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The Crystal Oscillator

Most electronic systems rely on a precise reference frequency or time base for their operation. Examples include wireless and wireline communication transceivers, computing devices, instrumentation, and the electronic watch. The crystal oscillator has served this purpose for nearly a century. In this article, we study the design principles of this circuit.

Brief History

In 1880, Pierre and Jacques Curie discovered "piezoelectricity" [1], namely, the ability of a device to generate a voltage if subjected to mechanical force. In 1881, Lippman predicted that a converse effect must also exist, which was confirmed by the Curies shortly thereafter [1].

The use of a piezoelectric device—a "crystal"—to define the oscillation frequency of a circuit can be traced to Cady's 1922 paper [2]. Cady proposes the oscillator shown in Figure 1, which applies feedback around a three-stage amplifier through two coupled piezoelectric resonators.

Crystal oscillators continued to advance in the ensuing decades, naturally migrating to bipolar and, eventually, MOS technologies. The interest in such oscillators was rekindled with the conception of the electronic watch in the 1960s and 1970s. In Figure 2, (a) shows a MOS realization reported by Luscher as prior art in a patent filed in 1969 [3], and (b) depicts a more familiar structure that dates back to a patent filed by Walton in 1970 [4]. The need for an extremely low-power, high-precision time-base circuit motivated extensive studies on crystal oscillators in that time frame [5], [7].

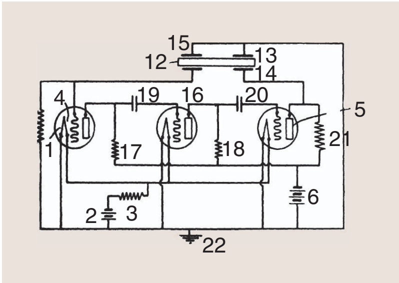

FIGURE 1: Cady's crystal oscillator.

In addition to a precise resonance frequency, piezoelectric devices exhibit extremely high quality factors (Qs), a property that has proved essential in communication transceivers. While resonance frequency drifts can be eventually compensated as the received signal is processed, the phase noise of the crystal oscillator cannot. In other words, crystal oscillators have found new importance for their low phase noise in addition to their long-term frequency stability. The low temperature coefficient of crystals also proves critical in most applications.

Crystal Model

For circuit design purposes, we need an electrical model of the electromechanical crystal. The mechanical resonance is fundamentally represented by a series *RLC* branch, with a resistor modeling the loss [Figure 3(a)]. These components are called the "motional" resistance, inductance, and capacitance of the crystal, respectively. With this series branch, the crystal can act as a short circuit at resonance. In addition, since the crystal is formed by two parallel plates, a parallel capacitance must also be included. The load capacitance presented to the crystal by the printed circuit board and other devices can also be absorbed by C_P.

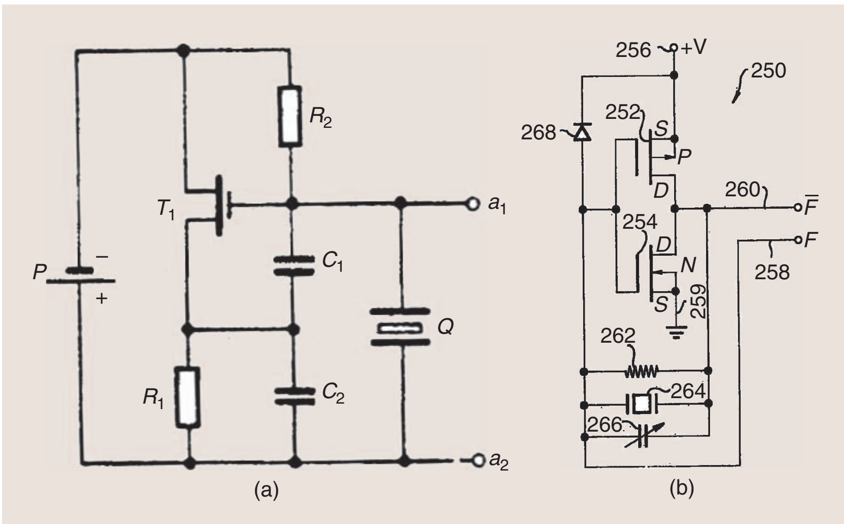

FIGURE 2: The MOS crystal oscillators patented by (a) Luscher and (b) Walton.

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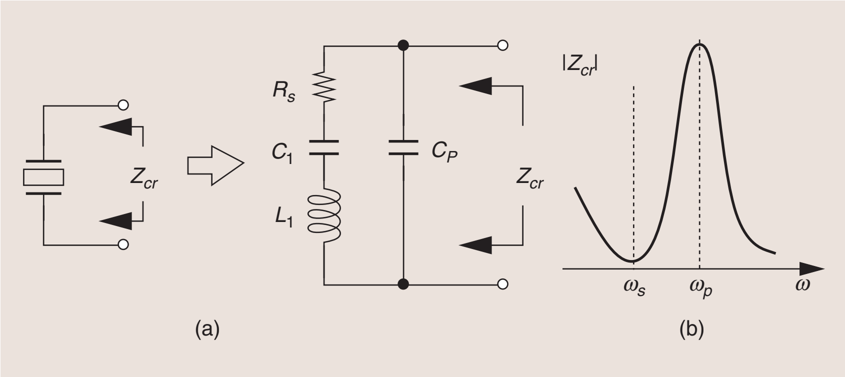

FIGURE 3: (a) A crystal model and (b) a crystal impedance plot showing series and parallel resonance frequencies.

