Review of SAW Oscillator Performance

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ABSTRACT

State-of-the-art phase noise performance has been demonstrated for both surface acoustic wave (SAW) resonator and delay line stabilized oscillators [1 - 5]. The same basic feedback-loop oscillator design philosophy [6, 7] was applied in each case in order to achieve these results. This paper reviews the design, fabrication, component selection, and performance for an extremely low-noise SAW resonator hybrid circuit oscillator. Finally, several recent results including the flicker noise of SAW resonator devices and the vibration sensitivity of all quartz package SAW resonators are discussed in the context of potential SAW oscillator performance enhancements.

1. Introduction

The residual phase noise properties of an oscillator's electronic components, for example RF amplifiers and electronic phase shifters, are extremely important if reproducibly low white PM and flicker FM oscillator noise levels are to be achieved. For SAW oscillators, it goes without saying that the residual flicker noise of the SAW resonator or delay line must also be minimized if truly state-of-the-art performance is to be achieved. For these reasons, residual phase noise measurement techniques which may be used to screen component noise properties are briefly discussed.

To illustrate the feedback-loop oscillator design procedure, a specific design example is presented. Recently, significant improvements have been realized in the vibration sensitivity performance of All Quartz Package (AQP) SAW hybrid circuit oscillators operating in the 150 MHz to 1 GHz frequency range, with typical vibration sensitivity magnitudes in the range from 1 to $5\times10^{-10}/g$. Data is presented to illustrate performance achieved to date. Other aspects of a SAW oscillator's performance, such as long-term stability and acoustic sensitivity, are also discussed.

2. Feedback-Loop Oscillator Design

Figure 1 shows a simple block diagram for a general purpose SAW device stabilized feedback-loop oscillator design. The feedback-loop oscillator's phase noise performance was first analyzed by Leeson [8]. Although individual oscillators will always differ in specifics of their particular implementation, they will all share the following common features: 1) one or more loop amplifiers (G_1, G_2) of sufficient gain to overcome total feedback-loop losses; 2) some means for gain-limiting (compression) within the feedback loop to insure stable oscillation (in many instances this gain-limiting action will actually occur in the second-stage (G_2) or high-level feedback-loop amplifier); 3) provisions for both gain and phase adjustment within the feedback loop in order to establish the proper loop conditions for oscillation to occur, namely approximately 3 dB (2 to 4 dB) of excess small-signal gain (nominally 3 dB of gain compression when equilibrium is reached) and $2\pi N$ radians of net transmission phase shift through the loop, where N is an integer; 4) feedback-loop signal sampling, which may be capacitive, resistive, etc.; and 5) a buffer amplifier (G_3) to isolate the feedback loop from external load variations. The need for an electronic phase shifter in the feedback loop to

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provide frequency tuning or modulation and a low-pass filter at the output to suppress undesired harmonic signals may, or may not, be necessary depending upon a specific oscillator's performance requirements.

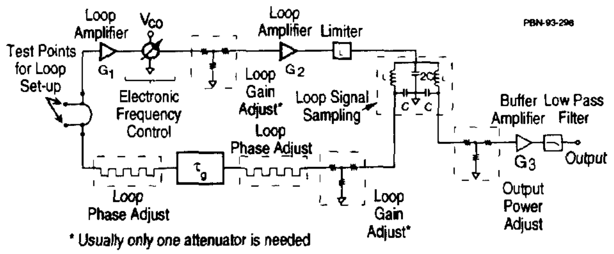

Fig. 1 Circuit diagram for a general purpose feedback-loop oscillator.

The simplest SAW oscillator may contain only an amplifier, a SAW device, an output coupler, and means for setting the loop's excess gain level and transmission phase shift, e.g., an attenuator and a short length of coaxial cable. Saturation of the loop amplifier's output power provides the necessary gain compression. More capable oscillators may contain a buffer amplifier, an electronic phase shifter, amplitude limiter, or any of the other components shown in Fig. 1.

Additional information regarding feedback-loop oscillator design may be found in References [1 - 7].

3. AQP SAW Devices

All of our recent SAW oscillator work is based upon the "All Quartz Package" (AQP) [9 - 13]. Subsequently, similar AQP devices have been reported by others [14 - 17]. The basic AQP structure is shown in Fig. 2, including the ability to laser-trim the device's resonant frequency after AQP sealing [12 - 13]. As indicated, two identically oriented pieces of single-crystal quartz are sealed together under high vacuum using a glass frit. The SAW device, which is fabricated on the inside surface of the lower substrate as noted, is thereby protected from any external sources of contamination. AQP SAW devices have demonstrated excellent long-term frequency stability (see Section 4), and the packaging technique is almost ideal for use in hybrid circuit oscillators (see Section 6). Development of the AQP has resulted in a significant reduction in vibration sensitivity at the AQP SAW device level [11], as well as more recently for AQP SAW hybrid circuit oscillators [18, 19].

