Design and Performance of Low-Phase Noise Microwave Oscillators

Eugene N. Ivanov and Michael E. Tobar
School of Physics, M013, University of Western Australia, Crawley WA, 6009, Australia
eugene@physics.uwa.edu.au

***Abstract*—This work verifies that the X-band microwave oscillators with the phase noise spectral density approaching $-157\ dBc/Hz$ at $1\,kHz$ offset frequency can be reproducibly constructed. Such a performance can be achieved by frequency locking a conventional loop oscillator to the room temperature stabilised sapphire dielectric resonator using the principles of microwave circuit interferometry and operating the resonator at the elevated level of dissipated power. We discuss the noise mechanisms responsible for the flicker frequency fluctuations of the high power microwave oscillators with interferoemtric signal processing , as well as the technique for the high resolution noise measurements at microwave frequencies.**

Index terms: oscillator frequency stabilisation, phase locking, microwave interferometry.

I. INTRODUCTION

Microwave oscillators with the phase noise spectral density approaching the standard thermal noise limit have previously been constructed based on the principles of microwave circuit interferometry [1-2]. In such oscillators a high-Q resonator based on a Sapphire Loaded Cavity (SLC) serves both as a band-pass filter of a loop oscillator and a dispersive element of the interferometric Frequency Discriminator (FD). The latter consists of a microwave interferometer and a phase sensitive readout system featuring a low-noise microwave amplifier and a mixing stage. Microwave signal reflected from the high-Q resonator interferes destructively with a fraction of incident signal at the "dark port" of the interferometer. This cancels the carrier of the difference signal while preserving the noise sidebands caused by frequency fluctuations of the loop oscillator. The noise sidebands are amplified and demodulated to DC producing an error voltage varying synchronously with the oscillator frequency. The filtered error voltage from the mixer's output is applied to the voltage controlled phaseshifter (VCP) in the loop oscillator steering the oscillator's frequency to a given resonant mode of a high-Q resonator.

The frequency discriminator, filter and VCP form a frequency control system (FCS) which detects and cancels the oscillator frequency fluctuations. Assuming a frequency control loop with sufficiently high gain, the quality of oscillator frequency stabilisation would be entirely determined by the noise properties of the frequency discriminator [1].

Our main goals of this work were:

1. To investigate the origin of a frequency flicker noise in the high-power microwave oscillators with the interferometric signal processing:
2. To design a servo-control system capable of referencing one oscillator to another and maintaining its synchronous operation for prolonged periods of time (days) to allow the study of the long-term variations in the intensity of the oscillator phase noise:
3. To improve the accuracy of oscillator noise measurement system due to the use of an interferometric phase detector:
4. To built the electronically tunable microwave oscillators with automatic carrier suppression and study the noise properties.

II. TWO-OSCILLATOR PHASE NOISE MEASUREMENT SYSTEM

The oscillator phase noise measurements involved phase locking of one oscillator (frequency tunable 'slave') to another (fixed frequency 'master'). First, we tried steering the 'slave' frequency by changing the operating temperature of the SLC resonator. This was implemented by altering the current of the thermoelectric cooler attached to the SLC base plate. The SLC temperature-to-frequency transfer function measured was similar to that of a 3rd order low-pass filter (possibly due to the imperfect thermal joints in the path of the heat flow). This approach was abondoned due to the complications in the design of the Phase-Locked Loop (PLL).

An alternative approach to oscillator frequency tuning relied on the power-to-frequency conversion in the SLC resonator. In such a case, the oscillator frequency was varied by changing microwave power dissipated in the SLC resonator with a voltage controlled attenuator (VCA) placed in front of the high-power loop amlifier. This technique enabled the SLC response similar to that of a 1st order low-pass filter with a time constant $\tau_{th} \approx 20\,s$. The magnitude of the SLC frequency tuning coefficient as a function of Fourier frequency is shown in Fig. 1.

