Phase Noise of a Tunable and Fixed Frequency Sapphire Loaded Superconducting Cavity Oscillator

Micheal E. Tobar and David G. Blair

The University of Western Australia, Nedlands 6009, W.A. Australia.

Abstract: Measured phase noise of two GaAs FET amplifiers, and a varactor phase shifter at 9.7 GHz, reveal that optimum FET and diode bias voltage changes when cooling from room to liquid helium temperatures. This understanding enables optimization of the noise in an all cryogenic Sapphire Loaded Superconducting Cavity X-Band loop oscillator. We show that we can reduce the current measured oscillator noise of -120 dBc/Hz at 1 kHz, by 20 to 45 dB.

INTRODUCTION

The frequency of a loop oscillator is determined by the resonant frequency of the resonator in the feedback path, while the stability and noise performance is determined by its quality factor [1]. In recent years researchers have focused on increasing state of the art quality factors in cavity and microstrip resonators by using low loss dielectrics such as sapphire and $LaAlO_3$, and superconducting materials such as low-T_c Nb and the more recent high-T_c YBCO and TBCCO materials. At temperatures below 2 K quality factors in Nb cavities greater than 10^{10} have been reported [2]. At the more accessible temperatures of 4.2 K (liquid helium) and 77 K (liquid nitrogen) sapphire dielectric resonators give the best current resonator Q values. The loss tangent decreases rapidly as the temperature is reduced [3], giving quality factors at X-band rising from $3 \cdot 10^5$ at 290 K, to $5 \cdot 10^7$ at 77 K, and exceeding 10^9 at 4.2 K. In comparison the recent work on HTS have produced microstrip resonators with loaded Q values at 10.2 GHz, in excess of $6 \cdot 10^3$ at 77 K [4]. However their advantage is in their relative small size compared to a sapphire resonator, and enhanced performance compared to the traditional copper microstrip resonators.

The ultra-low loss tangent of sapphire make it an ideal dielectric material for the construction of microwave resonators and oscillators. This has been demonstrated at the University of Western Australia [5] and the Jet Propulsion Laboratories [6], where both operate superconducting sapphire dielectric oscillators, with state of the art square root Allan Variance of less than 10^{-14}, for integration times from 1 to 300 seconds.

The relatively low dielectric constant of sapphire requires high mode number resonators to limit radiative losses. Alternatively, fundamental mode resonators with a superconducting shield may be used. The former is bulky with an enhanced spurious mode spectrum [7], while the latter eliminates spurious modes at the expense of the superconductor degrading the Q [8], as well as restricting operation to temperatures in which the shield is superconducting. The authors consider the Sapphire Loaded Superconducting Cavity (SLOSC), as the optimum configuration, trading off wall interactions with physical size by placing the resonator several evanescent field scale lengths from the walls.

This work compares the current and predicted optimized phase noise performance of the SLOSC oscillator [9], with the performance of HTS oscillators and other X-Band oscillators.

PHASE NOISE MODEL

The basic noise model [1] relevant for the SLOSC loop oscillator is shown in fig. 1. Here $S_{\phi a}$ is the phase noise introduced by the active components, $S_{\phi c}$ the oscillator noise from the non filtered port, and $S_{\phi osc}$ the oscillator phase noise from the filtered port. To obtain optimum phase noise the oscillator is configured to make use of the high Q resonator as a filter. This is at the expense of available output power accessible from the non filtered port.

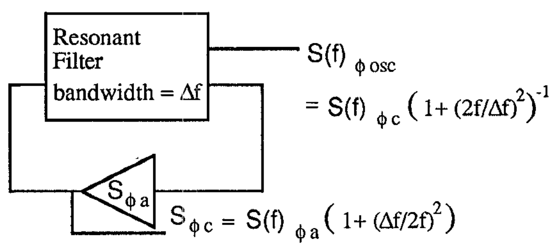

Figure 1. Illustrates the configuration of a SLOSC cavity in the loop oscillator, along with the phase noise model assumed.

To measure the phase noise $S_{\phi osc}$, we phase lock a tunable T-SLOSC [10] oscillator in quadrature to a fixed frequency SLOSC oscillator. A schematic of the measurement is shown in figure 2.