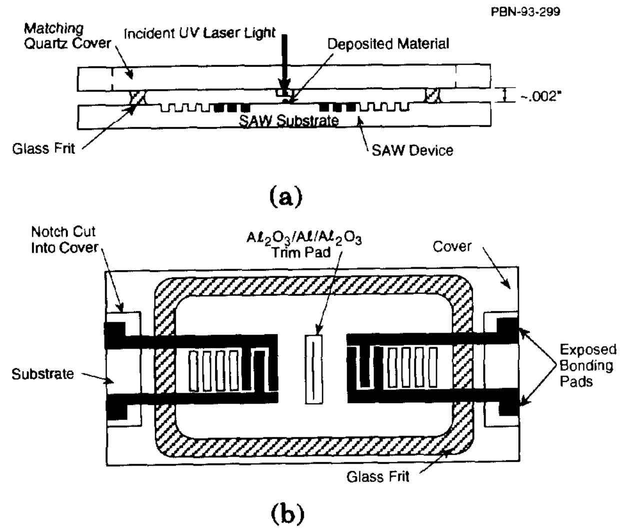

Fig. 2 Side (a) and top (b) views of an AQP SAW resonator, including provisions for laser frequency-trimming.

This unique packaging concept has also served as the basis for the development of a post-seal frequency-trimming technique [12 - 13], which makes it possible to set the frequency of an AQP SAW resonator to within ±1 PPM of a desired value. Although reactive ion etching (RIE) may be used to adjust the frequency of SAW devices prior to sealing [20, 21], it has the disadvantage that unpredictable shifts in frequency can, and indeed do, occur during the high temperature sealing process which is essential to insure good long-term frequency stability [6, 7]. Figure 2 serves to illustrate the post-seal frequency-trimming process, which is possible due to the optical transparency of the AQP. During SAW device fabrication a trim pad consisting of aluminum and aluminum oxide is deposited by E-beam evaporation on the inside surface of the cover piece, as indicated in Fig. 2 [12 - 13]. The trim pad is situated on the cover in such a way as to be located over the space between the transducers of the SAW device once the AQP is assembled. By focusing high intensity pulsed UV laser light (193 nm or 248 nm) on the $Al_2O_3/Al/Al_2O_3$ trim pad, material can be transported from the cover to the

SAW device's acoustically active surface area. The presence of this new material on the acoustically active portion of the SAW substrate slows the acoustic wave and hence lowers the resonant frequency of the SAW device. If the SAW device has been designed so that its resonant frequency after sealing is slightly higher than the ultimately desired value, the laser-trimming process can then be used to bring each device's frequency down to a specified value. Frequency adjustments as large as 100 PPM are possible with an accuracy of better than ±1 PPM. While there is some degradation in long-term frequency stability as a result of the laser-trimming process, we have shown that it is still compatible with long-term fractional frequency oscillator stability requirements of ±10 PPM over ten years [4].

Additional factors influencing SAW resonator and delay line designs for oscillator applications are discussed in References [1 - 7].

4. Long-Term Frequency Stability

The long-term frequency stability (aging) of SAW oscillators is an extremely important performance parameter for many system applications. In general, aging rates of less than about ±1 PPM/year (averaged over a period of years) are required for most, but not all, applications of high performance oscillators. For this reason, Raytheon has conducted an extensive aging test program for more than twenty years now. Good long-term frequency stability is critically dependent on the packaging of the SAW device. It is well known that the SAW device must be subjected to a high temperature (greater than 360°C) bake-out for at least one hour prior to sealing in an ultra-clean, hermetic package [1 - 7]. This point is illustrated in Fig. 3, which shows the beneficial influence of progressively higher bake-out temperatures on long-term stability for five different TO-8 cold-weld sealed SAW resonator based oscillators. Note the difference in vertical scale between the upper and lower portions of Fig. 3. As the bake-out temperature was increased, there is a definite trend toward significantly better long-term frequency stability as a direct result of the higher bake-out temperatures. The cold-weld sealing approach for SAW devices was the first to demonstrate SAW-based oscillator long-term frequency stabilities of ±1 PPM/year, or better. The AQP approach is almost ideal in this respect since the basic sealing procedure involves a high temperature processing step. AQP sealed SAW devices have been evaluated extensively during the last twelve years.

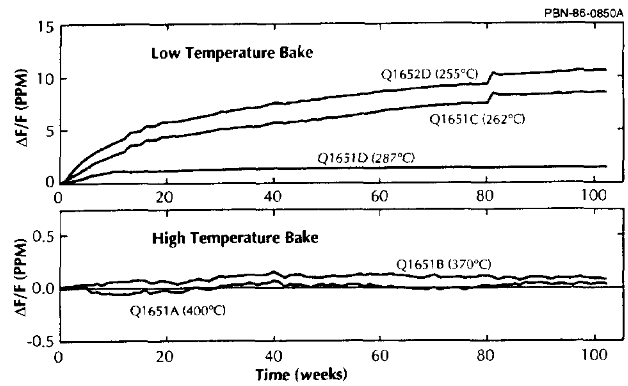

Fig. 3 Long-term fractional frequency stability measurements on five SAW oscillators illustrating the beneficial influence of a high temperature bake-out prior to sealing for TO-8 cold-weld sealed devices.

