

Reference Oscillator Crystal Requirements for the MC1320x, MC1321x, MC1322x, and MC1323x IEEE 802.15.4 Devices

1 Introduction

This document describes the reference oscillator crystal requirements for the MC1320x, MC1321x, MC1322x and MC1323x families of IEEE 802.15.4 2.4 GHz low power devices. These devices contain an on-board reference oscillator that is designed for very low power consumption and to meet tight frequency accuracy requirements. The IEEE 802.15.4 standard requires a frequency error of no greater than +/- 40 ppm. To ensure proper operation over temperature, limitations exist on the types of crystals that can be used.

For the Freescale IEEE 802.15.4 devices:

- The 20x and 21x devices both use a 16 MHz reference oscillator
- The 22x devices use a default 24 MHz reference (although a 13-26 MHz reference can be used)
- The 23x devices use a 32 MHz reference.

There are also differences between how the crystal load capacitance is provided for each family. This document details use of these reference oscillators and also

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provides specifications for the required crystals and lists of preferred crystals for each device.

2 Reference Oscillator Crystal Basics

The IEEE[®] 802.15.4 Standard requires that a wireless node frequency tolerances be kept within ± 40 ppm accuracy. This means that a total offset up to 80 ppm between transmitter and receiver will still result in acceptable performance. The following sections provide oscillator design and evaluation recommendations to obtain the required performance.

2.1 Basic Oscillator

Figure 1 shows the 16 MHz reference oscillator for the MC1320x/MC1321x families which is used here as a basic example. The oscillator is composed simply of the analog buffer amplifier, the crystal and the capacitive loading. The buffer is an inverting amplifier, and when the circuit is in resonant oscillation, the crystal provides the additional 180° phase shift required for oscillation (positive feedback).

