Application Report

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# AN100 - Crystal Selection Guide

Fredrik Kervel


## ABSTRACT

RF systems are highly dependent on accurate clocks for correct operation. A deviation in clock frequency is directly reflected as a deviation in radio frequency. This can degrade RF performance, violate legal requirements or in worst case lead to a non-functioning system.

The scope of this application report is to give the design engineer a quick guide on how to design, tune and verify the clock circuit for TI's LPRF products. A list of suggested crystals that can be used with CC253x and CC254x is presented. The designer must pick a crystal that satisfies their requirements on size, tolerance and temperature range. If other crystals are to be used, fundamental mode, AT cut crystals is highly recommended due to accuracy and ease of use.


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# 1 Crystal Oscillator Theory

## 1.1 Oscillator Operation

The circuit used as high frequency, high accuracy clock source for TI's low power RF products is called a "Pierce Oscillator" and is shown in Figure 1. The oscillator circuit consists of an inverting amplifier (normally a regular inverter), a feedback resistor, two capacitors and a crystal. The first two components are internal in the IC while the capacitors and the crystal are external and must be selected for each separate design.

During normal operation, the crystal and the capacitors form a pi filter providing 180° phase shift to the internal amplifier, thus keeping the oscillator locked at the specified frequency.

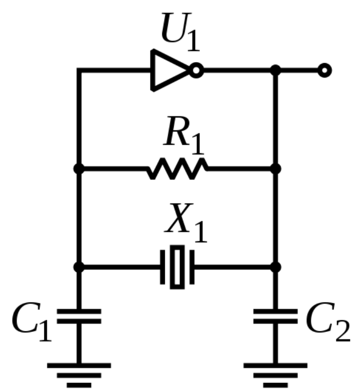


**Figure 1. Pierce Oscillator**

## 1.2 Crystal Tolerance

The total tolerance of a Crystal is dependent on three factors: production tolerance, temperature tolerance and age. All of these values are given in [ppm] (parts per million) and can be found in the manufacturer's data sheet. To get the total maximum tolerance of a certain crystal all these factors must be accounted for.

Crystal frequency deviation is directly transferred to RF deviation, thus a deviation in the crystal oscillator frequency of X ppm leads a deviation in carrier frequency of X ppm. Therefore, it is important to select a crystal with performance within the limits of the RF specifications. Of course, the end products expected age and operating conditions (temperature) must be taken into consideration.

For 802.15.4 (RF4CE), the max deviation in carrier frequency is limited to 40 ppm. [1]

For Bluetooth Low Energy, the limit is 40 ppm. [2]

## 1.3 Load Capacitance

Correct operation of the crystal oscillator is dependent on the values of the two external capacitors, $C_1$ and $C_2$ in Figure 1. These capacitors together with any parasitic capacitance in the PCB and the crystal terminals compose the total load capacitance seen by the crystal. The optimum load capacitance for the crystal, $C_L$, is given in the crystal datasheet and $C_1$ and $C_2$ should be matched to this value according to Equation 1:

$$C_L = \frac{C_1' \cdot C_2'}{C_1' + C_2'} \tag{1}$$

Where, $C_x'$ is the sum of the capacitance in $C_x$, the parasitic capacitance in the PCB trace and the capacitance in the terminal of the crystal. The sum of the two latter parts will typically be in the range of 2 – 8 pF.

The easiest way to find the optimum load capacitor values for a given circuit and layout is through experiments. The radio can be set to put out a constant carrier at a given frequency with SmartRF Studio. By measuring the output frequency with a Spectrum Analyzer, the offset can easily be found.

### 1.4 $R_S$ (ESR) and Negative Resistance

$R_S$ or equivalent series resistance (ESR) is a parameter of the crystal, which can be found in the device-specific data sheet. Negative resistance is a parameter of the complete oscillator circuit, including capacitor values, crystal parameters and on-chip circuit. To ensure correct function of the crystal oscillator, negative resistance should be at least 5 times greater than $R_S$.

$$R_S < \frac{R_{neg}}{5} \quad (2)$$

If this is not true the oscillator might not operate as expected or it might not start up at all.

The negative resistance of the circuit can be found by introducing a resistor in series with the crystal. To avoid parasitic effects it is recommended to use a 0201 resistor for this task. The threshold of resistance where the oscillator is no longer able to start up is approximately the same as the circuit negative resistance. An example of resistance vs. startup time and negative resistance threshold is shown in Figure 2.

Note that higher load capacitor values decreases the negative resistance and rises the startup time.

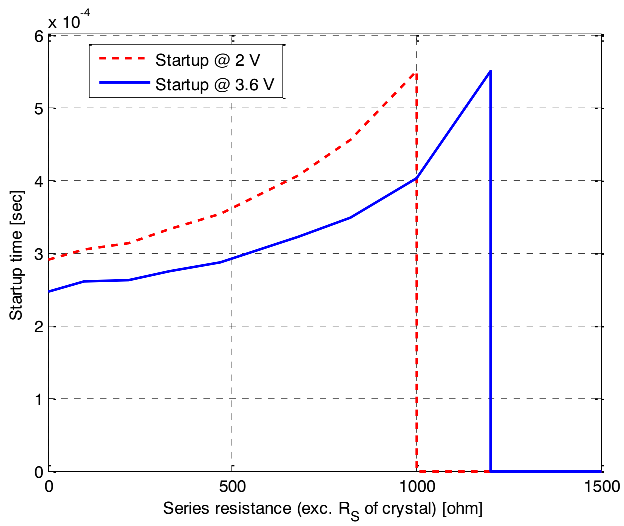


**Figure 2. Startup Time vs. Added Series Resistance [FA-128 on CC2540EM]**

### 1.5 FREQTUNE Register

The CC253x and CC254x radios have the possibility to add extra load capacitance on-chip for oscillator frequency tuning. The capacitance value is adjusted by the 4 last bits (3:0) of the 'FREQTUNE' register. The default value of the register is 0x0F which corresponds to no added capacitance. For each decrement in the register value, extra capacitance is added to the oscillator circuit, reducing the oscillator frequency.

