Ferroelectrics, 1982, Vol. 43, pp. 57–65
0015-0193/82/4301-0057/$06.50/0

QUARTZ CRYSTAL RESONATORS AND OSCILLATORS, RECENT DEVELOPMENTS AND FUTURE TRENDS

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(Received July 9, 1981, in final form December 11, 1981)

This paper deals only with the most recent and significant developments in the field, because excellent review papers on crystal resonators and oscillators are available and given in reference. A short historical review providing general concepts is presented first. Then, since important advances have recently been made in the resonator and oscillator field as well, the most significant improvements are pointed out and discussed. On the one hand, progress due to the use of doubly rotated cuts, new techniques (including "electrodeless", "flat pack" . . .) and various advances are presented. On the other hand, improvements in conception and realization of oscillators are widely discussed, pointing out that theoretical and technical progress in both resonator and oscillator fields is needed.

Recent progress leads to better performance in short term stability, aging, environmental sensitivity, etc., and even to possible competition with other frequency standards. Recent advances are summarized by a comparison of the most recent documented results. Probable future trends are also indicated.

I. INTRODUCTION

Since quartz oscillators are present in almost any frequency control equipment and are really the workhorses of time and frequency, tremendous effort has been made to improve their performance. Important *fundamental* as well as *technical* advances have been made in every domain related to the subject including resonator theory and design, material investigation, non-linear phenomena, oscillator theory and design, new components, etc.

Piezoelectric resonators (see E. Hafner, Ref. 1) are solids of given configuration, shape, and dimension prepared from piezoelectric crystals under precise control of geometry and orientation. Only certain vibrations are piezoelectrically driven. Electrodes provide the electric field necessary to excite the desired mechanical resonances (and others, through non-linear effects). Electromechanical coupling makes piezoelectric resonators very attractive since it provides easy excitation and detection of some resonances. Although the same basic phenomena are involved, a great difference exists between these bulk devices and Surface Acoustic Wave (S.A.W.) devices. S.A.W. devices will not be considered here; nevertheless, it is interesting to point out their interest for high frequencies and potential for short term stability.

The history of the piezoelectric resonator began in 1918. Between the two World Wars, resonators were developed at a slow rate. World War II, however, was the great booster of the quartz industry. The most important improvements have been made by R. A. Sykes who introduced the universal use of coated units in 1948, and A. W. Warner who in 1952 perfected the design which is still used today without any major change.

Quartz crystal oscillators already provide us with small, rugged, low power, low-cost units of excellent short term stability. The main effort in the future should be directed toward decreased aging, low amplitude-frequency (A.F.) effect (which will permit better short term stability), thermal stability, low thermal transient sensitivity, and low environmental dependence (acceleration, vibration, . . .).

II. RECENT DEVELOPMENTS IN RESONATOR FIELD

1. *Fundamental Studies*

Among various developments, recent improvements in theoretical understanding of bulk resonators must not be ignored. Due to H. Tiersten[2] and others, [3-6] it is now possible to compute almost any characteristic of a resonator design at least as far as regular thickness shear vibrating-mode resonators are concerned. In particular, for a given overtone and frequency it is possible to theoretically determine thickness, best diameter, contour, mounting location, electrode dimensions and so on. Theoretical prediction can be made accurate enough to be helpful in actual design using comparisons with experiments and X-ray topographic patterns. It must also be pointed out that temperature, thermal transient effects,[7-11] and non-linear behavior of crystals[12-16] have been widely studied yielding crystal cuts[21] with very small A.F. effect.

