

Crystal Oscillator and Crystal Selection for the CC26xx and CC13xx Family of Wireless MCUs

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ABSTRACT

The CC26xx and CC13xx family is a low-power wireless MCU platform supporting multiple standards (that is, *Bluetooth*® Low Energy, IEEE® 802.15.4, and proprietary RF protocols). The devices have integrated 24-MHz (CC13x0 and CC26x0) or 48-MHz (CC13x2 and CC26x2) and 32.768-kHz crystal oscillators TI designed for use with low-cost quartz crystals. The 24/48-MHz oscillator (XOSC-HF) generates the reference clock for the RF blocks and the MCU system. RF systems are dependent on accurate clocks for correct operation. A deviation in clock frequency is reflected as a deviation in radio frequency. This deviation can degrade RF performance, violate regulatory requirements, or lead to a nonfunctioning system. In power-down mode, the high-frequency oscillator is typically turned off and a low-frequency oscillator is the system clock. For time-synchronized protocols such as Bluetooth Low Energy, a tight tolerance on the sleep clock enables longer time in low-power mode and reduced power consumption important in battery-powered applications. For this low-frequency oscillator, typically a 32-kHz crystal oscillator (XOSC-LF) is used.

The scope of this application report is to discuss the requirements and trade-offs of the crystal oscillators for the CC26xx and CC13xx devices and provide information on how to select an appropriate crystal. This document also presents steps to configure the device to operate with a given crystal. You must configure the CC26xx and CC13xx based on the crystal used (that is, adjust the internal capacitor array to match the loading capacitor of the crystal for the XOSC-HF). This application report also discusses some measurement approaches that may be used to characterize certain performance metrics, including crystal oscillator amplitude, and start-up time.

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1 Oscillator and Crystal Basics

This section explains fundamentals of a quartz crystal and the oscillator operations required to understand the trade-offs when selecting a crystal for the CC13xx and CC26xx devices. The complete crystal oscillator circuit includes the loading capacitance, crystal, and the on-chip circuitry.

1.1 Oscillator Operation

The circuit used as high-accuracy clock source for TI's low-power RF products is based on a Pierce oscillator as shown in Figure 1. There is no on-chip damping resistor and none must be added by the customer. The oscillator circuit consists of an inverting amplifier (shown as an inverter), a feedback resistor, two capacitors, and a crystal. When operating, the crystal and the capacitors form a pi filter that provides an 180-degree phase shift to the internal amplifier, keeping the oscillator locked at the specified frequency.

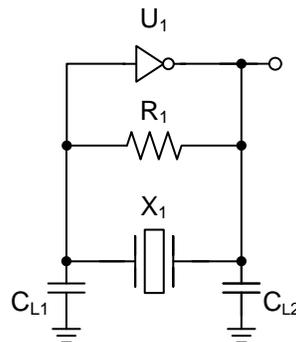


Figure 1. Pierce Oscillator

1.2 Quartz Crystal Electrical Model

A quartz crystal is a piezoelectric device that transforms electric energy to mechanical energy. This transformation occurs at the resonant frequency. Figure 2 shows the simplified electric model that describes the quartz crystal, where C_0 is the shunt capacitance, L_M is motional inductance, C_M is motional capacitance, and R_M is motional resistance. The model in Figure 2 is a simplified model and includes only the fundamental oscillation frequency. In reality, crystals can also oscillate at odd harmonics of the fundamental frequency.

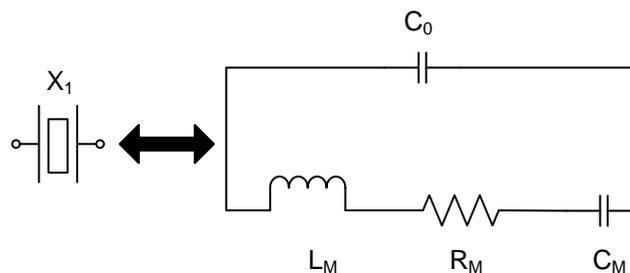


Figure 2. Crystal Symbol and the Electrical Model of a Quartz Crystal

1.2.1 Frequency of Oscillation

A crystal has two resonant frequencies characterized by a zero-phase shift. Equation 1 is the series resonance.

$$f_s = \frac{1}{2\pi\sqrt{L_M \times C_M}} \quad (1)$$

Equation 2 is the antiresonant frequency.

$$f_a = \frac{1}{2\pi \sqrt{L_M \times \frac{C_M \times C_0}{C_M + C_0}}} \quad (2)$$

As specified in the data sheet of the crystal, the frequency of oscillation is between the resonance frequencies. See Equation 3.

$$f_s < f_{XTAL} < f_a \quad (3)$$

1.2.2 Equivalent Series Resistance

The Equivalent Series Resistance (ESR) is the resistance the crystal exhibits at the series resonant frequency. Equation 4 gives the ESR.

$$ESR = R_M \left(1 + \frac{C_0}{C_L} \right)^2 \quad (4)$$

Because C_0 is typically on the order of 1 pF and C_L is 5–9 pF, ESR is approximately R_M for many crystals, sometimes ESR is approximated as motional resistance.

