A REVIEW OF SAPPHIRE WHISPERING GALLERY-MODE OSCILLATORS INCLUDING TECHNICAL PROGRESS AND FUTURE POTENTIAL OF THE TECHNOLOGY

C. McNeilage, J. H. Searls, E. N. Ivanov*, P. R. Stockwell, D. M. Green, M. Mossammaparast

Poseidon Scientific Instruments Pty Ltd,
1/95 Queen Victoria St, Fremantle WA 6160, Australia
*School of Physics, The University of Western Australia,
35 Stirling Hwy, Crawley WA 6009, Australia

Abstract - **In this paper we present the results of recent progress in the development of low phase noise signal generators based on sapphire "whispering gallery"-mode resonators, and look at the future potential of these oscillators to meet the ever-increasing demands for precision signal generation and processing. Beyond improving phase noise performance, future oscillators will be required to work over more demanding temperature ranges, with lower vibration sensitivity and greater reliability. We discuss the performance of sapphire oscillators, particularly those operating near room temperature, and present recent results of vibration sensitivity less than 10^{-10} per g, phase noise of -146 dBc/Hz at 1 kHz and -170 at 10 kHz offset from a 10.24 GHz carrier, and extended temperature operation.**

INTRODUCTION

Sapphire "whispering-gallery"-mode (WG) resonators have been used as the basis of low noise oscillators for more than 20 years. The exceptionally low loss-tangent of sapphire (Al_2O_3) allows very high-Q resonators at both cryogenic and room temperatures: the Q factor at 10 GHz exceeds 6 x 10^9 at 2K, 5 x 10^7 at 77K, and 200,000 at 300K.

Historically, the development of the "sapphire loaded cavity" (SLC) resonator began in Russia in the early 1970s, as the timeline of Figure 1 shows.

1973	Braginsky, Panov et al. (Moscow State University) Discovery of extremely low electro-magnetic loss of sapphire resonators at cryogenic temperatures [1]
Mid. '70s	Dobromyslov, Vzyatyshev (Moscow Power Engineering Institute – MEI) Theoretical analysis of WG-modes in dielectric disk resonators [2]
1980	Tsarapkin, Ivanov (MEI) First application of WG-mode resonators for frequency stabilisation of microwave oscillators [3]
Early '80s	Blair (University of Western Australia - UWA) Recognition that moving the metallic walls out from the surface of the sapphire cylinder could increase achievable Q-factor, leading to current 'SLC' designs [4].

Figure 1. Timeline of critical stages of sapphire whispering gallery-mode resonator development.

Since the late 1980s, sapphire WG-mode oscillators have been built by several groups around the world. In most cases, the SLC design is based on a sapphire cylinder or disk, suspended in a metallic can (made from copper, silver or superconducting material), as illustrated in Figure 2.

RF energy is coupled into the resonator, most-often using magnetic loop probes, to create an electro-magnetic field distribution that is confined primarily within the sapphire. The confinement of the RF energy can be understood by comparison with the optical concept of "total internal reflection," or by the acoustic "whispering gallery" phenomenon experienced in large circular halls.

Cryogenic WG-mode resonators use high order modes (generally between 8 and 14, although as high as 17 is reported). SLC resonators operating near room temperature use moderate order modes, typically around 5.

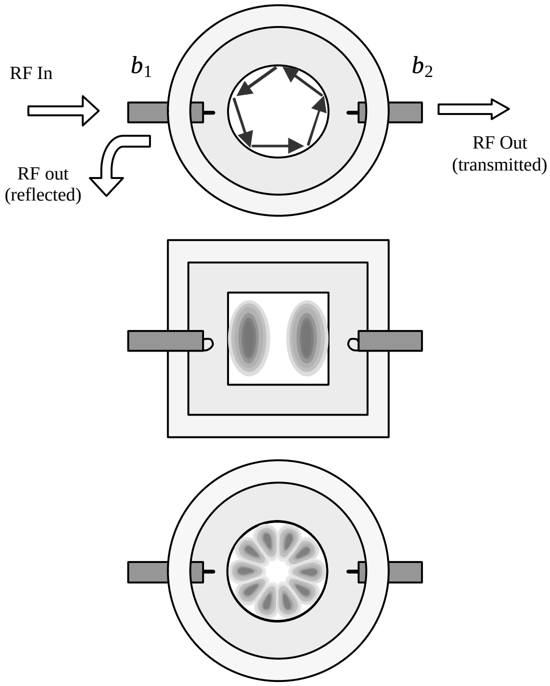

Figure 2. Basic SLC design.

The sapphire cylinder is suspended in the metal cavity. One or more probes are used to couple RF energy into and out of the resonator, generating a field pattern that is confined within the sapphire. The top illustration indicates "total internal reflection," while the bottom figures illustrate a typical field pattern for the $TE_{5,1,\delta}$ mode. Although a cylinder with rectangular cross-section is shown, various other shaped sapphires have been used successfully, including 'H' cross-section and hollow "donut" styles.

There are currently two main fields in microwave oscillator development based on sapphire WG-mode technology:

(i) cryogenic ‘clocks’ for ultra-high stability, and
(ii) higher temperature oscillators for low phase noise.

Ultra-stable clocks

With cryogenic resonators (operating between 2K and 80K), the focus has been on high stability at integration times of 1 to 100 seconds or greater, with a target Allan deviation (square-root of Allan variance) of 10^{-14} or lower. The motivation here is for local oscillators for cold-atom clocks (atomic fountains), and in fundamental physics research, such as verification of physical constants.

