Fundamental Limits on the Frequency Stabilities of Crystal Oscillators

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***Abstract*—The frequency instabilities of precision bulk acoustic wave (BAW) quartz crystal oscillators are reviewed. The fundamental limits on the achievable frequency stabilities, and the degree to which the fundamental limits have been approached to date are examined. Included are the instabilities as a function of time, temperature, acceleration, ionizing radiation, electromagnetic fields, humidity, atmospheric pressure, power supply, and load impedance.**

Most of the fundamental limits are zero or negligibly small, a few are finite. We speculate about the progress which may be achievable in the future with respect to approaching the fundamental limits. Suggestions are provided about the paths that may lead to significant stability improvements.

I. Introduction

Timekeeping accuracy has improved about 10 orders of magnitude during the past 600 years [1]. The last 10^6-fold improvement occurred during the first sixty years after the introduction of quartz crystal oscillators (about 1920). During the last two decades, however, progress in certain areas, *e.g.*, in long term aging [2], [3], has not shown significant improvement. Does this mean that we have reached some fundamental limit and, therefore, further improvements are no longer possible?

The task undertaken by the authors of this paper was to examine the fundamental limits, and the degree to which further progress in stability improvements will be limited by these limits. The discussions will concentrate on oven controlled crystal oscillators (OCXO's), as they are the most stable.

II. Oscillator Instabilities—General Discussion

Fig. 1 shows a block diagram of the essential components of a precision crystal oscillator. Each of the three main parts of the oscillator, *i.e.*, the crystal resonator, the sustaining circuit, and the oven, contribute to instabilities. The general expression for the oscillator's instabilities is [4]

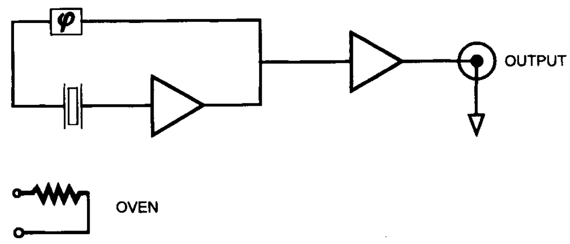

Fig. 1. Simplified block diagram of a quartz oscillator. Loop gain = 1.0 and loop phase = $2np$, with $n = 1, 2, 3, \cdots$ (From [4]).

$$\frac{\Delta\nu}{\nu_{\rm osc}} \approx \frac{\Delta\nu}{\nu_{\rm res}} + \left[1 + \left(\frac{2fQ_L}{\nu_o}\right)^2\right]^{-(1/2)} \frac{d\varphi(f)}{2Q_L} \qquad (1)$$

where Q_L is the loaded Q-factor of the resonator and $d\varphi(f)$ is a small change in loop phase at offset frequency f away from carrier frequency ν_o. Phase changes and phase noise within the loop can originate in either the resonator or the sustaining electronics. Maximizing Q_L helps reduce the effects of noise and environmental effects in the sustaining electronics. In a properly designed oscillator, the short-term frequency stability or phase modulation (PM) noise is controlled by the resonator for Fourier frequencies smaller than the half bandwidth of the resonator. For frequencies larger than the half bandwidth of the resonator, the phase noise is determined by the sustaining circuit and the oscillation power (*i.e.*, the amount of power delivered from the oscillation loop). More detailed discussions are found in [4]–[7].

The main influences on the stability of an oscillator can be categorized as follows [4]–[7]:

1) *time*: short-term (phase noise), intermediate-term (*e.g.*, due to oven fluctuations), and aging (*i.e.*, long-term stability),
2) *temperature*: static frequency versus temperature characteristics, dynamic frequency versus temperature effects (warmup, thermal shock), and thermal history dependence ("retrace"),
3) *acceleration*: gravity ($2g$ tipover), vibration, acoustic noise, and shock,
4) *ionizing radiation*: photons (X-rays, γ-rays), and particles (neutrons, protons, electrons, α-particles); and pulsed and steady state effects,

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5) *other*: sustaining electronics power supply voltage, load impedance, atmospheric pressure (altitude), humidity, and electromagnetic fields.

The fundamental and some practical limits to frequency stability due to each of these influences are discussed below [4]–[7].

Short-Term Instabilities

The significant causes of short-term instabilities of fundamental nature are as follows:

1) Johnson noise in the motional resistance of the resonator and within the oscillator circuitry [8],
2) phonon scattering noise in the resonator [9].

Causes of frequency instability which are mostly technical rather than fundamental in nature are [4] as follows:

1) changes in external load,
2) thermal response of resonator—static and dynamic,
3) oven temperature fluctuations—an activity dip at the oven set point can greatly magnify the frequency fluctuations caused by oven temperature fluctuations [6], [7],
4) random vibration [10],
5) fluctuations in the number of adsorbed molecules [11],
6) stress relief and fluctuations at interfaces (between the quartz plate and its electrodes and its mounting and bonding structure) [2], [4], [6], [7].

Thermal noise (Johnson noise) due to the resonator's motional resistance creates white FM noise [8]:

$$\mathcal{L}(f) = \frac{kT}{2Q_L^2 P f^2} \tag{2}$$

and

$$\sigma_y(\tau) = \frac{1}{Q_L}\sqrt{\frac{kT}{2P\tau}} \tag{3}$$

where $\mathcal{L}(f)$ is the phase noise at offset frequency f from the carrier frequency, k is Boltzmann's constant, T is the temperature in K, Q_L is the loaded Q of the resonator in the circuit, $\sigma_y(\tau)$ is the two-sample deviation, τ is the measurement time, and P is the total power dissipated in the resonator plus load. For example, for $Q_L = 10^6, P = 10^{-5}$ W, and $T = 330$ K, $\sigma_y(\tau) = 1.4 \times 10^{-14}\tau^{-(1/2)}$.

Phonon Scattering in the Resonator

Scattering of the phonons within the crystal lattice due to defects and scattering at the crystal-electrode or, in the case of BVA resonators [12], crystal–vacuum interface, dissipates energy. This lowers the Q-factor, and there is theoretical and some preliminary experimental evidence that it also increases the flicker, *i.e.*, $1/f$ frequency modulation (FM) noise in the resonator. Data from many sources show (see for example [5], [9], [13]) that the best flicker level obtained from a given resonator design generally scales as $1/Q^4$; however, there are other processes that cause flicker FM to vary between resonators of the same design and same Q-factor [5], [9], [13]. Data from [14] shows that the phase noise or short-term frequency stability can exhibit flicker FM from about 0.02 s to beyond 10^6 s, indicating that this is a fundamental process within the resonator and not an accidental coincidence of several types of noise processes to mimic flicker FM.

At present flicker FM sets the limit for short- and medium-term frequency stability in all quartz resonators. There is beginning to be some evidence that appropriate changes in the electrodes in AT- and SC-cut resonators may reduce the flicker FM noise [9], [15]. If the flicker FM is reduced, then Johnson noise could become the limiting effect in the short-term stability [16], [17].

