AN AC JOSEPHSON SOURCE FOR JOHNSON NOISE THERMOMETRY†

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Abstract

We have adapted the Josephson arbitrary waveform synthesizer to create a quantized voltage noise source suitable for calibrating the cross-correlation electronics of a Johnson noise thermometer system. The requirements of long term stability and low voltage amplitude allow dramatic simplification of the bias electronics compared to previous circuits. We describe the bias technique and the superconducting integrated circuit used to generate the pseudo-noise waveforms.

Introduction

The goal of the Johnson noise thermometry program at NIST is to build an electronic temperature standard based on the quantum voltage pulses of superconducting Josephson junctions [1]. In a Johnson noise thermometer (JNT) system [2], the temperature T is inferred from a cross-correlation measurement of the Johnson noise voltage V_T across a calibrated resistance R. The noise power is given by the Nyquist formula $\overline{V_T^2} = 4kTR\Delta f$, where Δf is the bandwidth for the measurement and k is Boltzmann's constant. A stable, programmable, and intrinsically accurate noise source would enable direct calibration of the cross-correlation electronics, matching of the calibration noise power to that of the sense resistor, and matching of the source impedance to both the sense resistor and the output transmission-line impedance. These features of the quantum voltage noise source (QVNS), which we will describe in this paper, reduce the measurement uncertainty, increase the measurement bandwidth, and decrease the measurement time. An accompanying paper in this publication will describe the correlation electronics and recent data [3].

Bias Technique

Using a QVNS we hope to achieve uncertainties better than a few parts in 10^5 for temperatures in the range of a few hundred kelvins [1]. At these temperatures the noise signals are small, on the order of 1 nV/Hz$^{1/2}$. However, in order to achieve such small uncertainties for such low voltage signals the noise power must be integrated for a long time and/or over a wide bandwidth. Thus the QVNS must be stable for long integration times but does not need to generate large voltages. These requirements allow the QVNS to be much simpler than the Josephson arbitrary waveform synthesizer, where the primary focus has been to obtain the highest voltages [4-6].

Both the Josephson arbitrary waveform synthesizer and the QVNS produce voltage signals with calculable magnitudes based on the perfectly quantized voltage pulses of Josephson junctions. This is because the time-integrated area of every Josephson pulse is precisely equal to the flux quantum, $h/2e$, the ratio of Planck's constant to twice the electron charge. Knowledge of the number of pulses and their position in time is sufficient to precisely determine the time-dependent voltage of any synthesized waveform. Thus, digital synthesis using perfectly quantized pulses enables the generation of waveforms with amplitudes that are dependent on only fundamental constants and a time standard [4].

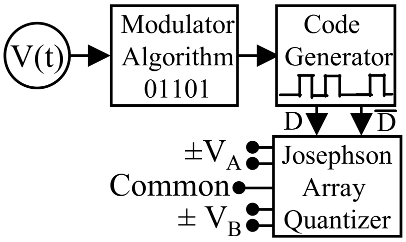

Fig. 1. Block diagram of the quantized voltage noise source for Johnson noise thermometry. A desired analog pseudo-noise voltage waveform V(t) is converted to a digital code by the modulator algorithm. Using this code, a two-level, 12 Gbit/s code generator drives two Josephson arrays using both Data and Data-complement channels. Two separate differential voltage taps (V_A and V_B across the series-coupled arrays) and a common line are used for calibrating the cross correlation electronics of the JNT system.

Using the original concept for the pulse-driven Josephson digital-to-analog converter [4], we can simplify the Josephson synthesizer for application as a QVNS as shown in Fig. 1. In the Josephson arbitrary waveform synthesizer, large output voltages were achieved by adding a sine wave to the input drive, thereby producing Josephson pulses of both polarities and bipolar output voltage waveforms [5]. Since low voltages are adequate for the JNT, the QVNS does not use the sinusoidal drive, so that the Josephson quantizer is biased only with unipolar pulses from the high-speed digital code generator. In response to these unipolar input pulses, the Josephson quantizer likewise produces only unipolar output pulses of a single polarity. The QVNS will thus generate low-voltage unipolar waveforms, which is fine for the small voltages needed for the JNT.

