# Quartz Crystal Oscillators with Direct Resonator Heating

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## Abstract

This paper describes a newly patented, low power, ovenized oscillator with the crystal heated directly by means of a thin film resistive heater deposited on its surface. Mounting the resonator inside an evacuated enclosure forms a miniature "thermos" bottle. The only significant path for heat loss is through the resonator mounting ribbons and posts and these, being long and thin, have quite high thermal resistance. Pulse duration modulation controls resonator heating current. Phase noise, Allan variance, and aging all appear unaffected by direct resonator heating. Practical results for an oscillator employing these concepts are encouraging. Frequency-temperature stability better than ± 2.5 x $10^{-8}$ from 0 to 70°C has been achieved using a third overtone 10.230 MHz SC-cut resonator with room temperature power consumption of about 300 mW. Theoretical analysis shows substantial heating power reduction is possible by introducing additional thermal resistance in the form of a glass ring as part of the resonator mounting structure. Room temperature power consumption under 100 mW appears feasible.

## Introduction

Quartz crystal resonators are the backbone of modern communications electronics. One observer remarked "Quartz existence might well be recalled in any debate over the benevolence of the creator". [1] But quartz crystal resonators are not perfect. In many applications the basic frequency temperature stability of the resonator is insufficient. Assuming the crystal cut has been wisely selected, and the angle precisely maintained during manufacturing, only two general techniques exist to improve oscillator frequency temperature stability. The first is compensation. In Temperature Compensated Crystal Oscillators (TCXO), temperature sensitivity is reduced by adjusting the oscillator circuit to compensate for temperature induced frequency shifts. The prevailing technique employs a thermistor network developing a temperature dependent correction voltage applied to a voltage variable capacitance thereby restoring frequency stability.

## TCXO Limitations

Every resonator has a unique frequency temperature characteristic requiring custom compensation-a major liability in mass production. Low cost TCXOs have thermistor compensation networks designed solely upon the basis of the crystal frequency temperature curve. Better TCXOs are subjected to a requirement run revealing the frequency temperature behavior of the oscillator as a whole. A second frequency temperature test, the confirmation run, confirms correct compensation. Additional temperature testing and adjustment of the thermistor network is often necessary.

Temperature compensated oscillators have not improved greatly in recent years. The factors limiting TCXO performance are exhaustively researched and documented. One important factor is hysteresis. Repeated frequency temperature curves, or curves made in opposite directions fail to overlap. While speculation to the cause of hysteresis is plentiful, practical measures for its elimination or reduction are scarce. Process control and cleanliness have some effect but hysteresis is also in part an unavoidable intrinsic property of quartz. As a practical matter, hysteresis guarantees temperature compensated oscillators rarely perform quite as well in the field as they do during the factory confirmation run.

Quartz crystal resonators age. Accordingly most precision oscillators have a electrical or mechanical frequency adjustment. Unfortunately, aging adjustment upsets temperature compensation. This inconvenient phenomenon is the trim effect. Aging adjustment changes the slope or linearity of the varactor tuning network. Correction voltage from the thermistor network is no longer accurate. Attention to tuning network linearity and using the same tuning network for both temperature compensation and aging adjustment reduces the trim effect. Some digitally compensated oscillators avoid the varactor tuning network altogether. Pulse dropping corrects oscillator frequency, circumventing the trim effect. However, hysteresis still limits compensation accuracy and the missing pulses play havoc with the oscillator short term stability.

TCXO stability also suffers if temperature changes too quickly. It is not possible to place the thermistor network directly on the resonator as it is mounted inside an evacuated enclosure for high Q and low aging. Thermistors mounted on the crystal case respond to sudden temperature changes before the resonator. The compensation network compensates for the wrong temperature causing large transient frequency shifts.

Finally, high performance doubly rotated resonators cannot be used in TCXOs. TCXO crystals often have frequency temperature inflection points just outside the specified temperature range. This sets up a largely linear frequency temperature characteristic across the specified temperature range simplifying the compensation network, but also demands a wide frequency adjustment range from the oscillator. TCXO resonators cannot be "stiff". Doubly rotated resonators, especially the SC-cut, have many desirable properties including lower phase noise, better aging and reduced acceleration sensitivity, but are too stiff to temperature compensate. Consequently, TCXOs are limited to AT-cut resonators and the improved performance possible with doubly rotated resonators remains out of reach.