Noise in Sustaining Circuit

Flicker PM noise in the sustaining circuit causes flicker FM contribution to the oscillator output frequency given by

$$\mathcal{L}_{\text{osc}}(f) = \mathcal{L}_{\text{ckt}}(1\,\text{Hz})\frac{\nu^2}{4f^3Q_L^2} \tag{4}$$

and

$$\sigma_y(\tau) = \frac{1}{Q_L}\sqrt{\ln 2\mathcal{L}_{\text{ckt}}(1\,\text{Hz})} \tag{5}$$

where f is the frequency offset from the carrier frequency ν, Q_L is the loaded Q of the resonator in the circuit, (1 Hz) is the flicker PM noise at $f = 1$ Hz, and τ is any measurement time in the flicker floor range. For $Q_L = 10^6$ and (1 Hz) $= -140$ dBc/Hz, $\sigma_y(\tau) = 8.3 \times 10^{-14}$.

To achieve $\sigma_y(\tau)$ lower than this value will require improvements in Q_L-factors or amplifier PM noise performance. Since the maximum $Q\nu_o \cong$ a constant for BAW resonators of a given cut, these effects strongly favor oscillators at the lowest practical frequency. The highest (room temperature) resonator Q-factor reported is 10 million for 1 MHz AT-cut resonators manufactured more than 35 years ago, and the highest $Q\nu_o$ for AT-cut resonators is 16×10^6 when ν_o is in MHz [18].

BT-cut resonators can have higher Q-factors by approximately a factor of two over AT- or SC-cut resonators. The use of crystal cuts which are not stress compensated, however, leads to serious problems with dynamic temperature fluctuations, amplitude changes, and stress effects as discussed below. We are not aware, however, of any fundamental work which shows a maximum theoretical value for the Q-factor. All of the evidence is empirical (based on physically realized resonators). Changes in resonator design, material purity, isotopic purity, crystallographic perfection, processing, and new piezoelectric materials, might lead to higher Q-factors.

The lowest flicker PM reported in amplifiers is approximately $\mathcal{L}$ (1 Hz) $= -152$ dBc/Hz [16]. Flicker PM noise depends on the amplifier design as well as on the active element. As transistor fabrication techniques have improved, so has the flicker PM noise. We expect further reductions in amplifier $1/f$ PM noise of at least 5–10 dB.

Loop Phase, Mode Selection, Matching, and Filter Circuits

Many oscillators contain tuned circuits to suppress unwanted modes, as matching circuits, and as filters. The effects of small changes in the tuned circuit's inductance and capac-

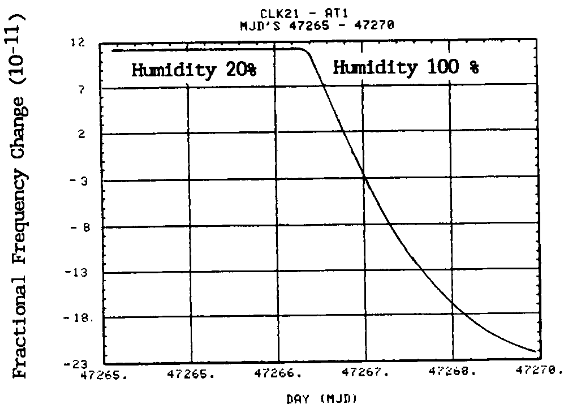

Fig. 2. Fractional frequency change of quartz oscillator due to a change in humidity [4].

itance is given by [4], [5]

$$\frac{\Delta\nu}{\nu_{\text{osc}}} \approx \frac{d\phi(f_f)}{2Q_L} \approx \left(\frac{1}{1+\dfrac{2f_f}{BW}}\right)\left(\frac{Q_c}{Q}\right)\left(\frac{dC_c}{C_c}+\frac{dL_c}{L_c}\right) \tag{6}$$

where BW is the bandwidth of the filter, f_f is the frequency offset of the center frequency of the filter from the carrier frequency, Q_L is the loaded Q of the resonator and Q_c, L_c, and C_c are the tuned circuit's Q, inductance and capacitance, respectively. Many environmental parameters cause a change in the phase around the oscillator loop. The most important are temperature, humidity, pressure, acceleration and vibration, magnetic field, voltage, load, and radiation. These environmental sensitivities often lead to increases in the level of wide-band phase noise in the short-term, random-walk frequency modulation in the medium-term, and drift in the long-term. The loop phase shift depends on the circuit design and the loaded Q-factor of the oscillator. Fig. 2 illustrates the effect of humidity on an oscillator with a nominal $\sigma_y(\tau)$ of 3×10^{-13}. Pressure and humidity effects can be eliminated by a hermetically sealed, rigid oscillator enclosure.

Equation (6) indicates that notch filters are much less likely to perturb the phase of the carrier than bandpass filters because, in (6), $f_f = 0$ for a bandpass filter and the circuit, therefore, sees the full instability of the filter. However, for a notch filter, f_f can be large compared to the BW, and the effect of the instability of the filter on the oscillator is reduced by f_f/BW. All circuit elements, especially reactances in the signal path should be selected with great care. If bandpass filters are used, Q_C should be as small as feasible. Inductors are often noisy and are susceptible to magnetic field disturbances.

Although careful design and component selection is essential, we are not aware of any fundamental limit to oscillator frequency stability due to loop phase, mode selection, matching, and filter circuits.

Changes in the External Load

If the external load changes, there is a change in the amplitude or phase of the signal reflected back into the

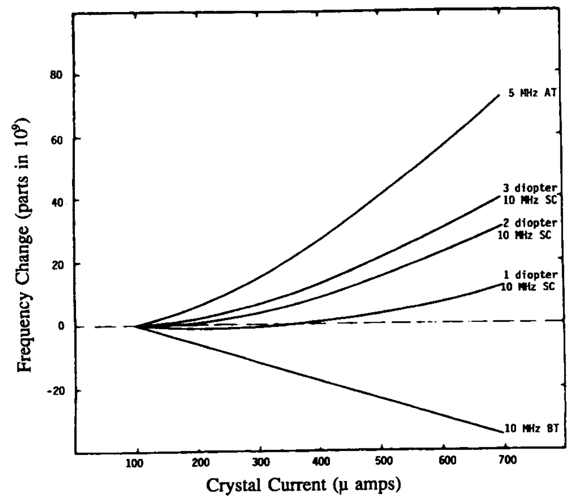

Fig. 3. Fractional frequency change versus RF drive level for AT-, BT-, and several SC-cut resonators [22].

oscillator [19]. The portion of that signal which reaches the oscillating loop changes the oscillation phase, and hence the frequency by

$$\frac{\Delta\nu}{\nu_{\text{osc}}} \approx \frac{d\phi(f_f)}{2Q} \approx \left(\frac{1}{2Q}\right)\left(\frac{\Gamma-1}{\Gamma+1}\right)(\sin\theta)\sqrt{\text{isolation}} \tag{7}$$

where Γ is the VSWR of the load, and θ is the phase angle of the reflected wave. If $Q \sim 10^6$, isolation 40 dB ($\sim10^{-4}$), then the worst case (100% reflection) pulling is $\sim 5\times10^{-9}$. A VSWR of 2 reduces the maximum pulling by only a factor of 3. The problem of load pulling becomes worse at higher frequencies, because both the Q and the isolation decrease. Although careful control of external load effects is essential, we are not aware of any fundamental limit to oscillator frequency stability due to external load changes.