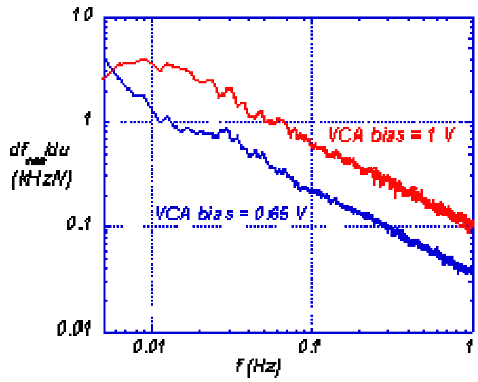

Figure 1. Magnitude of frequency tuning coefficient of a 9 GHz low-noise oscillator at different VCA bais voltages.

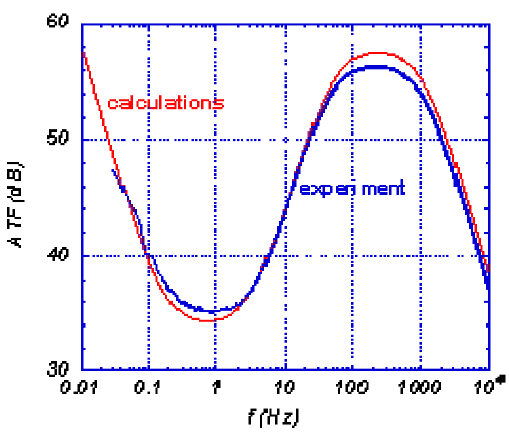

Figure 2. Calculated and measured amplitude transfer functions of the PLL filter.

The data from Fig. 1 were used for designing of the PLL filter whose amplitude transfer function in shown in Fig. 2. The filter contained an integrator to compensate for the temperature induced variations of the beat frequency between two oscillator and a 'quasi-differentiator" to 'balance out" the phase lag associated with the SLC thermal time constant. The noise suppression factor of the PLL based on the above filter is shown in Fig. 3. It is worth noticing a relatively broad bandwidth of the PLL (~30 Hz) due to the use of the 'quasi-differentiator" with more or less optimally chosen parameters.

The measurements of the oscillator phase noise were conducted in the temperature stabilised laboratory where variations of the difference frequency between two free-running oscillators were of the order of a few kHz. Under such conditions the 'slave' oscillator could remain in phase synchronism with the 'master' for days without the need for any manual frequency corrections.

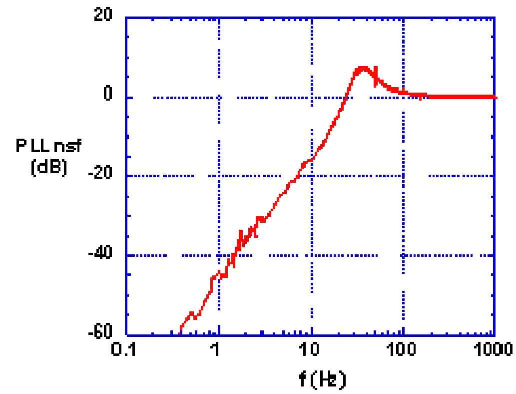

Figure 3. Phase-locked loop noise suppression factor.

It is possible that having a high-gain quasi-differentiator inside the PLL could induce extra phase noise in the 'slave' oscillator due to instabilities associates with high gain. To examine this hypothesis, the phase noise floor of the PLL low-frequency electronics was evaluated. This was done in two steps, first, we measured the amplitude transfer function of a closed phase-locked loop between the FM input of the 'slave' oscillator and the output of the phase detector. Secondly, having terminated the input of the PLL filter we measured the voltage noise spectrum at its output. From these two measurements the contribution of the PLL electronics to the 'slave' oscillator phase noise was calculated (see Fig. 4). Fig.4 also shows a typical phase noise spectrum of a high power oscillator. Clearly, the effect of PLL electronics on the oscillator phase noise performance is negligible.

