10 kHz Offset	-134
30 kHz Offset	-136
100 kHz Offset	-145
1 MHz Offset	-148
10 MHz Offset	-140

8. Recommended Crystals

8.1 General Notes for Crystal Selection

When deciding upon which crystal to employ, the following considerations could be helpful to ensure a proper functioning oscillator.

Operating environment

Temperature, humidity, and mechanical vibration affect the stability properties. For crystals, define what crystal cut is most appropriate for the application. For most applications, AT cut is an excellent choice due to good temperature 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 exists.

Package

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

Find load capacitors

Ensure that C_L is within range specified by the MCU Series 1 or Wireless SoC Series 1 datasheet.

Calculate negative resistance

If the magnitude of the negative resistance is less than $2xESR_{max}$, then find another crystal or adjust the load capacitance.

The recommended crystals are chosen from a selection of popular crystals with different ESR, cost, frequency stability, and tolerance. By examining the list of considerations above, one should be able to find a suitable crystal.

All the recommended crystals are fundamental mode, as is recommended for MCU Series 1 or Wireless SoC Series 1.

8.2 Crystal Specifications for MCU Series 1 or Wireless SoC Series 1

The following crystals may be considered for use with MCU Series 1 or Wireless SoC Series 1. Suitability for a particular application should be verified. Different frequency tolerance / temperature ranges may be available. Contact the crystal vendor for details.

Table 8.1. 38.4 MHz Crystals

Mfg	Part	ESR (Ω)	C_0 (max) (pF)	Temp (°C)	Temp Tolerance (ppm)	Mfg Tolerance (ppm)	C_L (pF)	Footprint (mm)
KDS	DSX211SH 1ZZHAE38400AB0A	50	2	-40 to +85	± 20	± 10	10	1.6 x 2.0
KDS	DSX211SH 1ZZHAE38400AB0B	50	2	-40 to +105	± 20	± 10	10	1.6 x 2.0
Kyocera	CX2016DB38400F0FSRC1	40	1	-40 to +125	± 40	± 10	10	1.6 x 2.0
Kyocera	CX2520DB38400F0FSRC2	50	1.2	-40 to +125	± 40	± 10	10	2.0 x 2.5
Kyocera	CX2520DB38400F0FSRC3	40	1.2	-40 to +125	± 40	± 10	10	2.0 x 2.5
NDK	EXS00A-CS08361	40	1.26	-40 to +125	± 32	± 10	10	2.0 x 2.5
NDK	NX2016SA-38.4MHz-EXS00A-CS08973	60	0.61	-30 to +85	± 12	+-10	10	1.6 x 2.0
TaiSaw	TZ0909E	50	3	-40 to +125	± 30	± 10	10	2.0 x 2.5
TaiSaw	TZ2205E	40	3	-40 to +125	± 30	± 10	10	1.6 x 2.0

Table 8.2. 38.4 MHz TCXOs

Mfg	Part	Supply Voltage (V)	Output Voltage (V_{pk-pk})	Temp (°C)	Current Consumption (mA)	Frequency Tolerance (ppm)	Footprint (mm)
NDK	NT2016SA-38.4MHz-END5109A	1.8 to 3.6	0.8	-40 to +105	1.7	± 2	1.6 x 2.0

Table 8.3. 32768 Hz Crystals

Mfg	Part	ESR (kΩ)	C_0 (typ) (pF)	Temp (°C)	Tolerance (ppm)	C_L (pF)	Footprint (mm)
Abracon Corporation	ABS07-32.768KHZ-7	70	1.2	-40 to +85	± 20	7	3.2 x 1.5
Epson	FC-135	65	1.0	-40 to +85	± 20	9	3.2 x 1.5
KDS	DST210AC	70	1.3	-40 to +85	± 20	7.0	2.0 x 1.2
KDS	DST310S	70	1.3	-40 to +85	± 20	12.5	3.2 x 1.5
Micro Crystal	CM8V-T1A	55	1.1	-40 to +85	± 20	13	2.0 x 1.2

8.3 Crystal Specifications for Z-Wave Modem SoC Series 1

The following crystals may be considered for use with Z-Wave Modem SoC Series 1. Suitability for a particular application should be verified. Different frequency tolerance / temperature ranges may be available. Contact the crystal vendor for details.