Current state-of-the-art is the UWA 4K ‘CSO’ [5], with a measured stability given by Allan deviation less than 3×10^{-16} at 4 s.

The technical progress in this field has been reviewed comprehensively recently [6][7].

Low phase noise oscillators

Oscillators for low phase noise are concerned with minimising phase noise over offset frequencies from 1 Hz to 1 MHz or wider. Primary applications include radar, data communications (where integrated phase jitter is critical), and emerging technologies such as high speed analogue-to-digital converters (using combined microwave and optical methods).

The remainder of this paper is associated with oscillators for low phase noise.

LOW PHASE NOISE TECHNIQUES

The phase noise performance of an oscillator is limited in general by the resonator Q-factor and the phase noise of the active elements in the oscillator circuitry. Figure 3 shows a “free-running” loop oscillator.

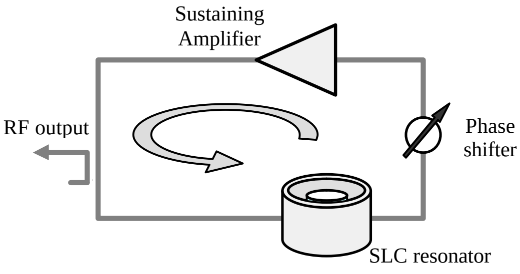

Figure 3. Basic loop oscillator.

The phase noise of the loop oscillator can be determined using Leeson’s model [8][9]:

$$\mathscr{L}'_{osc}(f_m) = \mathscr{L}'_{amp}(f_m)\left\{1+\left(\frac{f_{0.5}}{f_m}\right)^2\right\} + \mathscr{L}'_{res}(f_m) . \quad (1)$$

Here f_m is offset frequency from a carrier frequency f_0, $\mathscr{L}'_{amp}(f_m)$ and $\mathscr{L}'_{res}(f_m)$ are the amplifier and resonator phase noise, and $f_{0.5}$ is the resonator “loaded half-bandwidth”:

$$f_{0.5} = \frac{f_0}{2Q_L} . \quad (2)$$

Q_L is the “loaded Q” for the resonator, which is determined from the “unloaded Q” (Q_0) by

$$Q_L = \frac{Q_0}{1+\sum b_i} \quad (3)$$

where b_i is the coupling at port *i* of the resonator.

Throughout this paper, phase noise is represented in single-sideband form, $\mathscr{L}'(f_m)$, where

$$\mathscr{L}'(f_m) = \tfrac{1}{2} S_j(f_m) . \quad (4)$$

Here the dash after the ‘$\mathscr{L}$’ represents linear units, to prevent confusion with $\mathscr{L}(f_m)$ in dBc/Hz, calculated as

$$\mathscr{L}(f_m) \text{ in dBc/Hz} = 10 \log \mathscr{L}'(f_m) . \quad (5)$$

From (1) and (2) it is clear that oscillator phase noise is reduced if Q is increased, and that the phase noise of the sustaining amplifier impacts directly. For SLC resonators, $\mathscr{L}'_{res}(f_m)$ can generally be ignored.

A bandpass filter is usually included in the loop (not shown in Figure 3), to prevent oscillation on other modes of the SLC resonator.

The first sapphire oscillators were free-running, using Gunn diode amplification around 77K. GaAs FET amplifiers were used in free-running loops from the late 1980s, with useful results at cryogenic temperatures, but the poor flicker noise of GaAs amplifiers meant that free-running room temperature results were inadequate.

The focus then shifted to the development of *frequency discriminators* based on SLC resonators, to stabilise the frequency (and hence the phase noise) of oscillators. The following sections discuss frequency discriminator methods that have been applied to sapphire oscillators for low phase noise applications. Also mentioned is a novel reflection oscillator with enhanced effective Q-factor.

Basic Frequency Discriminator

A frequency discriminator is a system that has an output voltage that is a function of input frequency. One such system can be formed by combining an SLC resonator with a double-balanced mixer, as shown in the stabilised oscillator of Figure 4.

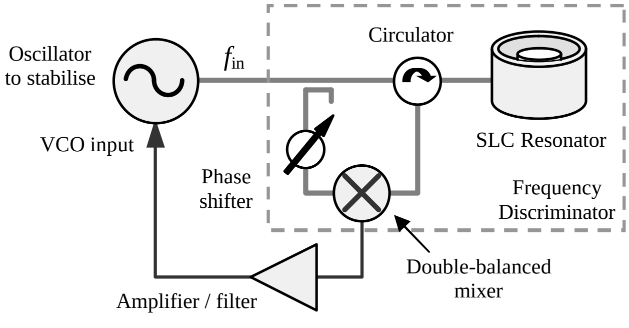

Figure 4. Oscillator stabilised by a frequency discriminator, based on the reflection from an SLC resonator.

The input signal f_{in} is directed through a circulator to the resonator, while a sample of f_{in} is input to the LO port of the mixer via a phase shifter. The signal reflected from the resonator has phase that is shifted by the reflection characteristics of the resonator (see Figure 5), and is input to the RF port of the mixer.

