Crystal Oscillators

by
Troy Ruud
email: libdev-support@poci.amis.com

Introduction

This section explains the basics of the set-up and operation of AMI's crystal oscillator drive cells. The purpose is to aid in design of the required off-chip components, and to ensure proper operation of the oscillator cell within its frequency range. A table giving approximate component sizes is included at the end of this section.

Definition

An AMI crystal oscillator consists of two pad sites, a quartz crystal, lead capacitors, and a start-up and feedback resistor. The IDQ** cell is the input to the oscillator circuit and is connected to the second cell, the ODQ*****. The second cell is the output driver of the oscillator circuit. It is within this cell that the signal receives the appropriate phase and gain to drive the input of the off-chip crystal and produce oscillation. Figure 1a shows a typical connection of a fundamental mode oscillator circuit, and Figure 1b shows a typical connection of a third overtone oscillator circuit. These modes will be defined in the 'Crystal Types' section.

Design Modeling

Closed loop transient analysis of crystal oscillator circuit configurations is very difficult. However, open loop analysis allows determination of phase and gain characteristics of the circuit. Figure 2 shows one open loop model used in simulation. Notice the break in the circuit loop at points A and B. A frequency sweep generator is connected to node A using an extra IDQ** in order to properly bias the input. An extra ODQ***** is hooked to B to provide proper loading for the output. Using SPICE, an AC analysis extracts the phase and gain of the circuit. Using these simulations in the design of the oscillator pad piece cells allows for a range of frequencies to be driven from each cell. For a specific application, this range would be controlled through the R-series, C_{in} and C_{out} external components.

Design Methodology

A methodology was developed to specify the external component sizes that best control oscillator gain and phase at the break in the circuit model. A gain to provide robust operation across simulation corners was chosen using actual data from the model. External component sizes were varied during simulation until the test circuit obtained these desired performance requirements. These experiments were repeated for different frequencies within the oscillator's range. To understand the simulation data, refer to Figure 3, which displays an example result: a graph of gain and phase versus frequency.

The series resonance point ω_S or operational frequency of the crystal oscillator occurs when the gain is greater than one and the phase crosses 0° going negative.