1.2.3 Drive Level

The drive level of a crystal refers to the power dissipated in the crystal. The maximum drive level of a crystal is often specified in the data sheet of the crystal in μW . Exceeding this value can damage or reduce the life of the crystal. Equation 5 gives the drive level in W.

$$DL = 2 \times ESR (\pi f (C_L + C_M) V_{PP})^2 \quad (5)$$

where V_{pp} is the peak-to-peak voltage across the crystal.

Calculating the DL and comparing this value to the maximum specified DL in the crystal data sheet may reveal if the crystal is likely to have reliability issues during operation. Section 5 describes how to measure the value of V_{pp} .

1.2.4 Crystal Pulling

The crystal frequency can be pulled by changing the load capacitance. The parameter ΔF is the resonance frequency change of the crystal due to a change in its load capacitance. The pulling is given by Equation 6 around the specified (parallel) resonance frequency of the crystal.

$$\Delta F = \frac{F \times C_M}{2} \frac{C_{LMAX} - C_{LMIN}}{(C_0 + C_{LMAX})(C_0 + C_{LMIN})} \quad (6)$$

C_{LMAX} and C_{LMIN} are the maximum and minimum load capacitance that can be presented to the crystal. For more information, see [CC13xx/CC26xx Hardware Configuration and PCB Design Considerations](#).

1.3 Negative Resistance

Negative resistance (R_N) is a parameter of the complete oscillator circuit, including capacitor values, crystal parameters, and the on-chip circuit. The CC13xx and CC26xx devices dynamically adjust the oscillator parameters to ensure sufficient oscillator margin during crystal startup and then relax the margins for steady state to decrease the current consumption. This means that when using a crystal within the requirements outlined in the CC13xx and CC26xx datasheets, proper start-up and steady-state margin is ensured over operating conditions.

Equation 7 approximates the negative resistance and shows that a low C_L gives a larger negative resistance.

$$R_N \approx \frac{-g_m}{(2\pi f)^2 (2C_L)^2} \quad (7)$$

where:

g_m — is the transconductance of the active element in the oscillator

C_L — is the load capacitance

You can also find the negative resistance of the circuit by introducing a resistor in series with the crystal. To avoid parasitic effects, TI recommends using a 0201 resistor for this task. The threshold of the sum of the extra 0201 external resistance and ESR or the crystal where the oscillator is unable to start up is approximately the same as the circuit negative resistance.

1.4 Time Constant of the Oscillator

The start-up time of a crystal oscillator is determined by transient conditions at turn-on, small-signal envelope expansion due to negative resistance, and large-signal amplitude limiting. The envelope expansion is a function of the total negative resistance and the motional inductance of the crystal. The time constant of the envelope expansion is proportional to the start-up time of the oscillator given by Equation 8.

$$\tau = \frac{-2L_M}{(R_M + R_N)} \approx \frac{-2L_M}{R_N}, |R_n| \gg |R_m| \quad (8)$$

A crystal with a low L_M gives a shorter start-up time and so does a high-magnitude R_N (low C_L). A trade-off exists between pullability due to low-motional capacitance (C_M) and fast start-up time due to low-motional inductance (L_M), because the frequency of the crystal is dependent on the both C_M and L_M . Crystals in smaller package sizes have larger L_M , and start more slowly than those in larger package sizes (see Section 1.2.1). Lowering C_L also reduces the drive level, allowing for an increase in oscillation amplitude.

Table 1 summarizes crystal parameters and their values for the reference crystals recommended by TI for use with CC26xx and CC13xx.

Table 1. Crystal Parameters

Parameters	Description	24-MHz Crystal Used in TI CC26x0 Characterization	TI-Assumed Default 32.768-kHz Crystal
Motional Inductance (L_M)	Partly determines crystal speed (how quickly the crystal responds to a change from the oscillator). Lower $L_m \rightarrow$ crystal responds more quickly to changes from the oscillator. Along with C_M , a major determiner of the crystal quality factor	12.6 mH	5.0 kH
Motional Capacitance (C_M)	Partly determines crystal speed. Lower $C_M \rightarrow$ crystal responds more slowly to changes from the oscillator.	3.4 fF	4.718 fF
Motional Resistance (R_M)	At resonance, L_m and C_M cancel and R_M is presented to the oscillator. $R_M \sim$ ESR assuming $C_L \gg C_O$.	20 Ω (60- Ω maximum)	37 k Ω (70-k Ω maximum)
Load Capacitance (C_L)	The amount of load capacitor to tune the crystal to the correct frequency. This load capacitance also helps determine drive level.	9 pF	7 pF
Shunt Capacitance (C_O)	This is a parasitic capacitance due to crystal packaging. It helps determine the acceptable drive level.	1.2 pF	1 pF
ESR	Equivalent Series Resistance. If $C_L \gg C_O$, then $ESR \sim R_M$	20 Ω (60- Ω maximum)	37 k Ω
Drive Level	The maximum level of power in the crystal for reliable long-term operation. $2 \times ESR (\omega (C_L + C_O)) \times V_{osc}$ where V_{osc} is the amplitude of the crystal oscillations.	200 μ W	<500 nW