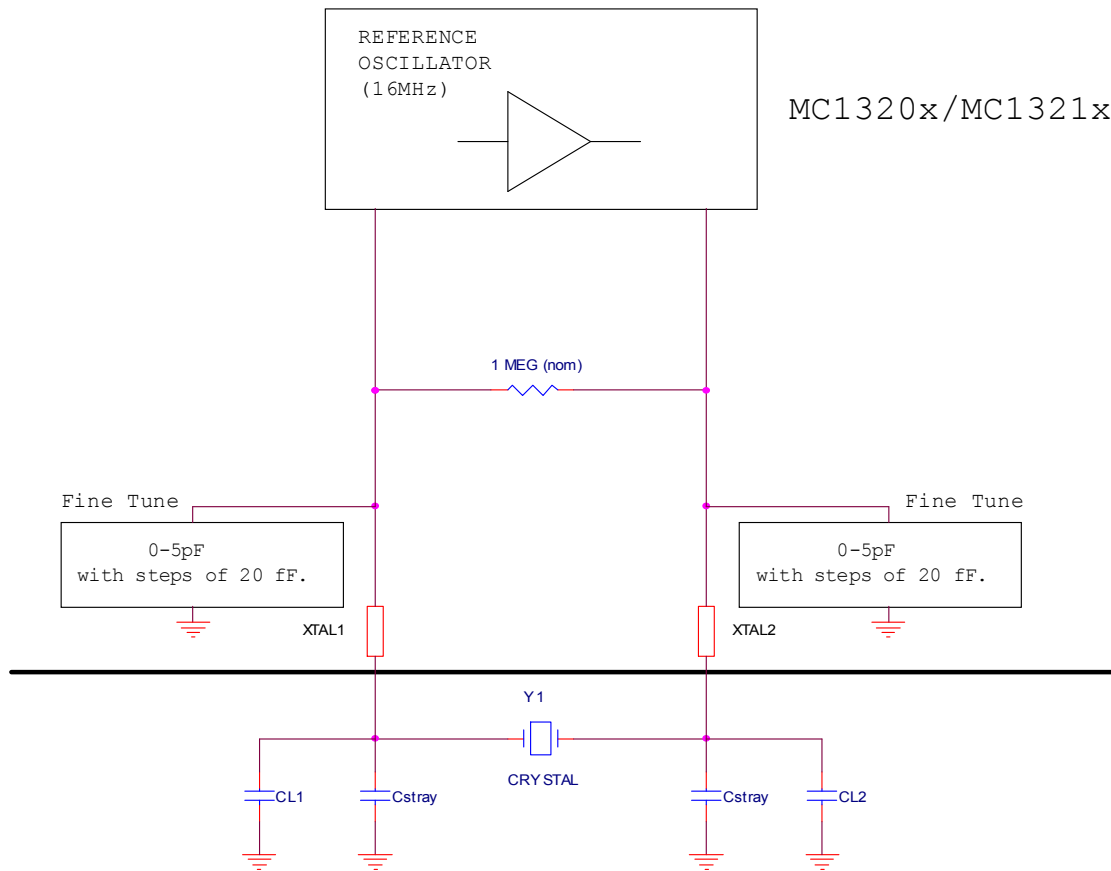


Figure 1. 16 MHz Crystal Oscillator for MC1320x and MC1321x Devices

The buffer output is fed back to the input through a resistor to DC bias the amplifier in the midrange of its analog swing. The resonant frequency of the crystal sets the frequency of operation. The resonant frequency of the crystal is set and specified at a particular capacitive loading.

The accuracy of the resonant frequency is dominated by:

- Capacitive loading on the crystal
- Temperature characteristics of the crystal.

The sum or net capacitive load to the crystal can consist of three components:

- External discrete load capacitors - properly sized as determined by the crystal spec and other load components
- Programmable onboard trim capacitors - to provide the user with best possible accuracy, Freescale provides trimmable load capacitors on these devices.
- Stray capacitance - for these frequencies, the specified load capacitance is small, typically at 7-9 pF. With such a low desired load value, the stray capacitance due to the device pads and pcb traces impact the other load components.

2.2 Crystal Considerations

The primary determining factor in meeting the 802.15.4 Standard of +/-40 ppm is the tolerance of the crystal oscillator reference frequency as set by the crystal. A number of factors can contribute to this tolerance and a crystal specification will quantify each of them:

1. The initial tolerance, also known as make or cut tolerance, of the crystal resonant frequency itself (at a specified load capacitance).
2. The variation of the crystal resonant frequency with temperature .
3. The variation of the crystal resonant frequency with time, also commonly known as aging.
4. The variation of the crystal resonant frequency with load capacitance, also commonly known as pulling. This is affected by:
 - a) The external load capacitor (C_L) values - initial tolerance and variation with temperature.
 - b) The internal trim capacitor (C_{trim}) values - initial tolerance and variation with temperature.
 - c) Stray capacitance (C_{stray}) on the crystal pin nodes - including stray on-chip capacitance, stray package capacitance and stray board capacitance

2.2.1 Crystal Load Capacitance

For any of the 2.4 GHz wireless devices, Freescale requires crystal load capacitance to be in the range of 5-9 pF. This low capacitance is required because these oscillators are designed for low power and larger capacitance can load the amplifiers more heavily.

The crystal manufacturer defines the load capacitance as that total external capacitance seen across the two terminals of the crystal. The oscillator amplifier configuration used here has two balanced load capacitances from each terminal of the crystal to ground. As such, the capacitance net loads for each pin are seen to be in series by the crystal, and the total load seen at each crystal terminal is the sum of the C_L , C_{trim} , and C_{stray} .

For the 16 MHz example, the external load capacitors are typically about 6.8 pF each, used in conjunction with a crystal that requires an 8-9 pF load capacitance. This value is used with the default internal nominal trim capacitor value (2.4 pF) and estimated stray capacitance value of 5-7 pF.

The value for the stray capacitance is determined empirically for a specific board layout. A different board layout may require different external load capacitor values. The on-chip trim capability may be used to determine the closest C_L standard value by adjusting the trim value and observing the frequency accuracy of the device. Each device provides trim capability, although each family differs in its configuration (see Section 2.3, “Design Evaluation and Optimization”).

Because of the trim capability, it is possible during manufacturing test, to trim out virtually all of the initial tolerance factors and put the frequency within less than 2-3 ppm on a board-by-board basis. Individual trimming of each board in a production environment may allow use of a lower cost crystal, but requires that each board go through a trimming procedure with added test cost. If the crystal is specified properly and the load capacitance is centered properly, production trimming is commonly not required.

A tolerance analysis budget may be created using all the previously stated factors. It is an engineering judgment whether the worst case tolerance will assume that all factors will vary in the same direction or if the various factors can be statistically rationalized using RSS (Root-Sum-Square) analysis. The aging factor is usually specified in ppm/year and the product designer can determine how many years are to be assumed for the product lifetime. The total budget must fit within the +/-40 ppm limit of the IEEE 802.15.4 Standard.