In the past we have published considerable data covering a wide variety of test conditions (dissipated RF power, acoustic stress density, transducer metalization, etc.) for a number of AQP SAW device designs [1 - 7, 9, 12 - 13]. Figure 4 shows the measured long-term fractional frequency stability of four AQP SAW resonator oscillators operating in the 300 to 800 MHz frequency range. These are lower power oscillators with approximately +5 dBm incident RF power on the AQP SAW devices. Roughly one-half of the incident RF power is actually dissipated in the resonator. The four curves shown are representative of results obtained on printed circuit board test oscillators where the AQP SAW devices were attached using a four-corner RTV mounting approach. This approach insures a stress-free mounting environment for the AQP SAW device. The AQP SAW oscillator which has been on test for approximately eleven years incorporates one of the first AQP SAW resonator devices which we fabricated! This particular oscillator's total fractional frequency variation has been less than ±0.4 PPM (peak-to-peak) during the entire test period.

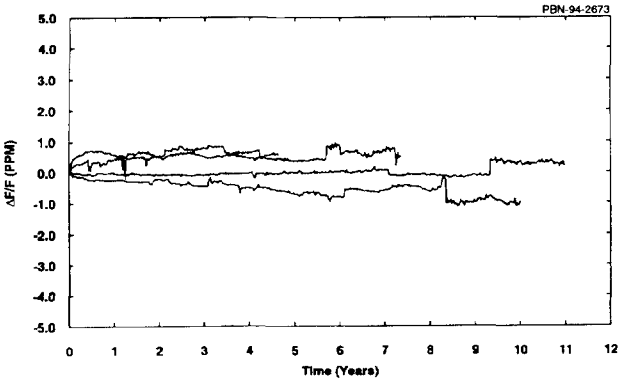

Fig. 4 Long-term fractional frequency stability for four AQP SAW resonator printed circuit board oscillators.

AQP SAW devices are particularly well suited to hybrid circuit applications, and in fact it is in hybrid circuit oscillator designs that their potential for inherently low vibration sensitivity may be leveraged [18, 19]. However, in order to achieve good vibration sensitivity performance the AQP SAW device should be mounted up-side-down using a uniform mounting material for support [11, 18, 19, 35 - 37]. The mounting material must be sufficiently "soft" so as to not introduce stress and thereby interfere with, or bias, either the device's basic static fractional frequency versus temperature characteristic or its long-term frequency stability properties [7]. At the same time the mounting material should uniformly support the AQP SAW device, while introducing no mechanical resonances. A number of materials have been examined for this application. At the present time we are using a double-sided silicone pressure sensitive adhesive (PSA) tape with considerable success. While the aging characteristics for hybrid circuit oscillators where the AQP SAW device is mounted using the PSA are not quite as good as those shown in Fig. 4, they are still consistent with long-term fractional frequency stabilities of ±10 to ±15 PPM over a ten year period.

5. Residual Noise Measurements

Residual phase noise measurements have been used for some time to characterize devices in the transmission [22 - 25], as well as reflection [26] modes. The realization of extremely low phase noise VHF, UHF and microwave oscillators is critically dependent upon the use of components, e.g., amplifiers, SAW devices, electronic phase shifters, etc., which possess verifiably low residual phase noise levels. The basic residual phase noise measurement set-up is shown in Fig. 5. The choice of a test source depends upon a number of factors. Generally, a frequency synthesizer based test source configuration is most useful when evaluating the residual flicker phase noise level of a SAW resonator or delay line device, since it may readily be adjusted in frequency in order to test a wide variety of relatively narrow bandwidth devices. We have previously shown [27, 28] that a state-of-the-art, extremely low-noise (both PM ***and*** AM) SAW resonator oscillator is quite useful when evaluating the residual phase noise properties of components which may exhibit appreciable AM-to-PM conversion sensitivities, e.g., amplifiers, electronic phase shifters, etc.

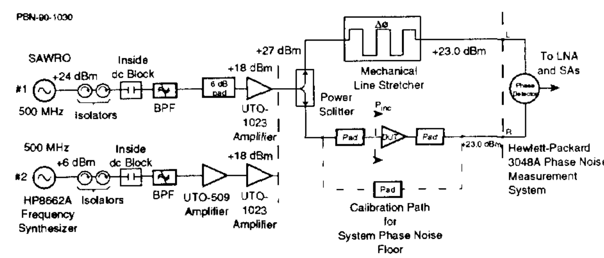

Fig. 5 Residual phase noise measurement set-ups at 500 MHz.

If a suitably low-noise test source is used, then the basic residual phase noise test set-up shown in Fig. 5 is capable of evaluating the residual phase noise properties of electronic components, e.g., amplifiers and electronic phase shifters, for carrier offset frequencies from 1 Hz to 40 MHz with unprecedented sensitivity and reproducibility [27, 28]. Figure 6 illustrates the measurement technique for three similar amplifier designs from three different vendors. The specific amplifiers are: 1) Cougar AC-509, 2) Watkins-Johnson PA3-1, and 3) Avantek UTO-509. For all three amplifiers the test conditions were identical, namely an incident RF test power level of +12.0 dBm at the amplifier's input. This incident RF test power level corresponds to approximately 3 dB of gain compression. These three amplifiers are all remarkably similar in their nominal electrical performance parameters. The UTO-509's residual phase noise performance shown in Fig. 6