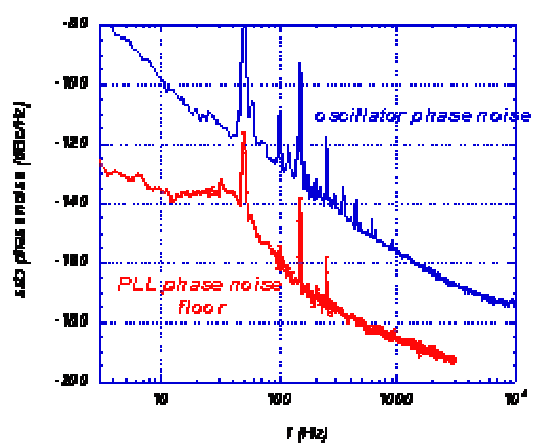

Figure 4. PLL phase noise floor and oscillator phase noise spectral density.

III. ORIGIN OF THE EXCESS PHASE NOISE IN THE EARLIER EXPERIEMNTS WITH HIGH-POWER OSCILLATORS

The first prototypes of the high power oscillators seemed to exhibit an excess phase noise whose spectral density was a non-monotonic function of the frequency control system loop gain: the initial suppression of the oscillator phase noise with the loop gain was followed by its increase at the higher gain values [3]. Such behavior was typically observed at Fourier frequencies around 1 kHz, where we expected to see the lowest noise itensity. We linked this effect to the onset of instability in the feedback loop controlling the oscillator frequency.

After a few unsuccessful attempts to establish the origin of the excess phase noise we tried to eliminate it by:

- Improving the noise properties of a free-running oscillator with the idea of avoiding the operation of the frequency control system at the high loop gain.
- Redesigning the electronics of the frequency control system in order to improve its phase margin.

By following this approach, first, we built a simple mixer based servo control system suppressing phase fluctuations of the microwave loop amplifier. This enabled us to improve the phase noise of a free-running oscillator by $\sim 13\,dB$ at the Fourier frequencies below a few kHz as shown by Fig. 5. Secondly, we switched to the high speed operational amplifiers in the frequency control system loop filter, but all the above changes had only marginal effect on the intensity of the excess phase noise.

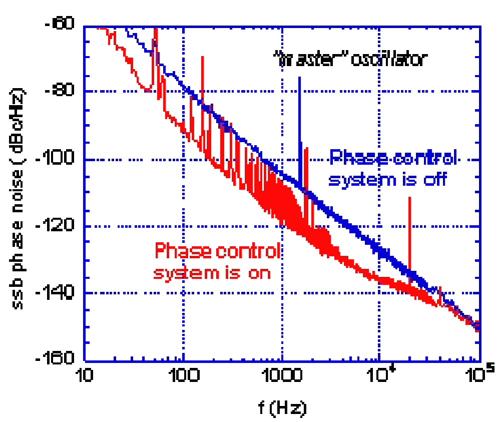

Figure 5. Effect of the additional phase control system on the SSB phase noise spectrum of a free-running loop oscillator.

The problem of the excess noise turned out to be related to the properties of the noise measurement system, as well as to the shape of the noise spectrum to be measured. The point is that the spectral density of oscillator phase fluctuations is a highly non-monotonic function of Fourier frequency due to the action of the frequency control system. The 'signature' of the frequency servo is especially clearly visible in the spectrum of voltage noise at the output of the in-loop frequency discriminator where the noise intensity reaches a deep minimum at a few hundred Hz and then increases by almost three orders of magnitude at frequencies above $100\,kHz$ due to the diminishing gain of the frequency servo loop (see Fig. 6). It was this high frequency noise with the relatively large intensity which was saturating a pre-amplifier of the noise measurement system *(a pre-amplifier was required in front of the FFT spectrum analyzer as the latter alone was not sensitive enough to resolve the extremely weak voltage fluctuation at frequencies around $1\,kHz$).* It was saturation of the pre-amplifier which was responsible for the increase of its intrinsic voltage fluctuations and which we initially misinterpreted as the excess phase noise of a microwave oscillator [3].