An important advantage of the unipolar approach is that it removes the difficulty of maintaining phase lock between the code generator and the sine drive. For the long integration times, perhaps hours or days, needed for the JNT, checking and maintaining that phase lock would

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be difficult to automate and dramatically increases the total measurement time.

Unfortunately, the digital code drive signal has frequency components at exactly the same frequencies as the desired output voltage of the Josephson quantizer. Thus, the input drive signal can produce unwanted voltages on the output as a result of input-output coupling or due to the inductance of the transmission line along which the Josephson junctions are distributed. For the QVNS, we can reduce these unwanted signals by using dc blocks to ac couple the input drive signal to the quantizer. The blocks act as high-pass filters for the gigahertz-frequency pulses and as attenuators for the low frequencies in the output signal band. This ac-coupled approach is also used for the Josephson synthesizer in order to remove common-mode signals on the transmission-line termination resistor [6].

In order to maintain operating margins for the Josephson synthesizer, the low-frequency signals must typically be reapplied across the quantizer through separate low-speed bias leads [6]. Fortunately, the low-amplitude QVNS signals are of sufficiently low amplitude that we do not need to apply a matching low-frequency compensation bias. This is advantageous because the additional bias leads would add unwanted complexity to the QVNS and could add significant noise to the low-amplitude output signal.

However, when we use a unipolar drive for the QVNS, the drive signal has a significant dc offset. This offset is necessary for biasing the quantizer on its operating margins. Fortunately, the dc offset can be minimized by applying a dc offset in the input waveform of the modulator algorithm. This causes the digital code to have many more zeros than ones so that the quantizer does not need to produce unnecessary pulses to generate the dc offset. With the dc offset minimized, the Josephson quantizer is essentially self-biased within its operating margins. The operating margins are optimized by adjusting the amplitude of the ac-coupled high-speed digital code signal. Figure 1 shows the block diagram of the simplified QVNS bias technique, where two Josephson arrays in the quantizer are driven by two high-speed bias leads, data (D) and data-complement ($\overline{\mathrm{D}}$).

Quantizer Circuit Design

The circuit design for the Josephson quantizer is shown in Fig. 2. Since a common reference point is needed for the correlation electronics, the quantizer is divided into two symmetric circuits with separate arrays of Josephson junctions. Each array is embedded in a coplanar waveguide transmission line that is terminated by a 50 Ω resistor. The data and data-complement signals drive each respective array through dc blocking capacitors. The arrays are series-connected through superconducting low-pass filters. The center point between these filters is used as the common reference for the cross correlation electronics. V_A and V_B are the output voltages across both arrays that are applied to the differential inputs of the two cross correlation channels. Each of these four taps has a 25 Ω resistor and a low-pass filter to keep the high-speed pulses in the coplanar transmission line.

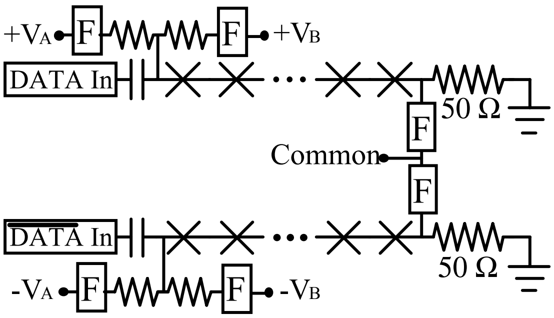

Fig. 2. Diagram of the superconducting integrated circuit for the quantized voltage noise source. X's indicate Josephson junctions. F's are low-pass filters.

For a unipolar pulse drive, the maximum output voltage of a series array of junctions is $V_p = nNf/(2K_{J\text{-}90})$, where n is the number of quantized output pulses per input pulse, N is the number of series junctions in the array, $K_{J\text{-}90}$ = 0.4935979 GHz/μV, and f is the clock frequency. The QVNS is usually operated with one output pulse per input pulse ($n = 1$). The clock frequency is 12 GHz, corresponding to a maximum unipolar pulse repetition frequency of $f/2 = 6$ Gbit/s. For the measurements presented in [3] each array uses 3750 junctions. In the full proceedings we will describe the modulator algorithm and the analog-to-digital conversion of the pseudo-noise waveforms.

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