RF Excitation Level

The frequency of the resonator is also a function of the amplitude of the signal level (*i.e.*, the drive level), as shown in Fig. 3 [4], [19]–[22]. The sensitivity to this effect, usually called the amplitude-frequency effect, is a function of a number of resonator design and fabrication details. The frequency change varies as the square of the drive current [20]–[22]. Fig. 3 shows the SC-cut's dependence on blank curvature, with most other parameters held constant [22].

Typical sensitivities to this parameter range from approximately $10^{-9}/\mu$W for 5th overtone AT- or BT-cut resonators to parts in $10^{-11}/\mu$W for 3rd overtone, SC-cut resonators at 5 MHz. The sensitivities decrease with overtone and crystal plate curvature [21]. The primary environment drivers for this effect are temperature, humidity, or radiation changing the excitation level, *e.g.*, through interaction with the automatic gain control (AGC) and the gain of the sustaining stage. Changes in circuit components can also affect the amplitude of oscillation by changing the AGC circuitry.

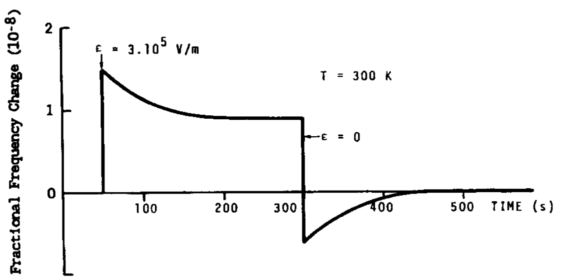

Fig. 4. Fractional frequency change as a function of applied voltage for an AT-cut resonator. The slow variation after the change in voltage is due to the movement of ions in the quartz [29].

Although careful control of drive level is essential in high stability oscillators, we are not aware of any fundamental limit to oscillator frequency stability due to this effect.

Electromagnetic Fields

The frequency of certain resonator cuts is directly affected by the application of even small electric fields through changes in dimension and through interaction with the nonlinear coefficients. The application of electric fields also tends to cause ions within the crystal to move and change the frequency [26]–[30]. The result is that the change in frequency generally has a fast component due to piezoelectricity and the interaction with the crystal constants, and one or more slower components associated with the movement of ions, as shown in Fig. 4. The shorter time constants depend exponentially on temperature.

The aging of resonators can be significantly changed by applying a dc voltage to the electrodes, even at "normal" temperatures [30]. The electric field effect has also been used to vibration-compensate SC-cut resonators [31] and to create an ultralinear phase modulator [24]. The sensitivity to this effect is highly dependent on resonator cut, material, and electrode configuration. Coefficients range from approximately 10^{-11} to 10^{-8}/V applied across the resonator and scale approximately as the reciprocal of the plate thickness or ν_o. For a resonator to exhibit a sensitivity, the dc electric field must have a component along the x axis of the crystal. True AT-cuts with regular electrodes therefore exhibit little, if any, sensitivity to electric fields. Doubly rotated cuts, such as the SC-cut, generally show significant sensitivity to electric fields.

Large electric fields and elevated temperatures are sometimes used to "sweep" ions out of a quartz bar before resonator fabrication [4], [26], [27]. This is typically used on resonators intended for radiation environments and also, to reduce the etch-channel density of the quartz. Perturbations due to unintentional electric fields are virtually eliminated by placing a dc resistance of $\sim 10^5\,\Omega$ across the resonator.

Quartz resonators' inherent magnetic field sensitivity is probably smaller than 10^{-11}/T for fields smaller than 10^{-4}T [29], [32], [33]. Many resonators are, however, constructed with magnetic holders. As the magnetic field changes, the force on the various components of the resonator changes. This causes a frequency shift through the force-frequency coefficient and the circuit phase shifts discussed above. Generally, the magnetic field effect is unchanged under field reversal and maximized for rotation through 90°. This effect is reduced to below 10^{-9}/T by using nonmagnetic holders and shielding all inductors within the oscillator [33]. Eddy currents induced in metal electrodes can also produce a frequency shift, although this effect is negligible under normal circumstances [32]. Induced ac voltages due to motion in the earth's magnetic field and due to magnetic fields near coils can affect, *e.g.*, varactors, AGC circuits, and power supplies. These are practical problems. We are not aware of any fundamental limit to oscillator frequency stability due to electromagnetic field effects.

Power Supply Voltage

Instabilities in the oscillator can often be traced to instabilities of the power supply. The frequency changes occur because changes in various voltages change the capacitance of active and some passive devices. The gain of the sustaining or buffer amplifiers can also change, causing a phase shift. If the phase shift is in the sustaining stage, there is a frequency change given by (1), whereas if the phase shift is in the buffer amplifier, there is no first-order frequency change if the isolation is high enough and a matched load is used. The gain changes can change the amplitude of drive, thereby causing a frequency change.

The remedy is to measure the coefficient for frequency and phase changes with voltage in various parts of the circuit, and design the voltage regulation to provide regulation that does not compromise the performance. We are not aware of any fundamental limit to oscillator frequency stability due to this effect.

Stress

Changes in stress on the resonator plate can change the resonance frequency [34]–[40]. Stress can be transmitted to the resonator through the mounting structure or from the electrodes. It can originate from temperature-driven dimensional variations in the enclosure, changes in the pressure surrounding the hermetically sealed enclosure, changes in the magnetic field causing a change in the mounting force due to the use of magnetic components, or from changes in the body forces due to acceleration and vibration as described below. There are also stresses in the quartz due to defects introduced during the growing process. The stresses on the resonator can change with time, temperature, resonator drive level, and radiation exposure. The stress effects due to the electrodes have been estimated [35]–[37].

The change in frequency due to diametrically opposed forces in the plane of the resonator as a function of the angle between the applied force and the x-axis has been measured for a variety of cuts [38]. Bending stresses can also produce significant frequency shifts [39], as can stresses due to the bonding of the mounting clips to the resonator plate [40]. The influences due to the mounting stresses can be minimized in traditional resonators by proper choice of the mounting angles and procedures. Mounting stresses in BVA resonators are minimized by both the choice of mounting angle and by the use of a supporting ring machined from the same piece of quartz as the resonator [12], [41]. The effects of electrode stresses are also absent from electrodeless resonators.

Stress effects present significant practical problems and may limit the performance of conventional resonators; however, we are not aware of any fundamental limit to oscillator frequency stability due to stress effects.

Aging

The main causes of aging [2] are: mass transfer due to contamination, stress relief in the resonator's mounting and bonding structure and in its electrodes, sustaining circuitry aging, and oven control circuitry aging. Another possible aging mechanism is the outgassing of the quartz, which only recently has been investigated [42].

Nearly all precision oscillators use resonators which are enclosed in either metal or glass enclosures. These metals and glasses are known to outgas orders of magnitude more than some other materials, such as the high-alumina ceramics and sapphire [43]–[46].

Stainless steel has been the material of choice for ultrahigh vacuum (UHV) systems, however, aluminum has been shown to allow better vacuums. A capability of achieving 10^{-11} Pa (10^{-13} torr) has been demonstrated with a vacuum chamber the interior of which was coated with high purity aluminum, and which used aluminum seals [47], [48]. The ultimate pressure in such an extremely high vacuum system is determined by the desorption of hydrogen from the chamber walls [48]. An aluminum alloy vacuum chamber which had been extruded and tempered in an oxygen and argon atmosphere (in order to form a dense oxide layer on the inner surfaces) has also been shown to allow vacuums in the 10^{-11} Pa (10^{-13} torr) range [49].

