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REDUCTION OF QUARTZ CRYSTAL OSCILLATOR FLICKER-OF-FREQUENCY AND WHITE PHASE NOISE (FLOOR) LEVELS AND ACCELERATION SENSITIVITY VIA USE OF MULTIPLE RESONATORS

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ABSTRACT

Through the use of N number of series-connected, quartz crystal resonators in an oscillator circuit, a $10\log_N$ reduction in both flicker-of-frequency noise and white phase noise (floor) levels is possible and has been demonstrated. The reduction in flicker noise occurs as a result of the uncorrellated short-term frequency instability in each of the resonators, and the reduction in noise floor level is a simple result of the increase in net, allowable crystal drive level [1].

This technique has been used in 40-MHz, 80-MHz, 100-MHz, AT, BT, and SC-Cut crystal oscillators using low flicker-of-phase noise, modular amplifier sustaining stages, and four series-connected crystals. Total (four-crystal) power dissipations of up to 30mW have been utilized. State-of-the-art, flicker-of-frequency noise levels characterized by $\mathcal{L}(100\text{Hz}) = -156$dBc/Hz at 40MHz and -143 dBc/Hz at 80MHz and 100MHz have been obtained with noise floor levels (80MHz) as low as -180dBc/Hz.

Further, the use of four crystals allows crystal mounting in fixed, relative orientations so that, if the direction and amplitude of each individual crystal's acceleration sensitivity vector is identical, exact cancellation occurs for all directions [2]. In practice, unit-to-unit sensitivity vector amplitude and direction are non-identical. However, even under these circumstances, a four- to five-fold reduction in acceleration sensitivities has been demonstrated.

INTRODUCTION

As indicated in figure 1, the output signal phase noise spectrum of a low-noise, acoustic resonator-stabilized oscillator may be divided into two distinct regions: a near-carrier region and a (white phase noise) floor region. If the resonator itself were perfectly stable, the near-carrier noise level would be characterized by flicker-of-frequency noise resulting from the conversion of oscillator sustaining stage signal (open-loop) flicker-of-phase noise to (closed-loop) flicker-of-frequency noise. As shown by curves 1 and 2 in figure 1, the effect of the conversion is a 20dB/decade increase in near-carrier noise for carrier offset frequencies less than the reciprocal of the closed loop signal (i.e., resonator) group delay. In this regard, the resonator loaded Q may thought of as a measure of its ability to suppress the effects of near-carrier phase noise in the oscillator sustaining stage circuitry [3].

Silicon bipolar transistor (sustaining stage) amplifier flicker-of-phase noise performance has improved to a point where oscillator output-signal, near-carrier noise characteristics are not limited by the sustaining stage circuit, but by short-term frequency instability in the resonator itself (figure 1, curve 3) [4-9]. Curve 4 in figure 1 shows additional, near-carrier spectral degradation that can occur as a result of resonator frequency sensitivity to environmental stress such as vibration [10-12]. In addition, attainable oscillator signal noise floor levels are more related to limitations in resonator maximum drive level than to small variations in sustaining stage amplifier noise figure. This is especially true in the case of conventional, bulk-wave, quartz crystal resonators whose maximum drive level (3-dBm to 8-dBm dissipation) capability is smaller, compared to that of surface-acoustic-wave resonators.

Figure 1 indicates that, for low noise oscillators employing high Q acoustic resonators, limitations in attainable signal spectral performance can be traced to corresponding limitations in resonator performance parameters such as maximum drive level, short-term frequency stability, and vibration sensitivity. Oscillator spectral performance improvement is possible via: (1) improvement in individual resona-

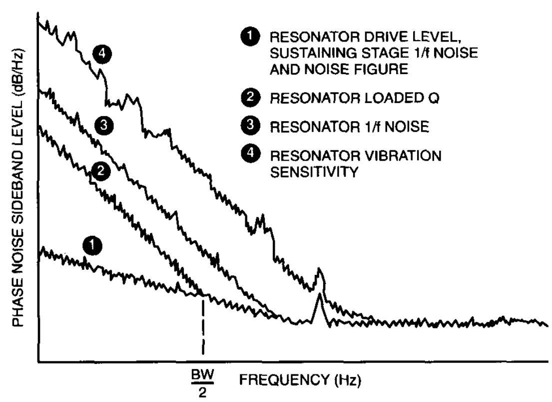

Figure 1. Resonator and Sustaining Stage Parameters Affecting Oscillator Short-Term Frequency Stability

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tor characteristics, (2) use of multiple, phase-locked oscillators, or (3) use of multiple resonators in a single oscillator.