2 Overview of CC26xx and CC13xx Crystal Oscillators

The CC26xx and CC13xx have integrated 24-MHz, 48-MHz and 32.768-kHz crystal oscillators that TI designed for use with low-cost quartz crystals. High-frequency (48 MHz) and low-frequency (32 kHz) RC oscillators are also available on the CC26xx and CC13xx devices, which are beyond the scope of this application report.

2.1 24-MHz and 48-MHz Crystal Oscillator

Figure 3 shows a simplified block diagram of the XOSC-HF. The oscillator circuit consists of an inverting amplifier, a feedback net, capacitors, and a crystal. The CC13xx and CC26xx have an internal capacitor array that can be adjusted and eliminates the requirement for external loading capacitors. The cap-array can be adjusted by CCFG configuration within a range of 2 pF to 11 pF. For reliable operation, TI requires operating the crystal with C_L from 5 to 9 pF. [CC13xx/CC26xx Hardware Configuration and PCB Design Considerations](#) shows how to set this value. If no external capacitors are used then the value of C_L is determined by the internal loading capacitors plus board parasitic capacitance.

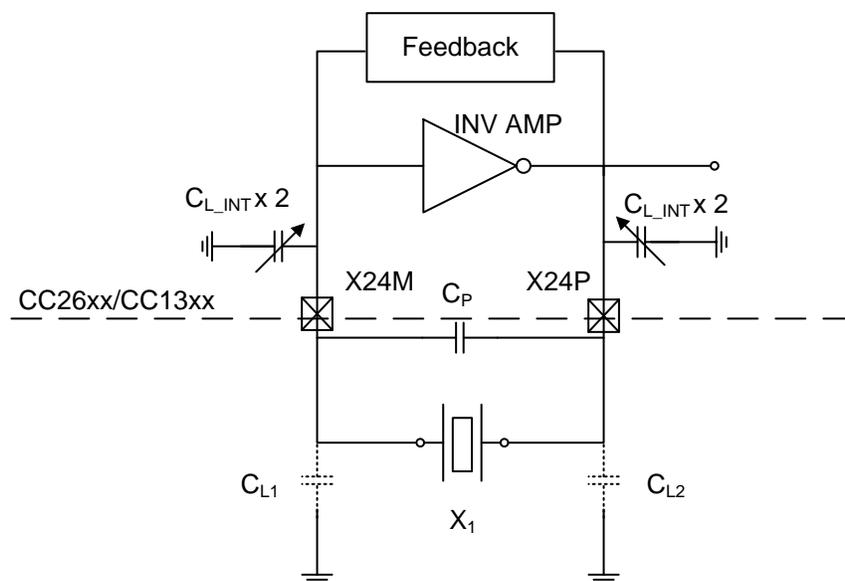


Figure 3. Simplified Block Diagram of the CC26xx and CC13xx High-Frequency Oscillator With Quartz Crystal

The 24-MHz or 48-MHz crystal is controlled with a complex control loop described in [Section 2.2](#) and [Section 2.3](#).

2.2 24-MHz and 48-MHz Crystal Control Loop

TI intends the amplitude control loop to regulate the amplitude of the oscillations of the crystal for optimal performance. The following are the two primary portions of the control loop:

- Start-up: The control loop injects as much current as possible into the oscillator that drives the crystal resonator.
- Steady state regulation: The amplitude of the crystal oscillator can be regulated in a steady state manner if required.

To turn on the crystal so that the radio can operate, start-up is required. Steady state amplitude regulation is not required for the crystal or radio to function.

2.3 32.768-kHz Crystal Oscillator

Figure 4 shows a simplified block diagram of the 32.768-kHz crystal oscillator. The oscillator circuit consists of an inverting amplifier, a feedback net, capacitors, and a crystal. The 32-kHz crystal lacks internal capacitors and requires external loading capacitors.