Figure 1a
TYPICAL CONNECTION OF A FUNDAMENTAL MODE OSCILLATOR CIRCUIT

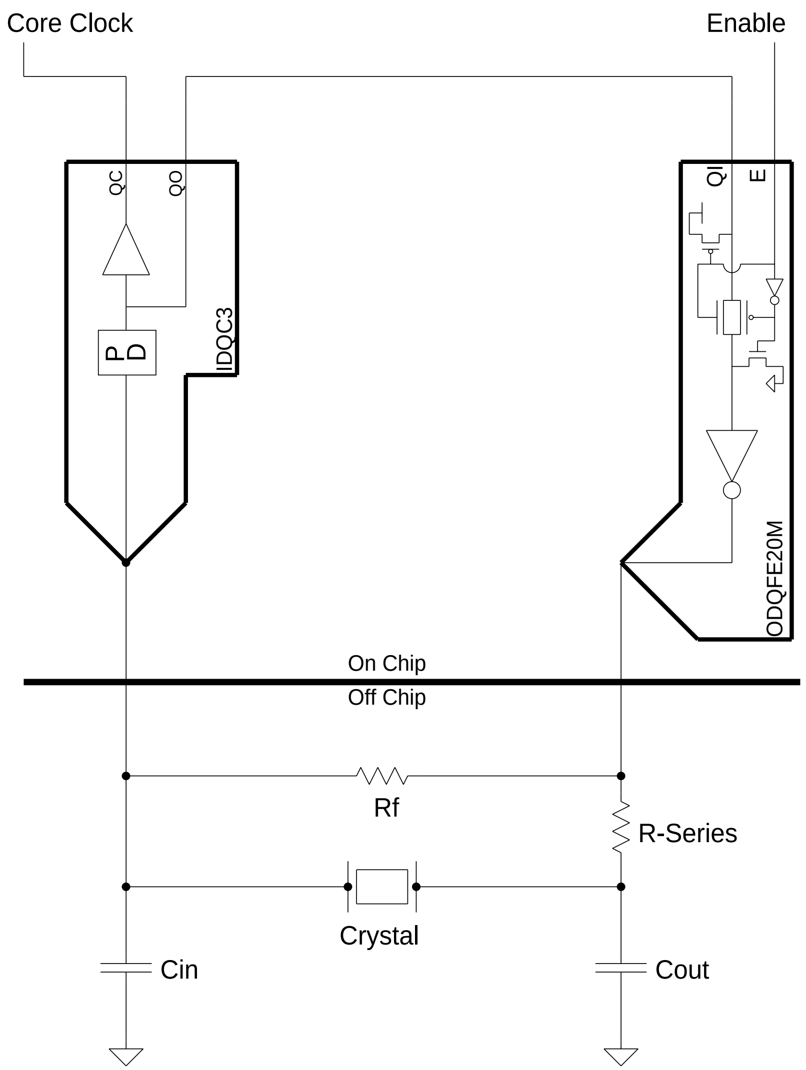

Figure 1b
TYPICAL CONNECTION OF A THIRD OVERTONE OSCILLATOR CIRCUIT
(with parallel tank circuit)