USE OF N SERIES-CONNECTED RESONATORS

Figure 2 shows a method for obtaining reduced levels of oscillator noise. As shown in the figure, the in-phase carrier signal outputs of N phase-locked oscillators, all locked to a common reference signal, can be summed using sets of two-way power combiners. At carrier offset frequencies in excess of the narrow loop bandwidths, the phase noise spectra of each oscillator is uncorrelated, and half the noise appears at each combiner internal load. Thus, there is a net reduction of $10\log_N$ in noise level in the final (summed) output. The disadvantages associated with this method are (1) large overall circuit component count and power consumption, and (2) the fact that spectral improvement is not obtained for carrier offset frequencies within the loop bandwidth. A much simpler, more efficient solution consists of use of multiple resonators in a single oscillator circuit.

Figure 3 shows a series connection of N individual quartz crystal resonators, each fabricated to have near-identical impedance characteristics. It is apparent that, in the vicinity of the (desired overtone) series resonant operating frequency, the impedance characteristic of the resonator combination is simply N times that of each resonator. Further, the net series-resonant frequency of the combination is the average of the individual resonator series-resonant frequencies. As shown the figure, anti-resonating individual crystal static capacitance with parallel inductors provides a means of accommodating larger value, unit-to-unit resonant frequency variation. Undesired series resonant frequencies that can occur between non-coincident resonator anti-resonant frequencies can be made desirably lossy via inclusion of relatively large-value, parallel resistors.

Referring to figure 3, if the individual resonator short-term, resonant frequency instability spectra are uncorrelated and denoted by $S_{Y1}(f)$, $S_{Y2}(f)$, etc, then the resonant frequency instability for the four-crystal combination is:

$$S_{YT}(f) = S_{Y1}(f)/N^2 + S_{Y2}(f)/N^2 \ldots\ldots + S_{YN}(f)/N^2 \quad (1)$$

For resonators exhibiting near-equal levels of short-term frequency instability, there is a net $10\log_N$ stability improvement for the multiple N series-connected resonator combination. This improvement is realized in the near-carrier portion of the oscillator output signal spectrum, where resonator flicker-of-frequency noise constitutes the dominant source of instability.

For the case where the instability of one of the resonators is much higher than that of the others, a $20\log_N$ noise level reduction is achieved, compared to that exhibited by the high-noise unit. Therefore, in less severe spectral performance applications, the scheme depicted in figure 3 has an additional advantage of allowing use of otherwise unacceptably high-noise resonators.

With regard to oscillator output signal (white phase) noise floor performance, a $10\log_N$ improvement is also realized. This improvement simply results from being able to drive the multiple-resonator combination at an N-times higher drive level. For a given resonator circuit insertion loss (i.e., resonator loading factor), this means that N-times higher relative sustaining stage amplifier drive level can be utilized. For a fixed, sustaining stage amplifier noise figure, then, the signal-to-noise (floor) ratio also improves by a factor of N.

Certain sources of individual resonator frequency instability, such as those resulting from environmental stress, are somewhat correlated. Individual resonator frequency change due to acceleration can be characterized by a vibration sensitivity vector, Γ [10-14]. If one considers an ideal (albeit unrealistic) case of identical amplitude and direction resonator Γ vectors, four series-connected resonators, may be oriented with respect to each other such that exact Γ vector cancellation occurs. Unlike the case of a single pair of resonators that may be oriented for anti-parallel Γ vector cancellation [13], cancellation can be obtained in the four-resonator case regardless (without measurement) of the vector direction. Figure 4 shows one example of such an orientation, with each resonator mounted on the four faces of a cube-type resonator assembly. Similar, in-plane

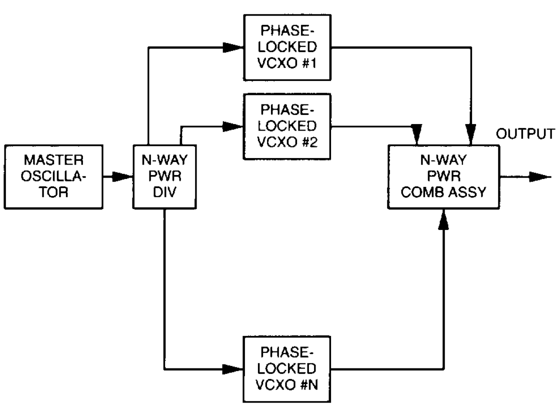

Figure 2. Use of Multiple, Phaselocked Oscillators for Short-Term Frequency Stability Improvement (In Region $f_m \geq$ PLL BW)