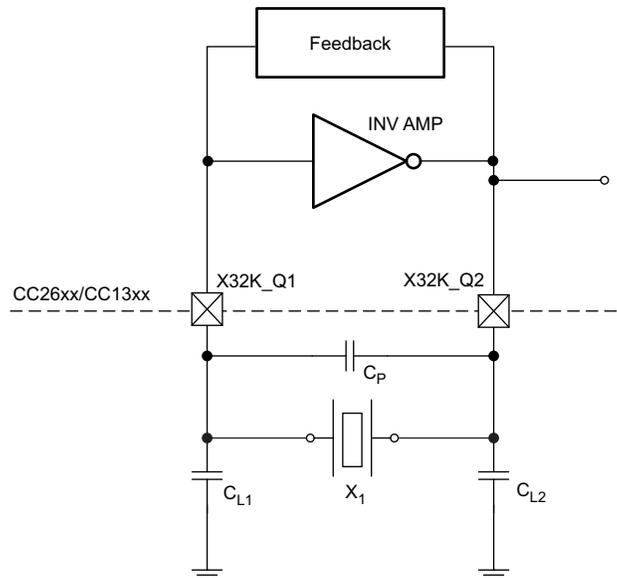


Figure 4. Simplified Block Diagram of the 32.768-kHz Oscillator With Quartz Crystal

3 Selecting Crystals for the CC26xx and CC13xx

This section presents some important considerations when selecting crystals for the CC13xx and CC26xx. Selecting a crystal for a specific application depends on the following three factors:

- Size (footprint area and height)
- Performance (accuracy over temperature, lifetime, power consumption, and start-up time)
- Cost

Consider the following when selecting a crystal:

- Crystals must be selected to meet requirements listed in the CC13xx and CC26xx data sheets or specifications.
 - ESR must not be greater than can be driven by CC13xx and CC26xx.
 - Capacitive loading and frequency tolerance must meet the specifications of the standard used (for example, Bluetooth).
 - Motional inductance must also meet specifications. Many crystal manufactures provide only motional inductance data upon customer request.
- Some other considerations when selecting a crystal include the following:
 - To improve start-up time and reduce power consumption, the crystal must have the following:
 - Low-capacitive loading, at the expense of greater susceptibility to frequency variation caused by the environment
 - Low-motional inductance
 - Low-motional resistance

3.1 Mode of Operation

Quartz crystals are used at the fundamental resonance frequency for frequencies relevant to the CC13xx and CC26xx, but there are crystals that operate at an odd overtone of the fundamental frequency. TI recommends using a crystal that operates at the fundamental mode for the CC13xx and CC26xx devices.

3.2 Frequency Accuracy

The total tolerance of the frequency accuracy of a crystal is dependent on several factors:

- Production tolerance
- Temperature tolerance
- Aging effects
- Frequency pulling of the crystal due to mismatched loading capacitance

When selecting the crystal, consider these parameters. Equation 9 gives the total crystal tolerance.

$$Tol_{tot} = Tol_{prod} + Tol_{temp} + Tol_{age} + Tol_{pull} \text{ (ppm)} \quad (9)$$

These values are given in parts per million (ppm) and can be found in the device-specific data sheet of the crystal manufacturer, except pullability, which can be calculated by the formula in Section 1.

3.2.1 24-MHz and 48-MHz Crystal

Because the 24-MHz crystal oscillator is used as a reference to generate the RF signal, any crystal frequency deviation is directly transferred to deviation of the RF signal. For example, 10 ppm leads a deviation in RF carrier frequency of 10 ppm. Select a crystal with performance within the limits of the RF specifications.

- For 802.15.4 (Thread/ZigBee®), the maximum deviation in carrier frequency is limited to ± 40 ppm (see [1]).
- For Bluetooth Low Energy, the limit is ± 40 ppm (see [2]).

3.2.2 32.768-kHz Crystal

The 32.768-kHz crystal oscillator is used as the RTC and is kept running when the device is in Standby mode. Because Bluetooth Low Energy is a time-synchronized protocol, an accurate clock also enables longer periods of time in a low-power mode. If a lower-accuracy crystal is used, the device must wake up early to accommodate for the lower accuracy of the clock. If the 32.768-kHz crystal oscillator is used as the low-frequency clock in Bluetooth Low Energy, the clock must have a maximum of ± 500 ppm of inaccuracy. For more information, see [2]. TI recommends using a tighter tolerance 32.768-kHz crystal to reduce the average power consumption in a typical Bluetooth Low Energy connection. In the *SimpleLink™ CC2650 EVM Kit 4XD (CC2650EM-4XD) v1.0.3 Design Files*, TI uses the Epson FC-135 crystal. If a crystal with different specifications is used, this setting must be adjusted for in the Bluetooth Low Energy stack. For more details, see the BLE Stack Users Guide.