Once the origin of the excess noise was found, the solution to this problem was simply to make the noise measurements with a passive low-pass filter in front of the pre-amplifier. The results of such measurements where the voltage noise at the output of the in-loop frequency discriminator was reconstructed from the low-pass filtered noise are shown in Fig. 6. By using the noise filtering-reconstruction technique we were able to measure voltage fluctuations with spectral densities close to $-180\,dBV/\sqrt{Hz}$ which was more than $20\,dB$ below the frequency discriminator voltage noise floor. Also, for the first time we were able to confirm that the suppression of the voltage noise at the output of the 'in-loop' frequency discriminator is perfectly consistent with the loop gain of the frequency control system.

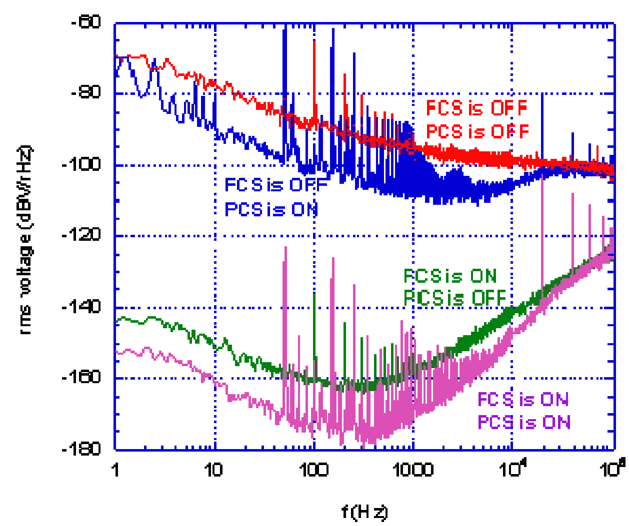

Figure 6. Reconstructed voltage noise spectra at the output of the 'in-loop' frequency discriminator measured at the different states of the frequency and phase control systems.

IV. INTERFEROMETRIC PHASE NOISE MEASUREMENT SYSTEM

A schematic diagram of the interferometric two-oscillator noise measurement system is shown in Fig. 7. Here, signals of two oscillators are first combined in a 3dB Hybrid coupler before being demodulated to DC. Carrier of the difference signal from the 'dark' port of the 3dB Hybrid is suppressed to allow the low-noise amplification of the residual fluctuations which improves the spectral resolution of the measurement system [1]. The sum of two signals from the 'bright' port of the 3dB Hybrid serves as a reference signal for the mixer's LO port. A passive band-pass filter (BPF) is used in front of the pre-amplifier to avoid its saturation by the high-frequency noise from the mixer output (see discussion above).

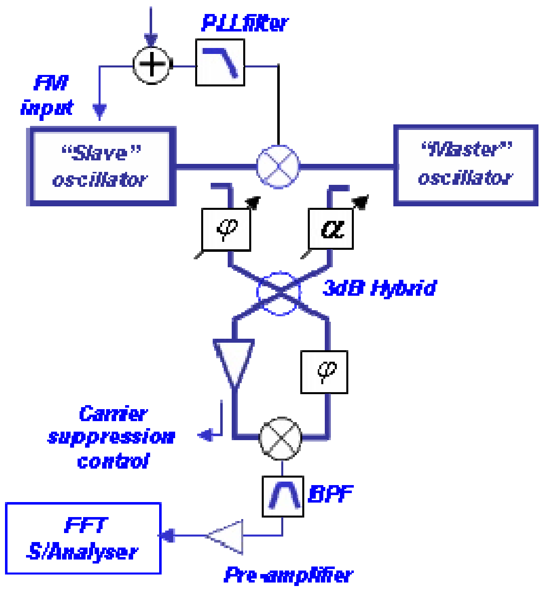

Figure 7. Two-oscillator phase noise measurement system based on the interferometric phase detector.