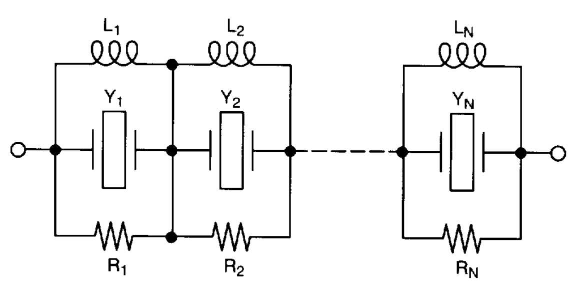

Figure 3. Use of Multiple, Series-Connected, Quartz Crystal Resonators for Reduction of (Net) Resonator Short-Term Frequency Instability

orientations can also be used. Unfortunately, resonator processing and mounting inaccuracies are such that unit-to-unit uniformity in Γ-vector amplitude and direction are not achieved. A more realistic situation is one where Γ-value amplitude variations of 2:1 are encountered, and Γ-vector direction variations are typically such that, at best, unit-to-unit direction variations are confined to a single spherical quadrant. In spite of these variations, typical reductions in (four-resonator combination) vibration sensitivity by factors of four to five have been achieved using the four-resonator configuration.

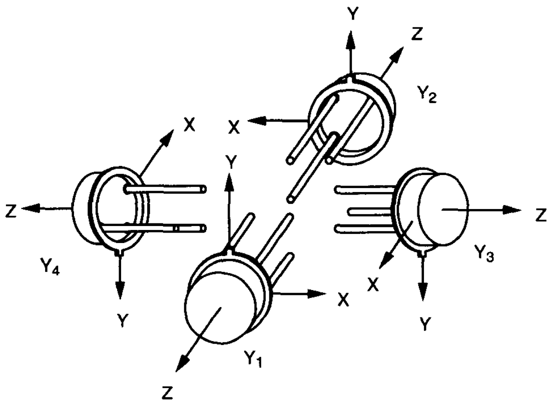

Figure 4. An Example of a Four-Crystal Resonator Mounting Orientation for Vibration Sensitivity Reduction

MULTIPLE CRYSTAL, PROTOTYPE OSCILLATOR DESIGN

The design used for the multiple crystal oscillator is nearly identical to that described in an earlier paper by the author [8]. As shown in figure 5, the sustaining stage incorporates: (1) a low flicker-of-phase noise, 14-dB gain, modular amplifier, (2) a phase shift circuit used to set $2N\pi$ closed-loop phase shift at the operating frequency, (3) a tuned circuit providing requisite frequency selectivity in order to prevent oscillation in undesired crystal resonator overtone modes, and (4) a schottky diode limiter providing symmetrical waveform clipping and assuring oscillator steady-state operation just below amplifier compression.

The crystal resonators are connected to the sustaining stage via a quarter-wavelength transmission line that inverts the four-crystal, series-resonant impedance characteristic to a parallel-resonant characteristic whose resonant parallel resistance is on the order of 20-22 ohms. All or a portion of the transmission line may be synthesized in lumped element form. For vibration measurements, however, a portion of the line is composed of coaxial cable, and this allows individual placement of the resonator and/or sustaining stage assemblies on the shake table for individual measurement of the vibration sensitivity associated with each assembly. As was described in an earlier paper by the author, this configuration also allows separate determination of resonator and coaxial cable vibration effects [14]. A photograph of one of the test oscillators is shown in figure 6.

MEASUREMENT RESULTS: NOISE REDUCTION

Figures 7 through 10 show phase noise measurement results for oscillators utilizing four series-connected resona-