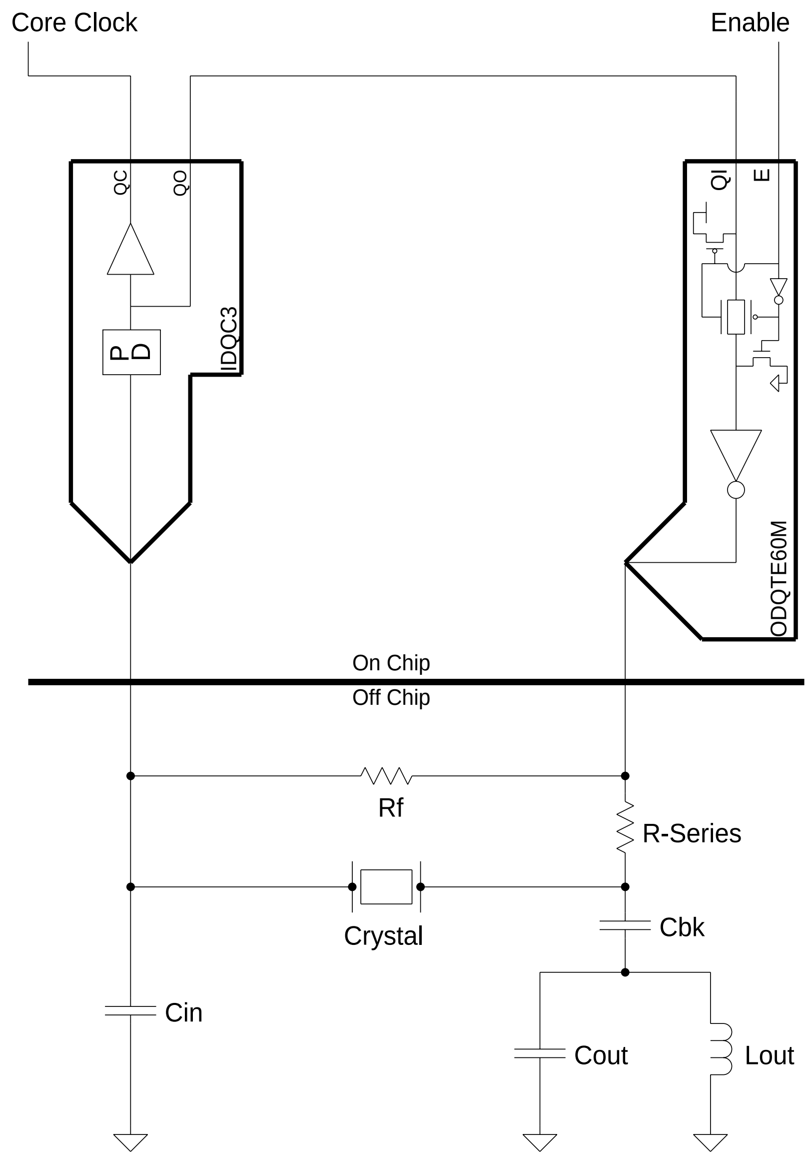

Figure 2
OPEN LOOP MODEL USED IN SIMULATION

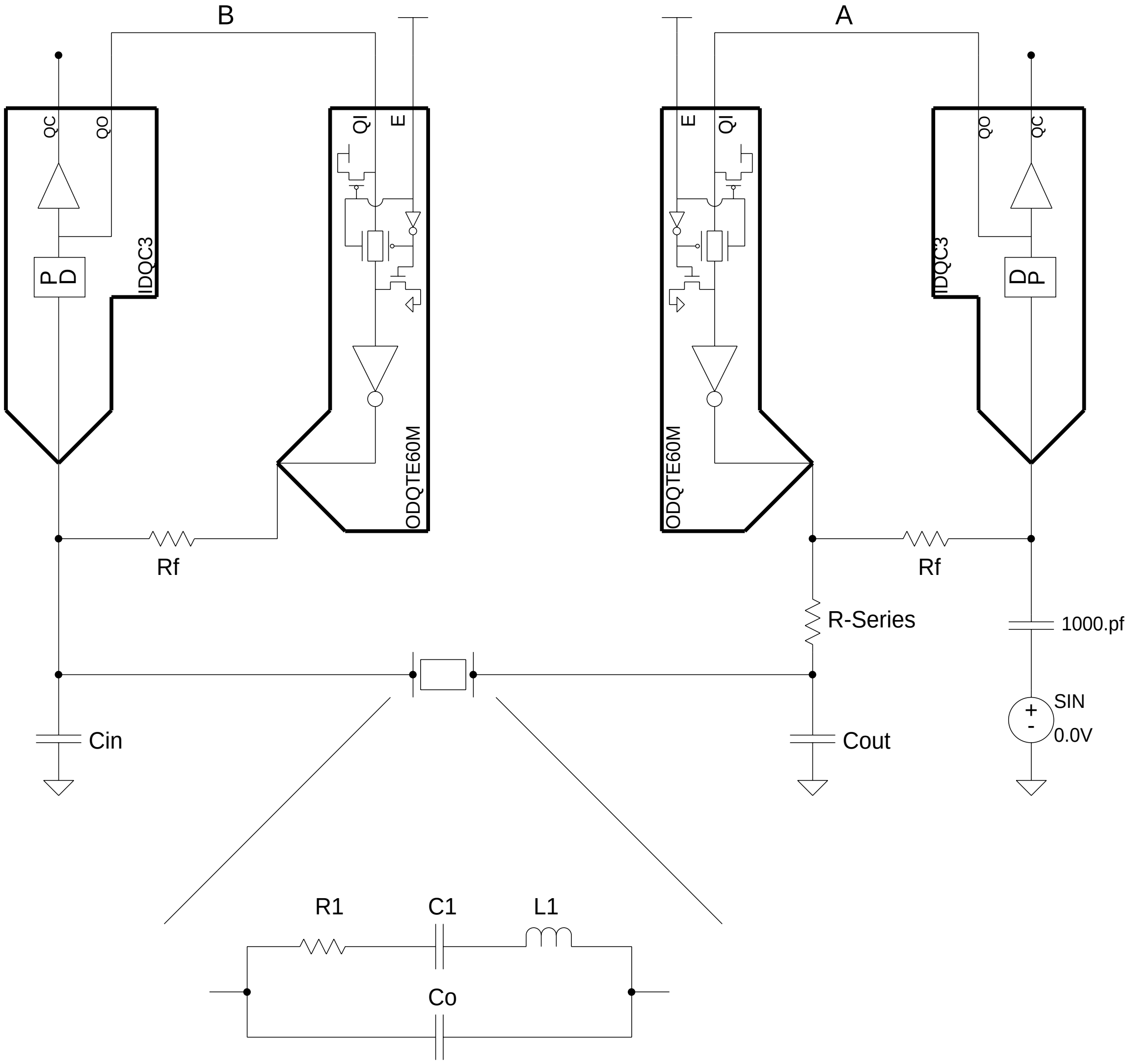

Figure 3
GAIN AND PHASE VERSUS FREQUENCY

The depth of the phase trough should be close to -90° in order to maintain maximum stability during operation. The final point of concern is at parallel resonance ω_L. This occurs at the frequency at which the phase crosses 0° rising. At this point, the gain of the circuit should be much less than one, thus eliminating the possibilities of harmonic amplification.

The performance of an oscillator is determined by the following criteria:

1. The corresponding gain at ω_S for WCS (Worse Case Speed) and WCP (Worst Case Power) simulation corners is greater than 2V/V and less than 12V/V, respectively.
2. The gain at ω_L is much less than 1V/V to eliminate harmonics.
3. The trough depth is approximately equal to -90° to provide maximum stability.

Crystal Modeling

Within a crystal package is a cut piece of quartz. This quartz piece is plated and contacted to leads within the package. The range of frequencies offered are provided through variations in the cut of the quartz crystal. To simulate the effect of the crystal in a design circuit, a piezoelectric model is used. This model simulates the mechanical vibrations of the quartz with an electrical circuit. See Figure 2 for the circuit configuration of a quartz crystal model. R_1, C_1, and L_1 are considered the motional arm of the crystal, and C_0 is the shunt capacitance of the package. The series resonance frequency of the crystal is then determined by the formula:

$$f_s = \frac{1}{2\pi\sqrt{L_1 \cdot C_1}}$$