2. *Doubly Rotated Resonators*

A very promising development has been the introduction of doubly rotated thickness mode resonators which offer superior solutions to thermal and thermal transient problems. [Doubly rotated thickness mode plate vibrators will not be studied here because an excellent paper by A. Ballato is available,[17] providing complete information and references on the subject.] Doubly rotated crystals exhibit many advantages, among which the most important for practical purposes are listed below:

(1) greatly improved thermal behavior[18] (including static and ther-transient) usually yielding better ultimate frequency stability and faster warmup without overshoot;

(2) intrinsic temperature sensor (B mode) available in the vibrating crystal;[20]

(3) reduced A.F. effect[21]

(4) essentially no activity dips (coupled modes);

(5) reduced acceleration and environmental sensitivity;

(6) low sensitivity to stress in cut's plane.[19]

However, doubly rotated crystals are only beginning to become commercially available because industrial production of these units is more difficult and costly (orientation is more difficult requiring tighter tolerances on ϕ and Φ angles). Also, the B mode is close to the C mode and is usually of nearly equal strength.[17] In addition, it is not yet clear whether or not the aging characteristics are better than the AT cuts. Nevertheless, the advantages largely overcome the disadvantages. Of importance is the fact that several large companies have decided to produce SC cut quartz oscillators commercially to obtain improved performances.[22]

3. *Some New Techniques*

Some other interesting and recent developments are due to the strict control of *boundary conditions* at the limits of the vibrating piezoelectric body. Figure 1 schematically shows a piezoelectric bulk resonator in a standing wave pattern situation interacting with the external world through mountings, electrodes, and any limit of the piezoelectric body. Each question mark calls attention to a given boundary condition or a given exchange process with the external world. Unfortunately, the external world is accelerating, vibrating and changing in temperature, pressure, etc. Of course, the results will not only depend on the piezoelectric material but also on solutions adopted to solve the boundary condition problems. Obviously, the conventional design of resonators exhibits badly or incompletely solved boundary problems[23,24] and important improvements can be obtained by giving proper care to these challenges. As examples we will consider two attempts toward providing better boundary conditions.

a. *B.V.A. technique* This new technique[25] has recently been developed in Besancon, France. Prototype resonators covering approximately 10 different types according to goals or environmental conditions have been developed and studied for frequencies between the MHz and GHz ranges. At this point, some types are in industrial production, in particular B.V.A.$_2$ 5 MHz units. The new structures, all using "electrodeless" crystals are called B.V.A.$_n$ designs.

(1) if n is odd, a rather conventional bonding and a special fixation is used;

(2) if n is even, the design uses improved bonding and mounting.

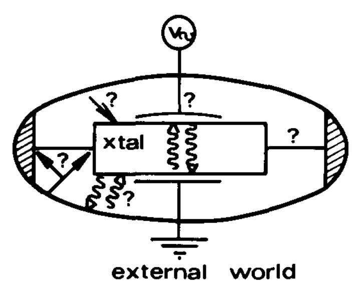

FIGURE 1 Schematic diagram showing the coupling of a crystal resonator to the real world.

The denomination indicates two successive steps in the attempt to reduce the crystal's noise and frequency drift contribution.

Since the new structures have already been described elsewhere,[23,24] we will only summarize here the most important features and results related to B.V.A.$_2$ type resonators. The B.V.A.$_2$ type resonator basically corresponds to the following:

An "electrodeless design". All problems that relate to electrode deposition, such as damping, stresses, contamination, and ion migration, are removed.

A crystal mounting made of quartz. Small "bridges" connect the vibrating part of the crystal to the dormant part, with the following key advantages:

(1) negligible discontinuities or stresses in the mounting points;

(2) very high precision in the shape and location of the bridges;

(3) symmetry and reproducibility when needed;

(4) versatility in the design of bridges, according to specific goals.

Additional parameters. The B.V.A.$_2$ design exhibits the following additional construction parameters, as compared to classical designs:

(1) the electrode (and thus the electric field) can have a radius of curvature different from that given to the vibrating crystal;

(2) heaters and sensors can be placed in vacuum close to the crystal without contacting the vibrating crystal;

(3) connecting bridges can have a great variety of shapes, locations, and other features.

Provision for any material, crystal, cut, or frequency. Construction of the B.V.A.$_2$ also provides for very high frequencies.

Reproducibility and versatility. The use of technological means (e.g., ultrasonic machining) allows both reproducibility and versatility. For example, the external shape of the crystal does not need to be circular or rectangular.