Note that low-frequency tuning fork crystals have a resonance frequency that changes with temperature with a parabolic coefficient of $(-0.04 \times 10e - 6) / ^\circ\text{C}^2$ typically. Figure 5 shows an example of this. In Figure 5, 40-ppm accuracy is maintained only from -10°C to 50°C .

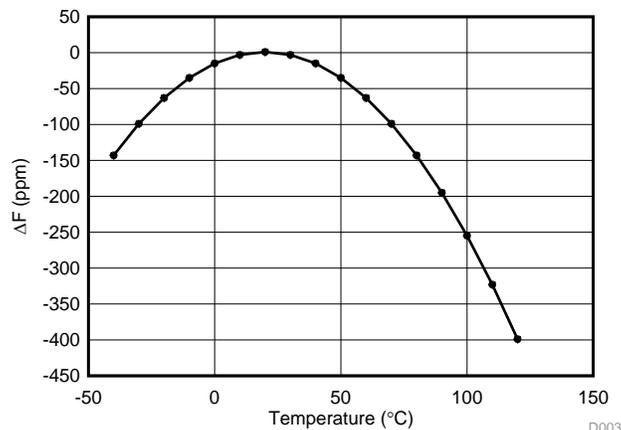


Figure 5. Typical Frequency vs Temperature Curve for a 32.768-kHz Tuning Fork Crystal

3.3 Load Capacitance

The crystal oscillator frequency is dependent on the values of the capacitive loading of the crystal. These capacitors with any parasitic capacitance in the PCB and the crystal terminals compose the total load capacitance that helps set the crystal resonance frequency. The crystal data sheet provides the optimum load capacitance for the crystal, C_L . This total C_L typically consists of both the loading capacitors and the parasitic capacitance of the layout and packaging.

Using external capacitors to get the correct frequency means that the internal caps must be set to minimum. For example, an application could use near minimum on-chip capacitance of approximately 2 pF and 7 pF of off-chip capacitor to get 9 pF. Table 2 shows using external caps this way gives slightly worse frequency stability with temperature than using internal capacitors.

Table 2. Using External Capacitor Results in Worse Frequency Stability Over Temperature

	9-pF Internal C_L	Minimum Internal C_L
Frequency variation –40°C to +90°C	Set by crystal	Set by crystal + 5 ppm
Voltage accuracy, ppm/V	6.9	9

The following presents the relative advantages of crystals with different C_L values.

The disadvantages of lower C_L are as follows:

- Crystals with < 7-pF C_L are more difficult to source with short lead times.
- Frequency becomes more sensitive to changes in board capacitance as C_L decreases. It is possible to meet frequency stability specifications with a C_L as low as 3 pF.
- Lowering C_L results in degraded RF phase noise.

Advantages of lower C_L are as follows:

- Lower C_L causes a much faster start-up time. (Start-up time goes as $\infty \left(\frac{1}{C_L^2} \right)$)
- Lower C_L causes a faster amplitude control loop response time.
- Lower C_L makes it easier to use small size crystals (2.0 × 1.6 and so on) and maintain a start-up time at or less than 400 μ s. Start-up time worsens with smaller crystals due to an increase in L_M .

3.4 ESR and Start-Up Time

ESR (equivalent series resistance) is a parameter of the crystal in the data sheet of the crystal. Negative resistance is a parameter of the complete oscillator circuit, including capacitor values, crystal parameters, and an on-chip circuit. To ensure best start-up of the crystal oscillator, the negative resistance magnitude must be at least 5 times greater than R_N (see Equation 10 and Equation 11) during initial start up but can be 2 to 3 times greater when the crystal has reached steady state.

$$ESR < \frac{|R_N|}{5} \tag{10}$$

$$R_N = \frac{-g_m}{(2\pi f)^2 (2C_L)^2} \tag{11}$$

If the negative resistance magnitude is not 5x greater than R_N during initial start-up, the oscillator might not operate optimally or might fail to start. An increasing negative resistance magnitude leads to a faster the start-up time of the oscillator.

NOTE: Crystals with higher ESR typically result in longer start-up times than crystals with lower ESR. An higher-load capacitance decreases the negative resistance of the oscillator and increases the start-up time.

3.5 Drive Level and Power Consumption

The maximum drive level of a crystal is often specified in the data sheet of the crystal in μW . Exceeding this value can damage or reduce the lifetime of the crystal. The CC13xx and CC26xx devices drive the crystal with a maximum $1.6 V_{pp}$ for the 24/48-MHz crystal and $600 mV_{pp}$ for the 32.768-kHz crystal. As [Section 1.2.3](#) explains, [Equation 5](#) gives the drive level in W.

A higher total capacitance load and ESR require more power to drive the crystal, increasing the power consumption of the oscillator. Because the 32.768-kHz crystal is on for an extended period of time, this increase is important. Selecting a low ESR and low- C_L 32.768-kHz crystal is important to achieve low-power consumption in a low-power mode.

