Technology Brief 19
Crystal Oscillators

Circuits that produce well-defined ac oscillations are fundamental to many applications: frequency generators for radio transmitters, filters for radio receivers, and processor clocks, among many. An ***oscillator*** is a circuit that takes a dc input and produces an ac output at a desired frequency. Temperature stability, long lifetime, and little frequency drift over time are important considerations when designing oscillators.

A circuit consisting of an inductor and a capacitor will resonate at a specific natural frequency $\omega_0 = 1/\sqrt{LC}$. In such a circuit, energy is stored in the capacitor's electric field and the inductor's magnetic field. Once energy is introduced into the circuit (for example, by applying an initial voltage to the capacitor), it will begin to flow back and forth (oscillate) between the two components; this constant conversion gives rise to oscillations in voltage and current at the resonant frequency. In an ideal circuit with no dissipation (no resistor), the oscillations will continue at this one frequency forever.

Making oscillating circuits from individual inductor and capacitor components, however, is relatively impractical and yields devices with poor reproducibility, high temperature drift (i.e., the resonant frequency changes with the temperature surrounding the circuit), and poor overall lifetime. Since the early part of the 20th century, resonators have been made in a completely different way, namely by using tiny, mechanically resonating pieces of quartz glass.

Quartz Crystals and Piezoelectricity

In 1880, the Curie brothers demonstrated that certain crystals—such as ***quartz***, topaz, and tourmaline—become electrically polarized when subjected to mechanical stress. That is, such a crystal exhibits a voltage across it if compressed, and a voltage of opposite polarity if stretched. The converse property, namely that if a voltage is applied across a crystal it will change its shape (compress or stretch), was predicted a year later by Gabriel Lippman (who received the 1908 Nobel Prize in physics for producing the first color photographic plate). Collectively, these bidirectional properties of crystals are known as ***piezoelectricity***. Piezoelectric crystals are used in microphones to convert mechanical vibrations of the crystal surface, caused by acoustic waves, into electrical signals, and the converse is used in loudspeakers. Piezoelectricity can also be applied to make a quartz crystal resonate. If a voltage of the proper polarity is applied across one of the principal axes of the crystal, it will shrink along the direction of that axis. Upon removing the voltage, the crystal will try to restore its shape to its original unstressed state by stretching itself, but its stored compression energy is sufficient to allow it to stretch beyond the unstressed state, thereby generating a voltage whose polarity is opposite of that of the original voltage that was used to compress it. This induced voltage will cause it to shrink, and the process will continue back and forth until the energy initially introduced by the external voltage source is totally dissipated. The behavior of the crystal is akin to an underdamped RLC circuit.

In addition to crystals, some metals and ceramics are also used for making oscillators. Because the resonant frequency can be chosen by specifying the type of material and its shape, such oscillators are easy to manufacture in large quantities, and their oscillation frequencies can be designed with a high degree of precision. Moreover, quartz crystals have good temperature performance, which means that they can be used in many applications without the need for temperature compensation, including in clocks, radios, and cellphones.

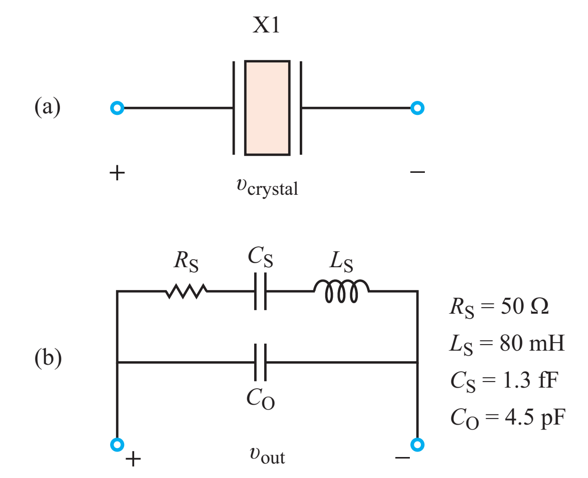

Figure TF19-1: (a) Quartz crystal circuit symbol and (b) equivalent circuit. Values given are for a 5 MHz crystal.