Very roughly speaking, the B.V.A. design is capable of an order of magnitude improvement in short-term stability, long-term drift, and acceleration sensitivity over conventional designs. More precisely, the following have been demonstrated as compared to traditional design:

Slightly higher Q *factors.*

Better frequency adjustment.

Better short-term stability. A frequency stability, $\sigma_y(\tau) = 6 \pm 8 \times 10^{-14}$ for 128s, has been achieved[66] in one laboratory test and 1×10^{-13} has been achieved in another laboratory test.

Lower drift rate. Nominal drift rates of 5×10^{-12}/day are routinely achieved. Also important is the fact that final aging is established within days and then remains constant.

Lower g *sensitivity.* A maximum sensitivity of the order of 10^{-10}/g can be achieved in the case of AT-cut units, and a sensitivity lower than 5×10^{-11}/g has been realized in SC cut crystals. No residual frequency shift[23] occurs after static *g* loading to within a few parts in 10^{11}.

Reduced amplitude-frequency effect. This effect has been reduced by a factor of 2 to 15.

Extremely high drive levels. Drive levels up to 60 mw can be used without degrading aging badly. More precisely, experimental and theoretical considerations show that the resulting aging can, at least on a provisional basis, be precisely modeled[26] versus drive level and time. Phase noise is also improved.

Zero aging drive level. From theoretical models and experiments it is possible to demonstrate that a "zero aging" drive level exists. This drive level yields an aging rate which crosses zero with small changes in drive level. For *natural quartz* 5 MHz units, the zero aging drive level is roughly 80 μW for AT cuts and 160 μW for SC cut. The best aging rates obtained so far correspond to a frequency change of 10^{-10} over a six month period.

Internally heated crystals. With very high drive levels previously quoted, it is possible to heat up the crystal internally, leading to various applications.[27]

b. *Ceramic flat pack configuration*[28–31] *with improved fixations* As pointed out by several authors, especially Hafner and Vig, regular packaging techniques of resonators can lead to lack of hermeticity and contamination. It is also desirable to obtain a mass production process with almost no contamination. In the past the major difficulty in the use of ceramic material enclosures was the lack of a strong, low temperature, non-contaminating hermetic seal. The ceramic flat pack technique uses aluminum gaskets and provides almost all previously quoted advantages including mass production. The technique was first designed for both 5 MHz and 20 MHz units and has been completed by the use of improved mountings (nickel electrobonding and then polimide bonding). Of course, all the techniques to obtain cleanliness and decontamination described by White, Vig, and others[32–34] are used. Another improvement uses the four point mounting configuration[35] proposed by Art Ballato. The whole new configuration leads to a small, highly reliable, rugged crystal able to survive 20,000 g shocks with low aging.

c. *Crystals for Severe Environments* Many investigations have taken place in the field of crystals for severe environments. Substantial improvements have been obtained after the paper by Valdois *et al.*[36] in 1974. Important contributions have been made by P. C. Y. Lee, A. Ballato, D. Janiaud and others from theoretical and experimental points of view.[37–41] In particular the theoretical model[42] proposed by Janiaud, together with technical efforts, has led to very low g units[43] yielding maximum sensitivities of 10^{-10}/g for AT cut 5 MHz 5th overtone units and 5×10^{-11}/g for SC cuts. T. Lukaszek and Art Ballato have also proposed important improvements based on prescribed lateral contour for singly and doubly rotated plates.[44] Ballato and Besson have proposed dual crystal configurations for acceleration compensation,[45,46] whereas Valdois, Przyjemski, and some others have proposed to compensate acceleration effects[47] using acceleration sensors. In conclusion, we now have everything available to make negligible one of the most important effects, i.e. acceleration effect on crystal frequency.

