

Precision Noise Measurements and Oscillator Frequency Stabilization

E. N. Ivanov and M. E. Tobar

*School of Physics, University of Western Australia, Perth, WA 6009
eugene@physics.uwa.edu.au, mike@physics.uwa.edu.au,*

Abstract

This paper summarizes recent advances in two closely related research fields: precision noise measurements and generation of low-phase noise microwave signals. The progress achieved in those fields over the past decade was largely associated with the applications of microwave circuit interferometry, which is a powerful noise measurement technique born out of the quest to detect gravitational waves in the beginning of 90's.

1. Introduction

The concept of interferometric measurements at microwave frequencies was first suggested in the late 50's [1], but it took another 40 years before such a concept was fully developed and its high potential realized. At that time, we developed the first broadband interferometric noise measurement system with almost thermal noise limited sensitivity [2]. It was capable of measuring intrinsic fluctuations in quietest microwave components in "real time" and brought about the first experimental evidence of intrinsic fluctuations in microwave components, which had been earlier considered to be "noise free".

Further improvements in sensitivity of spectral measurements were associated with the more efficient use of signal power [3]. By combining the principles of microwave circuit interferometry with those of the power recycling we demonstrated the possibility of "real time" noise measurements with spectral resolution beyond the standard thermal noise limit [4].

While working on the Gravitational Wave project at the University of Western Australia [5], we realized the similarities between high-resolution measurements of weak mechanical forces induced by the gravity waves and frequency fluctuations of microwave signals. This realization, largely assisted by technological developments in the areas of high Q-factor dielectric resonators and low-noise microwave amplifiers, enabled a real breakthrough in the field of oscillator frequency stabilization resulting in almost 300 times improvement in phase noise performance of microwave signal sources relative to the previous state-of-the-art [6]. The first generation of such low phase noise oscillators featured a manually balanced microwave interferometer, which required a stable temperature environment to maintain the high sensitivity. The range of potential applications for these oscillators was soon extended with the implementation of a feed-back control system sensing the interferometer's amplitude mismatch and compensating for it by electronically adjusting loss in one of the interferometer's arms [6].

The arrival of high power solid-state microwave amplifiers offered further opportunity to lower oscillator's phase noise by increasing microwave power dissipated in the high-Q resonator. Recently, two oscillators with phase noise spectral density of -157 dBc/Hz at 1 kHz offset from a 9 GHz carrier have been reported [7]. These oscillators are currently the lowest phase noise microwave signal sources in the Doppler range of offset frequencies.

This work briefly summarizes the latest developments in the domain of precision noise measurements at microwave frequencies.

2. High Resolution Noise Measurements

Fig. 1 shows schematic diagram of the noise measurement system first reported in [8]. It consists of a Magic Tee waveguide coupler and a microwave readout system based on Low-Noise Amplifier (LNA), reference phase-shifter and Double-Balanced Mixer (DBM). The distinctive feature of this measurement system is a distributed resonator formed by an inductive diaphragm and a section of a waveguide with a phase-shifter. A test sample can be either inserted into the waveguide or (if it is a coaxial device) coupled to it with an adapter connected to the phase-shifter.

Signal reflected from the distributed resonator interferes destructively with a fraction of the incident signal at the 'dark port' of the Magic Tee (port 4). This cancels the carrier of the difference signal while preserving the noise modulation sidebands caused by *non-thermal* fluctuations in the test sample. The noise modulation sidebands are

amplified and converted into the voltage noise at the output of the LNA & DBM assembly. Depending on the setting of the reference phase shift θ the output voltage noise varies synchronously with either phase or amplitude fluctuations of the test sample. The use of the LNA overcomes the relatively high technical fluctuations of the DBM making the effective noise temperature of the readout system T_{RS} close to its physical temperature: $T_{RS} \approx T_o + T_{amp}$, where T_o is the ambient temperature and T_{amp} is the effective noise temperature of the microwave LNA. The use of a low-loss test sample also increases the sensitivity of noise measurements due to extended lifetime of the distributed resonator.

