A NEW APPROACH TO JOHNSON NOISE THERMOMETRY USING A QUANTUM VOLTAGE NOISE SOURCE FOR CALIBRATION[†]

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Abstract

We describe a new approach to Johnson Noise Thermometry (JNT) that takes advantage of the recent advances in Josephson voltage standards and digital signal processing techniques. Previous attempts of high- precision thermometry using Johnson noise have been limited by the non-ideal performance of the electronic systems. By using the perfect quantization of voltages from the Josephson effect, any arbitrary broadband waveform can be synthesized and used as a calculable noise source for calibrating the cross-correlation electronics. With better calibration, we should be able to achieve relative accuracies of parts in 10^5 for an arbitrary temperature in the range between 84 K and 430 K. We present the latest measurements of our recently constructed JNT system.

Introduction

In Johnson Noise Thermometry, temperature is typically determined by measuring the mean-square Johnson noise voltage V_T across a calibrated resistance $R(T)$. The Johnson noise voltage is given by the Nyquist formula[1],

$$\overline{V_T^2} = 4kTR(T)\Delta f, \qquad (1)$$

where Δf is the bandwidth of the measurement and k is Boltzmann's constant.

Despite the simple thermodynamic relation between the measured signal and temperature, the accuracies achieved to date with the best JNT systems have not been comparable to that of currently used gas-based thermometry techniques. In previous JNT system designs the accuracy has been limited by the non-ideal performance of the electronic measurement system. In the most successful JNT system developed by Brixby, et al. [2], a switched input digital correlator is used to compare the voltage of a resistor held at an unknown temperature with that of a resistor held at a known, calibrated temperature. In order to reduce systematic errors, the noise power to the correlator electronics is kept constant by keeping RT constant in the measurements.

We are developing a JNT measurement system [3] that also uses a switched input digital correlator, but in addition uses a quantum voltage noise source (QVNS) as the reference noise source. Details of the QVNS system are described elsewhere in these proceedings [4]. Use of a QVNS as a synthesized reference has several advantages such as reduced measurement time, simultaneous matching of noise power and sensing resistance in both channels of the correlator, and increased measurement bandwidth [3].

Experimental Setup

A block diagram of the JNT system appears in Fig. 1. Each arm of the digital correlator has an analog gain of $\sim10^6$ to amplify the small Johnson-noise voltage signals. The anti-alias filter is a 4-pole Bessel filter with a cutoff frequency at 2 MHz. Amplified and filtered signals are digitized at 50 MHz by a 14-bit analog-to-digital converter. Field-programmable gate arrays (FPGAs) at the output of the digitizers then digitally filter the signal with a low-pass frequency of 100 kHz. The digitally filtered data are transmitted via a 50 megabit/s optical link into a custom PCI card installed in a computer. Each channel transmits approximately 2 million samples per second. In the current system, a dual CPU computer is used to calculate two 2
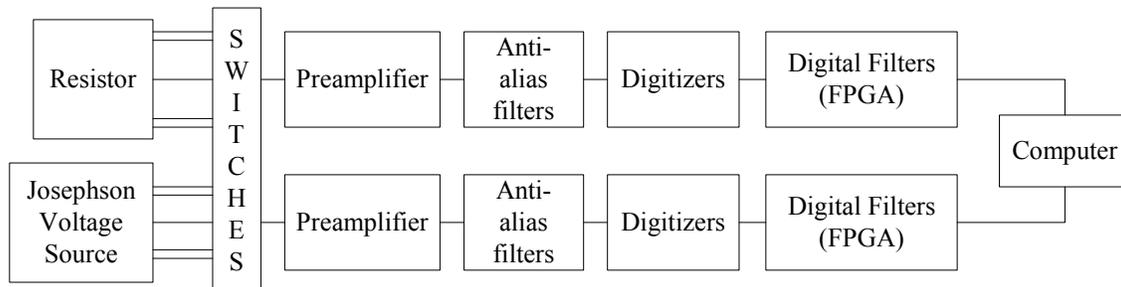
Fig. 1. Block diagram of the Johnson noise thermometry system. For both the resistor and the quantum voltage noise source, we use a five-wire (two signal pairs and a common line) connection to the preamplifiers. The entire electronic system is battery-powered except for the computer. The connections to the computers are made with optical fibers.
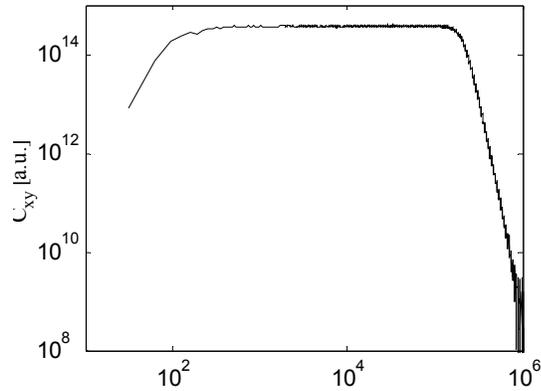
Fig. 2. Cross correlation spectrum of a 100Ω resistor at the triple point of gallium, 302.916 K