With the phase across the mixer set for quadrature, the mixer becomes a phase detector (a device that gives output voltage proportional to phase difference). So, a frequency discriminator is formed; consider the case for offset frequencies close to the centre of the resonator:

$$K_{FD}=\frac{\partial V}{\partial f_m}=\frac{\partial V}{\partial j_{11}}\cdot\frac{\partial j_{11}}{\partial f_m}\,. \qquad (6)$$

Here, $\partial V/\partial j_{11}$ is the phase detector sensitivity, and $\partial j_{11}/\partial f_m$ is the phase of the reflected signal as a function of frequency (it is assumed that f_{in} is close to the SLC resonant frequency f_{res}).

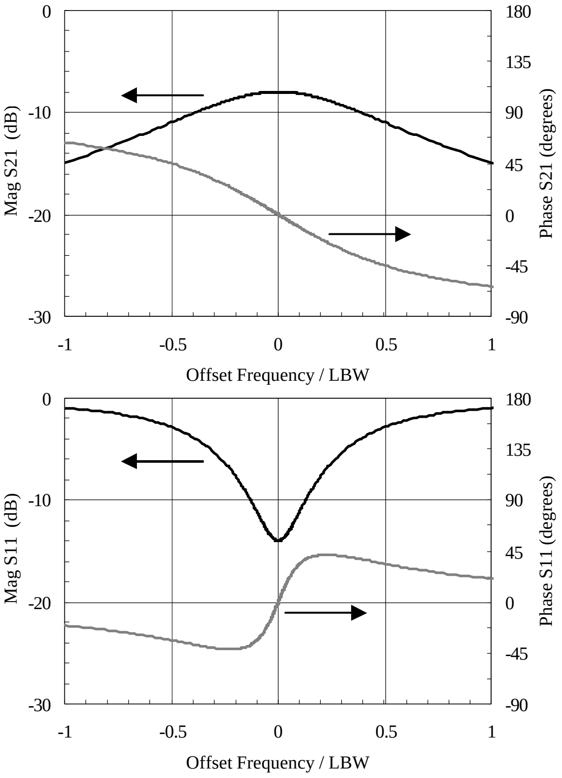

Figure 5. Transmission and reflection characteristics (‘S’ parameters) of an SLC resonator (for $b_1 = 0.8$, $b_2 = 0.2$).

The reflected signal from the resonator is generally preferred to the transmitted signal, since the phase-frequency slope is higher in reflection (it has been shown that comparing the transmitted and reflected signals can give even greater sensitivity, since the phase slopes have opposite sign [10]).

The sensitivity of the reflection frequency discriminator can be written:

$$K_{FD}\approx\frac{k\sqrt{P_{res}}}{f_{0.5}}\cdot\frac{2b}{1+b}\ \text{ in V/Hz, }\ f_m << f_{0.5} \qquad (7)$$

where k is the efficiency of the mixer (typically 10 V/√W), P_{res} is the power incident at the SLC in W, and in the case of a two-port resonator, $b = b_1/(1+b_2)$. The noise of this circuit has been analysed previously [11][12].

With the frequency discriminator output proportional to input frequency noise, a feedback control system can be used to stabilise the frequency of the oscillator (i.e. reduce its phase noise). Frequency discriminator sensitivity rolls off outside the half-bandwidth, so the control system filter is often an amplifier and lowpass filter (integrator) with phase lead for stability.

Reflection Loop Oscillator

Tsarapkin exploited the steep reflection phase-frequency characteristic of the resonator in a ‘reflection oscillator’ [13] (see Figure 6).

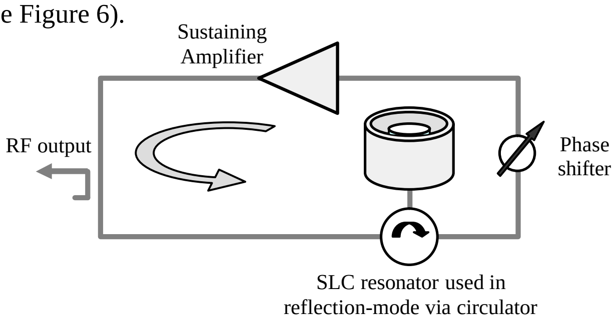

Figure 6. Reflection oscillator, exploiting higher phase-frequency slope in reflection than in transmission [13].

It was demonstrated that the effective Q of a reflection cavity is

$$Q_{eff}=\frac{2bQ_0}{\left|1-b^2\right|} \qquad (8)$$

which led to an effective Q of 10^6 at room temperature in the practical realisation of the circuit.

Dual Use Resonator

Tsarapkin [14], then Galani and Bianchini [11] exploited the same resonator as both the frequency-determining element in a loop oscillator, and the frequency-phase converter in a frequency discriminator. While only requiring one high-Q element, this also ensured that the oscillator and discriminator frequencies were tied together (see Figure 7).

Another advantage of the dual-use circuit of Figure 7 is that the lowpass characteristic of the frequency discriminator sensitivity is offset by the highpass nature of the oscillator frequency tuning coefficient, both with corner frequency of the cavity half-bandwidth. The oscillator tuning coefficient is

$$\frac{\partial f}{\partial V}=\frac{\partial f}{\partial j_{21}}\cdot\frac{\partial j_{21}}{\partial V}\,, \qquad (9)$$

where $\partial j_{21}/\partial V$ is the phase tuning of the loop phase shifter, and $\partial f/\partial j_{21}$ is the phase-frequency conversion in the resonator (which has a highpass response).