NOTE: Do not use the internal DC-DC when applying a probe to the 24-MHz crystal oscillator pins. Applying the probe can lead to the oscillator stopping and may lead to the internal DC-DC producing a high-output voltage that may damage the device.

3.6 Crystal Package Size

There are several different packages for crystals. The available board space and cost determines the package size used. Crystals with smaller packages have a higher ESR and motional inductance. These smaller packages cause a longer start-up time of the crystal oscillator. By choosing a crystal with a low C_L if a smaller package is required, this start-up time increase can be compensated.

4 PCB Layout of the Crystal

The layout of the crystal can reduce the parasitic capacitance and, more importantly, reduce noise from coupling on the input of the oscillators. Noise on the input of the oscillator can lead to severe side effects such as clock glitches, flash corruption, or system crashes because the CC26xx and CC13xx devices rely on the crystal oscillators as the high- and low-frequency system clock.

The following are a few recommendations for the layout of the crystals:

- Place the crystal as close as possible to the device to minimize the length of the PCB traces. (This placement reduces crosstalk and minimizes EMI.)
- TI recommends a solid ground plane under the crystal.
- Ensure no high-speed digital signals are close to the crystal to minimize cross-coupling of noise into the oscillator.

Figure 6 shows the top layer of the layout of the CC26xx reference design. The bottom layer is a solid ground plane. For more details, see the [SimpleLink™ CC2650 EVM Kit 4XD \(CC2650EM-4XD\) v1.0.3 Design Files](#). The same crystal layout can be used with CC13xx device.

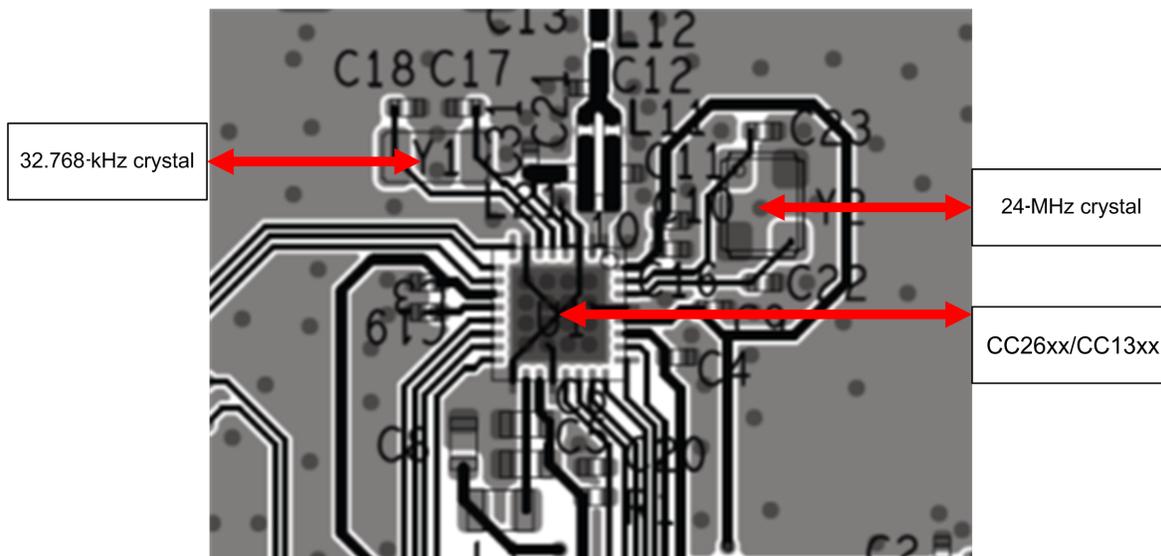


Figure 6. Layout of the CC26xx EVM

5 Measuring the Amplitude of the Oscillations of Your Crystal

Two functions exist in CC26XX/13XXWARE for measuring the amplitude of the oscillations of the crystal, and comparing this amplitude to the expected amplitude. These functions are as follows:

- `uint32_t OSCHF_DebugGetCrystalAmplitude(void);`
- `uint32_t OSCHF_DebugGetExpectedAvarageCrystalAmplitude(void);`

The first function inserted into a piece of code returns the amplitude of the crystal in mV. The second function returns the expected oscillation amplitude, also in mV. These are debug functions only. The first function uses an on-chip ADC to measure the amplitude of the crystal. If these functions return greatly different values, the crystal may have a problem. The uncertainty of the first function is ± 50 mV; a 50 mV deviation from the expected value is not cause for concern.