Table 8.4. 39 MHz Crystals

Mfg	Part	ESR (Ω)	C_0 (max) (pF)	Temp (°C)	Temp Tolerance (ppm)	Mfg Tolerance (ppm)	C_L (pF)	Footprint (mm)
Siward	XTL501140-S315-020	50	3	-40 to +90	± 14	± 8	10	1.6 x 2.0
TXC	8Y39072002	35	1.0	-40 to +95	± 13	± 8	10	1.6 x 2.0

Note: The crystal is a critical component of Z-Wave devices and calibration is **mandatory** for gateway designs. Please refer to *INS14498: Mandatory Crystal Adjustment for EFR32ZG14 Based Products* for additional information.

Table 8.5. 39 MHz TCXOs

Mfg	Part	Supply Voltage (V)	Output Type	Output Voltage (V_{pk-pk})	Temp (°C)	Current Consumption (mA)	Frequency Tolerance (ppm)	Footprint (mm)
Kyocera	KT2016K39000ZAZ18TAVG4	1.8 ± 5%	Clipped Sine Wave	0.8	-40 to +115	± 27	2	1.6 x 2.0
Siward	TXO973270-STO-4932	1.68 to 3.63	HCMOS Square Wave	—	-40 to +115	± 20	5.5	1.6 x 2.0
					-40 to +125	± 27		

9. Revision History

Revision 1.34

June, 2020
- Added DST210AC to Table 8.3 32768 Hz Crystals on page 16
- Fixed minor typos throughout the document

Revision 1.33

June, 2020
- Added EFR32ZG13L and EFR32ZG13S to 1. Device Compatibility.
- Updated Table 8.4 39 MHz Crystals on page 17 for Z-Wave devices (AN0016.1).
- Added Table 8.5 39 MHz TCXOs on page 17 with recommendations for Z-Wave devices (AN0016.1).

Revision 1.32

October, 2019
- Updated Table 8.3 32768 Hz Crystals on page 16. Removed crystals that exceeded Series 1 device max ESR specifications.

Revision 1.31

February, 2019
- Updated recommended crystals to include Table 8.4 39 MHz Crystals on page 17 for Z-Wave devices (AN0016.1).
- Added reference in Oscillator Configuration to a Knowledge Base article and spreadsheet which help configure HFXO register settings (AN0016.1).
- Removed redundant text.
- Updated 9. Revision History to adhere to new schema.

Revision 1.30

December, 2017
- Split application note into AN0016.0 and AN0016.1 for MCU Series 0 or Wireless MCU Series 0 and MCU Series 1 or Wireless SoC Series 1 device families, respectively.
- Updated recommended crystals for MCU Series 1 or Wireless SoC Series 1 (AN0016.1).
- Improved graphics.
- Added MCU Series 1 or Wireless SoC Series 1 LFXO GAIN recommendations.
- Updated/added TCXO information, including recommended input voltage and phase noise measurements (AN0016.1).

Revision 1.29

June, 2017
- Moved the device compatibility information from the front page to 1. Device Compatibility.
- Updated the references to the various device families.

Revision 1.28

February, 2017
- Updated content for new naming convention.
- Updated Table 8.1 38.4 MHz Crystals on page 16 to add a new crystal option and a C0 column.

Revision 1.27

May, 2016
- Updated the Kyocera crystal ESR value in Table 8.1 38.4 MHz Crystals on page 16.

Revision 1.26

May, 2016
- Updated the Kyocera crystal information in and added a new TaiSaw crystal to Table 8.1 38.4 MHz Crystals on page 16.
- Changed f_a to f_A in Figure 2.3 Reactance vs. Frequency on page 5.

Revision 1.25

November, 2015
- Added support for the Wireless SoC Series 1

Revision 1.24

October, 2015
- Formatting update
- Added support for MCU Series 1

Revision 1.23

October, 2013
- New cover layout

Revision 1.22

May, 2013
- Added crystals from River Eletec Corporation.
- Removed DL numbers for recommended crystals as they were misleading.

Revision 1.21

April, 2012
- Corrected typos in XO Configurator description.

Revision 1.20

April, 2012
- Updated recommendations on minimum negative resistance and removed recommendations on gain margin.
- Added information on timeout counter and glitch detection.
- Added PCB layout recommendations.
- Added information on external clock and buffered sine input.
- Added information on XO Configuration in energyAware Designer. Removed recommendations on how to use LFXOBOOST in CMU_CTRL as this is now covered by the eA Designer.
- Removed crystal selection spreadsheet.
- Added recommended 48 MHz crystals.

Revision 1.10

August, 2011
- Updated recommendations on use of LFXOBOOST.
- Updated recommended crystals in document and spreadsheet for LFXO.

Revision 1.00

July, 2010
- Initial revision.

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