(In fact, the half-bandwidth for the oscillator frequency tuning is $f_0(1+b_1+b_2)/2Q_0$ whereas the half-bandwidth for the frequency discriminator is $f_0(1+b)/2Q_0$, but these can be assumed equal for control system design, since b_2 is usually small, less than 0.3).

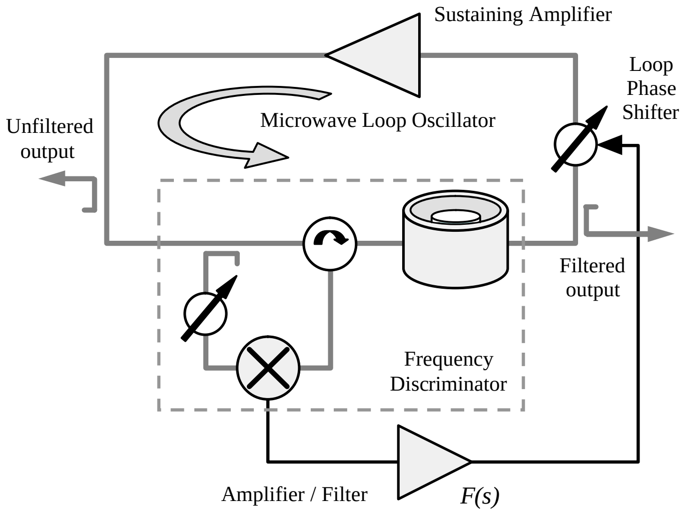

Figure 7. Dual use of the SLC resonator, as both the frequency-determining element in a loop oscillator and the frequency-phase converter in a frequency discriminator.

Having a combined ‘all-pass’ response allows the noise reduction bandwidth to be extended without increasing the complexity of the control system filter *F(s)*. However, the frequency discriminator sensitivity remains limited by the power handling of the mixer.

This circuit, originally used to reduce the FM noise of dielectric resonator oscillators (DROs), has been used with sapphire WG-mode oscillators by at least three groups [15] [16][17]. Since then, though, higher sensitivity discriminators have been built using carrier suppression methods.

Carrier Suppression using Critical Coupling

Carrier suppression methods have been exploited at microwave frequencies for many years, originally to reduce the carrier power to avoid over-driving detector and mixer diodes [18]-[21].

To realise greater efficiency in the frequency discriminator, it was realised that a low noise amplifier (LNA) could be inserted between the resonator reflected signal and the mixer. This provided three major benefits:

(i) sensitivity increased by the gain of the LNA;
(ii) lower discriminator white noise floor, since the noise figure of a low noise microwave amplifier may be 1 dB or lower, while the mixer may be 6 dB (its conversion loss); and
(iii) the large level signal from the mixer (due to preceding LNA) eases the voltage noise requirements of the following baseband amplifier/filter.

Simply inserting the amplifier in circuit was not reasonable, since the flicker noise of microwave amplifiers is generally worse than that of mixers (GaAs amplifiers at 10 GHz have 1/*f* noise through -130 to -135 dBc/Hz at 1 kHz offset, while silicon mixers range around -155 to -160 dBc/Hz).

In the early 1990s, Dick and Santiago [23] realised that by coupling to the resonator with a value near critical ($b \approx 1$), the power returned to the low noise amplifier would be low, thus preventing excessive flicker noise generation in the amplifier. It is important to note that as the coupling is increased towards unity, the reflected power decreases, but the phase-frequency slope ($\partial j_{11}/\partial f_m$) increases, so the frequency discriminator sensitivity remains near constant (for coupling $b > 0.7$).

This circuit (see Figure 8) has been used successfully at JPL for several years [23]-[25], to stabilise oscillators at various temperatures.

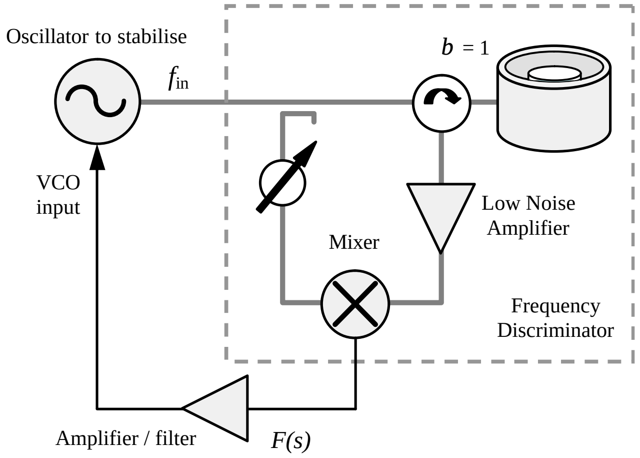

Figure 8. Oscillator stabilised by a carrier suppression discriminator, using critical coupling to the SLC resonator [23].

Carrier Suppression Interferometer

Ivanov et al. [26][27] combined concepts from the two discriminator types above with an interferometric method to suppress the carrier signal. The resulting circuit (see Figure 9) represents current state-of-the-art and has been used to produce a 9 GHz signal with phase noise $\mathscr{L}$(1 kHz) = -160 dBc/Hz at room temperature [28].

The carrier suppression interferometer (CSI) is a bridge circuit that cancels carrier power by matching inputs to a combining element, with necessary balance of both phase and amplitude [18]-[20][22][26]. The phase is balanced by a phase shifter, and the amplitude by an attenuator, both located in the ‘reference arm’ of the bridge.