5.1 Measuring Start-Up Time to Determine HPMRAMP1_TH and XOSC_HF_FAST_START

The following code can be used to estimate the start-up time of the 24-MHz crystal. The code counts the edges of the 32.768-kHz crystal before the 24-MHz crystal is operational. For more accurate results, external measurement equipment is required.

```
//MeasureStartup()
//Returns the startup time as 65536 * number of 1/2 LF clock cycles elapsed during startup
//To get result in seconds divide this number by 2^32
//Must have these includes:
#include <driverlib/osc.h>
#include <driverlib/aon_ioc.h>
//HF clock source should not already be XOSC_HF when function is called (e.g. function can be
placed near beginning of main())
//Must initialize I/Os before running this routine: e.g. PIN_init(BoardGpioInitTable);
//This function may not work correctly if compiler optimizations are turned on
uint32_t MeasureStartup(){
    uint32_t Count = 0;
    uint32_t PollCount = 0;
    uint32_t PrevPollCount=0;
    uint32_t State = 0;
    uint32_t PrevState = 0;
```

```

//Route SCLK_LF to DIO24, with DIO24 configured as input.
AONIOC32kHzOutputEnable();
HWREG(IOC_BASE+IOC_O_IOC_CFG24) = 0x20006307;
//Enable IOC input, connect DIO 24 to SCLK_LF

if (OSCClockSourceGet(OSC_SRC_CLK_HF) != OSC_RCOSC_HF) {
    OSCClockSourceSet(OSC_SRC_CLK_HF, OSC_RCOSC_HF);
    while (!OSCHfSourceReady());
    OSCHfSourceSwitch();
}

// Set XOSC_LF as SCLK_LF source
OSCClockSourceSet(OSC_SRC_CLK_LF, OSC_XOSC_LF);
//wait forever for SCLK_LF to be sourced from XOSC_LF

while((HWREG(AUX_DDI0_OSC_BASE+DDI_0_OSC_O_STAT0)&DDI_0_OSC_STAT0_SCLK_LF_SRC_XOSC_LF)!=DDI_0_OSC_S
TAT0_SCLK_LF_SRC_XOSC_LF) {};

State = HWREG(GPIO_BASE+GPIO_O_DIN31_0)&GPIO_DIO_24_MASK;
PrevState=State;
while(State != 0 && PrevState !=GPIO_DIO_24_MASK) //Wait for negedge of XOSC_LF
{
    PrevState=State;
    State = HWREG(GPIO_BASE+GPIO_O_DIN31_0)&GPIO_DIO_24_MASK;
}

PrevState=0;
OSCHF_TurnOnXosc();

while
((HWREG(AUX_DDI0_OSC_BASE+DDI_0_OSC_O_STAT0)&DDI_0_OSC_STAT0_PENDING_SCLK_HF_SWITCHING)!=DDI_0_OSC_ST
ATO_PENDING_SCLK_HF_SWITCHING)
{ //wait for pending bit
    State = HWREG(GPIO_BASE+GPIO_O_DIN31_0)&GPIO_DIO_24_MASK;

    PollCount=PollCount+1; //This counts number of polling cycles
    if(State!=PrevState) //This increments on every edge of XOSC_LF
    {
        Count=Count+1; //increase the count of detected XOSC_LF edges. This occurs at a rate
of 2 x freq of XOSC_LF
        PrevPollCount=PollCount;
        PollCount=0;
    }
    PrevState=State;
}
return 65536*Count+(65536*PollCount)/PrevPollCount;
//((65536*PollCount)/PrevPollCount is to get the fractional part of XOSC_LF cycles remaining
uncounted by Count
}

```

Figure 7 is an example plot generated with this code across temperature.

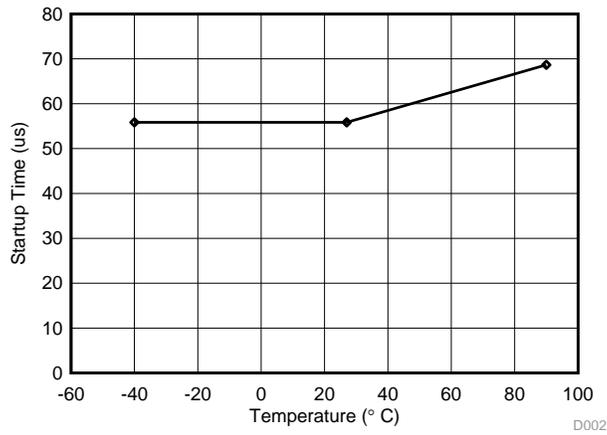


Figure 7. Example Start-Up Time Plot

6 Crystals for CC26xx and CC13xx

Table 3 through Table 5 provide appropriate crystals for use with the CC26xx and CC13xx devices.