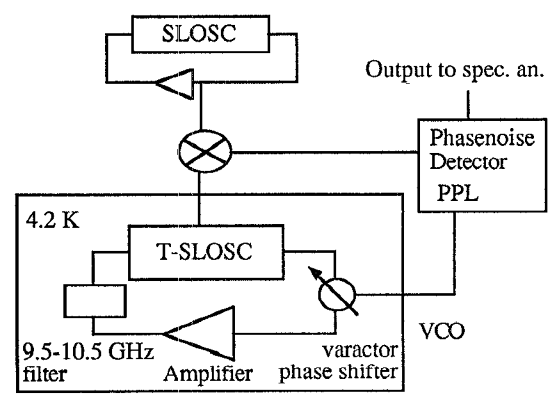

Figure 2. Schematic of the SLOSC oscillator phase noise measurement.

1992 IEEE MTT-S Digest

In the following section, we determine that the GaAs amplifiers and varactor phase shifter can limit the noise performance when the voltage biasing the FETs and varactor diodes is non optimum.

COMPONENT PHASE NOISE

The phase noise characteristics of an electronic varactor phase shifter and two cryogenic amplifiers, Miteq AMF-8012-CRYO and Miteq AFS3-4K, are presented in this section. Measurements were obtained using a phase bridge, with the components inside a vacuum can placed inside a dewar. Phase noise is measured at 290 K, 77 K (liquid nitrogen bath) and 8 K (liquid helium bath). Components did not exhibit any significant dependance on temperature, pressure or boiling cryogens. The main dependance is on the FET and diode bias voltages, with a temperature dependance manifesting due to the bias and gain conditions changing.

Varactor Phase Shifter

At 290 and 77 K the phase noise could not be measured above the noise floor, with the input bias voltage between 0 to 20.6 volts. This was not true at 4.2 K, as shown below in figure 3.

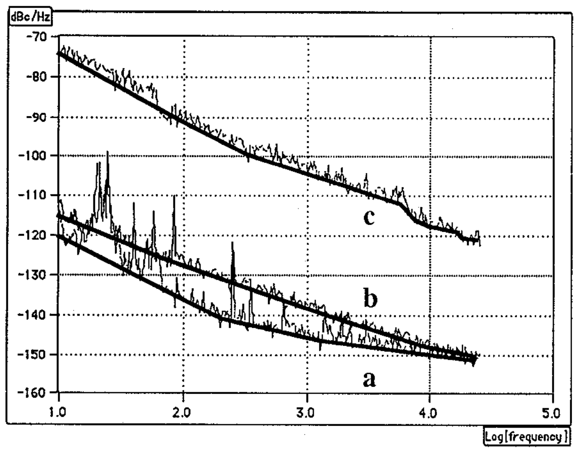

Figure 3. Varactor phase shifter noise at 4.2 K; **a**. phase noise floor; **b**. bias = 13.48 V; **c**. bias = 20.6 V. Below 10 volts bias, the noise cannot be measured above the noise floor, this is sufficient to get 360 degrees of low noise phase shift (see figure 3).

Miteq AFS3-4K

This GaAs FET amplifier is designed to operate at 6.0 V bias at room temperature. Measurements show that this is also the bias that gives minimum phase noise. At liquid helium temperatures the optimum bias condition changes to 3.5 V. Figures 4 - 7, show bias, saturation and temperature effects.

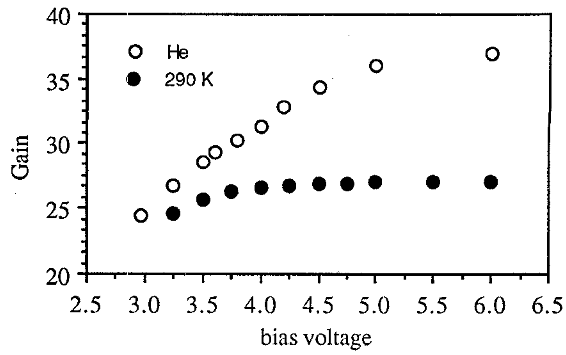

Figure 4. Gain versus bias voltage at liquid helium and room temperature.

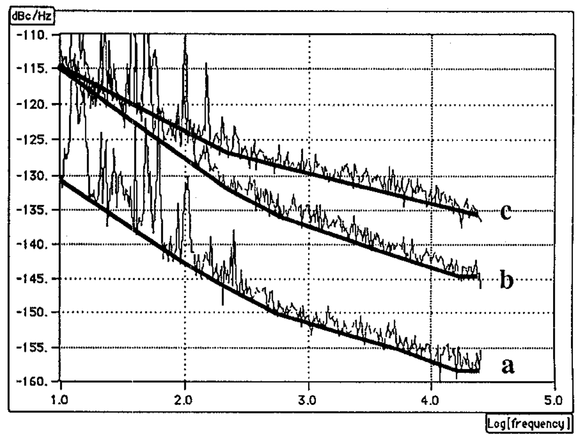

Figure 5. Saturation effects; **a**. phase noise floor for all proceeding amplifier measurements; **b**. phase noise with input power of 1.75 μw; **c**. phase noise with input power of 755 μw.