Aluminum's low outgassing rates and high thermal conductivity may make it a good candidate material for future resonator packages. It may provide a lower cost alternative to sapphire or ceramic packages.

Nearly atomically clean surfaces can be produced immediately before resonator sealing by a combination of UV/ozone cleaning [50] and high-temperature baking in ultrahigh vacuum. However, if the enclosure and the quartz outgas after the enclosure is sealed, aging will result. It is clear that current practices for making high-stability resonators leave room for improvement with respect to minimizing the mass transfer due to contamination resulting from the outgassing of the enclosure and of the materials inside the enclosure.

Aging due to stress relief can be minimized by "electrodeless" designs [12], [41], [51] and by a combination of an electrodeless design and levitation. (The possibility of using levitation is discussed below.)

The effects of sustaining circuitry component aging can be minimized by using: 1) maximum loaded Q-factor; 2) properly selected components; 3) resonator designs which provide a small motional capacitance, such as a fifth overtone SC-cut; and 4) a sufficiently large load capacitance.

The effects of aging in the oven control circuitry can be minimized by using: 1) properly selected components and design; 2) an SC-cut resonator the turnover points of which coincide with the inflection point; 3) an oven temperature set point which coincides with the turnover temperatures of the resonator; and 4) a temperature sensitive mode (*e.g.*, the B-mode [52] or a combination of the fundamental and third overtone [53]), at least for setting the oven temperature to the turnover temperature, if not for oven control. As is shown below, when conditions 2 and 3 are satisfied, small changes in the oven temperature result in negligible frequency shifts.

Although further progress in reducing the known aging mechanisms present serious practical problems, none of them appear to present a fundamental limit. With sufficient effort, significant improvements ought to be possible in the future. For example, in the "ideal" resonator described below, the known aging mechanisms would be virtually absent.

Frequency versus Temperature Stability

The frequency versus temperature (f versus T) stability of an OCXO depends on the static and dynamic f versus T characteristics of the resonator in the sustaining circuit, the difference between the oven set point and the point where the static f versus T characteristic has zero slope, the oven's temperature excursions from the set point, and the rate of change of temperature during the oven's temperature excursions [4], [54].

Although the f versus T effects discussed below present significant practical problems, we are not aware of any fundamental limit to oscillator frequency stability due to f versus T effects.

Dynamic f versus T Stability

The dynamic f versus T stability can dominate the static f versus T stability when the resonator is not thermal transient compensated (*i.e.*, when it is not an SC-cut). For maximum stability, a thermal transient compensated resonator must be used [54].

Many so-called SC-cut resonators exhibit a finite thermal transient effect. However, at angles near the "true" thermal transient compensated cut, small changes in the angles of cut can produce either positive or negative thermal transient effects, which indicates that the thermal transient effect vanishes at one set of angles of cut in the vicinity of θ =34° and f =22°. The exact values of the "true" SC-cut angles vary with resonator configuration. The dynamic f versus T performance can also be influenced by factors such as transient effects in the oven control and sustaining circuit components [55].

Although making an oscillator which exhibits zero thermal transient effect presents some nontrivial practical problems, the fundamental limit to the thermal transient effect is zero.

Static f versus T Stability

For a thermal transient compensated oscillator, the f versus T stability is determined by the static f versus T characteristic, the oven stability, and the difference between the oven set point temperature and the temperature where the f versus T characteristic has zero slope (the oven offset). Table I shows how the f versus T instabilities of an oscillator vary with oven characteristics. The static f versus T characteristic assumed in

TABLE I
FREQUENCY OFFSETS DUE TO THERMAL CYCLING AS A FUNCTION OF THE OFFSET OF THE OVEN SET POINT FROM THE RESONATOR TURNOVER POINT, FOR $T_i - T_{TP} = 10°C$

for $T_i - T_{TP} = 10°C$		Oven Cycling Range (mK)			
		10	1	0.1	0.01
Oven Offset (mK)	100	4×10^{-12}	4×10^{-13}	4×10^{-14}	4×10^{-1}
	10	6×10^{-13}	4×10^{-14}	4×10^{-15}	4×10^{-1}
	1	2×10^{-13}	6×10^{-15}	4×10^{-16}	4×10^{-1}
	0.1	2×10^{-13}	2×10^{-15}	6×10^{-17}	4×10^{-1}
	0	2×10^{-13}	2×10^{-15}	2×10^{-17}	2×10^{-1}

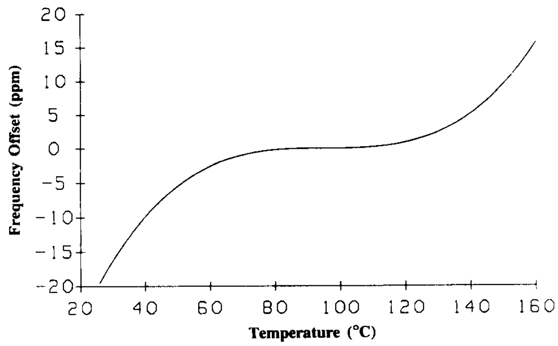

Fig. 5. Frequency versus temperature of an SC-cut resonator with zero f versus T slope at the inflection temperature. The frequency remains within ±1 ppm over ±25°C about T_i [6], [56].

TABLE II
FREQUENCY OFFSETS DUE TO THERMAL CYCLING AS A FUNCTION OF THE OFFSET OF THE OVEN SET POINT FROM THE RESONATOR TURNOVER POINT, FOR $T_i - T_{TP} = 0°C$ [57]

for $T_i - T_{TP} = 0°C$		Oven Cycling Range (mK)			
		10	1	0.1	0.01
Oven Offset (mK)	100	2×10^{-14}	2×10^{-15}	2×10^{-16}	1×10^{-17}
	10	4×10^{-16}	2×10^{-17}	2×10^{-18}	1×10^{-19}
	1	8×10^{-17}	4×10^{-19}	2×10^{-20}	1×10^{-21}
	0.1	6×10^{-17}	8×10^{-20}	4×10^{-22}	7×10^{-23}
	0	6×10^{-17}	6×10^{-20}	2×10^{-22}	2×10^{-23}

Table I is for an SC-cut resonator the turnover point of which is 10°C from the inflection point [4], [6].

Table I shows that for small oven offsets and high-stability ovens, the f versus T instability can be less than the oscillator's $\sigma_y(\tau)$. The assumed f versus T characteristic for Table I is not the best that can be achieved. Fig. 5 shows the f versus T for the optimum resonator, *i.e.*, for one where the turnover temperatures coincide with the inflection temperature [6]. Such a resonator is not easy to make; however, with careful cutting, angle correction, recontouring [56], design and fabrication, it is possible to make such a resonator. The frequency offsets in Table I become at least 100× smaller for such a resonator, as can be seen in Table II [57]. How accurately the oven temperature can be set to the optimum set point depends primarily on the hysteresis of the resonator and of the thermometer.