Table 3. 48-MHz Crystals Suitable for CC13x2 and CC26x2

Manufacturer	MPN	Package	ESR max [Ω]	CL [pF]	Tol [ppm]	Temp tol [ppm]	Temp range [deg C]	Used in TI reference	Comment
Kyocera	CX2016DB48000 C0FPLC1	2016	30	7	10	20	-40 / 85	Used on LaunchPads	-
NDK	NX2016SA 48.000MHz EXS00A- CS05517	2016	40	7	10	30	-40 / 85	Used on LaunchPads	Used in TI characterization
TXC	8Y48072007	2016	40	8	<-3,7>	<-14,12>	-40 / 95	-	-

Table 4. 24-MHz Crystals Suitable for CC13x0 and CC26x0

Manufacturer	MPN	Package	ESR max [Ω]	CL [pF]	Tol [ppm]	Temp tol [ppm]	Temp range [deg C]	Used in TI reference	Comment
Epson	TSX-3225 24.0000MF15X- AC3	3225	60	9	10	10	-0,470588235	Yes, all EMs	Used in characterization
Epson	TSX-3225 24.0000MF10Z- AC3	3225	60	9	10	10	-0,266666667	-	Similar spec to F15X, but narrower temperature range.
Epson	TSX-3225 X1E00002104800	3225	40	9	10	20	-0,380952381	CC2640Q1EM	AEC-Q200 compliant
NDK	NX2016SA 24 MHz EXS00A-CS08891	2016	60	6	10	15	-0,352941176	Yes	Used in CC2640R2F WCSP Charaterization.
NDK	NX2016SA 24 MHz EXS00A-CS07553	2016	60	7	10	15	-0,352941176	No	Tested by NDK
NDK	NX3225SA 24 MHz EXS00A-CS07532	3225	50	9	10	15	-0,352941176	No	Tested by NDK
Kyocera	CX2016DB24000C 0WPRC1	2016	60	7	10	15	-0,470588235	No	Tested by Kyocera
Kyocera	CX2016SA24000C 0FRNC1	2016	30	7	10	25	-0,380952381	No	AEC-Q200 compliant
TXC	8Q24030001	1612	70	5.8	15	15	-0,352941176	No	Tested by TXC
Murata	XRCGB24M000FB P12R0	2016	80	6.0	+/- 15	+/- 20	-0,470588235	No	Tested by Murata

Table 5. 32.768 kHz Crystals Suitable for CC13xx and CC26xx

Manufacturer	MPN	Package	ESR [Ω]	CL [pF]	Tol [ppm]	Temp tol [ppm]	Temp range [deg C]	Used in TI reference	Comment
Epson	FC-135	3215	70k	7	20	-0.04x10e-6/degC^2	-0,470588235	Yes, all EMs	Lowest current consumption. Used in characterization
Epson	FC-12M	2012	90k	12.5	20	-0.04x10e-6/degC^2	-0,470588235	No	Smallest size. 200 nA higher current consumption than FC-135
NDK	NX3215SA 32.768kHz EXS00A-MU00529	3215	70k	7	20	-0.04x10e-6/degC^2	-0,470588235	-	Lowest current consumption. Used in characterization
NDK	NX2012SA 32.768kHz EXS00A-MU00530	2012	80k	7	20	-0.04x10e-6/degC^2	-0,470588235	-	-
Seiko Instruments Inc.	SC-32S 6pF	3215	70k	7	20	-0.03x10e-6/degC^2	-0,470588235	-	Tested by Seiko
Seiko Instruments Inc.	SC-20S 7pF	2012	70k	7	20	-0.03x10e-6/degC^2	-0,470588235	-	Tested by Seiko
Seiko Instruments Inc.	SC-16S 7pF	1610	90k	7	20	-0.035x10e-6/degC^2	-0,470588235	-	Tested by Seiko
Kyocera	ST3215SB32768C 0HPWBB	3215	70k	7	20	-0.05x10e-6/degC^2	-0,470588235	-	Tested by Kyocera
Kyocera	ST2012SB32768C 0HPWB4	2012	70k	7	20	-0.05x10e-6/degC^2	-0,470588235	-	Tested by Kyocera
TXC	9H03270072	2012	90k	7	20	-0.04x10e-6/degC^2	-0,380952381	-	

7 References

1. *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), 802.15.4-2006*, <http://standards.ieee.org/getieee802/download/802.15.4-2006.pdf>
2. *Bluetooth Core Specifications, Version 4.2*, <https://www.bluetooth.org/en-us/specification/adopted-specifications>
3. Texas Instruments: *CC2650 SimpleLink™ Multistandard Wireless MCU*
4. Texas Instruments: *SimpleLink™ CC2650 EVM Kit 4XD (CC2650EM-4XD) v1.0.3 Design Files*
5. Texas Instruments: *CC13x0, CC26x0 SimpleLink™ Wireless MCU Technical Reference Manual*

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from F Revision (Augst 2017) to G Revision	Page
• Update in Section 1.2.3	4
• Added new Section 6	14

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