is typical of that observed on more than one hundred devices, while the specific PA3-1 and AC-509 data shown in Fig. 6 was essentially identical for samples of three and four devices, respectively. It is interesting to note that both the PA3-1 and the AC-509 have consistently higher levels of residual flicker noise, when compared to the UTO-509. Also, all four AC-509s which were tested exhibited an anomalous residual phase noise "bump" near 6 kHz carrier offset frequency. Finally, the higher residual white phase noise floor measured for the PA3-1 is consistent with the fact that its noise figure was found to be approximately 2 dB higher than that of the UTO-509. However, the comparatively high white phase noise floor for the AC-509 cannot be explained in a similar manner. Separate residual phase noise measurements were performed on each amplifier using a frequency synthesizer (Hewlett-Packard 8662A) based test source, primarily for its quantitatively higher AM noise level, thereby confirming that the AC-509 does indeed have a considerably higher AM-to-PM conversion factor than either of the other amplifiers [27, 28]. It is evident that even with the extremely low-noise SAW resonator oscillator based test source configuration, it simply isn't possible to accurately measure this particular amplifier's (the AC-509) residual white phase noise floor properties, at least when only a single device is tested at one time.

It should perhaps be noted that neither an amplifier's residual flicker noise level, nor the possible presence of "bumps" in its residual phase noise spectrum, are predictable based upon any other electrical characteristic that we are aware of, including a small-signal noise figure measurement. Furthermore, as has been shown, even very similar amplifier designs from different vendors can differ markedly in their residual phase noise characteristics, even though their other nominal electrical parameters are nearly identical. It has been our experience that every single amplifier must be "screened" before use in an oscillator design where truly state-of-the-art phase noise performance is desired. Otherwise, you will constantly be attempting to diagnose which component, or components, is the culprit when a particular oscillator's phase noise spectrum simply doesn't meet its intended specification.

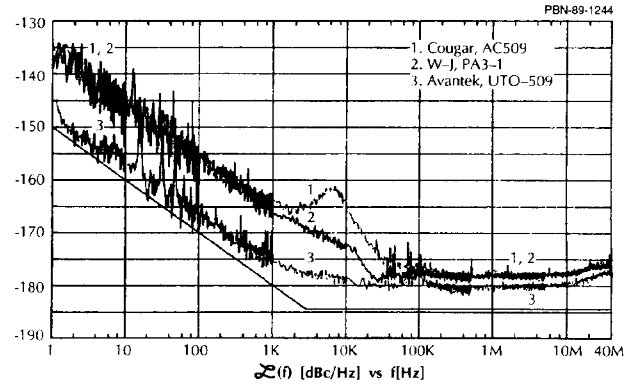

Fig. 6 Residual phase noise measured for three similar amplifiers using SAWRO test source.

Finally, the basic residual phase noise measurement technique may also be applied to other electronic components as well, e.g., electronic phase shifters, mixers, frequency dividers, frequency multipliers, etc., as has been shown in References [27, 28]. Many of these components are essential parts of low-noise microwave frequency sources based upon lower frequency (VHF or UHF), low-noise SAW oscillators.

6. SAW Oscillator Design Example

6.1 *Introduction*

While many factors enter into the design of an oscillator in response to a desired set of performance parameters, we have generally found that the specified phase noise spectrum is given considerable weight when evaluating whether a particular design is truly capable of addressing a specific oscillator requirement. Other performance parameters, e.g., vibration sensitivity, AM noise, harmonic and spurious output signal levels, load pulling sensitivity, dc power supply pushing sensitivity, etc., may take a back seat in comparison to phase noise although an increased emphasis is now evident for low phase noise oscillators with minimal vibration sensitivities ($\cong 1\text{x}10^{-10}/g$ per axis, or lower) for ground-based, as well as for airborne and missile, operating environments. References [6, 7] present detailed discussions of the various factors which may enter into the design of an oscillator in response to a particular set of requirements. In the example which follows, the oscillator's phase noise spectrum was considered of paramount importance, and every attempt was made to achieve the best overall phase noise performance.

6.2 *Low Noise Hybrid Circuit VCOs*

Figure 7 shows a detailed circuit schematic for an AQP SAW resonator hybrid circuit oscillator. The primary goal of this effort was to demonstrate for a hybrid circuit oscillator comparable, or even better, phase noise performance than that described in References [3, 5, 7] for PCB oscillators. Side benefits would be significantly reduced size and improved vibration sensitivity.

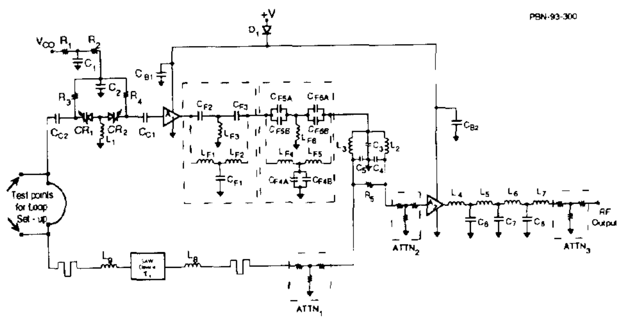

Fig. 7 Circuit schematic for a SAW based hybrid circuit oscillator.