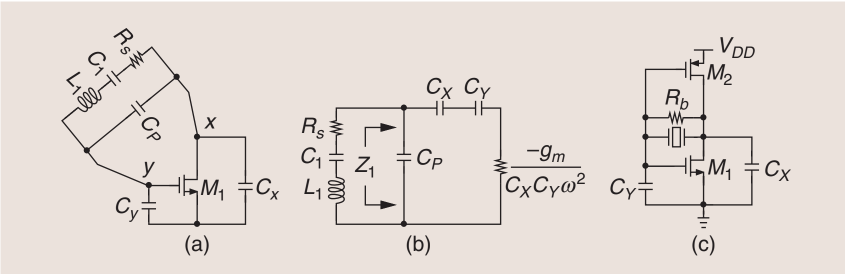

FIGURE 4: (a) A three-point oscillator consisting of a crystal and a negative resistance, (b) an equivalent circuit of (a), and (c) a complete oscillator using an inverter.

The series resonator devices, L_1 and C_1, in Figure 3(a) have peculiar values, e.g., $C_1 \approx 5$ fF, $L_1 \approx 50$ mH for a series resonance frequency of 10 MHz. This is because the quality factor, $Q = (L_1 \omega)/R_S$, reaches several thousand to several hundred thousand, translating to large inductance values. The value of C_1 is much less than C_P, which is in the picofarad range.

The network shown in Figure 3(a) exhibits a series resonance frequency, $\omega_s = 1/\sqrt{L_1 C_1}$, and a parallel resonance frequency, $\omega_p = 1/\sqrt{L_1 C_1 C_P/(C_1 + C_P)}$ [Figure 3(b)]. These can also be obtained by neglecting R_S and writing

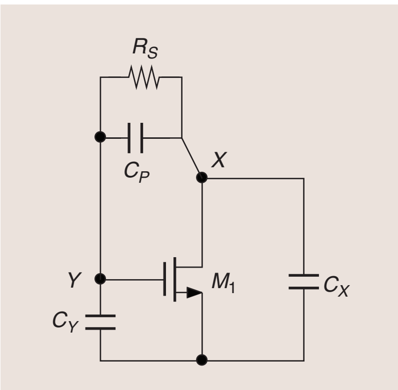

FIGURE 5: An equivalent circuit of a three-point oscillator in the case of series resonance.

$$Z_{cr} \approx \frac{L_1 C_1 s^2 + 1}{L_1 C_1 C_P s^2 + C_1 + C_P}. \quad (1)$$

Since $C_1 \ll C_P$, we have $\omega_p \approx \omega_s [1 + C_1/(2C_P)]$; that is, the two frequencies differ by less than 1%. As explained below, typical oscillators operate at ω_p. An important attribute of the crystal is that tolerances in C_P only negligibly affect ω_p. For example, with $C_1 = 5$ fF and $C_P = 2$ pF, an error of 10% in C_P translates to a 0.01% change in ω_p. On the other hand, this low sensitivity also means that the crystal oscillator can be tuned only over a very narrow range by varying C_P.

Basic Crystal Oscillator

If the crystal resonator in Figure 3(a) is attached to a negative resistance, its loss can be compensated and oscillation can be sustained. A common approach employs the "three-point" oscillator shown in Figure 4(a). The one-port network including M_1, C_X, and C_Y presents an impedance between X and Y given by

$$Z_{XY} = \frac{1}{C_X s} + \frac{1}{C_Y s} + \frac{g_m}{C_X C_Y s^2}, \quad (2)$$

which, for $s = j\omega$, reduces to a series branch consisting of C_X, C_Y, and a negative resistance equal to $-g_m/(C_X C_Y \omega^2)$ [Figure 4(b)]. For the circuit to oscillate, this resistance must cancel the crystal's loss. To arrive at a simple start-up condition, we compute the real part of the impedance Z_1 in Figure 4(b) as [8]

$$Re\{Z_1\} = \frac{-g_m C_X C_Y}{(g_m C_P)^2 + (C_X C_Y + C_X C_P + C_P C_Y)^2 \omega^2}, \quad (3)$$

where ω denotes the oscillation frequency. Interestingly, this resistance is a nonmonotonic function of g_m, reaching a maximum if [8]

$$g_m = \left(C_X + C_Y + \frac{C_X C_Y}{C_P}\right)\omega. \quad (4)$$

Since $Re\{Z_1\}$ appears in series with L_1, C_1, and R_S, we simply equate its magnitude to R_S, obtaining the oscillation condition as [8]

$$g_{m,\text{crit}} = \frac{\omega}{QC_1} \frac{(C_X C_Y + C_X C_P + C_Y C_P)^2}{C_X C_Y}, \quad (5)$$

where $Q = 1/(R_S C_1 \omega)$.