The oscillator frequency can be tuned by adjusting the phase in the reference arm, with the frequency control system active. The frequency tuning slope is set by the resonator coupling (which determines the reflection phase-frequency slope, see Figure 5).

The level of carrier suppression demonstrated is more than 100 dB, and this can be maintained using an ‘automatic carrier suppression’ (ACS) system, which adjusts the attenuator in the reference arm to match the amplitudes at the interferometer inputs (the ACS system contains an integrator to maintain long-term balance; the ACS is not shown in Figure 9).

The frequency discriminator sensitivity achievable is close to that of the previous circuit, reduced by the resistive loss of the power combiner (usually 3dB, although can be within 1 dB if a directional coupler is used as the combining element). However, the long-term carrier suppression control and the wide allowable coupling range (*b* from 0.6 to 1.0), provide advantages in this circuit.

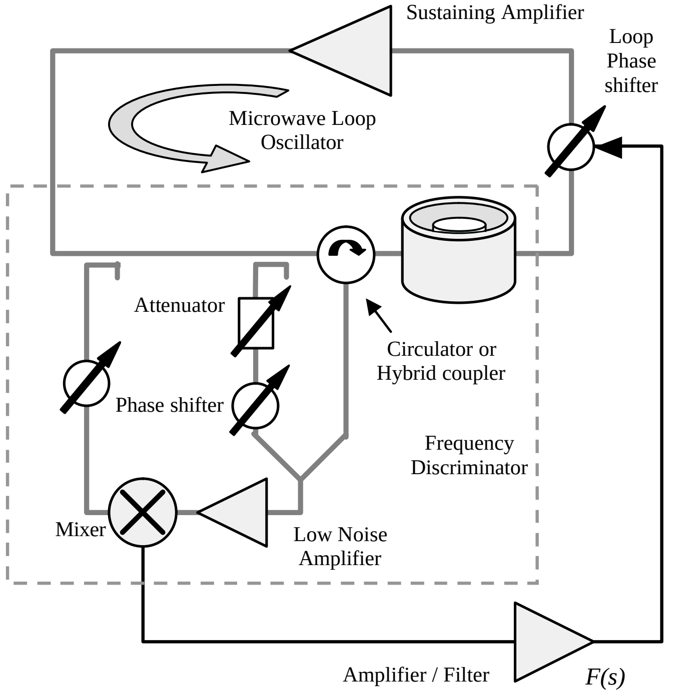

Figure 9. Carrier suppression oscillator using a microwave interferometer [26].

This type of circuit has been developed into the commercial ‘SLCO’ and ‘SBO’ oscillators, the performance of which is discussed in a later section.

Recent Carrier Suppression Techniques

New methods of suppressing carrier power (whilst maintaining phase sidebands) have been demonstrated recently [22][29]. Although these techniques may differ in their circuit topology and application, they are all variations on carrier suppression to prevent excess flicker noise in the low noise amplifier in the discriminator.

Naturally, as the flicker noise level in microwave amplifiers improves with device and material advances, the need for stringent carrier suppression reduces, allowing alternative arrangements to become viable. However, the underlying noise floors of current circuits are within a few dB of the thermal noise limit, so the emphasis now is on improving ease-of-manufacture, repeatability and long-term stability of carrier suppression networks.

Low Noise Amplifier Technologies

Amplifiers based on SiGe bipolar HBT technology are becoming available at X-band, with around 20 dB lower phase noise than GaAs FETs. This allows lower noise free-running oscillators [30], but amplifiers with $\mathscr{L}(1\ \text{kHz}) < -170$ dBc/Hz are required before the free-running oscillator will compete with carrier suppression methods. However, the use of SiGe amplifiers may reduce the complexity of existing carrier suppression systems, due to the less stringent demands on signal cancellation and control system loop gain to achieve equivalent low noise operation.

HISTORICAL LOW NOISE SLC OSCILLATOR DEVELOPMENT

The performance of sapphire WG-mode oscillators over time has shown consistent improvement, in terms of size and phase noise.

Size Reductions over Time

The original sapphire WG-mode oscillators were cryogenic units in research laboratories, larger than a household refrigerator and connected to test and measurement equipment. Since then, commercialisation of the technology has reduced the size and mass to the compact ‘SBO’ series [31], as shown in Figure 10.

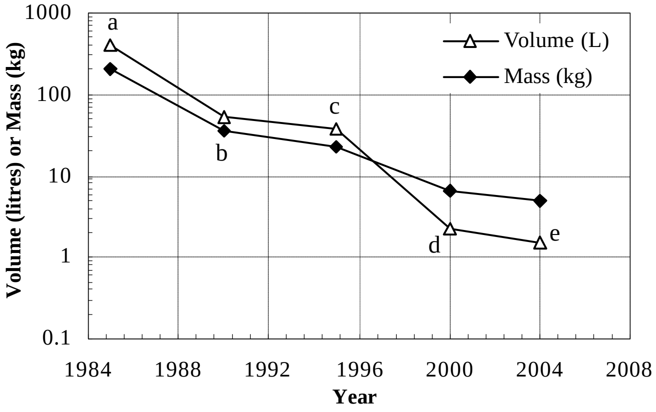

Figure 10. Size of sapphire WG-mode oscillators over time; a = typical cryogenic system (mid 1980s), b = compact 77K Gunn oscillator [32], c = 19” rack ‘SLCO’[33], d = ‘SBO’ [31], e = 2004 series ‘SBO’ oscillator.