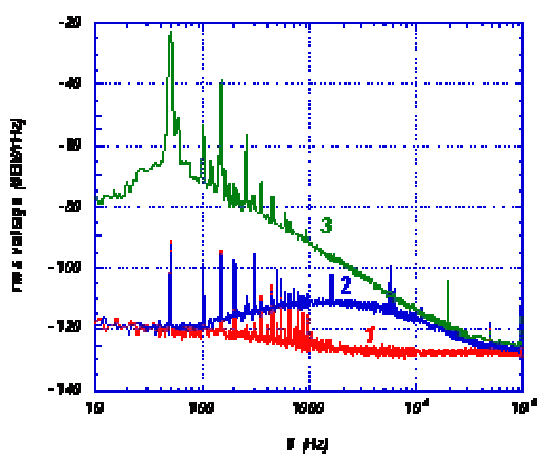

Figure 8. Voltage noise of the pre-amplifier alone (1), voltage noise floor of the pre-amplifier preceeded by the band-pass filter (2), typical voltage noise spectrum at the output of the interferometric phase detector.

Voltage noise floor of the interferometric phase detector is shown in Fig. 8 (curve 2). It was measured by driving both ports of the 3dB Hybrid from a single microwave oscillator. This noise floor is not very different from that of a pre-amplifier (curve 1). A relatively small difference between two noise floors is due to the Nyquist noise in the resistors of the BPF and can be further reduced if necessary.

Curve 3 in Fig. 8 shows a typical spectrum of voltage noise at the output of the pre-amplifier resulting from the phase fluctuations in two microwave oscillators. As follows from the data in Fig. 8 the spectral density of the voltage noise measured under the operating conditions remains well above the noise floor at Fourier frequencies up to $10\,kHz$. By increasing the signal power P_S at the input of the interferometric phase detector one can increase the margin between two noise spectra (curves 2and 3) and, therefore improve the accuracy of noise measurements. For example, the voltage noise spectra in Fig. 8 were measured at $P_S = 7\,dBm$. At this level of power the phase-to-voltage conversion efficiency of the phase detector was close to $18\,V/rad$. The latter parameter along with the knowledge about the amplitude transfer function of the BPF enables one to convert the measurement system's voltage noise floor into its phase noise floor. The result of such conversion is shown in Fig. 9.

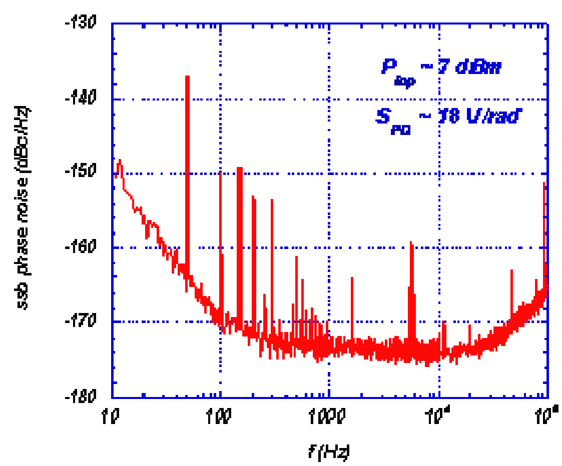

Figure 9. Phase noise floor of the interferometric phase detector at signal power $P_S = 7\,dBm$.

V. RESULTS OF NOISE MEASUREMENTS AND DISCUSSION

The phase noise spectrum of a frequency stabilized high-power oscillator is given by curve 3 in Fig. 10. Here, the steepest part of the noise spectra vary as f^{-5} and are due to the ambient temperature fluctuations affecting the SLC resonator. At Fourier frequencies above $30\,Hz$ the spectral density of oscillator phase fluctuations varies as the slower rate: $S_\varphi \sim f^{-3}$, which corresponds to oscillator flicker frequency noise. Below we briefly summarize some of our experiments related to the search for the origin of the flicker frequency noise in high power oscillators.