2.2.2 Crystal Temperature Variation

The make or cut frequency tolerance of a crystal is typically specified at 25°C (room temperature). The frequency of device (in the application) at room temperature should be set within the cut tolerance (typically +/-10 ppm) or better. The oscillator frequency variation with temperature from this set point is dominated by the crystal characteristics. Frequency stability (temperature drift) is a specified parameter for the crystal over its temperature range. Figure 2 shows a curve of frequency tolerance versus temperature for a typical AT-cut crystal. In this example, the crystal could meet +/-12 ppm max limit over a temperature range of -40°C to +85°C. A manufacturer can change the shape of this curve by varying the manufacturing of the crystal.

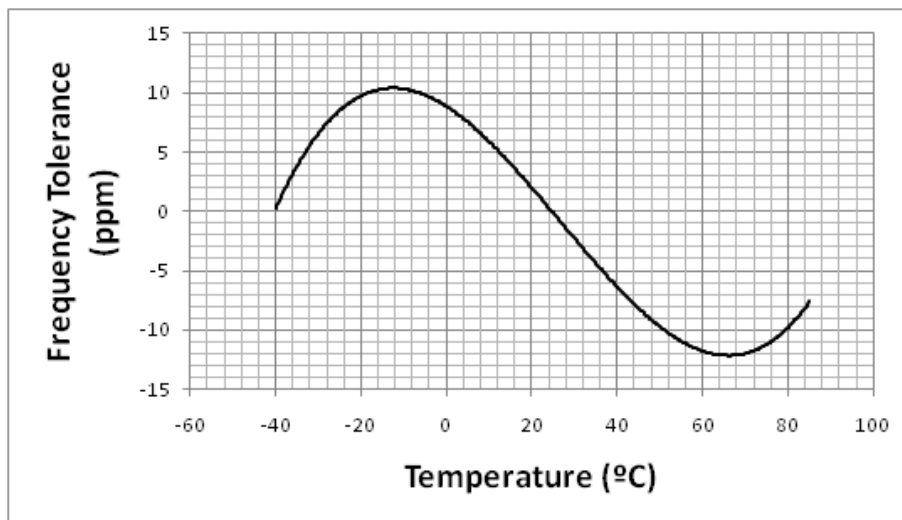


Figure 2. Typical AT-cut Crystal Frequency Tolerance vs. Temperature

Notice that the curve uses 25°C as its reference point, i.e., deviation is 0 ppm at this temperature.

2.2.3 Crystal Equivalent Series Resistance (ESR)

Another crystal characteristic important to performance is its equivalent series resistance. ESR is the resistive component of the crystal impedance at resonance. ESR is expressed in ohms, and the lower this number is, the better the crystal. As ESR gets higher, the start and run load to the amplifier gets higher can hinder oscillator start and run, especially at low temperatures.

2.2.4 Crystal Specification

Using the 16 MHz crystal for the MC1320x/MC1321x families as an example, [Table 1](#) shows recommended specifications. Freescale prefers to specify the crystal such that it is capable of maintaining to total frequency tolerance of +/-30 ppm over the desired temperature range; this allows a margin of +/-10 ppm for manufacturing variation, component tolerance, and aging.

In considering the table, critical parameters include:

- Desired frequency - specified to the Hz
- Frequency tolerance @ 25°C - this is maximum allowed for “cut” or manufacturing frequency variation.
 - This number may allowed to be larger than +/-10 ppm for a more limited temperature range, if the frequency stability allows it
 - This number may be allowed to be larger if the user is willing to trim the center frequency at manufacturing final test
- Frequency stability over the desired temperature range - this is the frequency drift of the crystal with temperature.
- Equivalent series resistance (ESR) - this a maximum series impedance for the crystal at resonance. Freescale recommends that this range from 40-60 Ω depending on the device.
- Load capacitance (C_L) - the number typically ranges from 5-9 pF.

Table 1. Recommended 16 MHz Crystal Specifications¹

Parameter	Value	Unit	Condition
Frequency	16.000000	MHz	
Frequency tolerance (cut tolerance) ²	± 10	ppm	at 25 °C
Frequency stability (temperature drift) ³	± 15	ppm	Over desired temperature range
Aging ⁴	± 2	ppm	max
Equivalent series resistance (ESR)	40-50	Ω	max
Load capacitance	5 - 9	pF	
Shunt capacitance	<2	pF	max
Mode of oscillation			fundamental

¹ User must be sure manufacturer specifications apply to the desired package.