Phase Noise over Time

Figure 11 shows the improvements in sapphire WG-mode oscillator phase noise performance over time.

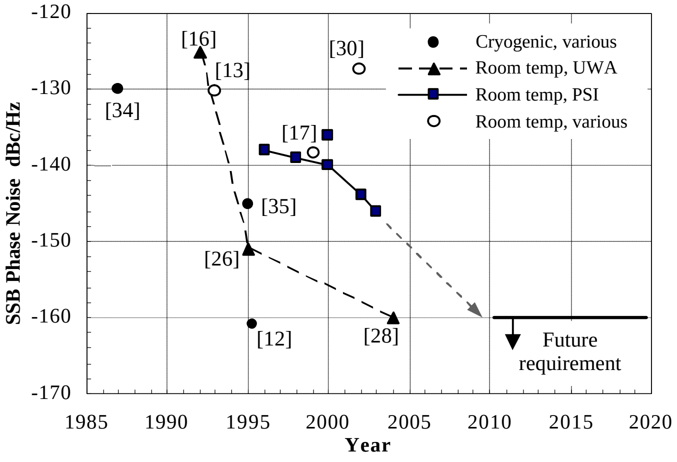

Figure 11. Phase noise improvements in WG-mode oscillators over time (individual references as shown). All data is at 1 kHz offset from X-band carrier frequencies.

The original work around 77K yielded phase noise of around -130 dBc/Hz at 1 kHz offset from a near-10 GHz carrier [34]. Room temperature results made significant headway when interferometric carrier suppression was employed [26].

The PSI oscillators are carrier suppression types, similar to those of UWA [26], with modifications as required for extended temperature and vibration environments. The PSI results shown in Figure 11 show a general improvement over time (not all PSI results are shown; the data represents average performance achieved over time). The improvement is attributed to an increased understanding of the noise mechanisms in the oscillators, and the management of these limits over the operating range.

Since the PSI oscillators need to be phase-locked to external references (for long-term frequency stability), they include 'VCO' tuning via a varactor phase shifter in the reference arm of the interferometer. The major oscillator phase noise limit (at offsets around 1 kHz) is set by the $1/f$ noise of the varactors, together with the resonator Q-factor and port 1 coupling (which determines the reflection phase-frequency slope).

Clearly, the achievable oscillator phase noise will be tied to the VCO tuning range requirements; eg. if large VCO tuning is required, then the influence of the varactor phase shifter will need to be increased, exposing the oscillator to more varactor-induced phase noise. It is worth noting that the result in 2000 of -136 dBc/Hz results from a customer requirement of wider guaranteed tuning range than typically built.

A second noise limit is due to thermal noise, which would present a $1/f^2$ floor in the oscillator phase noise plot. In UWA oscillators, the power available to the phase detector in the frequency discriminator is attenuated by the loss of a circulator (which is typically less than 1 dB, considering both forward and return paths). In PSI oscillators, a 6 dB hybrid is used, with about 1.5 dB through loss and 6 dB loss in the SLC reflected signal. A circulator is not used, because it would be susceptible to magnetic pick-up, in particular the fields present at line frequencies (eg. 60 Hz). The higher loss (hybrid versus circulator) leads to a higher thermal noise limit in the PSI 'SBO', by about 7 dB.

UWA has achieved -160 dBc/Hz at 1 kHz offset (without varactor tuning; frequency tuning was achieved by adjusting the resonator drive level) [28]. This level of performance meets the requirements of the next generation of applications, so the task is to develop oscillators that will achieve this performance over extended operating environments.

RECENT RESULTS AT PSI

The PSI 'SBO' series are compact, sapphire oscillators operating near room temperature, while the 'SLCO' is a 19" rack instrument. Since the first SLCOs were produced in 1996, the application-demanded requirements for temperature range, phase and amplitude noise performance, vibration sensitivity, and reliability have become more stringent.

Phase Noise Results

As mentioned above, the phase noise has shown steady improvement over the last few years, and Figure 12 shows the current level of performance.

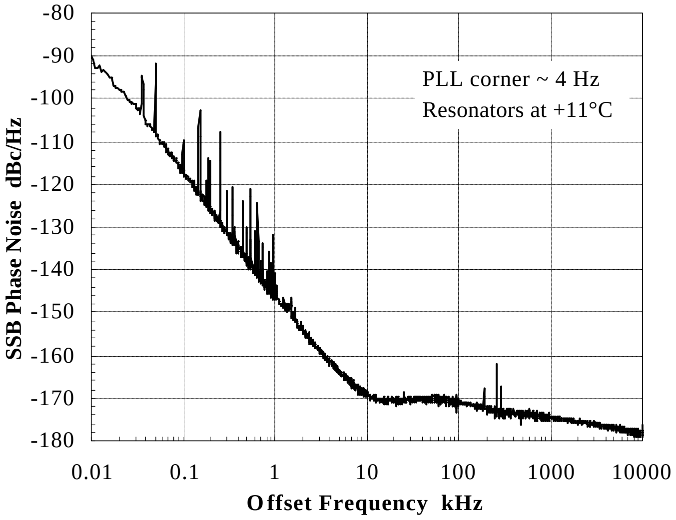

Figure 12. Measured phase noise of PSI room temperature SLCO at 10.24 GHz (August 2003).