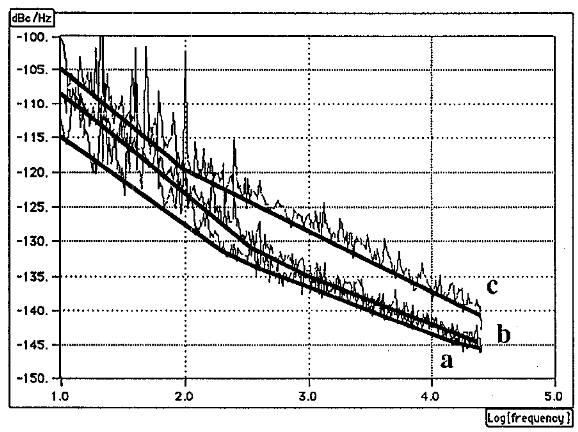

Figure 6. Phase noise at a bias of 6.0 V; **a**. room temperature; **b**. liquid nitrogen temperature; **c**. Liquid helium temperature.

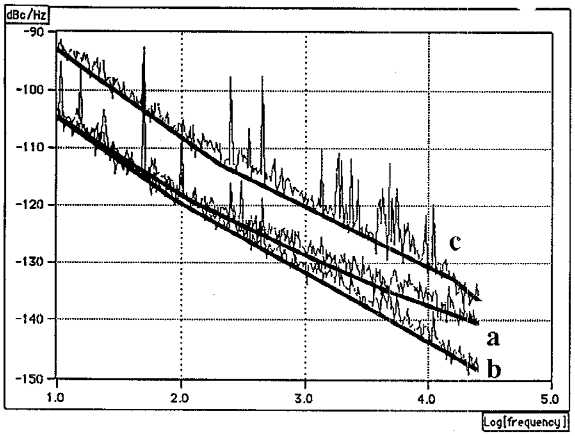

Figure 7. Phase noise at liquid helium temperature; a. bias = 6.0 V; b. bias = 3.5 V; c. bias = 3.0 V.

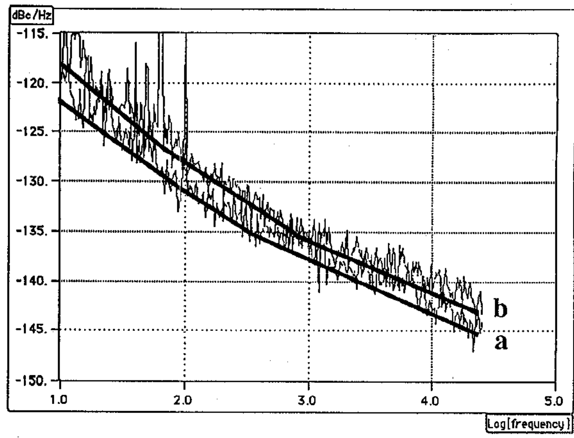

Figure 9. Saturation effects; a. phase noise with input power of 1 μw; b. phase noise with input power of 866 μw.

Miteq AMF-8012-CRYO

This GaAs FET amplifier is designed to operate at 3.9 V bias at room temperature. Measurements show that this is also the bias that gives minimum phase noise. At liquid helium temperatures the optimum bias condition changes to 2.6 V. Figures 8 - 11, show bias, saturation and temperature effects.

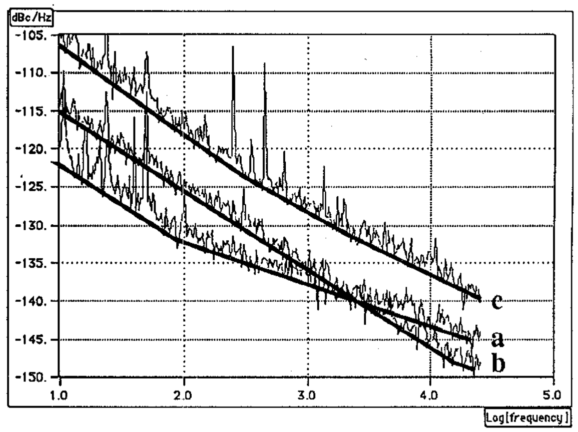

Figure 10. Phase noise at a bias of 3.9 V; a. room temperature; b. liquid nitrogen temperature; c. liquid helium temperature, this level is much greater than b. in figure 12, the non-linear kink causes the amplifier to saturate with an input power of only 4.56 μw.