At the series resonance point, described in the Design Methodology section, the ESR (Effective Series Resistance) of the crystal drops to approximately the value of R_1. This condition allows gain to increase around the loop, and oscillation occurs near f_s. At the parallel resonance point the ESR reaches its maximum resistive value. This differs from crystal to crystal and is in the megaohm range. These two points are shown in Figure 3 as the 0° crossings on the phase plot. The crystal oscillator “start-up” cycle occurs when the chip is powered-up and amplification of noise occurs until the oscillator is operating rail-to-rail.

Crystals can be produced to provide very exacting frequencies with high Q and low parts per million (ppm). The unit ‘ppm’ is used to define variation of a crystal’s series resonance frequency from its specified frequency. An example of this would be: a 20ppm, 1.0MHz crystal would not vary more than +/- 20Hz from its 1.0MHz specified frequency.

Crystal Types

Crystal oscillators are manufactured in two basic types for different modes of operation. Both types of crystals use the crystal model described in ‘Crystal Modeling’. For the remainder of this section, the crystal types are referred to by their mode of operation, one being *fundamental* and the other being *third overtone*. Crystals can also implement fifth or greater overtone modes, with similar principles.

The fundamental mode crystals are

designed and manufactured to oscillate at the crystal's fundamental frequency. The corresponding circuit configuration shown in Figure 1a works well for these types of crystals. Fundamental mode crystals can be found in various frequencies up to about 30 MHz. For frequencies beyond this, the second type of crystal and a different circuit configuration is required.