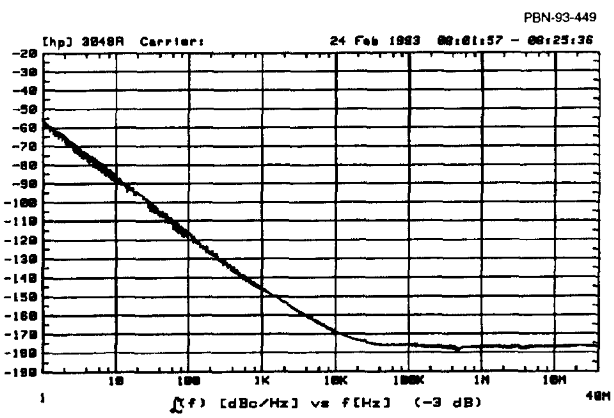

Fig. 8 Single-sideband PM noise spectrum for a low-noise AQP SAW resonator hybrid circuit oscillator.

The measured single-sideband phase noise spectrum for one 350 MHz AQP SAW resonator hybrid circuit oscillator is shown in Fig. 8. The white PM noise floor is approximately -177 to -178 dBc/Hz, which is comparable to our prior results for PCB based oscillators [3, 5, 7]. The flicker FM noise level of -89 dBc/Hz at 10 Hz carrier offset frequency is noticeably better than previously achieved performance (-83 dBc/Hz for a 500 MHz carrier frequency, even after taking into account the difference in carrier frequencies [7]. The SAW resonator's loaded Q, Q_L, in the feedback loop was approximately 6500. Several hybrid oscillators demonstrated flicker FM noise levels of -90 to -91 dBc/Hz at 10 Hz carrier offset. The phase noise performance shown in Fig. 8 represents the current state-of-the-art for a SAW resonator hybrid circuit oscillator, based upon measured results on more than forty pre-production engineering units.

A typical fractional frequency versus temperature characteristic for a 350 MHz AQP SAW hybrid circuit oscillator is shown in Fig. 9. The oscillator's turn-over temperature is approximately 72°C, which is about 4°C to 6°C lower than the AQP SAW resonator device's turn-over temperature. The lower turn-over temperature observed on the oscillator, compared to the SAW device, is attributable to the temperature sensitivity of the oscillator's electronic components. Typically, the variation in turn-over temperature from oscillator-to-oscillator is within a ±3°C to ±5°C window. Note that Fig. 9 also indicates the variation of the oscillator's RF output power versus temperature. As may be readily seen, the oscillator's output power varies by only ±0.2 dB over the temperature range from -55°C to +85°C. This is an extremely good result, and is a tribute to the RF amplifier's stability over temperature.

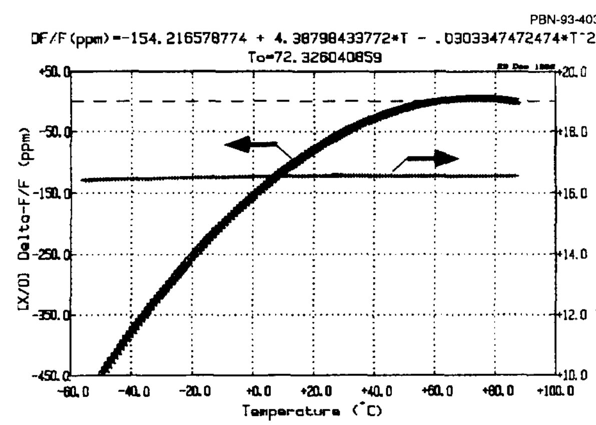

Fig. 9 Fractional frequency and RF output power stabilities versus temperature for a 350 MHz AQP SAW hybrid circuit oscillator.

The 350 MHz AQP SAW resonator hybrid circuit oscillator's AM noise spectrum is shown in Fig. 10. This measurement is basically consistent with previous results, although the 3 to 5 dB rise in the AM noise spectrum for carrier offset frequencies from 50 kHz to 2 MHz has not been observed previously. One possible design difference that may account for this behavior is the fact that the hybrid oscillator's buffer amplifier is operating with approximately 3 to 4 dB of gain compression. Additional measurements are planned to investigate this AM noise behavior since the AM noise level would ordinarily be expected to be comparable to, or less than, the PM noise level for all carrier offset frequencies.

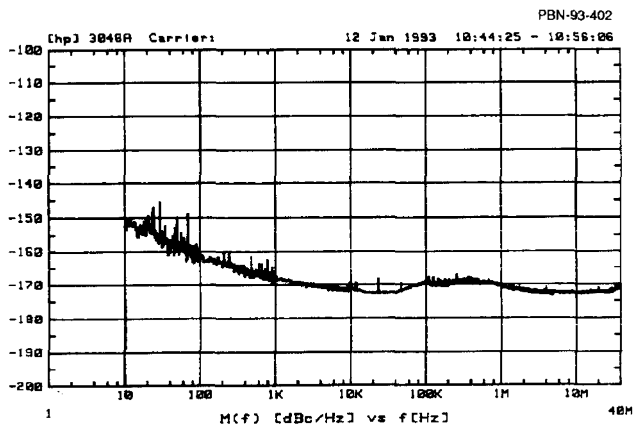

Fig. 10 Single-sideband AM noise spectrum for an extremely low-noise AQP SAW resonator hybrid circuit Oscillator.