The level of tuning possible, also known as pullability, will differ from crystal to crystal as shown in Figure 3. Some manufacturers present this value in the data sheet given in ppm/pF.

Note that parameters as $R_{neg}$ and startup time are dependent on the load capacitance, so changing FREQTUNE value also changes these parameters. Figure 4 shows how startup time will vary with added load capacitance.

In both Figure 3 and Figure 4 the load capacitance is tuned such that FREQTUNE = 0x0F corresponds to approximately 0 ppm offset from correct center frequency.

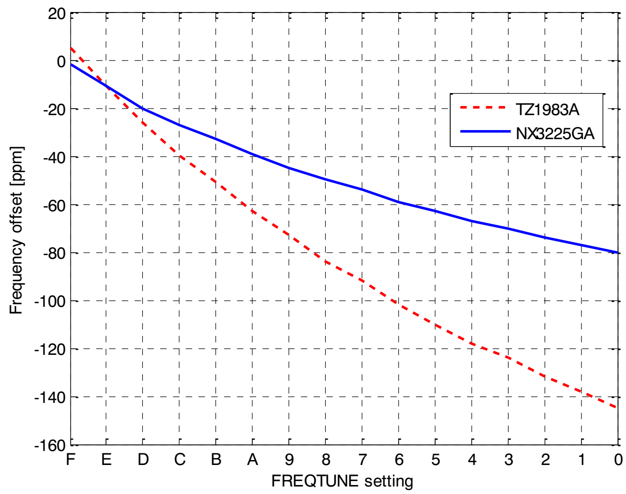


**Figure 3. FREQTUNE Pullability Example**

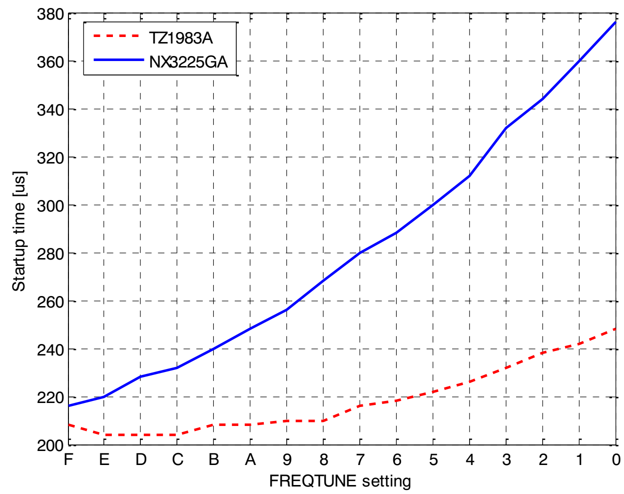


**Figure 4. Startup Time vs. FREQTUNE Setting**

## 2 Selecting Crystals

Some suggested crystals are presented in Table 1 and Table 2. These crystals are tested with the CC2540 on the two EVM boards “CC2540EM Crystal Eval” and “CC2540EM HC49smd Eval”. The first board has footprints for crystals varying in size from 2016 through 4025 while the latter board has footprints for HC49smd crystals.

Although the tests have been performed with CC2540, the crystals will have similar performance on any CC253x or CC254x devices as well.

The crystals are listed with their key data sheet values in Table 1. Table 2 contains data measured on TIs EVMs.

Note that measured data will differ from board to board as a result of layout and PCB characteristics. The capacitor values presented are valid for the TI crystal evaluation boards; other values might be needed on other boards.

Selecting crystals for a specific application will often be dependent on three factors: size (footprint area, height), performance (accuracy over temperature, lifetime) and cost (for example, higher performance and smaller package = higher price).

**Table 1. Data Sheet Values**

| Manufacturer | MPN | Package | ESR (Ω) | CL (pF) | freq (MHz) | Tolerance (ppm) | Temp Tolerance (ppm) | Again (ppm/ year) | Temp Range [°C] | |
|---|---|---|---|---|---|---|---|---|---|---|
| Epson Toyocom | FA-128 | 2016 | 60 | 10 | 32 | 10 | 10 | 5 | 85 | -40 |
| Epson Toyocom | FA-20H | 2520 | 60 | 10 | 32 | 10 | 10 | 3 | 85 | -40 |
| NDK | NX3225GA | 3225 | 50 | 12 | 32 | 20 | 30 | | 85 | -40 |
| NDK | NX3225JA | 3225 | 60 | 10 | 32 | 20 | 20 | | 70 | 0 |
| Tai-Saw Technology | TZ1983A | HC49smd | 50 | 10 | 32 | 10 | 20 | 1 | 70 | 0 |

**Table 2. Measurements on TI EM @25°C**

| MPN | C231 | C221 | Startup time | | Negative Resistance | FREQTUNE Pullability |
|---|---|---|---|---|---|---|
| | | | 2 V | 3 V | | |
| FA-128 | 12 pF | 12 pF | 290 µs | 251 µs | 1kΩ | -54 ppm |
| FA-20H | 12 pF | 12 pF | 408 µs | 352 µs | | -35 ppm |
| NX3225GA | 12 pF | 15 pF | 236 µs | 216 vs | 820 > $R_{neg}$ > 680 | -78 ppm |
| TZ1983A | 10 pF | 12 PF | 228 µs | 208 µs | | -150 ppm |

## 3 References


1. IEEE Standards Association 802.15.4-2006 (IEEE download)
2. IEEE Get Program 802.15.1-2005 (IEEE download)

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