Fig. 3 Cross correlation spectrum from the quantum voltage noise source. The peaks are the generated harmonic tones and are used for calibrating the correlation electronics.

million point fast Fourier transforms (FFTs) in real-time (less than one second). The cross-correlation and auto-correlation power spectra are then calculated, accumulated, and stored for later analysis.

Switched inputs allow the QVNS to be substituted for the passive resistor to calibrate the gain and frequency response of the electronic system. The QVNS generates a constant power spectral density that can be precisely calculated and set to any desired value to match the voltage noise at any arbitrary temperature.

Results

Figure 2 shows an averaged cross-correlated spectrum from a 100 Ω resistor at the triple point of gallium (~302.916K) in arbitrary units (digitizer bins). The spectrum is an average of 4096 traces with frequency bins spaced at ~32 Hz. The low-frequency knee is from the ac coupling of the readout electronics. The rolloff at 100 kHz is from the digital filters in the FPGAs.

Figure 3 shows an averaged cross-correlated spectrum from the QVNS. This is also an average of 4096 spectra with frequency bin size ~32 Hz. The tones are a sequence of harmonics of the fundamental tone which is ~5.722 kHz. Each tone has the same ~137 nV_{rms} amplitude but random relative phase. At this time we also see background noise contaminating the spectrum from electromagnetic interference (EMI). The non-EMI noise power between the tones decreases as expected with an increasing number of averages from the correlator.

We plan to use the QVNS in two different measurement modes. In the absolute measurement mode, the spectral density of the QVNS power is calculated from first principles and directly compared to the noise power from the resistor.   From Eq. 1, a thermodynamic temperature measurement of the resistor can then be made without a
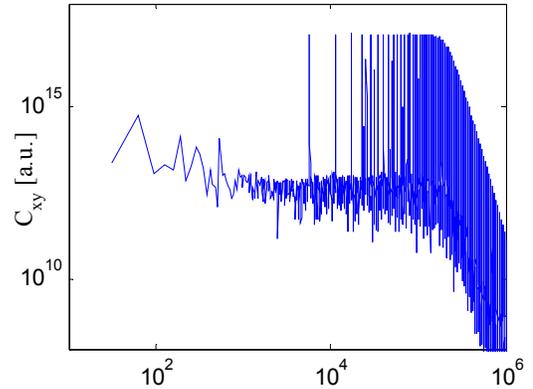
fixed-point reference. In the relative measurement mode, the Johnson noise power at both a known temperature and an unknown temperature is balanced with two different Josephson synthesized noise powers. The ratio of the unknown to known temperature is then given by the ratio of the Josephson-noise powers. This second method should be less sensitive to systematic errors.

Conclusions

In summary, we are developing a new type of Johnson noise thermometer that uses a quantum voltage noise source as a calibration reference for the readout electronics. We have measured both a sense resistor and a Josephson array using recently constructed cross-correlation electronics. Preliminary data indicate that wiring to the QVNS must be improved to reduce EMI and preserve signal integrity. Further work is also being done to improve the QVNS so that a higher density of tones can be generated to more closely approximate the Johnson noise from the sense resistor.

References

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