Sensitivity to vibrations is closely related[48] to g sensitivity but some work remains to be done to free oscillators from vibration effects.[36,49] As already pointed out, much attention has been paid to temperature effects in crystals. In particular, dynamic frequency temperature behavior has been extensively studied[50,8] exhibiting another advantage of doubly rotated crystals. In addition, digital temperature control seems very attractive for future applications.[51]

Perhaps the most difficult problem to be solved now is the frequency retrace of quartz oscillators.[52,53] This problem has received too little attention in the past and needs effort in resonator and oscillator construction as well. Although it is a difficult unsolved problem, there are some indications[53,26] that proper construction of resonators could reduce the retrace to some parts in 10^{-10}.

To be complete this paper should also call attention to fundamental limitations coming from the material itself and on material improvements; however, this subject will not be treated here. The quality of presently available material (with proper resonator construction) yields high Q and as a consequence good short term stability; however it can also be predominant in aging processes[26] and it is critical in radiation environments.[54–57]

d. *Ultra-high frequencies bulk resonators* As pointed out by Castellano and Hokanson[58] in 1975, ion beam milling techniques can be very appropriate for piezoelectric device fabrication. M. Berte[59] has shown that Bulk Acoustic Wave (B.A.W.) device fabrication can be extended up to U.H.F. ranges yielding very interesting resonators and filters (the upper limit seems to be in the GHz range). It is also possible to use thinned wafers in an "electrodeless" situation inside a reentrant quartz cavity.[60,61]

III. PRECISION QUARTZ CONTROLLED OSCILLATORS

One of the most significant advances in the past few years has been the introduction of a technique to test the quartz crystal *separately* from the oscillator electronics.[62,63] The short-term frequency stability of quartz crystal controlled oscillators has improved considerably over the past few years due primarily to a new understanding of the limiting mechanisms and the subsequent introduction of new electronic circuits. Until the last several years the medium-term stability has remained virtually unchanged over the past 20 years, limited in large part by the available crystal resonators.

As pointed out above, recent introduction of several new quartz crystal resonators, especially the SC cut, the B.V.A.$_2$ SC cut and AT cut resonators, is expected to make possible appreciable improvements in achievable frequency stability for measuring times from 1s to 10^4s.

1. *Short-term Frequency Stability*

The frequency stability of quartz crystal controlled oscillators for measurements times up to about Q/ν_o (where Q is the resonator's Q factor and ν_o the resonance frequency) is dominated by the noise added by the sustaining circuit at a level given by Cutler and Searle [64]

$$\sigma_y(\tau) = \frac{\Delta\nu}{\nu_0} = \sqrt{\frac{kT}{2P_0}\,\frac{FB}{2\pi^2\nu_0^2\tau^2}} \qquad (1)$$

where k is Boltzmann constant, T is the noise temperature of the resonator, ν_o is the resonance frequency, F is the noise figure of the first signal amplifier not filtered by the resonator, B is the noise bandwidth of the receiver plus measurement system, P_o is the output power received at the first amplifier not filtered by the resonator, and τ is the measurement time. This effect is characterized by a white phase noise at a level of

$$S_{\phi}(f) = \frac{kTF}{3P_0}.$$

The fractional frequency stability can therefore be improved by choosing a crystal resonator operating at the highest possible power and oscillation frequency.

Practical limitations come from the A.F. *effect,*[12,21] of approximately

$$\frac{\Delta\nu}{\nu} = 10^{-9}/\mu\mathrm{W}$$

for 5th overtone 5 MHz AT cut regular resonators and

$$\frac{\Delta\nu}{\nu} = 10^{-11}/\mu\mathrm{W}$$

for SC cut 3rd overtone 5 MHz resonators, and the difficulty of maintaining constant drive power. Operation at high drive power therefore generally degrades performance in the medium-term and sometimes changes the drift.[26] The present upper limit on crystal frequency is of order 1 GHz. As the frequency of the crystal resonator increases, the frequency stability for times of order Q/ν_o degrades as described below and illustrated in Figures 2 and 3.