Other compensation schemes develop correction voltage by means of a digital look-up table and a digital to analog converter, or by analog computation of the required cubic correction factor from a linear temperature sensor. These techniques, however, share the fundamental shortcomings mentioned before. In short, TCXO technology is inadequate in many applications with further improvement being unlikely.

**Ovenized Oscillators**

Of course, undesirable frequency temperature excursions can be avoided by simply maintaining the resonator at a constant elevated temperature by means of electrical heating controlled by a thermostat of proportional controller. This is the basis of oven controlled crystal oscillators (OCXOs). Frequency temperature stability can be as much as one thousand times better than a TCXO, but improved performance comes at a steep price. OCXO power consumption exceeds that of TCXOs by a factor of at least several hundred. Furthermore, OCXOs burdened by the need to surround the resonator and associated oscillator circuitry first by a heated metallic enclosure and then by thermal insulation, are difficult to miniaturize.

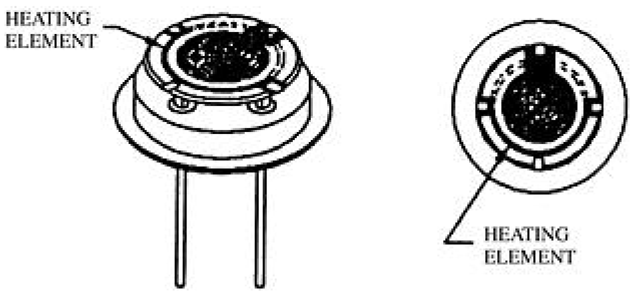
Ovenized oscillators, like TCXOs, represent mature technology. Recent introduction of doubly rotated resonators has enabled improvement in the areas of aging, phase noise and frequency temperature stability, but on the whole, the pace of development has slowed. Power consumption remains a critical issue.

**Oven Power Reduction**

There are two ways to reduce oven power. First, make the heated volume as small as possible. This reduces the area from which heat is lost and, for fixed outside dimensions, maximizes the volume available for insulation. Only the oscillator components that are unavoidably temperature sensitive should be heated. Ideally the resonator should be the only temperature sensitive component. Most oscillators have some temperature sensitivity which is minimized by stable bias, avoidance of active device saturation and high permittivity ferrites, and by using high quality temperature stable components. Second, the thermal insulation must be as effective as possible. While urethane foam and fiber glass type material are commonly used, vacuum is the ideal thermal insulator.

By this line of reasoning, the ultimate ovenized oscillator is a temperature insensitive amplifier and associated feedback loop components connected to a heated resonator, the latter suspended in an evacuated enclosure. This immediately suggests depositing a resistive thin-film heating element on an otherwise ordinary resonator inside a standard evacuated crystal enclosure forming a directly heated resonator. Figure 1 shows a directly heated resonator mounted inside a conventional TO-5 enclosure. The heating element, split into two semi-circular sections to avoid shorting the resonator electrodes, runs along the edge. The heating elements are applied with the same vapor deposition process used to deposit the resonator electrodes but with reduced thickness in order to increase electrical resistance.

**Figure 1. Crystal Resonator With Thin Film Resistive Heater**




**Quartz Crystal Thermal Model**

A quartz crystal resonator is a complex thermal system. Because the resonator enclosure is evacuated, heat is not conducted efficiently into the resonator. Convection is absent, and heat transfer by radiation is negligible for all but very large temperature differences. The only significant heat conduction path into the resonator is through the resonator support posts. The long thin posts present a substantial thermal resistance. Thermal resistance refers to a resistance to heat flow in any analogy with Ohms Law. Heat flow (in Watts) corresponds to electrical current. A heat source models as a current source. Thermal insulation offers a resistance to heat flow with units degrees Centigrade per Watt. In this analogy, a voltage drop corresponds to a temperature difference. Thermal resistance between the resonator and its enclosure is responsible in part for the poor performance of TCXOs in response to temperature slew. Ovenized oscillators are also affected. Because it takes time for heat to travel through the crystal leads into the resonator, ovenized oscillators continue to drift after the oven temperature has stabilized. The thermal time delay in both cases is analogous to an RC low pass filter with the specific heater of the quartz resonator functioning as the shunt capacitor. Quartz crystal resonators, especially AT-cuts, are further affected by mechanical stress accompanying the thermal gradients induced as heat flows from the mounting posts at the edge towards the active region underneath the electrodes in the center.