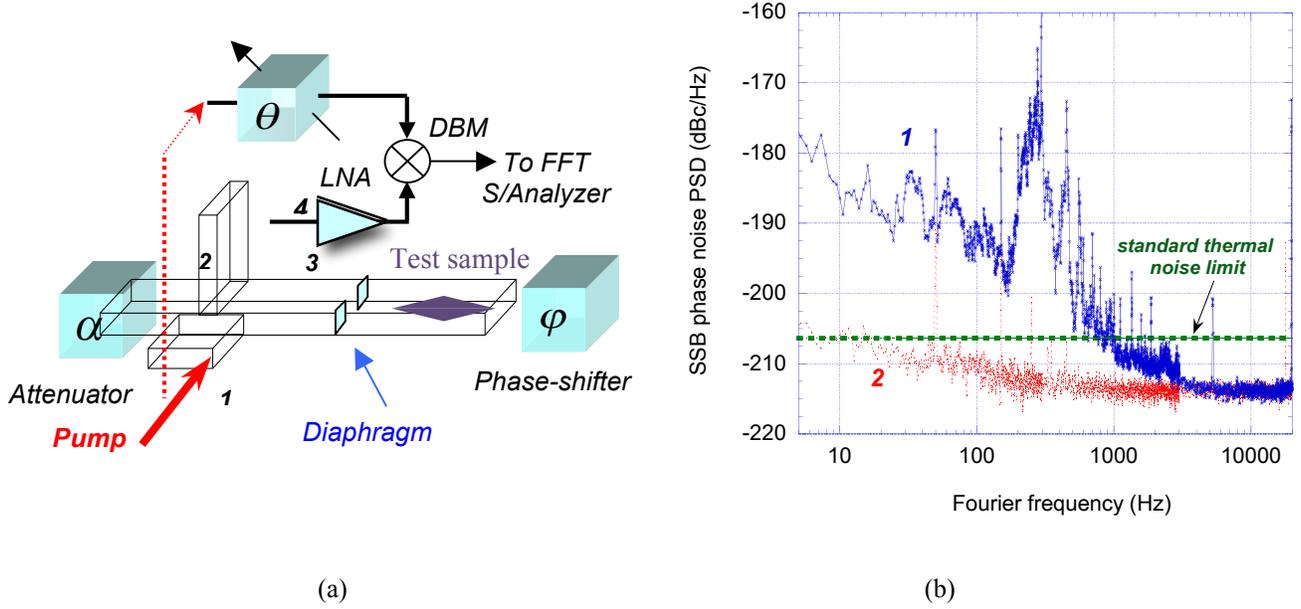


Fig. 1. Microwave interferometer with power recycling (a) and its phase noise floor (b)

Choosing the waveguide components instead of micro-strip ones [4] eliminates sources of technical fluctuations from inside the interferometer, as some micro-strip components tend to exhibit an excess noise when exposed to relatively high power levels. It also reduces the distributed loss in interferometer arms.

The phase sensitivity of the measurement system has to be optimized for a given test sample by adjusting the aperture of the inductive diaphragm and its distance from the symmetry plane of the Magic Tee. The highest value of phase sensitivity we measured was 1.4 kV/rad at power of the input signal $P_{inc} = 1 \text{ W}$. This was 4 times better relative to conventional interferometer operating at the same level of input power and resulted from more efficient use of signal power, which was almost completely absorbed inside the distributed resonator.

Curve 1 in Fig. 2 shows the Single Side Band (SSB) phase noise floor of the measurement system in question. The rough peaks in the noise spectrum are of vibration and acoustic origin. At Fourier frequencies $F > 5 \text{ kHz}$ environmental disturbances are no longer coupled to the measurement system and its noise floor flattens out at -213 dBc/Hz . This is $\sim 10 \text{ dB}$ below the standard thermal noise limit (dash line in Fig.2) calculated for the same set of parameters used in our experiment: $P_{inc} = 1 \text{ W}$, $T_o = 300 \text{ K}$ and insertion loss of the test sample of 0.5 dB . The obtained improvement in the resolution of spectral measurement relative to the standard thermal noise limit is less than the factor of 4 mentioned earlier. The discrepancy results from the intrinsic fluctuations of the LNA and is close to $\sqrt{T_o / (T_o + T_{amp})}$.