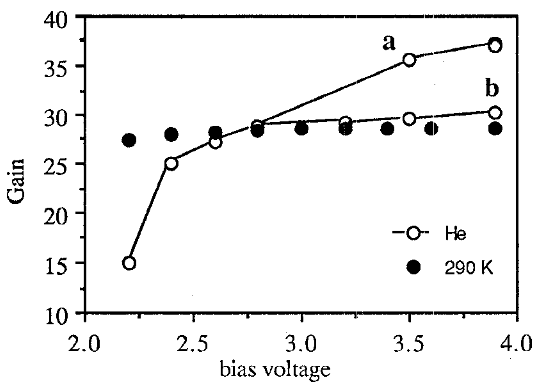

Figure 8. Gain versus bias voltage at liquid helium and room temperature. When bias voltages are > 2.8 V the amplifier becomes easy to saturate at low power inputs due to a manifesting non linear kink in the input to output power relation. a. Input power = 1.75 μw b. Input power = 4.56 μw (saturated gain response).

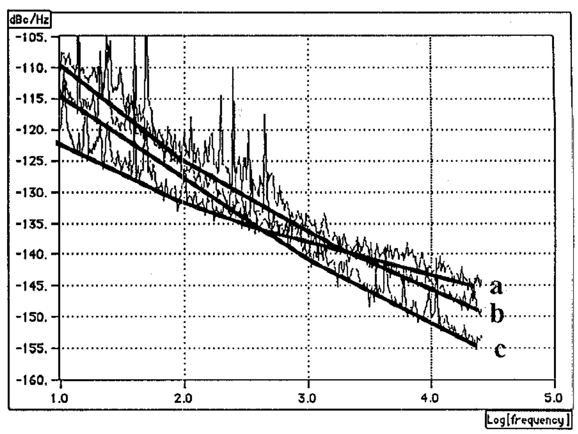

Figure 11. Phase noise at liquid helium temperature; a. room temperature; b. bias = 3.9 V, input power = 1.75 μw (non-saturated); c. bias = 2.6 V. Generally the gain and phase noise decreases as the bias voltage decreases.

OSCILLATOR PHASE NOISE

After understanding the phase noise of the cryogenic components, it is possible to optimize the oscillator design to minimize phase noise. The all cryogenic tunable oscillator is now configured with the AMF amplifier, biased between 2.2 to 2.8 volts, in the linear, low phase noise regime. The bias voltage is used as a gain limiter, as it can be controlled from 15 to 28 dB. Amplifying the signal from the transmission port must be avoided, as just the amplifier phase noise will be measured in this situation.

Past oscillator and amplifier measurements have determined the flicker noise component of similar active systems at liquid He temperatures to be, -87/f dBc/Hz [5], -90/f dBc/Hz [11] and -91/f dBc/Hz [9]. Our limiting component is the AMF amplifier, which is more than 10 dB better at 1 Hz, and rolls off at a greater slope; $-102.5/f^{1.25}$.

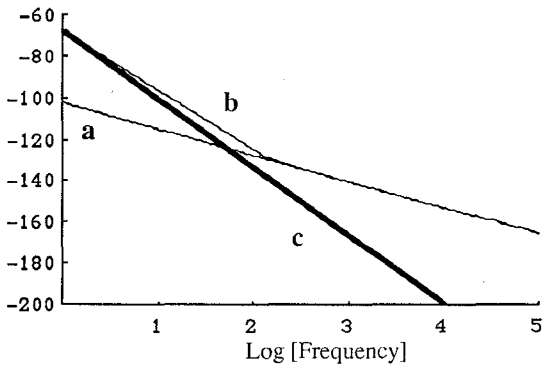

Figure 12. **a.** Measured device phase noise. **b.** Calculated phase noise from the non filtered port, with a loaded Q of 10^8. **c.** Calculated phase noise from the filtered port, with a loaded Q of 10^8.

We compare previous measured results [9] with expected optimized results, along with other oscillators in figure 13.