**Directly Heated Resonators**

The ideal of depositing a heating element directly upon the resonator surface has been around for some time-a patent was issued in 1969 [2]-but directly heated resonators have never been widely used. Two problems stand in the way of commercialization.

The first centers on the difficulty of controlling resonator temperature. Conventional ovenized oscillators sense the temperature of the heated enclosure surrounding the oscillator. This approach fails when the resonator alone is heated. In principal, a sensor could be placed on the resonator surface but several difficulties arise on the score. The sensor mass loads and damps the resonator, and might compromise aging.

The second problem is more fundamental. Directly heated resonators experience significant mechanical stress coming from large thermal gradients underneath the thinfilm heater. Quartz crystal resonators react to stress by changing frequency. Green house, et. al., [3] encountered stress induced frequency shifts in an AT-Cut ovenized crystal oscillator using a directly heated resonator to reduce warm-up time, reverting to conventional heating during operation. Thermal frequency shift is a central issue in the development of practical directly heated resonators.

**Resonator Temperature Control**

Maintaining a constant resonator temperature despite ambient temperature variations is the function of the heater control circuitry. The control circuit transfer function, having units of Watts per degree, may be thought of as an equivalent thermal conductance ideally the reciprocal of resonator thermal resistance. It increases heating current by a set amount for each degree drop of the enclosure temperature.

Three parameters are needed to accurately estimate resonator temperature without direct sensor contact; case temperature, resonator-to-case thermal resistance, and resonator heater power. Case temperature is easily measured by a variety of temperature sensors. Because thermal resistance is determined primarily by the resonator mounting structure, it can be measured once for a given mechanical configuration and considered constant thereafter. Measured variation between resonators is small. Resonator heating power is monitored by observing heating current.

Efficient control of heating current is necessary. Conventional ovenized oscillators control heating element current with a variable resistance pass element, typically a transistor.

Voltage division insures a sizable portion of the heating power dissipates in the control device instead of the heating element. This heat is wasted unless the control device is mounted on the temperature controlled structure, an impractical solution in the case of directly heated resonators. Control device dissipation also disrupts the otherwise linear relationship between heating current and element power.

Pulse width modulation of heating current overcomes both objections. Because the control device is either on or off and ideally dissipation free, heating power is applied directly and solely to the resonator. A single switching power supply integrated circuit provides all necessary control functions.

The control system described earlier is open loop having no feedback and it is not able to correct for errors in the controller gain setting or variation of resonator thermal resistance. Still it provides acceptable performance. Adding thermal insulation external to the resonator case is a worthwhile improvement as it introduces a useful measure of thermal negative feedback. Power consumption is also slightly reduced.

A fully closed loop control system, capable of compensating for all gain mismatch errors, can be built using a dual mode oscillator and resonator self-temperature sensing as described by Schodowski [4]. Two resonator modes are excited into oscillation simultaneously. One mode, being largely temperature insensitive, generates the oscillator output signal. The frequency of the second mode indicates resonator temperature.

Dual mode oscillators have generated a lot of interest lately. In the dominant concept, output pulses are dropped one at a time to maintain a constant average output frequency as the resonator frequency changes with temperature. This technique has potentially very low power consumption-no heating power is used-but the phase perturbations accompanying the missing pulses are severe. Phase locking and direct digital synthesis are proposed to overcome this limitation but these complicate an otherwise elegant scheme and increase power consumption.

Combining resonator self-temperature sensing and direct heating gives a stable, spectrally pure oscillator. A simple phase lock maintains a constant beat note frequency between the oscillation modes and insures constant resonator temperature. Crystal hysteresis is avoided and power consumption, while not as low as in the pulse dropping scheme, is still quite respectable when one considers additional phase noise clean up circuitry is not unnecessary.