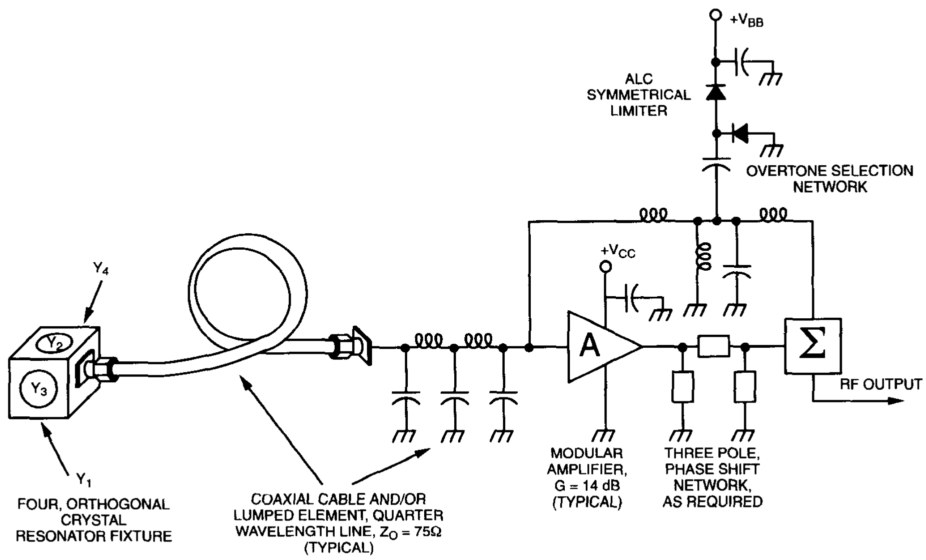

Figure 5. Simplified, Four-Crystal Oscillator Schematic Diagram

tors: (1) 40-MHz, 5th-overtone, AT-cut; (2) 80-MHz, 3rd-overtone, SC-cut; (3) 100-MHz, 3rd overtone, SC-cut; and (4) two series-connected, 100-MHz, 5th-overtone, BT-cut crystal resonators. The data shown in the figures are entirely for cases where all of the resonators (fabricated by Piezo Crystal Co. and Croven Crystal, LTD) were selected for lowest flicker-of-frequency noise level. The reduction in near-carrier noise level was uniformly achieved as predicted in equation (1), compared to single crystal oscillator performance. Because 100-MHz, BT-cut crystal series resistance values were twice that of the SC-cut crystals, the BT-cut crystal oscillator was evaluated using two (rather than four) crystals in order to use a common, 100-MHz sustaining stage design without modification. In the 80-MHz oscillator, a high-level sustaining stage amplifier was used to allow 9dBm-per-resonator (15dBm total) dissipation with 12-dBm amplifier input drive level. The results, shown in figure 8, when referred to the oscillator frequency prior to times-four frequency multiplication, and taking into consideration the noise floor contributions of the cascaded, high-level doublers and doubler interstage amplifiers, correspond to achievement of a per-oscillator noise floor level of −180dBc/Hz. The noise peaking in figure 8 at 6-MHz offset frequency is a result of doubler interstage bandpass filter passband ripple response.

MEASUREMENT RESULTS: VIBRATION SENSITIVITY REDUCTION

Vibration measurements were made for individual sets of 40-MHz, 5th-overtone, AT-cut and 3rd-overtone, SC-cut crystals. The results are shown in tables 1 and 2. As indicated in the table, unit-to-unit variations in AT-cut resonator Γ values were more uniform but larger in amplitude, compared to the SC-cut units.

The results of the measurements show that a typical four-fold reduction in vibration sensitivity is obtained using the four-crystal mounting orientation shown in figure 4. As indicated in table 2, unit-to-unit Γ-direction variations for the SC-cut resonators were confined to a single spherical quadrant, with the exception of resonator #05.

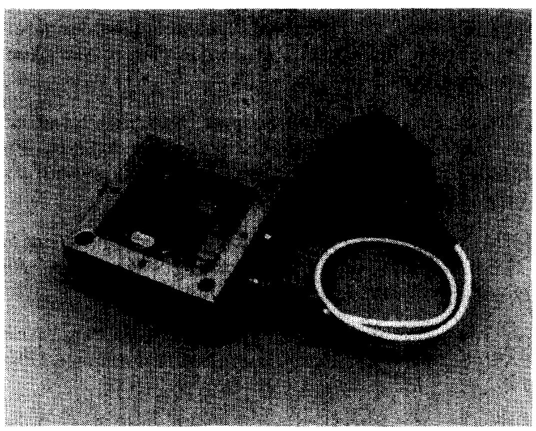

Figure 6. Photograph of the Four-Crystal Oscillator

Table 1. Vibration Test Results: 40-MHz, 5th-Overtone, AT-Cut Crystals (Γ Values in Parts in 10^{-10})

Crystal No.	ΓX	ΓY	ΓZ	ΓT
25	20.4	2.0	6.0	21.4
27	21.9	4.1	6.0	23.1
28	22.3	7.0	0.1	23.4
29	18.8	1.2	2.4	19.0
	ΓX′	ΓY′	ΓZ′	ΓT
Series Combination 25+27+28+29	3.0	3.3	1.7	4.8

Table 2. Vibration Test Results: 40-MHz, 3rd-Overtone, SC-Cut Crystals (Γ Values in Parts in 10^{-10})