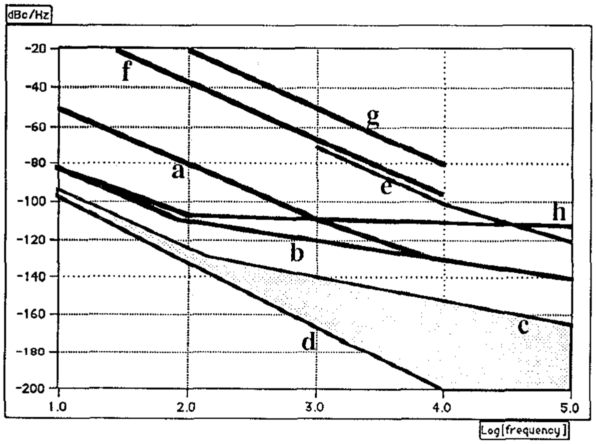

Figure 13. SLOSC oscillator SSB phase noise, **a.** liquid nitrogen, **b.** liquid helium, **c.** predicted liquid helium phase noise with the signal taken from the non filtered port **d.** Predicted liquid helium phase noise with the signal taken from the filtered port. **e.** HTS oscillator phase noise [4]. **f.** Typical X-band DRO. **g.** Typical X-band GUNN. oscillator. **h.** 5 MHz crystal oscillator performance at X-Band.

Figure 13 reveals that at present the best X-Band phase noise performance for carrier offsets greater than 10 Hz with output power greater than a milliwatt, is given by the cryogenic sapphire oscillators at the University of Western Australia. At the Jet Propulsion Laboratories a superior phase noise of $-80/f^3$ dBc/Hz was measured below 1 Hz, in a superconducting cavity maser [6]. However their system has an output power of only a nanowatt and is incapable of measuring any noise beyond a few hertz. In our next measurement we expect to measure phase noise in the shaded region of figure 13, depending on the effect of feed through between probes in the SLOSC filter.

CONCLUSION

We have successfully determined the optimum operating bias conditions to reduce flicker phase noise for the GaAs components in an all cryogenic SLOSC loop oscillator. Improvement from -120 dBc/Hz to between -140 and -165 dBc/Hz at 1 kHz is expected.

ACKNOWLEDGMENTS

The authors would like to thank Adrian Giles, Anthony Mann, Andre Luiten and Marco Costa for their general assistance. They would also like to thank MITEQ PTY. LTD. for supplying the test amplifier AFS3-4K for cryogenic measurements. This research was supported by the Australian Research Council.

REFERENCES

[1] D.B. Leeson, "A simple model of feedback oscillator noise spectrum," in Proc. IEEE, Vol. 54, No. 2, pp. 329-330, Feb. 1966.

[2] S.R. Stein and J.P. Turneaure, "Superconducting-cavity stabilized oscillators with improved frequency stability, "Proc. IEEE, 63, 1249, 1975.

[3] V.B. Braginsky, V.S. Ilchenko and Kh.S. Bagdassarov, "Experimental observation of fundamental microwave absorption in high quality dielectric crystals," Phys. Lett. A, vol. 120, pp. 300-305, Mar. 1987.

[4] A.P.S. Khanna and M. Schmidt, "Low phase noise superconducting oscillators," in IEEE MTT-S Dig., vol. 3, pp. 1239-1242, June 1991.

[5] A.J. Giles, S.K. Jones, D.G. Blair and M.J. Buckingham, "A high stability microwave oscillator based on a sapphire loaded superconducting cavity," in Proc. IEEE 43rd Annu. Symp. Freq. Contr., pp. 89-93, 1989.

[6] G.J. Dick and R.T. Wang, "Ultra-stable performance of the superconducting maser," IEEE Trans. on Instrum. and Meas., vol 40, No. 12, pp. 174-177, April 1991.

[7] M.E. Tobar and A.G. Mann, "Resonant frequencies of higher order modes in cylindrical anisotropic dielectric resonators," IEEE. Trans. MTT., Vol. 39, No. 12, Dec. 1991.

[8] M.M Driscol et al., "Cooled. ultra-high Q, sapphire dielectric resonators for low noise, microwave signal generation," in Proc. IEEE 45th Annu. Symp. Freq. Contr., pp. 700-706, 1991.

[9] M.E. Tobar and D.G. Blair, "Analysis of a low noise tunable oscillator based on a tunable sapphire loaded superconducting cavity," in Proc. IEEE 45th Annu. Symp. Freq. Contr., pp. 495-499, 1991.

[10] M.E. Tobar and D.G. Blair, "A generalized equivalent circuit applied to a tunable sapphire loaded superconducting cavity," IEEE Trans. MTT., vol 39, No. 9, pp. 1582-1594, Sept. 1991.

[11] C.P. Lusher and W.N. Hardy, "Effects of gain compression, Bias conditions, and temperature on the flicker phase noise of an 8.5 GHz GaAs MESFET amplifier," IEEE Trans. MTT., vol 37, pp. 643-646, Mar. 1989.