## Thermal Stress

Thermal stress induced frequency shift is a key issue affecting development of directly heated resonators. It has two components, a transient shift occurring whenever heating power is applied or removed, and a static shift present continuously while the resonator is heated. Figures 2 and 3 show the frequency shift of an oscillator using a directly heated 10 MHz, fundamental mode, FC-cut resonator. Transient shift stands out in Figures 2.1 and 2.2. With 300mW applied to the heater, the resonator temperature rises about 60°C. The transient shift dies out quickly without noticeable effect provided the heater PWM frequency is sufficiently high.

Figure 3 shows static frequency shift for five resonator heating powers. The horizontal axis represents estimated resonator temperature calculated from the product of the resonator to case thermal resistance and the resonator heating power. Without thermal stress, all curves should overlap being simply the same frequency-temperature curve repeated five times.

Measurements of this type were our first attempt to measure resonator to case thermal resistance. We hoped to shift the curves until they overlapped. Then, for a given heater power, the horizontal shift equals the resonator temperature rise and division yields the resonator thermal resistance. But the curves don't overlap. A hump or bulge begins to form below 25°C, growing larger with heating power. The family of curves in Figure 3 bears a striking resemblance to FC-cut frequency-temperature curves as a function of orientation angle. Direct resonator heating appears to shift the effective resonator angle.

At first we thought stress induced frequency shift would obstruct practical exploitation of directly heated resonators, but later observations suggest frequency shift is largely a linear function of applied heating power and can be dealt with by compensation, or by adjusting the heater control circuitry to slightly under heat the resonator. In the latter case, resonator temperature drops as the ambient temperature falls, but the thermal stress induced frequency shift compensates the frequency drop that would otherwise occur retaining frequency stability and slightly reducing power consumption. FC-cut resonators, which are only slightly stress compensated, give acceptable results used in this fashion and SC-cut resonators, having greater stress immunity, work better. The exact relationship between thermal stress and frequency shift is unknown, but the under-adjustment compensation scheme based upon the assumption of linearity works well. Dauwalter [5] reported a linear frequency shift accompanying compressive stress in 15 MHz AT-Cut resonators with less than one part in ten thousand non-linearity. This implies frequency shift compensation of DHXO oscillators can be simple and very accurate.

In the future we hope to modify the heating element shape in order to reduce resonator stress. The existing heater pattern applies heat more or less evenly around the outer edge of the resonator. Concentrating more heat near the resonator support posts which draw heat from the resonator is a step in the right direction.

Another untried approach sets the resonator operating temperature at the inflection point instead of the usual lower turn point. This relies upon the assumption thermal stress causes a precession of apparent resonator angle without affecting the location of the inflection point. If correct, this means thermal frequency shift is absent at the inflection point.

Finally, a method of increasing resonator thermal resistance is described latter in this paper. Decreased heating power consumption is the prime objective, but thermal stress is also reduced. To summarize, thermal stress induced frequency shift in directly heated crystal oscillators can be successfully circumvented and further prospects for improved performance via various stress reduction measures are promising.