Amplitude Noise Results

With phase noise at these low levels, amplitude (AM) noise can no longer be ignored. In fact, poor AM noise can readily degrade phase noise performance, particularly as temperature varies (an oscillator tuned for minimum AM-to-PM conversion at room temperature may well suffer at operating temperature extremes). At PSI, we have tested various amplifier designs and developed low noise power supplies to minimise oscillator AM noise, and Figure 13 shows the current 'SBO' performance.

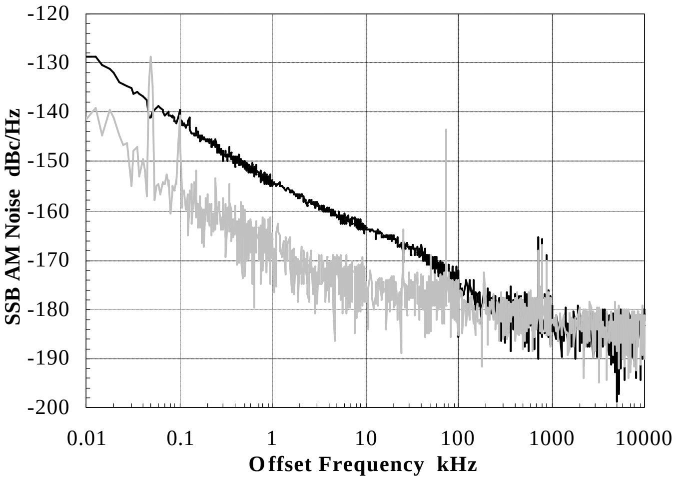

Figure 13. Measured amplitude noise of PSI room temperature SBO at 10.24 GHz (August 2004).

AM noise is -154 dBc/Hz at 1 kHz offset, with a $1/f$ characteristic through to 50 kHz, where the effect of resonator filtering is visible. The measurement was done using cross-correlation of the signals from two AM-sensitive mixers, to achieve a low measurement noise floor. The apparent steps in the data are due to limited averaging in the cross-correlation method (a higher number of averages was taken at higher frequencies).

It is worth noting that the amplitude noise tends toward the thermal floor. With +15 dBm output power, the AM thermal floor is at -192 dBc/Hz (the thermal floor is at -177 dBm/Hz, since AM represents half of the power in thermal noise ‘kT’). Since the measured AM noise is not at all visible above the measurement noise floor beyond 1 MHz (both around -182 dBc/Hz), it can be assumed that the AM reaches the thermal limit by about 1 MHz offset.

Vibration Sensitivity

The vibration sensitivity has been measured for the SBO oscillator, and is shown in Figure 14.

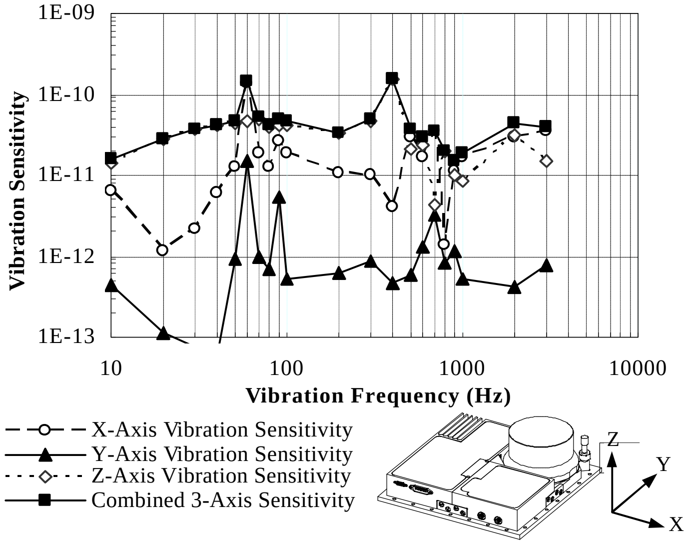

Figure 14. Measured vibration sensitivity of PSI SBO at 10.24 GHz (September 2003).

At this stage we believe the major contributor to the Z-axis sensitivity (the worst axis) is the ‘seam’ that runs down the middle of the SBO structure (see Figure 15). Also, the large, round, vacuum can (which houses the SLC resonator) can resonate like a drum, which will modulate the microwave field in the resonator (due to non-perfect confinement of the field).

To address these effects, we are producing a new version of the SBO oscillator (see Figure 15), with an ‘L’-shaped housing for the microwave loop components, and a new vacuum can design to minimise the drum effect. The loop enclosure has an ‘H’ cross-section and solid exterior walls to maximise strength.

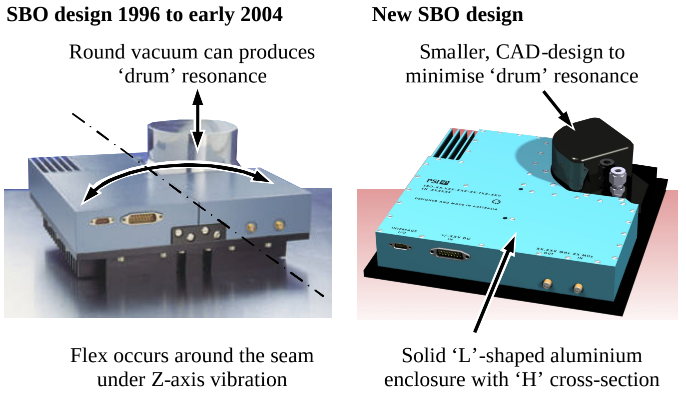

Figure 15. Modified SBO enclosure to address Z-axis vibration sensitivity.