² A wider frequency tolerance may acceptable if application uses trimming at production final test.

³ A wider frequency stability may be acceptable if application uses trimming at production final test.

⁴ A wider aging tolerance may be acceptable if application uses trimming at production final test.

2.3 Design Evaluation and Optimization

Each design should initially be optimized and verified as different crystals, layouts and printed circuit board characteristics can impact the frequency accuracy. Refer to the *Freescale IEEE 802.15.4 / ZigBee Node RF Evaluation and Test Guidelines*, Document No. ZRFETRM.pdf for more information.

NOTE

- Freescale provides several reference designs for each device family with specific layouts and crystals. It is recommended that a designer use one of these reference designs as their starting point to get the best oscillator performance as well as best RF performance
- In this application note, Freescale lists a number of recommended crystals for each family. It is recommended to use these devices.
- If the user chooses a custom crystal, it is suggested reference oscillator start-up and LOW POWER run be evaluated at low temperature. High ESR is a most critical characteristic. It is the user's responsibility to qualify their selected crystal in their application.

In evaluating a new layout and design, the first consideration is to center crystal loading such that the default load causes the oscillator frequency to be near its designed center frequency.

- External load capacitors, when present should be of equal value.
- The frequency accuracy of the reference oscillator must be observed to adjust the load and trim capacitance.
 - The CLKO (clock out) signal is available on the MC1320x and MC1321x families and is enabled by default
 - On the MC1322x and MC1323x families, a peripheral timer (TPM) output must be programmed and enabled to observe the system clock
 - Be sure the frequency counter has a reference oscillator that allows measurement accuracy within 1-2 ppm or better
- The load centering procedure is dependent on family
 - For the MC1320x and MC1321x families allow the onboard trim capacitance to remain at default (center range) and adjust the external load capacitors to center the reference frequency by observing signal CLKO. If the external capacitors do not adjust the frequency with sufficient accuracy, trim the onboard capacitance to center the frequency.
 - For the MC1322x family no external load capacitors are normally present and the default value of the onboard load capacitance is “no load”. Observe the system clock accuracy with a timer output and trim the onboard load capacitance to set the center frequency. This trim value should become the value programmed by user software at start-up; it may be adjusted at final test.
 - For the MC1323x family, allow the onboard trim capacitance to remain at default (center range) and adjust the external load capacitors to center the reference frequency by observing a timer output. If the external capacitors do not adjust the frequency with sufficient accuracy, trim the onboard capacitance to center the frequency.

Once a design has been characterized, it is good practice to verify the center frequency as part of the manufacturing final test. Unit-by-unit trimming is commonly not required if the design has been characterized properly. However, Freescale devices provide trim capability and it can be incorporated into the final test procedures.

3 16 MHz Oscillator (MC1320x and MC1321x)

The MC1320x and MC1321x devices all use a common 16 MHz crystal reference oscillator design.

3.1 16 MHz Oscillator Description

The 16 MHz reference oscillator is used as an example of a basic oscillator and is shown in [Figure 1](#). To add additional detail, an on-board regulator provides constant operating voltage to the oscillator under varying supply voltage, and the on-chip feedback resistor around the buffer is typically 1 Megohm.

With this design, external load capacitors (CL1 and CL2) provide the bulk of the required load capacitance, and on-board mirrored trim capacitor networks provide the remainder of the required load capacitance.

The trim capacitance:

- Used for fine-tuning the reference frequency
- Capacitance value range is 0 to 5 pF, in 256 steps with a default value of 2.4 pF. Experience has shown that frequency changes 3-4 Hz/step which allows for excellent control.
- Value is software programmable through a control register

Because of the IEEE[®] 802.15.4 Standard requirements and desired battery operation, the oscillator is a very low power design. To provide higher start margin, current drive is increased during power-up and start. After oscillation begins and is stable, a counter is used to “count” the device out of reset, and in turn, operating current is reduced for lower power operation.

The characteristics of a crystal are such that it is high impedance at start, and much lower impedance at resonance. As a result, the reduced operating current is not problematic in that the crystal is in resonance and presents this low ESR.

3.2 Recommended 16 MHz Crystal specifications

The suggested 16 MHz crystal specifications are shown in [Table 1](#). A number of the stated parameters are related to desired package, desired temperature range and use of crystal capacitive load trimming.