First, we measured the phase noise floor of the interferometric frequency discriminator (FD) of each oscillator. The initial measurements were conducted with the input of the low-noise microwave amplifier terminated. This gave us the lowest value of the FD noise floor due to microwave electronics of the frequency discriminator only.

At the next stage, a microwave interferometer was connected to the input of the low-noise amplifier. During these measurements the SLC resonator was replaced with a $50\ \Omega$ termination (the latter was considered to be a good substitution for the almost critically coupled resonator). The noise measurements which followed revealed large variations in spectral density of voltage fluctuations in the range of Fourier frequencies $(10^2 ... 10^4)\ Hz$. In some cases the voltage noise was close to the noise floor set by the microwave electronics, in other cases it was $\sim 20\ dB$ higher. This inconsistency found its explanation in the type of $50\ \Omega$ terminations we used for mimicking the tuned SLC resonator

The high intensity noise turned out to be always observed when the thin-film $50\ \Omega$ terminations were used. We speculate that it is probably due to the exposure to high levels of microwave power (measurements were conducted at $0.5\ W$) that 'switches on' some noise mechanisms in the resistive thin films.

The measurements of the frequency discriminator noise floor were repeated with the SLC resonator replaced either with the distributed $50\ \Omega$ termination or with an equivalent load consisting of a distributed attenuator and a phase-shifter. This, however, did not eliminate the inconsistency of the results. We continued seeing the $1/f$ - type voltage noise spectra (at Fourier frequencies below $100\ Hz$) with the spectral density varying by $\sim 10\ dB$ from one run to another.

The microwave interferometers used in the above measurements were of a traveling wave type with the arms formed by the variable attenuators and phase shifters. Two 3dB Hybrids were used to split and recombine the signals. Suspecting that the noise we were measuring was associated with the 3dB Hybrid (hybrids with poor adhesion of the metal film to the dielectric substrate were known to exhibit the excess noise) we built a standing wave interferometer based on a waveguide based magic-T coupler.

Having replaced the potentially noisy 3dB Hybrid couplers with a noise free magic-T coupler, we, nonetheless, continued seeing the $1/f$ - type voltage fluctuations with spectral density $10...15\ dB$ above the microwave electronics noise floor at Fourier frequencies below $100\ Hz$. The only possible explanation of these results was to assume that the excess voltage noise was originating from the variable mechanical attenuators used for balancing of the microwave interferometer. An additional argument in favor of such explanation was the dependence of the intensity of the excess voltage noise on the type of the attenuator used, as well as its value (a combination of a large fixed attenuator and a small variable one seemed to exhibit less noise than a large variable

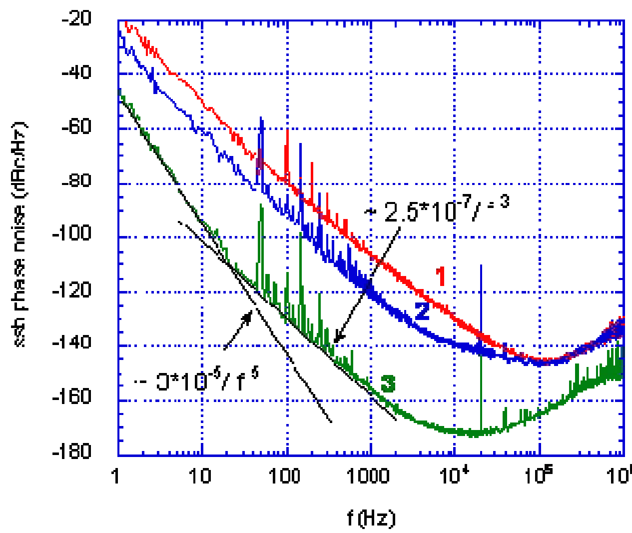

Figure 10. SSB phase noise spectra of a high-power microwave oscillator in the different regimes of operation: free-running oscillator (1), free-running oscillator with an additional phase control system (2) and frequency stabilised oscillator (3)

attenuator). It is also worth pointing out that the spectral density of the excess voltage noise was practically independent on the phase tuning of the mixing stage of the frequency discriminator. This suggested that such a noise originated from both phase and amplitude fluctuations of the microwave signal at the 'dark' port of the microwave interferometer.