The AQP SAW hybrid circuit oscillator must be mounted on a very stiff (non-bending) surface in order to achieve good vibration sensitivity performance [18, 19]. Our current approach was described in References [18, 19], where the base of the hybrid circuit oscillator's package is bonded to a 0.4" (1.0 cm) thick alumina stiffener. Alumina is a good choice of material since it is about five times stiffer than aluminum. A thinner (0.040" {0.1 cm}) piece of alumina is bonded to the cover of the oscillator's package in order to eliminate a cover resonance around 3 kHz. This stiffened oscillator assembly is capable of providing exceptionally good vibration sensitivity performance. This is illustrated in Fig. 11 for a typical 350 MHz AQP SAW resonator hybrid circuit oscillator. The vibration sensitivity magnitude for this oscillator is only about $2x10^{-10}/g$, dominated by the vibration sensitivity vector's component in a direction normal to the plane of the SAW substrate. Using this basic approach, we have consistently been able to achieve vibration sensitivity magnitudes in the 1 to $6x10^{-10}/g$ for AQP SAW resonator hybrid circuit oscillators operating in 300 to 500 MHz frequency range. In fact, one 900 MHz AQP SAW hybrid circuit oscillator exhibited a vibration sensitivity magnitude of $5x10^{-11}/g$ [7]. Vibration sensitivity magnitudes this low are approaching theoretically predicted values in the 1 to $2x10^{-11}/g$ range [30]. We have not as yet been able to reproducibly achieve oscillators with vibration sensitivities below $1x10^{-10}/g$.

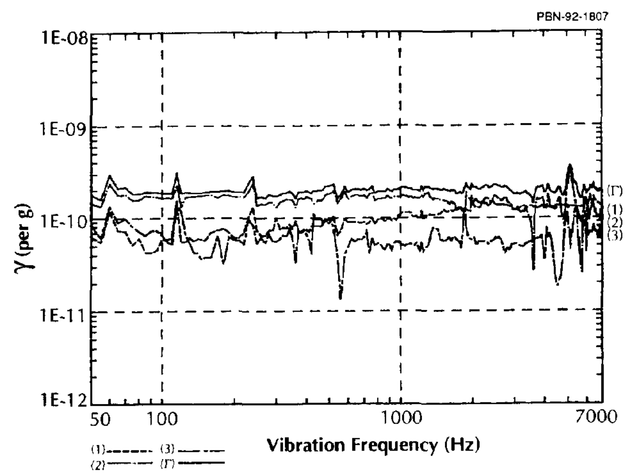

Fig. 11 Vibration sensitivity performance for a 350 MHz AQP SAW resonator hybrid circuit Oscillator.

Figure 12 illustrates typical aging data taken on several AQP SAW resonator hybrid circuit oscillators where the dissipated power and peak stresses in the SAW resonators are comparable to the corresponding levels in the prototype hardware just described. This level of performance, basically less than ±1 ppm/year, is perfectly well suited to a wide range of ground based and airborne radar system applications. These results clearly demonstrate, for the first time, that good long-term frequency stability, vibration sensitivity, and phase noise may be achieved simultaneously in a hybrid circuit SAW oscillator.

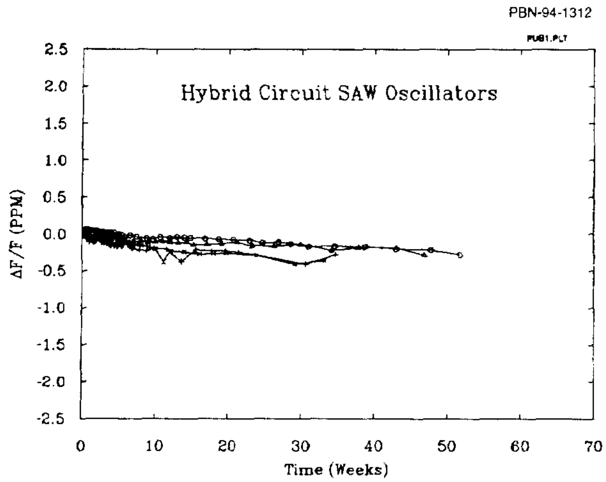

Fig. 12 Typical long-term fractional frequency stability for several AQP SAW resonator hybrid circuit oscillators.

6.3 *Summary*

It is indeed gratifying that the basic feedback-loop oscillator design, whose phase noise was first analyzed by Leeson [8], may be successfully applied under such a wide variety of circumstances, including the potential use of many different classes of frequency stabilizing element, with equally satisfactory results. In fact, it is perhaps appropriate to conclude with the observation that when properly designed and implemented, the feedback-loop oscillator configuration is well suited to the realization of truly state-of-the-art oscillator performance. Based upon our own experience, this statement applies not only to the exceptionally low phase noise levels which have been achieved, but also to virtually all other measures of an oscillator's performance which might be applied, as previously demonstrated [1 - 7].

7. Recent Results

In this section we will endeavor to illustrate, using several examples, that there is still much to be accomplished by way of improved SAW oscillator performance. Improvements will likely require more capable SAW devices, as well as electronic circuitry.

Figure 13 shows the phase noise measured for one laboratory prototype AQP SAW resonator hybrid circuit oscillator. It is evident that the oscillator's white phase noise floor is approximately -185 dBc/Hz, for carrier offset frequencies greater than 400 kHz. The oscillator's flicker FM noise level is approximately -80 dBc/Hz at 10 Hz carrier offset. This performance represents the current state-of-the-art for a hybrid circuit SAW oscillator [32], and essentially duplicates previously reported results for PCB oscillators [3, 5, 7].