Experimental verification that the white phase floor observed in crystal controlled oscillators was due to the electronics was provided by the work of Walls and Wainwright (1975).[62] This work also pointed out that by terminating the crystal circuit in a reactive load one could substantially increase the size of the signal voltage filtered by the crystal with little increase in added noise voltage. This effectively decreases the noise figure F of Eq. 1 and significantly reduces the white phase floor as compared to traditional circuits. A white phase floor of order $S\Phi$ (white) $= -175$ dB relative to one radian squared per Hz has been achieved for quartz crystal controlled oscillators operating at 5 MHz and at 60 MHz.[65] More typical values range for $S\Phi$ (1 KHz) from -135 dB to -165 dB.

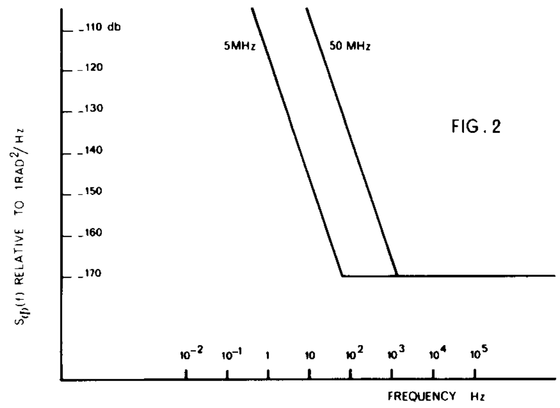

FIGURE 2 Spectral density of phase fluctuations of idealized and 5 MHz and 10 MHz oscillators.

2. *Medium-term Frequency Stability*

The frequency stability of quartz crystal controlled oscillators for measurement times ranging from Q/ν_o to 10^3s is composed of two contributions. The first is an effect characterized by flicker of frequency of unknown origin while the second contribution is due to the dynamic thermal response of the resonator due to thermal fluctuations of the oven. Although the source of the flicker of frequency effect is unknown, the level is generally related to the Q factor.

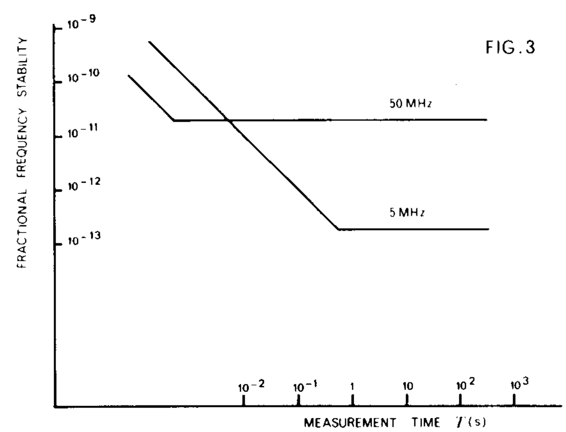

FIGURE 3 Fractional frequency stability, $\sigma y(\tau)$, as a function of measurement time τ.

Phenomenologically, the frequency stability is given by

$$\sigma_y(\tau) \cong \frac{\sqrt{2 \operatorname{Log} 2}}{Q^2}$$

in the time domain and

$$S_\phi(f) \cong \frac{\nu_0^2}{Q^4 f^3}$$

in the frequency domain for AT cut resonators.[16] There is some evidence that flicker of frequency level is about a factor of 2 lower for the SC cut resonators.[66]

Since the product of crystal resonator Q factor and frequency for the best resonators is about $Q\nu \cong 1.2 \times 10^{13}$ for AT cut resonators and 1.8×10^{13} for SC cut resonators, the best phase noise achievable with an oscillator circuit of noise performance will scale approximately as shown in Figure 2 for constant crystal drive. The time domain resulting from these two noise processes is shown in Figure 3 and generally applies to bulk quartz crystal resonators for 5 MHz to at least 100 MHz and perhaps higher. A measurement bandwidth of 1 KHz has been assumed. To date, no single oscillator has achieved the performance for both white phase floor and flicker level since one requires high drive level while the other requires stable low-power excitation. The performance shown in Figure 2 can be approached by phase-locking two oscillators together, one optimized for short term and one optimized for medium-term.[67]

Thermal transients in the oven coupled with the temperature response of the crystal[68] often are responsible for a random walk of frequency term, i.e.

$$\sigma_y(\tau) = \frac{\Delta\nu}{\nu} = K'\tau^{1/2}.$$

The temperature response of the resonator[50,51] near the turn over point is approximately

$$\frac{\Delta\nu}{\nu} = K''\Delta T^2 + \tilde{a}\frac{\Delta T}{\Delta t}$$

where T is temperature and t time.