In addition to the above experiments we also investigated the vibration sensitivity of the high power oscillators, as well as their sensitivity to the random magnetic fields. In the former case, we did not see any correlation between the oscillator phase noise and displacement fluctuations of the platform on which both oscillators were mounted. A more than $10\ dB$ increase in the level of vibration applied to the oscillators resulted only in a few extra peaks on the otherwise smooth $1/f^3$ spectrum of oscillator phase noise.

In the latter case, the idea was to find the relationship between the phase fluctuations of the microwave circulators (used for the extraction of the signal reflected from the resonator) and oscillator phase noise. The experiments involved applying the external random magnetic field to the circulator and measuring, first, its phase noise and then measuring the phase noise of the oscillator in which the circulator was used. With the details of these experiments to be discussed elsewhere, our preliminary conclusion was that the phase fluctuations in the microwave circulators were not responsible for the oscillator $1/f^3$ phase noise.

Finally, one of the oscillators was complemented with an automatic carrier suppression system based on the voltage controlled attenuator inside the microwave interferometer [1].

It was possible to tune the oscillator frequency by $\pm 0.5\ kHz$ without any noticeable loss of carrier suppression (power at the interferometer 'dark' port remained below $-65\ dBm$) and, most importantly, without any degradation of oscillator phase noise performance. The power spectral density of oscillator phase noise remained close to $-157\ dBc/Hz$ at $f = 1\ kHz$ offset from the carrier. when operating $0.5\ kHz$ away from the SLC's natural resonance frequency.

VI. CONCLUSION

Two $9GHz$ oscillators with the SSB phase noise spectral density close to $-157\,dBc/Hz$ at Fourier frequency $f = 1kHz$ were constructed. Each oscillator featured a room temperature stabilized SLC resonator used both as a narrow-band filter of a loop oscillator and a highly dispersive element of the interferometric frequency discriminator. These oscillators are currently the lowest phase noise sources in the microwave frequency range.

In this work we:

- Described the design of a phase-locked loop capable of keeping two microwave oscillators in a tight synchronism by controlling the level of microwave power dissipated in the sapphire dielectric resonator;
- Discussed the noise properties of the interferometric phase detector used for the high resolution measurements of phase fluctuations in the ultra-low phase noise microwave oscillators;
- Summarized the results of our search for the origin of the flicker frequency fluctuations in the high power microwave oscillators with the interferometric signal processing.

ACKNOWLEDGMENT

The authors are very grateful to J.-M. LeFloch for the development of the data acquisition software extensively used thoughout all experiments. This work is jointly supported by the Australian Research Council and Poseidon Scientific Instruments.

REFERENCES

[1] E. N. Ivanov, M. E. Tobar and R. A. Woode, *Applications of interferometric signal processing to phase noise reduction in microwave oscillators*, IEEE Transactions on MTT, vol. 46, N10, October 1998, pp.1537-1545.

[2] McNeilage, C.; Searls, J.H.; Ivanov, E.N.; Stockwell, P.R.; Green, D.M.; Mossamaparast, M, "A review of sapphire whispering gallery-mode oscillators including technical progress and future potential of the technology" in Proc. of the 2004 IEEE Frequency Control Symposium, pp. 210-218, August 2004.

[3] E. N. Ivanov and M. E. Tobar, *"Low Phase Noise Microwave Oscillators with Interferometric Signal Processing"*, IEEE Trans. on MTT, v. 54, no. 8, pp. 3284-3294, 2006.