Secondary factors are the noise of the resonator, thermometer, and amplifier. If, for example, the normalized beat frequency between three times the fundamental mode frequency minus the third overtone frequency is used as the thermometer [53], then the slope of this frequency is about 10^{-4}/K, and the hysteresis of the best such SC-cut resonators (over a much wider temperature than is necessary for setting the oven to turnover) is less than 10^{-8}. Therefore, in principle, the temperature can be set to about 10^{-4} K of the optimum set point. Because the hysteresis over the very narrow temperature range needed for oven temperature setting can be expected to be much smaller than 10^{-8}, the fundamental limit to setting the oven temperature may ultimately be limited only by the $\sigma_y(\tau)$ of the resonator. If so, then the oven temperature can be set much closer to the optimum temperature than 10^{-4} K, if necessary.

Therefore, the fundamental limit due to f versus T changes is negligibly small, with the following proviso. The above discussion assumes that the f versus T characteristic near the turnover temperature is smooth, and can be represented by a cubic polynomial. These assumptions seem to be correct in most measurements, however, most measurements of f versus T are made with resolution of parts in 10^9 or coarser. This is especially true for other than SC-cut resonators for which the thermal transient effect would make higher resolution measurements virtually impossible. There is some preliminary information [58], [59] which indicates that when the f versus T characteristics of SC-cut resonators and oscillators are examined with a high resolution, fine structure is revealed, *i.e.*, the f versus T is not smooth. It has also been found that a cubic polynomial representation of f versus T is insufficient over a wide temperature range; much higher order polynomials or segmented polynomials or splines are needed in order to obtain a good fit to the data [53], [59]. Should fine structure in the f versus T be a universal phenomenon, the difficulty of setting the oven temperature to a zero temperature coefficient point would be greatly increased and the frequency offsets in Tables I and II would also increase.

Oven Stability

Most ovenized crystal oscillators use a thermistor to sense and ultimately control the temperature of the oven shell. All thermistors exhibit drift of the apparent temperature with time and also change with large temperature cycling [60].

Fig. 6 shows a simplified electrical analog for a thermal enclosure around a crystal resonator. The temperature of the heater, T_H, is replaced by V_H; the temperature of the resonator, T_R, by V_R; and the outside temperature T_o by V_o. The heat capacity of the heater is represented by C_H and that of the resonator is represented by C_R, the thermal impedance between the outside and the heater by R_{OH} and between the heater and resonator by R_{HR}, and the thermal impedance between the resonator and the outside by R_{RO} [61], [62].

If we assume that the thermal sensor and heater are tightly coupled, the fundamental thermodynamic limit for temperature stability of the heater is [63]

$$\Delta T_H = \sqrt{\frac{kT_H^2}{C_H}} \tag{8}$$

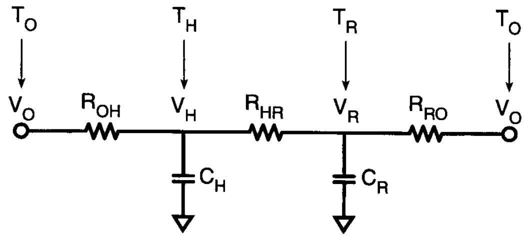

Fig. 6. Simplified electrical analog of an oven [61].

where k is Boltzmann's constant and C_H is the heat capacity of the sensor/heater system. For an aluminum heater shell and sensor weight of approximately 7 g and T_H =80°C, (8) indicates a minimum temperature fluctuation of 0.5 nK. At equilibrium, the rate of change of heater temperature due to the temperature fluctuations is given by

$$\frac{dT_H}{dt} = \frac{T_H}{\tau_H}\sqrt{\frac{k}{C_H}} \tag{9}$$

where $\tau_H = R_{OH}C_H$ is the thermal time constant of the sensor/heater system to the outside. For τ_H longer than 0.01 s the temperature fluctuations due to fundamental thermodynamic processes are so small that they can be ignored (unlike in infrared imaging technology, where the much smaller heat capacities of pixels makes this effect a significant fundamental limit.)

For simplicity, let us assume a thermistor with a resistance of 50 kΩ at 25°C and a slope of 0.8 kΩ/C at 80°C. If the current passing through the thermistor is 0.5 mA, then the power dissipated in the thermistor is 1.8 mW. If the time constant for the oven cooling is 100 s and the heat capacity is 6 J/K, which corresponds to roughly 7 g of aluminum, then the thermal conductance is (6 J/K)/100 s = 0.06 W/K. This results in a self heating error of 30 mK. The error signal from the thermal sensing circuit is roughly

$$dV/dT = 0.5\,\text{mA} \times 0.8\,\text{k}\Omega/\text{K} = 0.4\,\text{V/K}. \tag{10}$$

A change in the sensing current of 5×10^{-6} will change the self heating by about 300 nK. Reducing the sensing current will reduce the self heating and the inherent sensitivity to small changes in current but will also reduce the error signal.

The noise in the thermal bridge, due to shot noise in the current, Johnson noise in the thermistor, and typical noise in amplifiers, can be roughly estimated to be 340 nK at a few seconds for a dc bridge, and about 70 nK for an ac bridge. The long-term stability in both cases should be dominated by the thermistor aging of approximately 0.1–0.001 K/y [60].

The rate of change of the resonator temperature is approximately given by

$$\frac{dT_R}{dt} = \left[\frac{dT_H}{dt} + \frac{dT_0}{dt}\frac{R_{HR}}{R_{RO}}\right]\left(\frac{\tau}{\tau + \tau_R}\right) \tag{11}$$

where

$$\tau_R = C_R \frac{R_{RH}R_{RO}}{R_{RH} + R_{RO}}.$$

The first term in (11) is due to fluctuations in the oven temperature and the second term is due to changes in the outside temperature. For times longer than τ_R the temperature of the resonator follows

$$T_R \approx T_H - \frac{(T_H - T_O)R_{HR}}{R_{RO}}. \tag{12}$$

The temperature error of the resonator is due to the thermal coupling to the outside and the finite thermal impedance to the sensor/heater system. The thermal isolation of the resonator G_{iso} is limited to

$$G_{\text{iso}} = \frac{R_{RO}}{R_{HR}} \tag{13}$$

even if the average temperature of the sensor and heater are perfectly stable. A typical value of G_{iso} is of order 1000. A change in the outside temperature of 1°C results in a transient change in the resonator of approximately (1/1000)$(\tau/\tau + \tau_R)$. If τ_R is 100 s then the thermal transient is approximately 10 μK/s with a total offset of 1 mK.

The temperature error of the resonator can be greatly reduced if the set point for the sensor is changed slightly to compensate for the changes in the outside temperature. This can be accomplished by applying a signal proportional to the difference between the current outside temperature and the nominal outside temperature, to change the temperature of the heater by an amount

$$dT_H = (T_H - T_O)G_{ff}. \tag{14}$$

This results in a resonator temperature of

$$T_R = T_H - (T_H - T_O)\left(\frac{R_{HR}}{R_{RO}} - G_{ff}\right). \tag{15}$$

By adjusting the feedforward gain G_{ff}, it is possible to compensate for the thermal coupling to the outside and thereby improve the thermal isolation by a factor of 10–100 over the simple traditional approach. Practical limits to achievable thermal isolation are due to temperature gradients. Thermal gains of 10^5 in a single oven have been achieved using this technique. The transient response of this feed forward compensated oven arrangement can also be greatly improved over conventional ovens, as demonstrated in [61].