Crystal No.	ΓX	ΓY	ΓZ	ΓT
01	0.6	7.6	0.9	7.7
02	0.5	3.8	1.4	4.0
05	−0.8	6.1	−3.2	7.0
15	0.3	5.7	3.3	6.6
	ΓX′	ΓY′	ΓZ′	ΓT
Series Combination 01+02+05+15	1.5	0.9	0.7	1.9

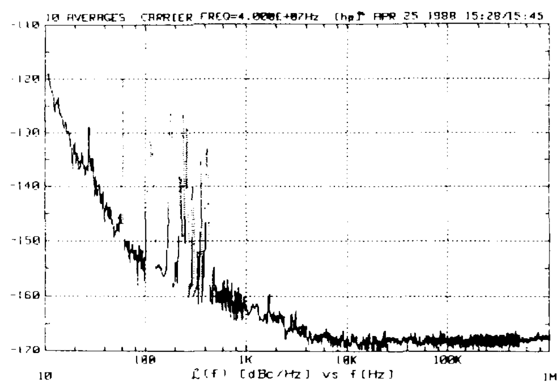

Figure 7. Measured Phase Noise Spectra for Two Phaselocked, 40-MHz (5th-Overtone, AT-Cut), Four-Crystal Oscillators

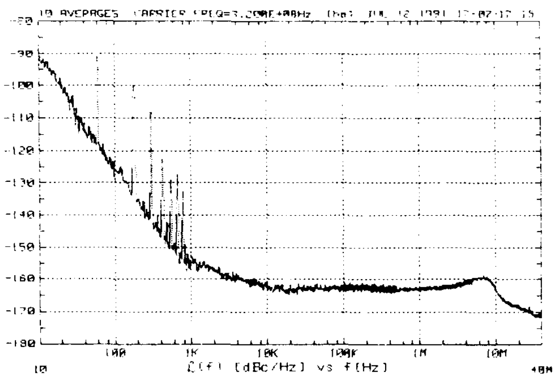

Figure 8. Measured Phase Noise Spectra for Two Phaselocked, 80-MHz (3rd Overtone, SC-Cut), Four-Crystal Oscillators After Frequency Multiplication to 320MHz

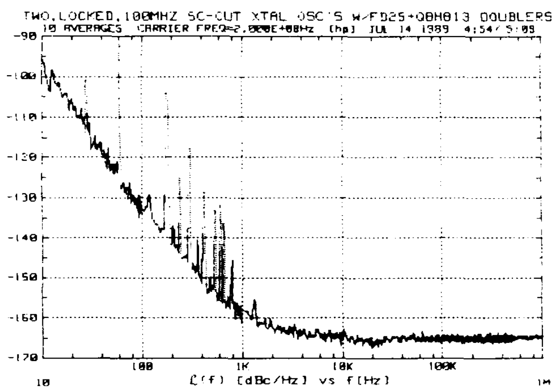

Figure 9. Measured Phase Noise Spectra for Two Phaselocked, 100-MHz (3rd-Overtone, SC-Cut), Four-Crystal Oscillators After Frequency Multiplication to 200MHz

CONCLUSIONS

Utilization of multiple series-connected resonators in a quartz crystal-controlled oscillator can provide significant reduction in near-carrier, flicker-of-frequency noise and (white phase) noise floor levels.

Using this technique, other non-correlated portions of resonator frequency instability, including random-walk and long-term drift, may be reduced as well.

At least four resonators may be oriented with respect to one another in a repeatable manner in order to obtain reduction in (net resonator) vibration sensitivity.

The technique described here applies to oscillators incorporating other types of frequency control elements (such as surface acoustic wave resonators) as well.

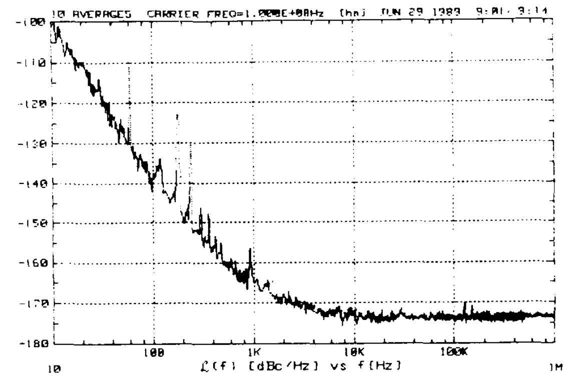

Figure 10. Measured Phase Noise Spectra for Two Phaselocked, 100-MHz (5th-Overtone, BT-Cut), Two-Crystal Oscillators

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