3.3 Evaluated 16 MHz Crystals

Freescale has evaluated crystals from several manufacturers that are available as standard part numbers for this application. These are presented in [Table 2](#).

Table 2. 16 MHz Crystals for MC1319x, MC1320x, and MC1321x

Manufacturer	Part Number	Package	Cut Tolerance (ppm)	Temperature Range	Comment
Nihon Dempa Kogyo (NDK)	NX3225SA-16MHZ	3.2x2.5 mm	±15	-30°C to +85°C	Type NX3225SA, Spec # EXS00A-03311
Epson Toyocom	TSX3225-16M-26360	3.2x2.5 mm	±18	-40°C to +85°C	Package TSX-3225
AVX / Kyocera	CX3225SB 16000E0FPZ25	3.2x2.5 mm	±16	-40°C to +85°C	Model CX3225SB, Spec # K1101-06368-433
Daishinku KDS	DSX321G-16.0MHZ	3.2x2.5 mm	±20	-10°C to +60°C	Type DSX321G, Spec # 1B216000BB0B

4 13-26 MHz Oscillator (MC1322x, 24 MHz Default)

The MC1322x devices all use a common crystal reference oscillator design that is 24 MHz by default, but can be used with crystals ranging from 13-26 MHz

4.1 13-26 MHz Oscillator Description (24 MHz default)

The 13-26 MHz reference oscillator consists of an analog buffer/amplifier and its associated loading (see [Figure 3](#)). The oscillator uses an off-chip fundamental mode crystal of 13-26 MHz with 24 MHz the recommended nominal frequency. An on-board regulator provides constant operating voltage to the oscillator under varying supply voltage. An on-chip 1 MΩ feedback resistor around the buffer provides DC-bias such that the buffer operates in analog mode.

The crystal is specified with a particular load capacitance (typically ≤ 9 pF) and all the load capacitors are internal and programmable. For the purpose of reference, the integrated load capacitors on each leg include:

- A single 4pF capacitor (1 program bit)
- Coarse tune capacitor array of 1, 2, 4 and 8pF (4 program bits)
- Fine tune capacitor array of 5 pF in 160 fF steps (5 program bits).

Therefore, the trimmable crystal load capacitance range can be between a load of 0 pF to 24 pF for each leg. Experience has shown that frequency changes about 8 Hz/step for the course tune and about 1.25 Hz/step for the fine tune. The load value is software programmable through a control register.