Retrace

An OCXO's frequency offset upon turn-on and stabilization, after a temperature excursion due to an off-period, is called "retrace." The magnitude of retrace is a function of the duration of the off period and the oscillator's temperature-time profile during that period. A larger temperature excursion from the oven set point and a longer duration usually result in a larger frequency offset upon turn-on and stabilization.

Retrace is closely related to the hysteresis exhibited by temperature compensated crystal oscillators [64]. The mechanisms responsible for retrace are believed to be the same as those responsible for aging and hysteresis. In addition to the aging mechanisms discussed above, stress changes resulting from the temperature excursion, from temperature gradients, and from thermal expansion coefficient mismatches can worsen the effect.

Although minimizing retrace presents serious practical problems, none of the known retrace mechanisms appear to present a fundamental limit. For example, for the "ideal" resonator described below, nearly all known retrace mechanisms would be absent.

Acceleration Sensitivity

Acceleration sensitivity [10] was not well understood until recently. Thanks to the theoretical work of Tiersten [65] and his students, and others [66], [67], the origin of acceleration sensitivity and how it can be minimized, is now understood (provided that the resonator plate and its mounting are linearly elastic).

Leaving out tensor notation for simplicity, the acceleration-induced normalized frequency shift $\Delta\nu/\nu$ can be represented as

$$\frac{\Delta\nu}{\nu} = \int_V cg^2\, dV \tag{16}$$

where c represents the change in the effective elastic constants due to the biasing deformation field resulting from the acceleration, g is the gradient of the normalized mechanical displacement vector associated with the mode of vibration (*i.e.*, of the "mode shape"), and V is the undeformed volume of the resonator. Theoretically, the integral can be zero for bulk acoustic wave quartz resonators, *e.g.*, for SC-cuts, when the mounting is completely symmetrical with respect to the mode shape.

So, although many practical limits must be overcome before zero acceleration sensitivity resonators can be produced, the fundamental limit to acceleration sensitivity is zero. Because of defects in the quartz and finite fabrication tolerances, it may be necessary to adjust the mode shape in order to achieve nearly zero acceleration sensitivity [66].

Shock Resistance

The frequency excursion during a shock is due to the resonator's acceleration sensitivity. The magnitude of the excursion is a function of resonator design, and of the shock induced strains in the resonator. (Resonances in the mounting structure amplify the strains.)

A shock-induced permanent frequency offset can be due to: shock induced stress changes (*e.g.*, due to exceeding an elastic limit in the mounting structure), the removal or deposition of contamination from or onto the resonator surfaces, and changes in the oscillator circuitry, such as a load reactance change resulting from displacement of a wire or other component. If a resonator with zero acceleration sensitivity to low level accelerations is shocked so that its mounting structure deforms inelastically, then the symmetry conditions required for zero acceleration sensitivity may be destroyed and the shock induced frequency shift can become nonzero.

Survival under shock is primarily a function of resonator surface imperfections. Chemical-polishing-produced scratch-free resonators have survived shocks of up to 3.6×10^4 g in air gun tests, and have survived the shocks due to being fired from a 155 mm howitzer (1.6×10^4 g, 12 ms duration) [68], [69]. The feasibility of achieving shock resistance in excess of 10^5 g has been shown [70].

The integral in (16) for the acceleration induced frequency shift is valid at all accelerations, provided that the resonator plate and its mounting are linearly elastic [71]. The quartz plate remains sufficiently linear until near its breaking point, and, in principle, the mounting structure can also be designed to behave linearly (*e.g.*, by using quartz for the mounting). Therefore, although currently available resonators do generally exhibit a frequency shift upon experiencing a shock, the fundamental limit to shock induced frequency shift is zero, and the fundamental limit to the shock level which resonators can survive is greater than 10^5 g.

Ionizing Radiation

Ionizing radiation can be divided into two categories: photons (X-rays and γ-rays), and particles (mostly neutrons, but also protons, electrons, α-particles, and other elementary particles) [6], [7], [72]–[74].

The response of an oscillator to a pulse of ionizing (photon) radiation consists of two parts. Initially, there is a transient frequency change that is due primarily to impurity motion and the thermal-transient effect caused by the sudden deposition of energy into the crystal unit. This effect is a manifestation of the dynamic f versus T effect discussed earlier. The transient effect is absent in SC-cut resonators made of high purity quartz.

In the second part of the response, after steady state is reached, there is a permanent frequency offset that is a function of the radiation dose and the nature of the crystal unit. The frequency change versus dose is nonlinear, the change per rad being much larger at low doses than at large doses. At doses above 1 krad (SiO_2), the rate of frequency change with dose is quartz-impurity-defect dependent.

The impurity defect of major concern in quartz is the substitutional Al^{3+} defect with its associated interstitial charge compensator, which can be an H^+, Li^+, or Na^+ ion, or a hole. This defect substitutes for a $Si4^+$ in the quartz lattice. Radiation can result in a change in the position of weakly bound compensators, which modifies the elastic constants of quartz and thereby leads to a frequency change. The movement of ions also results in a decrease in the crystal's Q (*i.e.*, in an increase in the crystal's equivalent series resistance), especially upon exposure to a pulse of ionizing radiation. If the oscillator's gain margin is insufficient, the increased resistance can stop the oscillation for periods lasting many seconds.

A strong pulse of ionizing radiation produces photo currents in the circuit which results in a momentary cessation of oscillation, independent of the type of quartz used in the resonator. In oscillators using properly designed oscillator circuitry and resonators made of swept quartz, the oscillator recovers within about 15 μs after exposure.

Sweeping is a high-temperature, electric-field-driven, solid-state purification process in which the weakly bound alkali compensators are diffused out of the lattice and replaced by more tightly bound H^+ ions and holes [26], [27], [34], [72], [73]. Crystal units made from swept quartz exhibit neither the radiation-induced Q degradation nor the large radiation-induced frequency shifts. Swept quartz (or low aluminum content quartz) should be used in oscillators which are expected to be exposed to ionizing radiation. For example, at a 1 Mrad dose, the frequency change can be as large as 10 parts per million (ppm) when the crystal unit is made from natural quartz, which is usually relatively impure; it is typically 1 to a few ppm when the crystal is made from cultured quartz, and it can be as small as 0.02 ppm when the crystal is made from swept cultured quartz.

At low doses (*e.g.*, a few rads) the frequency change per rad can be as high as 10^{-9}/rad [74]. The low-dose effect is not well understood. It is design and fabrication dependent. It is not impurity-dependent, and it saturates at about 300 rad. At very high doses ($\gg$1 Mrad), the impurity-dependent frequency shifts also saturate because, since the number of defects in the crystal are finite, the effects of the radiation interacting with the defects are also finite.

When a fast neutron hurtles into a crystal lattice and collides with an atom, it is scattered like a billiard ball. A single such neutron can produce numerous vacancies, interstitials, and broken interatomic bonds. The effect of this "displacement damage" on oscillator frequency is dependent primarily upon the neutron fluence. The frequency of oscillation increases nearly linearly with neutron fluence. The rates for AT-cut and SC-cut resonators are: 8×10^{-21} per neutron per square centimeter (n/cm^2) at a fluence range of 10^{10} to 10^{12} n/cm^2; 5×10^{-21}/n/cm^2 at 10^{12} to 10^{13} n/cm^2; and 0.7×10^{-21}/n/cm^2 at 10^{17} to 10^{18} n/cm^2.