For an AT cut 5th overtone 5 MHz resonator K'' is of order $10^{-9}/K^2$ and $\tilde{a}$ of order 10^{-5}s/K while for SC cuts $\tilde{a}$ is of order 10^{-7}s/K and K'' is a little smaller than $10^{-9}/K^2$.

3. *Long-term frequency stability*

The frequency stability of quartz crystal controlled oscillators from about 10^4 to 10^7s and longer is generally poorly understood because the causal factors are numerous. It is quite likely that for many types of these oscillators which exhibit fractional frequency drift from 10^{-6} to 10^{-10} per day, the cause is frequency drift of the quartz resonator.

There can be many causes for the drift of the resonant frequency in a crystal resonator,[70] including:

(1) changes in absorbed gases on the crystal surfaces;[33]

(2) stress relief due to the electrodes which are generally plated on the resonator;[19,69,23]

(3) ion migration[23] due to electrode deposition or mounting processes;

(4) changes in the background pressure within the enclosure;[28]

(5) discontinuities and stresses[23] (and their variations) at the mounting points;

(6) changes in the drive power which acts via the A.F. effect.

These effects have received considerable attention in the past and many of the most serious influences have been largely corrected. The measured frequency drift of several types of commercially available oscillators ranges from 10^{-10} to about 10^{-11} per day after an initial "burn in" period. Selected oscillators have achieved drifts of less than 10^{-11} per day. At a drift of order 10^{-12} per day the problem of loop phase stability which also affects long term stability, becomes very important.[67]

The traditional circuitry for a crystal-controlled oscillator uses the resonator inside of the oscillating loop as shown schematically in Figure 4. A necessary condition for oscillation is that the phase shift around the loop be a multiple of

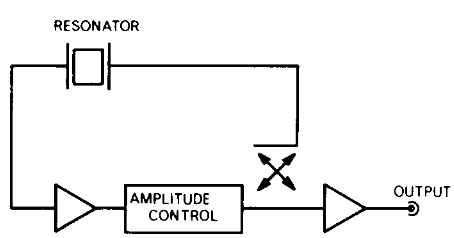

FIGURE 4 Block diagram of a crystal oscillator.

2π rad. A small phase fluctuation Φ away from this state causes a fractional frequency change

$$y = \Delta\nu/\nu = \phi/2Q$$

where Q is the loaded quality factor of the resonator. In order to achieve a long-term fractional frequency stability of 10^{-13} with a resonator having a loaded Q of 2.5×10^6, the phase variations must be less than 5×10^{-7} rad. For standard coaxial cable with phase stability of approximately 100 ppm/°C, this corresponds to a temperature change of 1°C over a 5 cm length. Since nearly all components are phase-sensitive, it is doubtful that the required stability around the oscillating loop can be achieved for extended periods of time.

The phase shift around the loop is also perturbed by output loading and pickup of stray signals. For example, a 20 percent change in the load resistance from the matched condition produces a reflected signal back into the oscillator output whose amplitude is 10 percent of the output voltage. The reflection changes the phase in the oscillating loop by an amount:

$$\phi = (1/10)\beta \cos\theta$$

where β is the isolation from the output to the oscillating loop expressed as a voltage ratio and θ is the phase of the reflected signal relative to the unperturbed loop signal. In order to assure that Φ is less than 5×10^{-7} rad for arbitrary θ, β must be less than 5×10^{-6} or -106 dB.