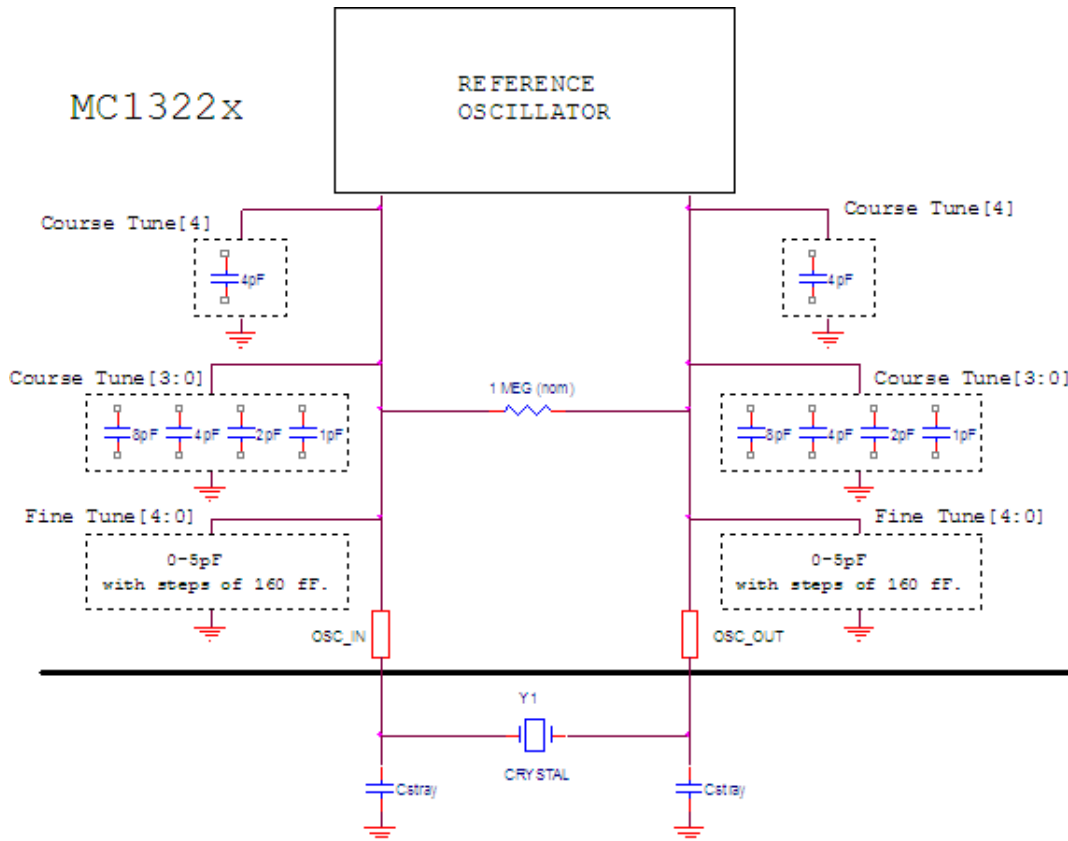


Figure 3. 13-26 MHz Reference Oscillator

The onboard load capacitance is totally disabled by default when exiting reset. The only default crystal load capacitance are the signal pads and stray capacitance. The oscillator will start with a frequency higher than its specified cut tolerance. The applications software must program the required load capacitance into the device to properly load the crystal for the cut tolerance and loading.

4.2 Recommended 24 MHz Crystal specifications

The recommended 24 MHz crystal specifications are shown in [Table 3](#). A number of the stated parameters are related to desired package, desired temperature range and use of crystal capacitive load trimming.

Table 3. Recommended 24 MHz Crystal Specifications

Parameter	Value	Unit	Condition
Frequency	24.000000	MHz	
Frequency tolerance (cut tolerance) ¹	± 10	ppm	at 25 °C
Frequency stability (temperature drift)	± 15	ppm	Over desired temperature range
Aging	± 2	ppm	max
Equivalent series resistance ²	40-50	Ω	max
Load capacitance	5 - 9	pF	

Table 3. Recommended 24 MHz Crystal Specifications (continued)

Parameter	Value	Unit	Condition
Shunt capacitance	<2	pF	max
Mode of oscillation			fundamental

¹ A wider frequency tolerance may be acceptable if application uses trimming at production final test.

² The higher ESR may be acceptable with lower load capacitance.

4.3 Evaluated 24 MHz Crystals

Freescale has evaluated crystals from several manufacturers that are available as standard part numbers for this application. [Table 4](#) shows these values.

Table 4. 24 MHz Crystals for MC1322x

Manufacturer	Part Number	Package	Cut Tolerance (ppm)	Temperature Range	Comment
Nihon Dempa Kogyo (NDK)	NX3225SA-24MHZ	3.2x2.5 mm	±10	-30°C to +85°C	Type NX3225SA, Spec # EXS00A-CS02020
Nihon Dempa Kogyo (NDK)	NX3225SA-24MHZ	3.2x2.5 mm	±10	-40°C to +105°C	Type NX3225SA, Spec # EXS00A-CS00225
Epson Toyocom	TSX-3325-24MHZ	3.2x2.5 mm	±10	-40°C to +85°C	Package TSX-3225 Spec # OUTD-2B-0418(2)
Daishinku KDS	DSX321G-24.0MHZ	3.2x2.5 mm	±10	-40°C to +85°C	Type DSX321G, Spec # 1C224000AB0D
CTS	CTS_55012_X2_24M_40-85	3.2x2.5 mm	±10	-40°C to +85°C	Spec # 55012

5 32 MHz Oscillator (MC1323x)

The MC1323x devices all use a common 32 MHz crystal reference oscillator design.

5.1 32 MHz Oscillator Description

[Figure 4](#) shows the 32 MHz reference oscillator. The crystal has an amplifier block with Amplitude Level Control (ALC) to optimize power consumption and help startup. It uses an off-chip 32 MHz crystal and has internal programmable trim load capacitors. The primary load capacitors are external.

With this design, external load capacitors (CL1 and CL2) provide the bulk of the required load capacitance, and on-board mirrored trim capacitor networks provide the remainder of the required load capacitance.