Because the lattice damage produced by neutrons is unavoidable (except for using a great deal of shielding), the frequency changes produced by neutrons appear to be unavoidable at first. However, because the frequency change per neutron per square centimeter is constant for a given resonator, it is possible, in principle, to sense the neutron fluence and compensate for the frequency changes [6], [75].

Would an SC-cut crystal made of quartz that is free of impurities exhibit a frequency change due to radiation? Because the reported frequency offsets produced by photons are attributed to changes at impurities, the answer is probably that there would be no permanent frequency offset produced by photons. Would there be a temporary frequency change? Probably yes, because a pulse of radiation liberates electrons which can produce temporary local electric fields in the quartz, and on the surfaces of the resonator. The magnitude of this frequency change is unknown, but is probably small because the integral of the charge distribution between the electrodes remains zero (except for charges that may be emitted from the surfaces under an intense pulse).

Background radiation due to radioactive trace elements in the soil and in building materials, α-particle emitters in the resonator package [76], and cosmic rays will produce drift that is difficult to distinguish from aging. This drift is not aging according to the definition of the term "aging," it is a radiation effect. The definition of aging [77] is that it is "the systematic change in frequency with time due to internal changes in the oscillator." Added to the definition is: "Note—It is the frequency change with time when factors external to the oscillator (environment, power supply, etc.) are kept constant." Drift is defined as "the systematic change in frequency with time of an oscillator." Drift is due to aging plus changes in the environment and other factors external to the oscillator.

Alpha-particle induced errors in high-density integrated circuits have been of concern in the design and manufacturing of such devices [76]. These particles originate from radioactive trace impurities, such as uranium and thorium, which are present in many materials, including packaging materials. Although α-particles originating from outside a resonator package would not be able to reach the resonator (because α-particles typically penetrate solids to depths of only $\sim 10 - 30\ \mu$m), α-particles can originate from materials inside the package, *e.g.*, from gold-plated Kovar, sealing glasses and adhesives. Some of these α-particles can have energies as high as 8.8 MeV; however, the flux is low, typically $<1/\text{cm}^2/\text{h}$. Because the sensitivity of AT-cut resonators to energetic a-particles is linear, with a slope of $\sim -2 \times 10^{-17}$ per cm^2/particle [78], the effect of α-emitters on long term stability appears to be $<1 \times 10^{-13}$y. The effect of radiation on noise (or frequency jumps) appears to be negligible, unless there is a significant transient effect whenever a high-energy alpha particle penetrates the resonator surface.

The effect of cosmic rays depends on the altitude [32], the effect being more significant at higher altitudes, and on the mix of photon and particle energies in the cosmic rays. The amount of background radiation depends on location. The average annual radiation dose from natural sources in the USA has been reported to be on the order of 0.1 rad [79]. The frequency shift due to irradiation with 0.1 rad/y is unknown, because the annealing of radiation effects over such a long period is unknown. However, if we conjecture that the sensitivity to a dose of 0.1 rad is independent of the dose rate and that $\sim$0.1 rad/y reaches the resonator, then the reported sensitivity to low doses of about 10^{-10}–10^{-9}/rad [74] would produce apparent aging rates of $\sim 10^{-13}$/d, which is about the order of magnitude of the best aging reported to date [2]. Therefore, background radiation (on the surface of the earth) may be a significant practical limit to the achievable long term stability of crystal oscillators. Presumably, there may be locations, *e.g.*, in a deep mine, where the background radiation is negligible, so the limit is a practical one, not a fundamental one.

III. Fundamental Limit to Oscillator Frequency

The highest frequency bulk-acoustic-wave (BAW) quartz resonator reported to date is a 1.655 GHz AT-cut resonator made with a chemical polishing etching technique [80]. Such a resonator is 1 μm thick. The performance of this resonator was probably limited by the lack of sufficient parallelism of the quartz plate, and by the electrodes, which at such a resonator thickness can no longer be a negligible portion of the total thickness.

How thin can a resonator be? If an electrodeless design is used, and resonators can be polished and etched uniformly enough to maintain the required flatness and parallelness, then

TABLE III
SUMMARY OF THE FUNDAMENTAL LIMITS OF INSTABILITIES. THE BEST INSTABILITY VALUES REPORTED TO DATE ARE INCLUDED FOR COMPARISON

Instability	Best Reported	Fundamental Limit
Aging	10^{-13}/d [2]	0
2-sample deviation floor, $\sigma_y(\tau)$	4×10^{-14} @ $\tau = 10$ s [85]	$<1 \times 10^{-14}$
f versus T, static	10^{-10} (−55°C to +85°C) [86]	0
f versus T, dynamic	0 for a true SC-cut [55]	0
f versus T, retrace	10^{-10} after 24 h at −55°C [86]	0
f versus T, hysteresis	10^{-9} (−55°C to +85°C) [64]	0
Acceleration sensitivity, Γ	9×10^{-11}/g [87]	0
Radiation—photons, steady state	10^{-14}/rad @ 1 Mrad [72], [88] 10^{-11}/rad @ 1 rad [87]	0? @ 1 Mrad 0?
Radiation—photons, pulse	? (e.g., 10^{-9} @ 10^{11} rad/s) [72]	?—no permanent offset
Radiation—neutrons	$10^{-21}/(\mathrm{n/cm^2})$ [89]	$10^{-21}/(\mathrm{n/cm^2})$ (but can compensate)
Atmospheric pressure	0 if hermetically sealed	0
Humidity	if hermetically sealed	0
Power supply	negligible	0
Load impedance	$\sim 10^{-15}$ for VSWR = 2	0
Magnetic field	$\sim 10^{-9}$/T [33]	0
Electric field	~ 0	0

it ought to be possible to achieve frequencies far above 1.6 GHz; *e.g.*, at 0.1 mm thickness, the frequency of an AT- or SC-cut resonator would be about 16 GHz. At such a thickness, since the molecular spacing is about 0.5 nm, a resonator is about 200 molecular layers thick. At 100 molecular layers, the frequency would be 32 GHz, and so forth. However, as the frequency increases, the Q and the resonance to antiresonance frequency separation decrease. For a given type of resonator, there exists a frequency limit above which the separation is zero, *i.e.*, no positive reactance region exists above this limit. For example, for a fundamental mode AT-cut resonator, the limit is 42 GHz, and the limit is lower for higher overtone resonators. For resonators made of some other piezoelectric materials, the limit is above 100 GHz [81].