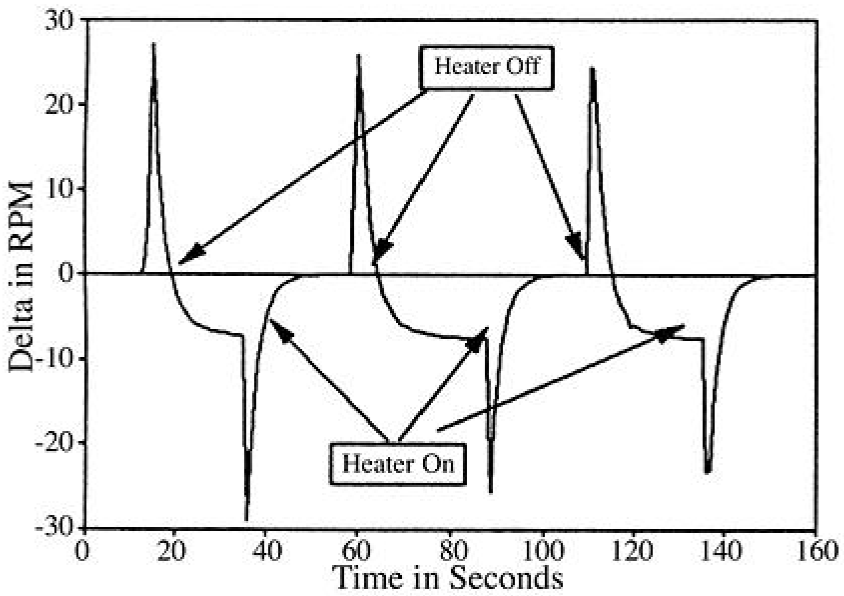
## Applications and Results

Our development effort so far concentrates on two specific embodiments. The first is a very low power oscillator intended for battery operation as encountered in rescue beacons. The most important factors in this application are power consumption and short term frequency stability under temperature slew. Phase noise, aging and frequency-temperature stability are secondary, but still important factors. The expected ambient temperature ranges from -20 to+60°C.

The second variation is a low power high performance oscillator suitable for use in portable instrumentation and navigation equipment. This oscillator consumes more power but the frequency-temperature stability is much better. The standard commercial temperature range, 0 to 70°C, applies to this oscillator. The primary difference