- The onboard capacitors consist of two arrays on each pin, each trimmable by a 4-bit control field.
- The larger or coarse array can be from 0 - 4.215 pF with steps of 281 fF. The rate of frequency change is about 125 Hz/step

- The smaller or fine array can be from 0 - 300 fF with steps of 20 fF. The rate of frequency change is about 11 Hz/step.
- The is software programmable through a control register

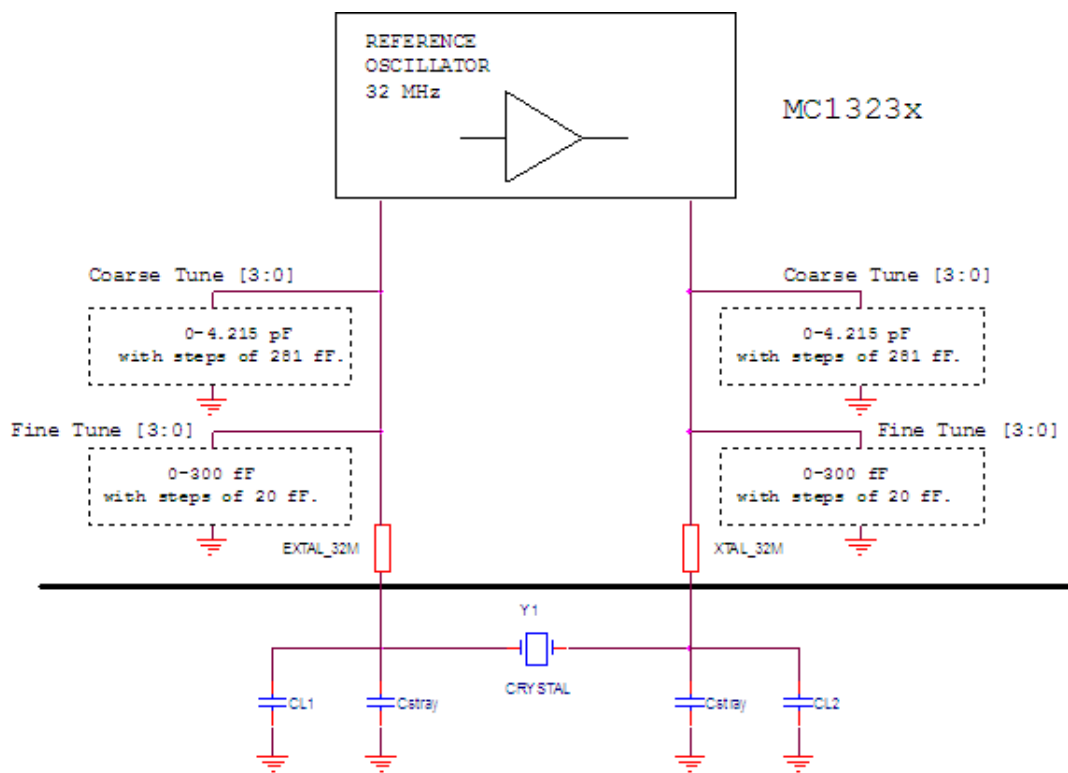


Figure 4. 32 MHz Reference Oscillator

5.2 Recommended 32 MHz Crystal specifications

Table 5 shows the recommended 32 MHz crystal specifications. A number of the stated parameters are related to desired package, desired temperature range and use of crystal capacitive load trimming.

Table 5. Recommended 32 MHz Crystal Specifications

Parameter	Value	Unit	Condition
Frequency	32.000000	MHz	
Frequency tolerance (cut tolerance)	± 10	ppm	max at 25 °C
Frequency stability (temperature drift)	± 16-18	ppm	Over desired temperature range
Aging	± 2	ppm	max
Equivalent series resistance	60	Ω	max
Load capacitance	9	pF	max
Shunt capacitance	<2	pF	max
Mode of oscillation			fundamental

5.3 Evaluated 32 MHz Crystals

Freescale has evaluated crystals from several manufacturers that are available as standard part numbers for this application. [Table 6](#) shows these values.

Table 6. 32 MHz Crystals for MC1322x

Manufacturer	Part Number	Package	Cut Tolerance (ppm)	Temperature Range	Comment
Nihon Dempa Kogyo (NDK)	NX3225SA-32MHZ	3.2x2.5 mm	±10	-40°C to +85°C	Type NX3225SA, Spec # EXS00A-CS02368
Epson Toyocom	TSX-3325-32MHZ	3.2x2.5 mm	±10	-40°C to +85°C	Package TSX-3225 Spec # OUTD-2B-0546



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