CURRENT WORK AT PSI

Several projects are underway to improve the performance of PSI sapphire oscillators, and to produce complementary products for systems designers.

Low Noise Regenerative Dividers

PSI oscillators operate with SLC resonators from 6 GHz to 11 GHz. In this range, the resonator geometry is manageable, and support technologies such as regenerative dividers can be readily made to operate from X-band down to VHF frequencies [36].

It is well understood that oscillator phase noise varies by ‘20 log N’ under frequency division, where N is the division ratio, $N = f_2/f_1$. However, since the ‘$Q.f$ product’ of sapphire resonators is constant (for a given SLC temperature), the phase noise of oscillators and frequency discriminators built with SLCs varies more dramatically with frequency.

In general, the oscillator phase noise is determined by the half-loaded bandwidth $f_{0.5}$ of the resonator, and not the carrier frequency directly, see (1) and (7). So, for deriving low phase noise, the best option is to start with the resonator frequency as low as possible, to minimise $f_{0.5}$, see (2).

Consider two oscillators, at frequencies f_1 and $f_2 = M.f_1$, with loaded Qs given by Q_1 and $Q_2 = Q_1/M$ (since $Q.f$ is constant). These have half-bandwidths given by $f_{0.5}^{(1)} = f_1/2Q_1$, and $f_{0.5}^{(2)} = f_2/2Q_2 = M^2.f_{0.5}^{(1)}$. This represents a ‘40 log M’ increase in phase noise as resonator frequency is changed by factor M. So, for example, to derive a 20 GHz signal, it is prudent to use an SLC-based oscillator at 10 GHz and multiply the frequency by 2, rather than build directly at 20 GHz (the 10 GHz signal will have 12 dB less noise than the 20 GHz direct signal, and result in 6 dB less phase noise when multiplied up to 20 GHz).

Note that the ‘40 log M’ rule-of-thumb applies within the resonator half-bandwidth, but not to regions far-from-the-carrier, where thermal limits apply (here the standard ‘20 log N’ is used).

For this reason, sapphire oscillators (with $Q.f \approx 2 \times 10^{15}$ at room temperature) will produce lower phase noise signals when divided to UHF and VHF frequencies than quartz generators (with $Q.f \approx 10^{13}$).

Current work at PSI is involved with exploiting the $3f_{in}/2$ product available from the standard divide-by-2 regenerative divider, and utilising other division products. We are also building a ‘six-pack’ divider ensemble to divide from 10.24 GHz to 320 MHz (with simultaneous outputs at 10.24, 5.12, 2.56, 1.28, 0.64 and 0.32 GHz).

Low Noise Voltage Regulators

To allow improvements in the amplitude noise of the SBO to the levels shown in the previous section, we needed to develop a low noise voltage regulator, with less than -150 dBV/√Hz voltage noise from 100 Hz to 100 kHz (voltage noise converts to AM noise directly under compressed amplifier operation).

Standard 'industrial' voltage regulators, such as the LM2940, have noise around -125 to -130 dBV/√Hz out to 40 kHz or so, but provide robust thermal overload and short-circuit protection. By appending a closed-loop noise reduction system to the regulator, we were able to achieve -160 dBV/√Hz, without compromising drive current capability, with successful operation confirmed over -10°C to +60°C and 1 mA to 800mA load current.

SLC Resonator Improvements

Current SBO oscillators operate over a 60°C range, within the window -10°C to +60°C (user specified). Work is currently underway to extend the operating range from -55°C to +65°C. We are also working on reducing the time taken for the resonator to lock to temperature at start-up. Currently, the SBO will be phase locked to an external reference within 10 minutes over the 60°C temperature range, but the next requirement is less than 2 minutes to lock over the extended temperature range (phase locking occurs after resonator temperature lock).

Toward these aims, we are working on a new SLC mechanical design, with reduced specific heat capacitance and optimised thermal paths, but as little compromise on mechanical strength as possible. We are also looking at improved thermo-electric modules to increase the efficiency of heat removal from the SLC.

To this date, we have demonstrated temperature lock within 2 minutes over the range 0 to +55°C, and we expect our next set of results in late 2004.

Reliability Improvements

To increase reliability of the SBO oscillators, we recently changed the design of the sustaining microwave amplifier, to minimise FET gate degradation caused by operation in compression. Also, we have developed new compensation networks to account for ageing and temperature effects, particularly due to the temperature coefficients (of dielectric constant and mechanical expansion) of the microstrip substrate used in the oscillator circuitry, and the long-term water absorption of the substrate.

With these improvements, SBO oscillators should be able to operate for 10 years without servicing.

CONCLUSIONS

We have reviewed the history of sapphire "whispering gallery"-mode resonators and oscillators, and shown circuits often used in producing these low phase noise oscillators. We have also presented recent results achieved at PSI, including room-temperature sapphire oscillators with phase noise of -146 dBc/Hz at 1 kHz and -170 at 10 kHz offset from an X-band carrier, amplitude noise of -154 dBc/Hz (f_m = 1 kHz), and vibration sensitivity less than 10^{-10}. Recent improvements in PSI oscillator design and current work were discussed.

Based on current performance, it is clear that sapphire oscillators remain the premier technology for low phase noise applications. Together with regenerative dividers and other complementary products (such as carrier suppression-based reduced noise amplifiers), sapphire oscillators can produce start-of-the-art phase noise at carrier frequencies from VHF to millimetre wave.

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