Third overtone crystals are designed and manufactured to operate at the third overtone frequency from the crystal's fundamental. Overtones differ from harmonics in that harmonics are integer multiples of the fundamental, whereas overtones are not an exact integer multiple. For example: a 48 MHz third overtone crystal would have a fundamental frequency of approximately 15.87 MHz. If these types of crystals are placed in a circuit configuration like Figure 1a, the crystal will operate at its fundamental frequency, it being more dominant than the third overtone. Therefore, a bandpass tank filter (see, as an example, Figure 1b) must be used to block out the fundamental frequency and allow the crystal to operate at its designated third overtone. C_{out} and L_{out} form the tank circuit or high pass filter to do this. C_{bk} is a DC blocking capacitor whose value is normally around 1000 pF. In designing this circuit, values for C_{out} and L_{out} should be chosen to tune the high pass filter for a corner frequency roughly halfway between the fundamental and the third overtone. This can be accomplished by the formula:

$$f_{tank} = \frac{1}{2\pi\sqrt{L_{out} \cdot C_{out}}}$$

Third overtone crystals can be found in frequency ranges from around 20 MHz to those well over 100 MHz.

Design Considerations

- Oscillators always operate at a frequency higher than that of the crystal. To calculate this frequency of operation use the following formulas:

$$f_{osc} = f_s \cdot \sqrt{1 + \frac{C_1}{C_0 + C_L}}$$

where

$$C_L = \frac{C_{in} \cdot C_{out}}{C_{in} + C_{out}}$$

Refer to Table 1 for variable descriptions.

- Gain and phase of an oscillator circuit are generally affected by the external components in the following manner:
  - -- As R-series goes up, gain and trough depth go down.
  - -- As C_{out}, C_{in} go up, gain and trough depth go down.
  - -- As R_f goes up, gain goes up and trough depth goes down.
- If specified frequencies are between those tested, then simply interpolate the values from the two end points given in Table 1.
- It must be noted that the data in Table 1 was obtained using particular crystal models. Variations of these models will change the output results. Therefore, these sizes are to be used as a reference only, and actual component values may vary.
- Also noteworthy is the sensitive nature of these crystal oscillators. Therefore, isolation from high drive pad cell applications should be observed.

Table 1, below, is a reference guide to the symbols that are presented in this section:

Table 1

C_0	shunt capacitance of the crystal model
C_1	series capacitance of the crystal model
C_{bk}	DC blocking capacitor
C_L	effective cap load
C_{in}	input capacitor
C_{out}	output capacitor
ESR	effective series resistance
f_{osc}	actual operating frequency
f_s	crystal series resonant frequency
f_{tank}	high pass corner frequency
L_1	series inductance of the crystal model
L_{out}	tank filter inductor
ppm	parts per million
R_1	series resistance of the crystal model
R_f	feedback resistor
R-series	series resistor
ω_L	parallel resonance (in radians)
ω_s	operating frequency (in radians)
WCS	-10% VDD @ 135˚C
WCP	+10% VDD @ -55˚C

AMI's oscillators are listed in Table 2, which recommends the discrete component sizes for designs using them.

Table 2

0.6 micron CRYSTAL OSCILLATOR
GENERAL EXTERNAL DEVICE SPECIFICATIONS (5V)

ODQFE99K (32 kHz—1.0 MHz)

FREQUENCY	R_f	C_{out}	C_{in}	R-series
32 kHz	10.0 MΩ	30 pf	30 pf	200 kΩ
1.0 MHz	1.0 MΩ	30 pf	30 pf	22 kΩ

ODQFE20M (1.0 MHz—20 MHz)

FREQUENCY	R_f	C_{out}	C_{in}	R-series
1.0 MHz	1.0 MΩ	33 pf	33 pf	22 kΩ
10 MHz	1.0 MΩ	22 pf	22 pf	2.7 kΩ
20 MHz	1.0 MΩ	18 pf	18 pf	220 Ω

ODQTE60M (20 MHz—60 MHz)

FREQUENCY	R_f	C_{out}	C_{in}	R-series	C_{bk}	L_{out}
25 MHz	1.0 MΩ	22 pf	22 pf	220 Ω	1000 pf	4.2 µH
40 MHz	1.0 MΩ	15 pf	15 pf	0 Ω (short)	1000 pf	2.4 µH
60 MHz	1.0 MΩ	10 pf	10 pf	0 Ω (short)	1000 pf	1.6 µH