between the two versions is the choice of crystal. The first uses a 10 MHz, fundamental mode FC-cut resonator. The second employs a 10 or 10.230 MHz, third overtone SC-cut resonator.

The wide region of near-zero frequency-temperature coefficient exhibited by FC-cut resonators between approximately 30 and 70°C enables significant power savings applications needing limited temperature stability. Conventional ovenized oscillators heat the resonator well above the highest expected ambient temperature achieving excellent frequency temperature stability at the expense of power consumption. At average and low ambient temperatures, power consumption is much larger than need be.

**Figure 2. Thermal Stress Induced Frequency Shift**



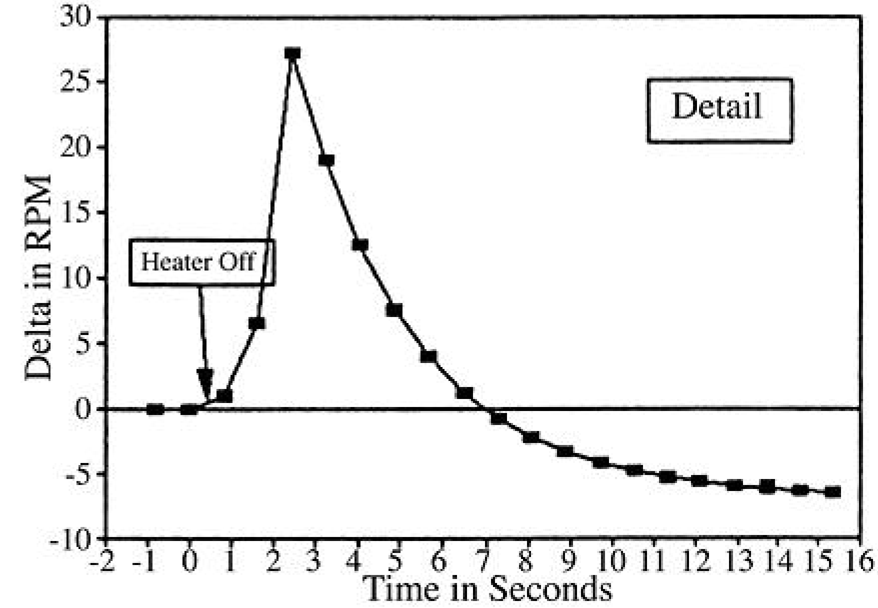
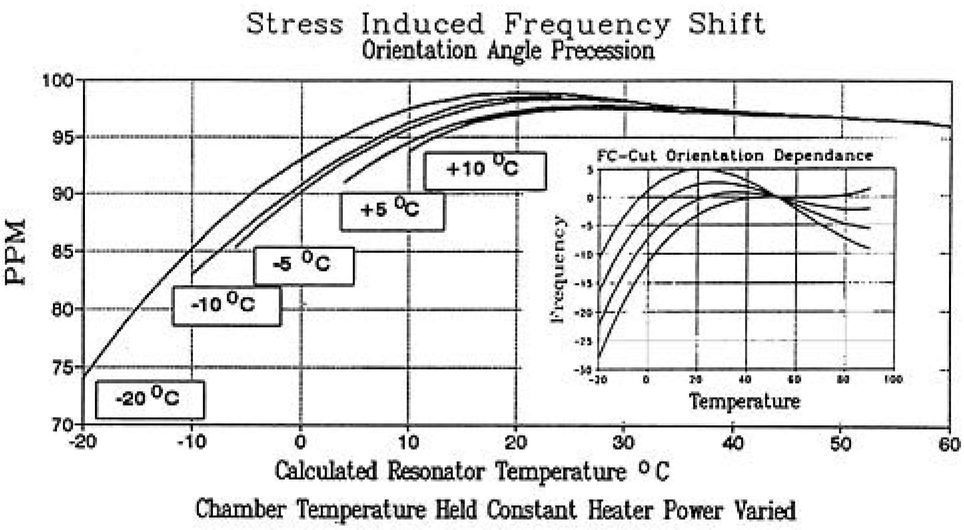
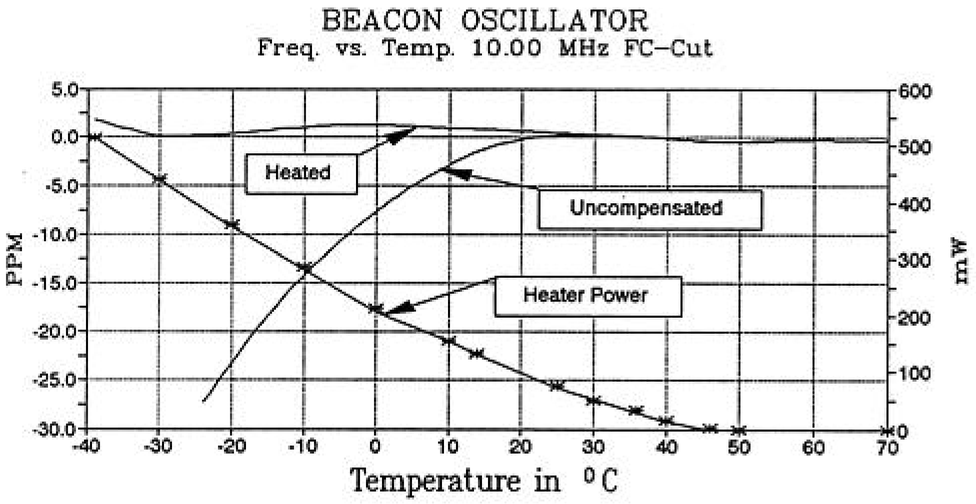