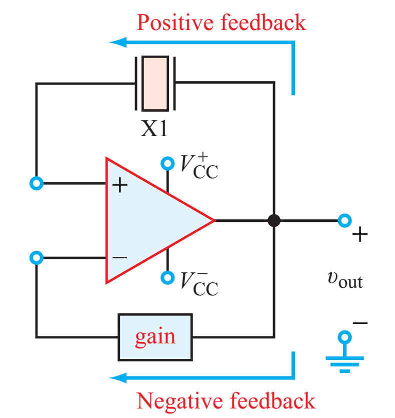

Figure TF19-2: Schematic block diagram of an oscillator circuit. An oscillator is wired into the positive feedback path, while a negative feedback path is used to control gain.

Crystal Equivalent Circuit and Oscillator Design

The electrical behavior of a quartz crystal can be modeled as a series RLC circuit (L_S, C_S, R_S) in parallel with a shunt capacitor (C_O). The RLC circuit models the fundamental oscillator behavior with dissipation. The shunt capacitor is mostly due to the capacitance between the two plates that actuate the quartz crystal. **Figure TF19-1** shows the circuit symbol, the equivalent circuit with sample values for a commercial 12 MHz crystal along with expressions and values for the resonant frequencies and Q.

The crystal is, of course, not sufficient to produce a continuous oscillating waveform; we need to excite the circuit and keep it running. A common way to do this is to insert the crystal in the positive feedback path of an amplifier (**Fig. TF19-2**). The amplifier, of course, is supplied with dc power (V_{CC}^{+} and V_{CC}^{-}). Note that no input signal is applied to the circuit. Initially, the output generates no oscillations; however, any noise at v_{out} that is at the resonant frequency of X1 will be fed back to the input and amplified. This positive feedback will quickly ramp up the output so that it is oscillating at the resonant frequency of the crystal. A negative feedback loop is also commonly used to control the overall gain and prevent the circuit from clipping the signal against the op amp's supply voltages V_{CC}^{+} and V_{CC}^{-}.

In order to oscillate continuously, a circuit must meet the following two ***Barkhausen criteria***: (1) The gain of the circuit must be greater than 1. (This makes sense, for otherwise the signal will neither get amplified nor establish a resonating condition.) (2) The phase shift from the input to the output, then across the feedback loop to the input must be 0. (This also makes sense, since if there is non-zero phase shift, the signals will destructively interfere and the oscillator will not be able to start up.)

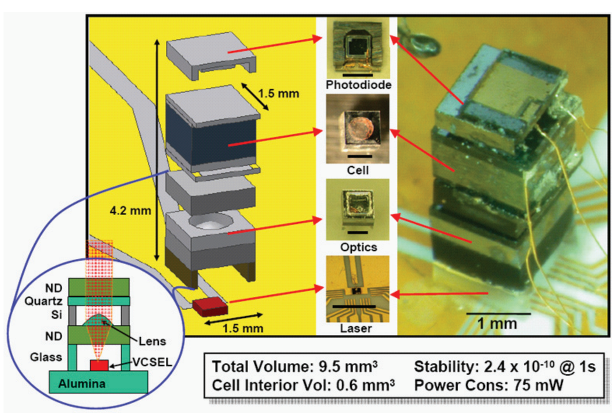

Figure TF19-3: Schematic (left) and photo (right) of a tiny atomic physics package used in a chip-scale atomic clock. (Courtesy of Clark Nguyen, U.C. Berkeley, and John Kitching, National Institutes of Standards and Technology.

Advances in Resonators and Clocks

As good as quartz resonators are, even the best among them will drift in frequency by 0.01 ppm per year as a result of aging of the crystal. If the oscillator is being used to keep time (as in your digital watch), this dictates how many seconds (or fractions thereof) the clock will lose per year. Put differently, this drift puts a hard limit on how long a clock can run without calibration. The same phenomenon limits how well independent clocks can stay synchronized with each other. Atomic clocks provide an extra level of precision by basing their oscillations on atomic transitions; these clocks are accurate to about 10^{-9} seconds per day. Recently, a chip-scale version of an atomic clock (**Fig. TF19-3**) was demonstrated by the ***National Institute for Standards and Technology*** (NIST); it consumes 75 mW and was the size of a grain of rice (10 mm^3). Other recent efforts for making oscillators for communication have focused on replacing the quartz crystal with a type of micromechanical resonator.