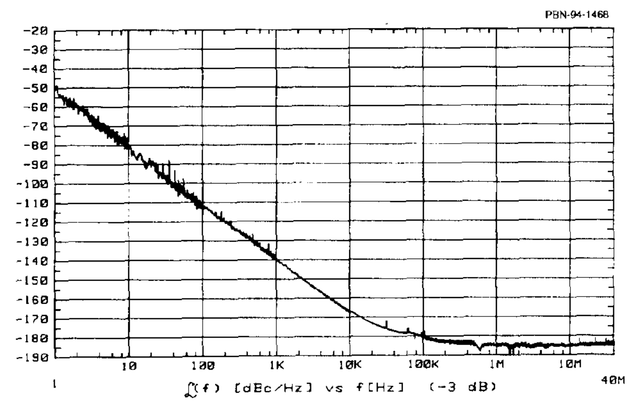

Fig. 13 Measured phase noise for one laboratory prototype oscillator.

Recent experimental results have indicated that there is an approximate inverse device size dependence to the 1/f phase noise in quartz SAW resonators fabricated with etched groove reflectors [33 - 36]. Figure 14 illustrates this observed behavior. A model has been proposed which is consistent with localized, uncorrelated velocity fluctuations in the quartz being the source of the 1/f noise. These results are significant in that ultimately the source of the velocity fluctuations may be identified, thereby leading to SAW resonator devices with even lower 1/f noise levels.

Vibration sensitivity data for AQP SAW hybrid circuit oscillators previously reported [18, 19] has exhibited a factor of five or six variation from oscillator-to-oscillator. Figure 15 shows the influence of the AQP's cover thickness on γ_1, the vibration sensitivity in a direction normal to the plane of the SAW substrate. Based upon finite element modeling and analysis, as well as these experimental results, it is now clear that much of the observed variation from oscillator-to-oscillator was due to uncontrolled differences in the uniformity of the mounting layer used to support the AQP. Thickening the cover effectively suppresses the influence of the mounting layer on the oscillator's γ_1 vibration sensitivity. This result is the basis for reproducibly achieving oscillator vibration sensitivity magnitudes in the 1 to $2\times10^{-10}/g$ range, or better.

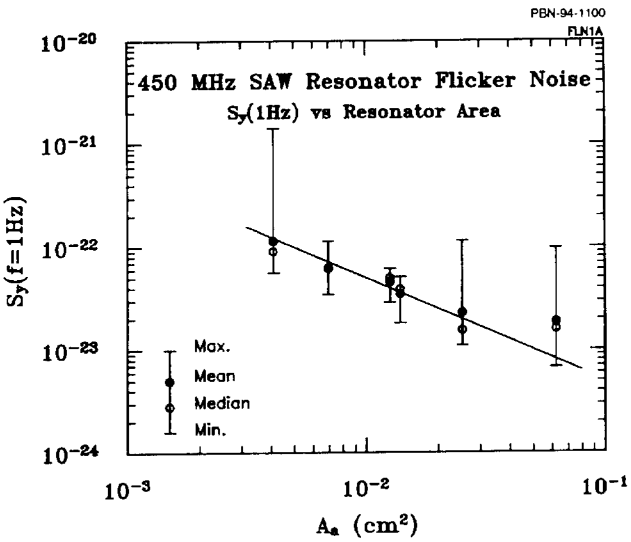

Fig. 14 Measured values of S_y(f=1 Hz) versus the resonators' active acoustic areas.

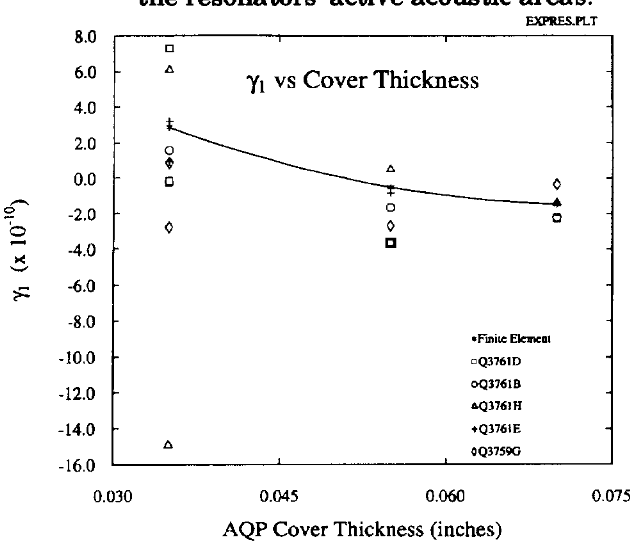

Fig. 15 Measured values of γ_1 as a function of AQP cover thickness.

Finally, a relatively new area of attention is the SAW oscillator's acoustic sensitivity. Many operating environments for high performance oscillators include relatively high levels of ambient acoustic noise, for example missiles and ground based radar shelters. Figure 16(a) shows the measured acoustic sensitivity for a 935 MHz AQP SAW oscillator with alumina base and cover stiffeners, while Fig. 16(b) shows the same oscillator's acoustic sensitivity with the base and cover stiffeners removed [37]. The typical sensitivity of 2×10^{-13} fractional change in frequency per Pascal is such that if the oscillator whose phase noise performance is shown in Fig. 8 were operating in a standardly specified missile environment, then its phase noise spectrum would be seriously degraded by the ambient acoustic noise level [37].