**Figure 3. Stress Induced Frequency Shift**




While rescue beacons can experience very high temperatures, daytime desert heat for example, less extreme temperatures are more likely, especially for beacons floating in seawater. Battery size is limited and the system frequency temperature stability needs are modest. Taken together, trading temperature stability for increased battery life is attractive. Between 30 and 60°C, FC-cut temperature stability is sufficient without heater power. Below 30°C, applying heater current as the ambient temperature drops maintains resonator temperature and oscillator stability. Figure 4 shows the result. Frequency-temperature stability between -20 and +60°C is better than ± 1.2 ppm. The transition between heated and unheated operation begins at 30 degrees. Temperature slew at a 1.5°C per minute does not affect stability. Allan variance is quite good, superior to comparable TCXO performance.

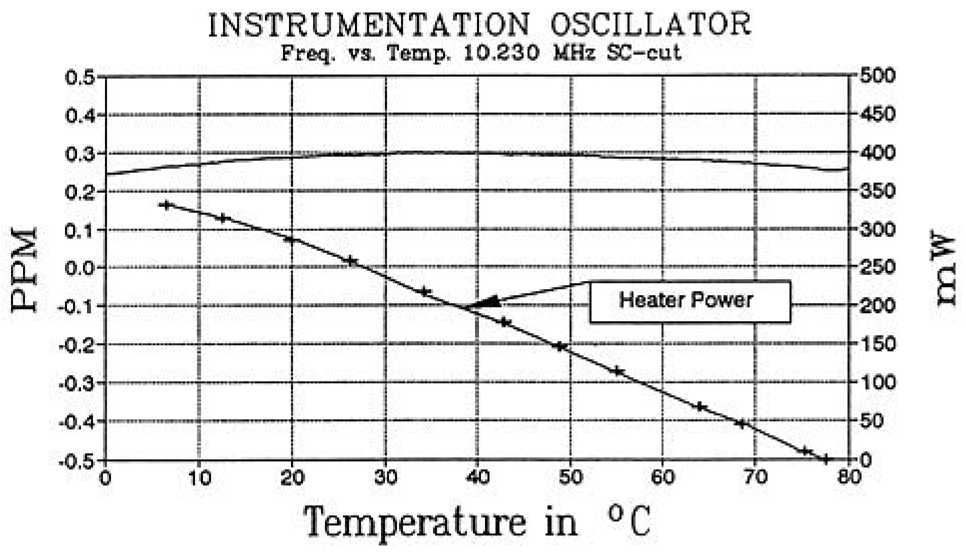
**Figure 4.**




A small production run of these devices showed quite acceptable unit to unit consistency. Initially, we thought each oscillator might require a unique controller thermal gain to compensate for unit to unit variations of the resonator thermal resistance and thermal stress compensation, however, after experimentally determining the correct setting for the first oscillator, the remaining oscillators showed nearly identical performance without additional adjustment. Further work directed towards size and cost reduction is underway.

The second directly heated crystal oscillator (DHXO) product under development offers an order of magnitude improvement in frequency temperature stability compared to the best TCXOs, at on tenth the power oscillators. Figure 5 shows the frequency temperature performance of a laboratory prototype. Total deviation over 0 to 70°C is less than ±2.5 x $10^{-8}$ with heating power consumption of 270 mW at 25° C.

**Figure 5.**




The oscillator uses the Piezo standard low phase noise circuit with no modification or component sorting. Crystal frequency is 10.230 MHz. Close in phase noise is quite good, -123 dBc at 10 Hz offset in a one Hertz bandwidth and is unaffected by direct resonator heating. Figure 6 shows oscillator phase noise with and without resonator heating. The close in phase noise slope of 30 dB per decade extends inward to within 10 MHz of the carrier. The phase noise floor beyond 100 Hz does increase by about three dB and spurious at multiples of the heating PWM frequency are present. Spurious had been much higher before some obvious ground loops were eliminated. Even then the laboratory breadboard construction and layout was less than ideal. Insufficient isolation remains a likely cause of switching frequency spurious. On the other hand, spurious might be thermal stress modulation of the crystal resonant frequency, but it must be noted, heating frequency sidebands were no higher on the FC-cut DHXO which should, in principal, be more susceptible to stress modulation. Stress modulation can be reduced by converting the heater current pulse train into direct current by means of an LC filter and a commutating diode. Increased switching rate also helps. Allan variance is unaffected by resonator heating, Figure 7.