In the above experiments, the high resolution of phase noise measurements was achieved by paying a careful attention to technical noise sources. First, signal carrier was strongly suppressed at the “dark port” to avoid flicker noise associated with saturation of the LNA. Secondly, the signal of the microwave pump source was band-pass filtered to remove the higher order harmonics from its spectrum. Such harmonics are not attenuated when the

interferometer is balanced and saturate the LNA. Also, we have to deal with the enhanced sensitivity of the measurement system to pump oscillator frequency noise due to dispersion of the distributed resonator. For this reason, measurements were performed with a composite source consisting of a low-phase noise microwave oscillator based on Sapphire Loaded Cavity (SLC) resonator [9] and a high power amplifier needed to generate a few Watts of useful power.

3. Generation of Low-Phase Noise Microwave Signals

A simplified diagram of the frequency stabilised microwave oscillator with an interferometric signal processing is shown in Figure 3. The high-Q resonator is used both as a band-pass filter in the loop oscillator and a dispersive element of a frequency discriminator. The oscillator phase noise is cancelled by applying a filtered signal from the output of the frequency discriminator to the Voltage Controlled Phase shifter (VCP) inside the loop oscillator. The VCP allows the tuning of the oscillator operating frequency by changing the effective electric length of the loop. The frequency discriminator and VCP constitute, respectively, sensor and actuator of a frequency control system, which locks oscillator to the selected resonant mode of the resonator.

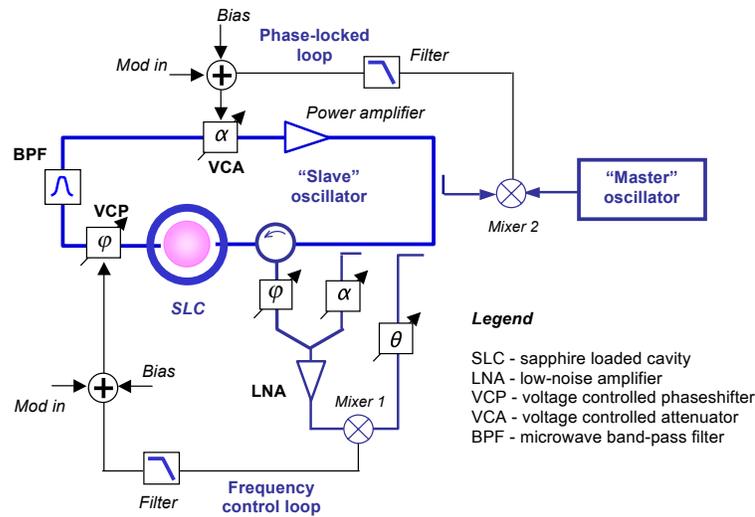


Fig. 3. Schematic diagram of microwave oscillator with interferometric signal processing. Also shown a phase-locked loop needed to perform the phase noise measurements.

Accurate measurements of phase fluctuations of high-performance oscillators is a challenging task involving construction of two almost identical oscillators, one of which (“slave”) must be frequency tunable, so it could be phase-referenced to the fixed frequency “master”. Furthermore, the technique used for frequency tuning must not degrade the phase noise of the “slave” oscillator, while enabling its tight phase synchronization with respect to the “master”. In our case, the phase-synchronous operation of the “slave” oscillator was achieved by stabilizing temperature of the SLC resonator to millikelvin accuracy and controlling phase of oscillations by varying microwave power dissipated in the resonator. The phase synchronous regime could be maintained for days with residual phase errors not exceeding a few milliradians. This was sufficiently small to permit small-signal operation of a very sensitive oscillator noise measurement system based on interferometric phase detector [7].