Finally, the frequency of the oscillator is usually adjusted with a tuning capacitance of approximately 25 pF for a 5 MHz unit. If the crystal has a Q of 2.5×10^6 and a motion resistance R_s of 70 Ω, the fractional frequency change due to a small change in the tuning capacitor C_L is

$$y = \frac{1}{2}\frac{1}{\omega RQ}\frac{1}{C_L}\frac{\Delta C_L}{C_L} \cong 4 \times 10^{-6}\frac{\Delta C_L}{C_L}$$

which can be derived from considering the LCR equivalent circuit of a quartz crystal. Thus, in order to achieve a long-term stability of 10^{-13} the tuning capacitor must be constant to 6×10^{-7} pF, which is very difficult at best.

It is possible to attack all these electronic problems in a single circuit which uses the precision crystal resonator as a frequency discriminating circuit similar to that used for atomic frequency standards or the super conducting cavity stabilized oscillator described by Stein and Turneaure.[72,73] Preliminary results reported by Stein *et al.*[66] indicate a frequency stability of $6 \pm 8 \times 10^{-14}$ at 128s for a prototype circuit of this type.

As better resonators become available it is anticipated that quartz crystal oscillators exhibiting frequency stability of order 7×10^{-14} from a few seconds to perhaps 100 to 1000s will become feasible. Frequency drift of order a few 10^{-10} per year is already achieved with B.V.A. resonators operated at their "zero aging drive level."

IV. CONCLUSION

Small, rugged, low consumption, low cost quartz controlled oscillators are already commercially available. However, tremendous progress has been made during the last years yielding fundamental tools, better understanding and some new techniques in the resonator and oscillator field as well. Among various improvements, doubly rotated resonators, B.V.A. techniques, ceramic flat pack configuration, crystals for severe environments, new electronic circuitry (including passive reference systems), and some other advances typically represent the latest efforts. These improvements are, or soon could be, commercially available. Together with advantages due to digital control of the oven,[51] dual mode operation of doubly rotated cuts,[74] use of resonators working on two or even three frequencies,[75] help of microprocessors, these recent advances lead to decreased and predictible aging, low amplitude frequency effect, better spectral purity and short-term stability, thermal stability, low thermal transient sensitivity and low environmental dependence together with a probable reduction in size.

Table I summarizes the results typically expected from commercial precision oscillators, those expected in the near future for precision commercial standards, and those recently achieved in 5 MHz laboratory units.

Of importance is the fact that possible competition between precision quartz controlled oscillators and rubidium atomic standards has already been discussed. (See, for instance, proceedings of 10th P.T.T.I. meeting 1978.) This very fact, incredible years ago, means that quartz controlled oscillators, though they cannot deliver accurate frequencies, have been significantly improved in the last decade.

TABLE I

Characteristics	Precision Commercial Oscillator	Near Future Precision Commercial Standards	Laboratory Results
Aging	$<10^{-10}$/day non modelable typ. 3 to 8 $\times 10^{-11}$/day	3×10^{-10} to 10^{-9}/year modelable and predictable	10^{-10} after 6 months modelable and predictable
Short-Term			
$\tau = 10^{-3}$ s	$<10^{-9}$	10^{-11}	
$\tau = 1$ s	$<10^{-12}$	$<5 \times 10^{-13}$	5×10^{-13}
$\tau = 100$ s	$<10^{-12}$	$<3 \times 10^{-13}$	6×10^{-14} to 10^{-13}
S.S.B. Phase Noise			
1 Hz	−118 dB	−122 dB	−122 dB
10 Hz	−136 dB	−152 dB	−142 dB
10^4 Hz	−140 dB	−164 dB	−160 dB
Acceleration Sensitivity	2 to 3 $\times 10^{-9}$/g max.	$<2 \times 10^{-10}$/g max.	3×10^{-11}/g max. SC 7×10^{-11}/g max. AT
Warm-up Time			
To $<10^{-N}$ of final frequency.	10^{-9} after 60 minutes	5×10^{-10} after 30 minutes	10^{-9} after 40 minutes
Influence of External Temperature.	$<5 \times 10^{-10}$ −20°C to +65°C	$<5 \times 10^{-10}$ −55°C to +71°C	2×10^{-10} −20°C to +60°C

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