How many molecular layers are needed to make a resonator, and how might one make an ultrathin resonator? From a theoretical point of view [82], [83], for fundamental mode thickness shear resonators, the results in terms of frequency and mode shape are similar for a fifteen molecular layer crystal whether it is a discrete or continuum model. By applying semiconductor and silicon micromachining [84] fabrication techniques, where nanometer feature sizes are now being fabricated, and using levitation and an electrodeless design in order to eliminate mounting, bonding, and electrode stresses, it may be possible to make ultrathin, ultraminiature quartz resonators in the future. Rather than using etching techniques, it may be possible to grow a few molecular layers of single crystal quartz (or langasite, which does not undergo a phase transition below its melting point). Such extremely thin resonators would be extremely sensitive to mass loading changes, *e.g.*, the frequency versus thickness sensitivity would be 1% per molecular layer at 32 GHz. On the other hand, if outgassing of the resonator material is a significant instability mechanism, then being ultrathin would be an advantage because the thinner the resonator, the easier it is to outgas it (as the impurity atoms have a shorter distance to travel before reaching the surfaces). If the electrode wafers of the electrodeless structure are made of, for example, quartz or silicon, then they could be made to be good getters by baking them at high temperature, or by depositing a getter material onto their inside surfaces.

IV. SUMMARY OF THE FUNDAMENTAL LIMITS

Table III summarizes the fundamental limits of the various instabilities. The best instability values reported to date are included for comparison.

V. SOME THOUGHTS ON THE PATHS TO APPROACH THE FUNDAMENTAL LIMITS

A large number of possibilities remain to be explored in order to approach the fundamental limits. In our opinion, the following are some of the more important ingredients in future attempts to make significant improvements in the stabilities of oscillators:

- use dislocation-free, high-purity, high-Q (and twinning-resistant) material—quartz or other,
- use defect-free surfaces, made, for example, by chemical polishing plus colloidal silica polishing followed by final chemical polishing [90],
- use SC-cut, biconvex, low-frequency (2.5 MHz 5th overtone), unconventional (noncircular) geometry,
- use designs with no electrodes in contact with the active area,
- mount symmetrically between two identically oriented quartz plates joined by clean-surface to clean-surface atomic bonding [43], [44], [91]–[93],
- use an alternative approach with no mounting (*i.e.*, levitate the resonator plate—see Fig. 7 and related discussion below),
- use UV/ozone for final cleaning [50],
- use a high-temperature bake in UHV immediately before sealing,
- use sapphire, or high-alumina ceramic, or pure Al or Al alloy or clad Al enclosure,

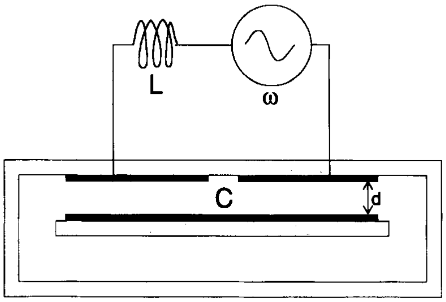

Fig. 7. Diagram illustrating levitation [94]–[96].

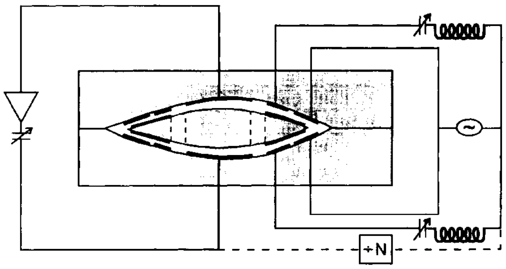

Fig. 8. One approach to combine levitation with the BVA style resonator [100].

- seal in UHV with clean-surface to clean-surface atomic bonding [43], [44], [91]–[93],
- compensate the oven for a thermal gain $>10^4$,
- use dual-mode techniques for temperature setting and control,
- use $R \sim 10^5\,\Omega$ across the resonator,
- use nonmagnetic mounting and electrode materials; shield transformers and inductors,
- use low flicker noise sustaining circuit,
- use notch instead of bandpass filter for mode selection,
- measure voltage and power sensitivities and regulate accordingly,
- use total isolation in loop and output amplifier >120 dB,
- use hermetically sealed and rigid oscillator enclosure,
- use intelligent compensation for all systematic effects.

VI. The Ideal Resonator?

The ideal quartz resonator may be a high-perfection quartz plate levitated in an atomically clean environment, with no electrodes, mounting structures or anything else in contact with the resonator plate.

Fig. 7 shows a method that may be applicable to levitating a quartz plate [94]–[96]. A resonant circuit is formed consisting of an inductor L that is external to the enclosure, and a parallel plate capacitor inside the enclosure. The capacitor consists of three plates, two of which are edge-to-edge, with a small spacing between them, and a third, which is a conducting surface on the plate being levitated. This third conductor is a distance d from the other two. The capacitance C of this arrangement is a function of the gap dimension d. The plate is in stable equilibrium with respect to vertical displacements when the LC-circuit is driven at an angular frequency $\omega \cong (LC)^{-1/2}$. This method is open-loop, *i.e.*, no feedback sensor is used. The concept has been demonstrated experimentally by the levitation of a 24 mm × 24 mm × 180 μm microscope cover slide.

In [94] it is shown that when the plate is displaced vertically there is a restoring force, *i.e.*, the plate is in a potential well (for vertical displacements). This confinement is similar to that used for ion traps [97], [98]. It is demonstrated in [96] for a flat plate, that with four sets of levitation electrodes it is possible to obtain stability in all six degrees of freedom required for a rigid body. Moreover, for capacitor plate area A, and a driving voltage V, the vertical levitation force F is proportional to $AV^2 d^{-2}$. It is possible to levitate a 10 MHz 3rd overtone SC-cut resonator with $V \sim 10$ V at a few micrometers of a gap distance.

In the currently used electrodeless (BVA) resonators [41], [99], the gap between the electrodes and the plate is 5 μm on either side of the plate, and the next generation BVA resonators are expected to use 1 μm gaps [99], so the BVA gap dimensions are highly compatible with the dimensions needed for levitation at reasonable voltages. Moreover, the frequency of an electrodeless resonator depends only on the sum of the two gaps [71], [99], *i.e.*, a displacement of the plate in the gaps does not affect the frequency (*e.g.*, if two equal 5 μm gaps are changed to a 4 μm gap on one side and a 6 μm gap on the other, the frequency is unaffected). Therefore, slight displacements of a levitated plate, for example, due to vibration, ought not affect the frequency. One possible way to approximate the ideal resonator is to combine levitation with a BVA-type structure, as shown conceptually in Fig. 8 [100].

The area on which the levitation electrodes are deposited is outside the active area of the resonator, separated from the active area by quartz bridges. The levitation frequency can be derived from the oscillator frequency.

An interesting side effect of levitation in vacuum is that heat losses from the resonator are limited to radiation losses. The amount of energy needed to heat the resonator to the turnover temperature is small, and the thermal time constant for heating the resonator to its turnover temperature is short. For example, when heated in the thickness direction by IR radiation [101], the time constant is a fraction of a second, even for a 5 MHz 5th overtone SC-cut resonator. The time constant is proportional to the square of the plate thickness, so the time constant for warmup can be in the ms range for high frequency resonators. The time constant for cooling is much longer, due to the small thermal conductance to the outside.

VII. Conclusions

We have explored many parameters that affect the stability of quartz crystal oscillators and find only two significant fundamental limits to stability: Johnson noise of the resonator, and phonon scattering within the resonator. Current technology appears to be sufficient to significantly reduce the effects of all other parameters on frequency stability below the best presently available in quartz oscillators. We expect advances in quartz (and possibly other) materials, resonator design, fabrication methods, and electronics to make possible crystal oscillators of greatly improved stability in the future.

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