Phase noise spectrum of a 9GHz frequency stabilized high-power oscillator is shown in Fig. 4. At Fourier frequencies $F < 10 \text{ Hz}$ phase noise power spectral density varies as $1/F^4$. This is typical for oscillator frequency random walk [9] caused by ambient temperature affecting the SLC resonator. At frequencies $30 \text{ Hz} < F < 1 \text{ kHz}$ the phase noise spectral density varies as $1/F^3$. This is typical for oscillator frequency flicker noise, but the origin of this noise is yet to be determined.

At Fourier frequency of 1kHz the SSB phase noise spectral density of an individual 9GHz oscillator is approximately -157 dBc/Hz . This is the lowest phase noise achieved at microwave frequencies.

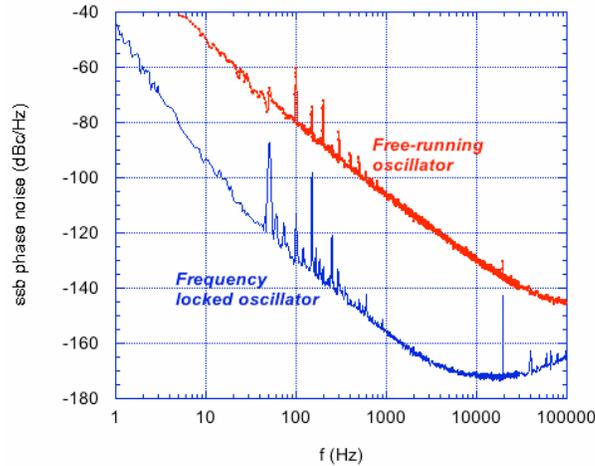


Fig. 4. Phase noise spectra of a microwave oscillator with interferometric signal processing

4. Conclusion

We showed the possibility of “real time” noise measurements with spectral resolution exceeding the standard thermal noise limit. This was achieved by combining the principles of microwave circuit interferometry with the efficient use of signal power (power recycling) and paying close attention to technical noise sources influencing the measurement process.

We also demonstrated that microwave oscillators with extremely low level of phase fluctuations could be constructed based on the principles of microwave circuit interferometry. Such oscillators are currently the lowest phase noise signal sources at microwave frequencies.

We believe that the future progress in the field of ultra-low phase noise signal generation may involve the use of cryogenic sapphire resonators, as well as development of photonic signal sources where frequency of a standalone microwave oscillator is locked to a free-spectral range of a high-finesse optical cavity.

References:

1. A. Whitwell and N. Williams, "A new microwave technique for determining noise spectra at frequencies close to the carrier", *Microwave J.*, 1959, pp. 27-32.
2. E. Ivanov, M. Tobar and R. Woode, "Microwave interferometry: application to precision measurements and noise reduction techniques, *IEEE Trans. on UFFC*, **45**, no. 6, 1998, pp. 1526-1537
3. R. Drever, "Interferomagnetic detectors of gravitational radiation," in *Gravitational Radiation*, NATO Advanced Study Institute, edited by N. Deruelle and T. Piran, pp. 321-337, Amsterdam, 1983.
4. E. Ivanov and M. Tobar, "Real time noise measurement system with sensitivity exceeding the standard thermal noise limit," *IEEE Trans. On UFFC*, **49**, no. 8, 2002, pp. 1160-1161.
5. D. Blair, E. Ivanov, M. Tobar et al, "High sensitivity gravitational wave antenna with parametric transducer readout", *Phys. Rev. Letters*, **74**, no. 11, 1995, pp. 1908-1911.
6. E. Ivanov, M. Tobar and R. Woode, "Applications of interferometric signal processing to phase noise reduction in microwave oscillators", *IEEE Trans. on MTT*, **46**, no.10, 1998, pp.1537-1545.
7. E. Ivanov and M. Tobar, "Low Phase Noise Sapphire Crystal Microwave Oscillators: Current Status", *IEEE Trans. on UFFC*, **56**, no.2, 2009, pp.263-269.
8. E. Ivanov and M. Tobar, "Microwave phase detection at the level of 10^{-11} rad", *Rev. Sci. Instrum.* **80**, 044701 (2009).
9. J. Barnes et al, *IEEE Trans on Instrum. and Meas.*, **20**, 1971, pp. 105–120.