**Figure 6.**

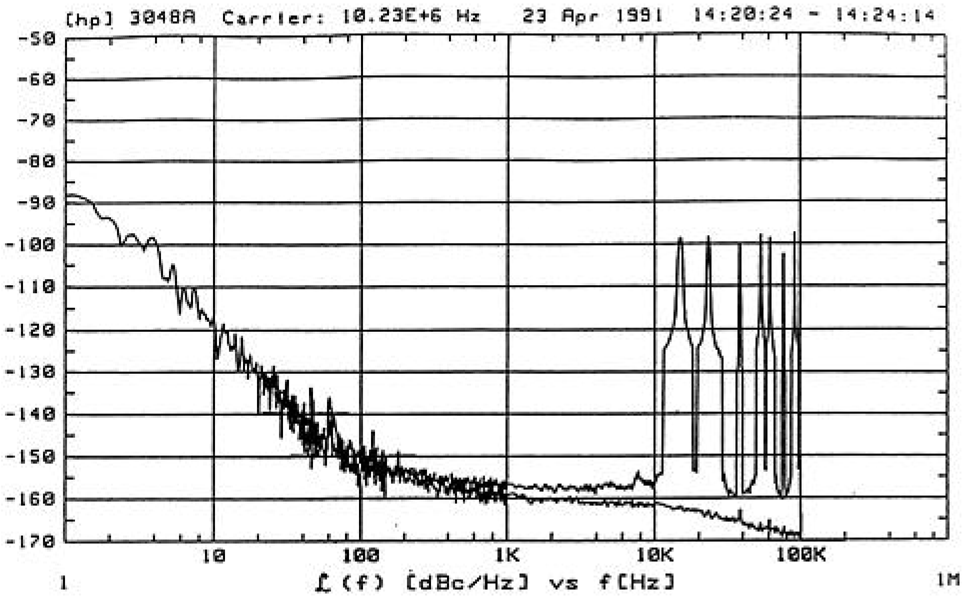
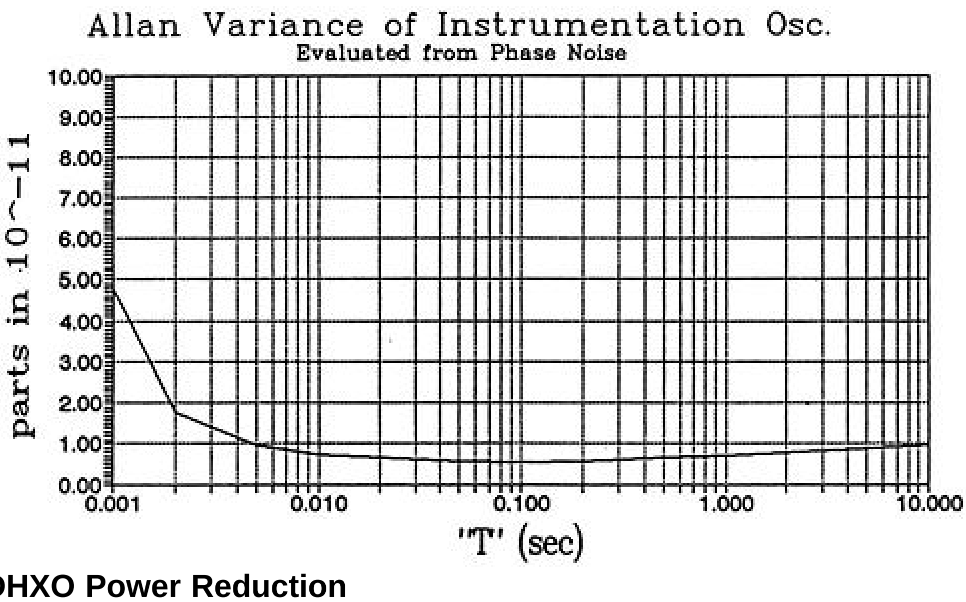


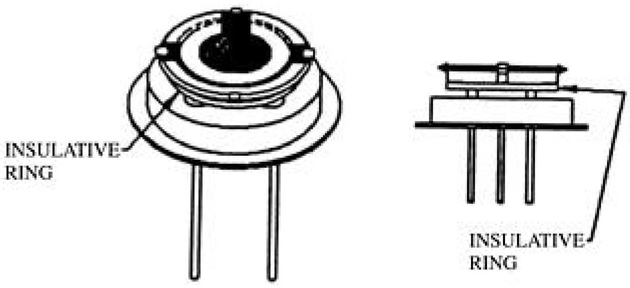

**Figure 7. Allan Variance of Instrumentation Osc.**




**DHXO Power Reduction**

A simple modification of the crystal mounting structure reduces DHXO heating power consumption. Thermal resistance of the mounting posts is increased by adding an insulative ring as illustrated in Figure 8. Resonator mounting ribbons attach midway between adjacent mounting posts providing maximum thermal resistance. Thin film conductors deposited upon the ring surface maintain electrical continuity. The insulative ring can be glass or quartz or any other thermally insulative material compatible with metallic surface thin films. A hand built prototype nearly halved heating power. Computer thermal modeling predicts much larger potential power savings suggesting the prototype thin film conductors might have been too thick. Reduced heating power brings about decreased stress induced frequency shift, easing concerns on that account. The insulative ring is also an ideal location for the temperature sensor. Reduced thermal time constant between the resonator and the sensor improves response to thermal transients including warm-up. Thermal resistance between the sensor and the ambient environment adds negative feedback to the control circuit reducing the sensitivity of the controller thermal gain adjustment.

**Figure 8. Directly Heated Resonator With Insulative Ring**

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***Editor's Note**:*
*The Piezo-Crystal Company is now a part of Corning Frequency Control Inc., a division of Corning Incorporated.*
*This article was previously available on the Piezo-Crystal web site.*