The core amplifier of the oscillator is typically configured as a self-biased inverter [Figure 4(c)]. The feedback resistor, R_b, must be chosen large enough not to degrade the crystal Q significantly.

It is interesting to explain why the topology of Figure 4(a) does not oscillate at the crystal's series resonance frequency. Suppose it does. Then, the circuit reduces to that shown in Figure 5. It can be proved that the phase shift around this loop is nonzero at any frequency, thereby prohibiting oscillation in this mode.

Start-Up Time

The very high Q of crystals leads to a long start-up time. Of course, the actual oscillation growth rate is given by the net negative resistance in Figure 4(b), following an envelope given by $\exp(t/\tau)$, where $\tau = R_n/(2L_1)$ and R_n is the absolute value of the net negative resistance. For example, a 10-MHz crystal oscillator with a Q of 5,000 can take roughly 0.5 ms to settle. This issue poses several difficulties. In low-power applications that operate with a low duty cycle—as in sensors—the start-up time translates to a higher power consumption. Also, communication systems that come out of the sleep mode cannot begin operation until the settling is completed. Finally, the simulation of the oscillator becomes a very lengthy task, especially if the circuit must reach steady state for its phase noise to be computed accurately.

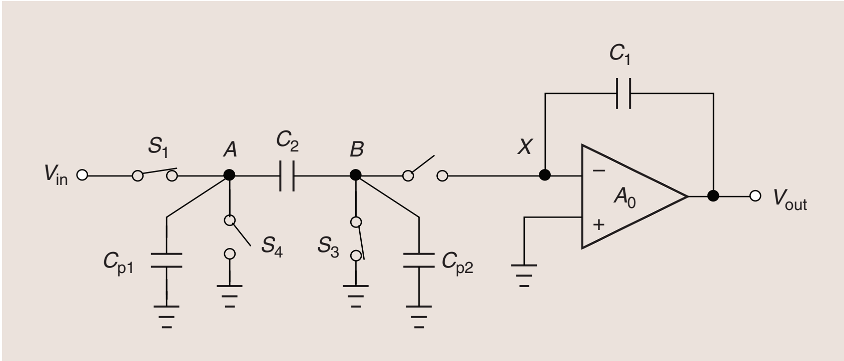

FIGURE 6: An integrator circuit including parasitics.

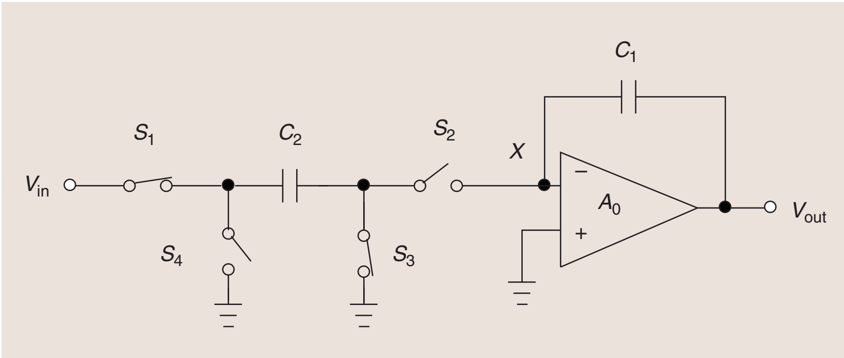

FIGURE 7: A noninverting integrator.

Drive-Level Dependency

Crystals behave peculiarly if they remain inactive: their equivalent series resistance rises considerably. The series resistance falls back to it original value after the crystal vibrates for some time. This effect is called drive-level dependency. A crystal oscillator that is turned on after a period of inactivity may fail unless the negative resistance is strong enough. As a rule of thumb, we select this resistance about four times R_S in Figure 4(a).

Oscillation at Overtones

Actual crystals also exhibit resonances at higher frequencies (overtones) that are approximately harmonically related to the first. Thus, the topology of Figure 4(c) can oscillate at an overtone, a property exploited in high-frequency designs. On the other hand, low-frequency oscillators must avoid a solution at overtones. This is possible by inserting a resistor in series with the output of the inverter in Figure 4(c) so as to reduce the loop gain at higher frequencies. This resistor can also limit the crystal's power dissipation, which, if excessive, could cause damage.

Questions for the Reader

1) Estimate the oscillation frequency of Figure 2(a) if R_1 and R_2 are large.
2) How does the finite output impedance of M_1 and M_2 in Figure 4(c) affect the oscillator's performance?

Answers to Last Issue's Questions

1) In the circuit of Figure 6, C_{p2} appears in series with C_2 when S_3 turns off. Does the charge injected by S_1 corrupt the sampled value in this case?

   No, it does not. The charge injected by S_1 is later removed by S_4.
2) Given that the op amp in Figure 7 is placed in an inverting configuration, how do we intuitively explain the noninverting operation of the integrator?

   The front-end passive sampling circuit in fact inverts the signal. This can be seen by noting that, if S_2 is absent, then the voltage generated on the right plate of C_2 in the hold mode is equal to $-V_{in}$.

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