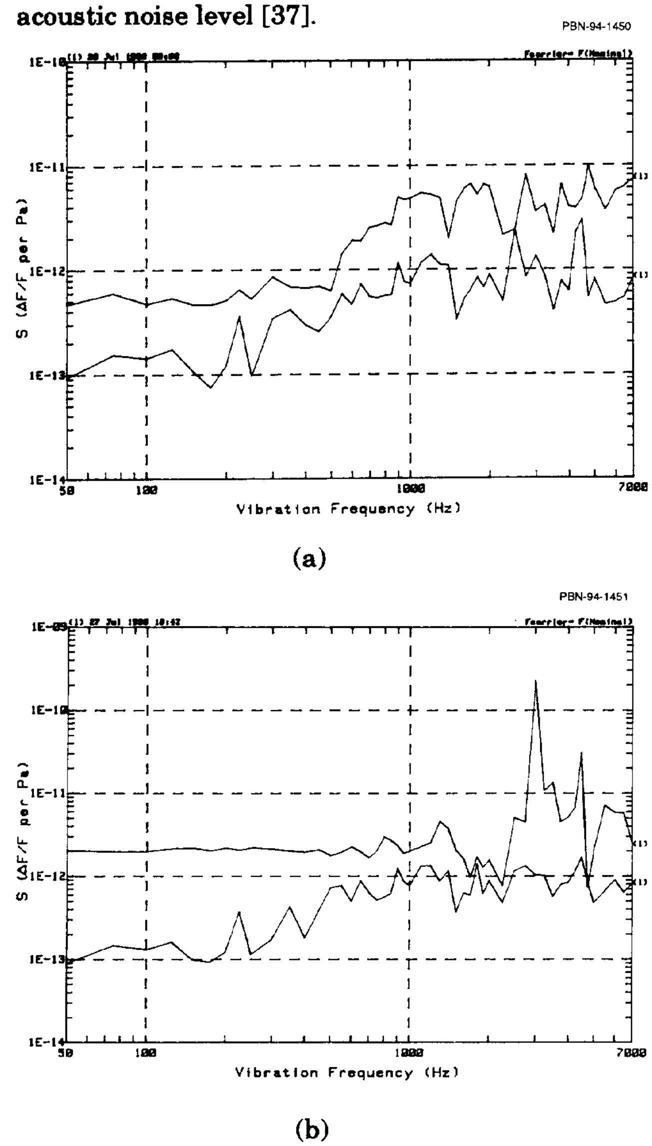

Fig. 16 Dynamic acoustic sensitivity for a 935 MHz AQP SAW oscillator: (a) with cover and base stiffeners, and (b) without cover and base stiffeners.

The exciting results just described indicate that there are still ample opportunities to improve the performance of SAW oscillators. This includes the obvious need for lower noise electronic circuitry, lower flicker noise SAW devices, better vibration sensitivity, etc.

8. Summary & Conclusions

We have shown, using a specific design example, that the basic feedback-loop oscillator configuration is well suited to high performance oscillator design in the VHF, UHF and microwave frequency ranges, based upon the incorporation of a two-port frequency stabilizing device. Using the techniques presented in References [1 - 7], state-of-the-art performance has been realized for AQP SAW resonator- and delay line-based oscillators [3, 5, 7].

While the phase noise spectra shown in Figs. 8 and 13 represent the current state-of-the-art for 350 to 450 MHz AQP SAW resonator hybrid circuit oscillators, by no means do they represent limits to what may ultimately be achieved with further improvements in both SAW resonator design and fabrication techniques, as well as anticipated improvements in RF amplifier residual phase noise levels. For 350 to 500 MHz AQP SAW resonator ***hybrid circuit oscillators*** current goals are to simultaneously demonstrate, while maintaining good long-term frequency stability, the following performance objectives: 1) flicker FM noise levels of -95 to -105 dBc/Hz at 10 Hz carrier offset, 2) -190 dBc/Hz white PM noise floors, and 3) vibration sensitivity ***magnitudes*** reproducibly less than $1 \times 10^{-10}/g$ (ultimately approaching $1 \times 10^{-11}/g$).

The design and evaluation techniques just discussed have proven to be invaluable in selecting the proper types of components for obtaining truly low-noise oscillator performance. As shown in Figs. 6, not all amplifiers are created equal, at least with regard to their residual phase noise levels. Residual phase noise measurements are also very valuable in screening out obviously defective components that would otherwise contribute unacceptably high levels of residual phase noise. The proper evaluation of amplifier characteristics has allowed us to predict an oscillator's white phase noise floor to within about ±1 to ±2 dB. However, the ability to predict flicker FM noise levels on individual oscillators (based upon component residual noise measurements) has been somewhat limited due to the fact that in many cases the residual flicker PM noise levels of the components are at or below measurable levels. Experience with more than one-hundred fully characterized printed circuit board and hybrid circuit oscillators (SAW resonator and delay line based) has given us considerable confidence in the feedback-loop oscillator based design procedures which have been described.

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