Superconducting Instrumentation for Precision Measurement and Control

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Abstract. The Josephson series-array voltage standard (JAVS) has dramatically improved the level to which high-accuracy electrical equipment may be monitored and stabilized. For example, a small pressure dependence in the output of some solid-state voltage standards has been measured with the JAVS. The use of two such series-arrays in a superconductive loop promises to be a new method of ultra-small frequency difference measurement. The accuracy of these new measurement configurations is set by the superconductive loop inductance and the Josephson junction parameters.

1. Introduction

Series-arrays [1] of Josephson junctions, all biased by a common microwave source, are in use within approximately twenty laboratories throughout the world as an intrinsic voltage standard. At Sandia National Laboratories (SNL), and similarly at many other laboratories, this standard is routinely used to track the drift, accuracy, and linearity of digital volt meters (DVM), voltage reference standards, and voltage calibrators to an uncertainty better than 0.1 ppm. In collaboration with the National Institute of Standards and Technology (NIST, formerly NBS) we have used this technology to detect small systematic variations in the output of some solid-state voltage standards with elevation. Such refinements in measurement technology would be impossible without this wide-spread use of the JAVS. Recently a powerful new measurement technique utilizing these series-arrays of Josephson junctions has been developed [2]. Here two such arrays have been placed in series-opposition in a superconductive measurement loop which is inductively coupled to a SQUID. We [3] have analyzed this interferometer circuit within the framework of the Steward-McCumber model [4] to determine the measurement accuracy [5]. This circuit, which we refer to as a macroscopic quantum circuit (MQC) due to its superconductive coherence throughout the loop, may prove useful as an ultra-accurate interferometric readout at millimeter wavelengths for such applications as gravity wave detection and Sagnac-effect gyroscopes [6]. The full utilization of a MQC requires

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the development of a superconductive positioner to fine-tune cavity oscillators used to bias the Josephson junctions and possibly to tune the MQC frequency response directly.

The SNL Josephson voltage standard is similar to that used by NIST [7] except that it incorporates cryogenic (rather than room-temperature) passive filtering [8], and it is cooled continuously by a refrigerated Dewar [9] which maintains the standard at 4K with no helium loss or routine operator intervention. In the near future this refrigerated Dewar will be used to simultaneously support the Josephson array and to re-liquify the ^{4}He boil-off from a nearby quantum Hall effect resistance standard.

2. Environmental effects on solid-state voltage standards

Solid-state voltage standards (SSVSs) utilizing Zener diode references are in common use today for dc voltage metrology [10]. The JAVS provides an extremely accurate measurement system against which these SSVSs may be critically evaluated. The thermal coefficient of many SSVS have been measured against the JAVS and found to be typically 17 ppm/K. Since the set temperature of the SSVS enclosure is stable to better than 2 mK, and when intentionally over-heated it returns to its set point to within 5 mK, thermal effects create inconsequential errors in all the SSVSs observed to date. A systematic variation in some SSVS with elevation (and hence pressure) has been detected. One such SSVS, designated SSVS#1, was transported between four locations within the United States during 1989. This device was operated at elevations ranging from sea-level to 1,500 meters and no elevation or pressure dependence was observed in its output. SSVS#1 displayed excellent repeatability and stability as measured against the JAVS from location to location (once its drift rate was taken into account, SSVS#1 typically deviated by no more than 0.1 ppm during shipment). No variation of the JAVS has been observed during controlled temperature and pressure changes [11].

In August, 1990 another SSVS (called SSVS#2) was shipped round-trip between SNL in Albuquerque and NIST in Gaithersburg. At each location the device was measured against a Josephson voltage standard. The average of its four 1.018V taps was 0.98 ppm higher at Gaithersburg than at Albuquerque - a factor of ten larger in variation than the SSVS#1 result! A comparison of the value of SSVS#2 after its return from NIST to its value before it was shipped agreed to within 0.15 ppm. In order to check for a pressure dependence in the SSVS#2 output, both SSVS#1 and SSVS#2 were measured in a mobile laboratory at an elevation of 3,260 meters (on the summit of Sandia Crest, which is located 50 km from SNL) in collaboration with S. L.

Kupferman. These measurements were made against a high-accuracy 8.5-digit DVM which was calibrated against the JAVS immediately before and immediately after the mountain measurements. SSVS#2 experienced a -3.40 ppm deviation in the average of its four 1.018V taps with the 1,760 meter elevation gain, while SSVS#1 displayed an inconsequential +0.8 ppm deviation. Given the previous performance of SSVS#1, this deviation was likely due to a systematic change in the DVM gain with elevations. Only the 1.018V taps of SSVS#2 displayed this variation with elevation, indicating that a resistive voltage divider within SSVS#2 was most likely the source of this systematic error. These results serve as a warning that all transportable voltage standards used in critical metrology applications must be individually qualified through their full range of environmental conditions against a JAVS. In the future we will use our JAVS and an automated pressure/ temperature/ humidity-controlled chamber to make these critical environmental qualification measurements. Notice also that these very small systematic effects could not have been detected without the JAVS.

3. Macroscopic Quantum Circuit Measurements

Consider two rf-biased series-arrays connected in series-opposition with superconductive wire, forming the MQC with a total self-inductance L. The supercurrent i_S in the MQC which builds up over time t due to the difference in electric potential ΔV between the two rf-biased devices is given by

$$i_S(t) = \frac{1}{L}\int_0^t \Delta V \, dt'. \qquad (1)$$

This supercurrent is then read out by a SQUID which is magnetically coupled to the MQC. This method of ultra-precise potentiometry was developed by Clarke [12], and more recently used by Jain et al. [13] to obtain measurements with a precision of $\Delta V/V \approx 3x10^{-19}$ using single rf-biased junctions operating at about 300 μV. Kautz and Lloyd [2] have used this technique to compare the voltage output of two series-arrays, each containing 2,076 Josephson junctions and biased to $V \approx 1$ volt, to a precision of $\Delta V/V \approx 2x10^{-17}$. In all the above measurements both Josephson devices were biased by the same rf source to check for deviations from $i_S = 0$ when both Josephson devices were biased to the same step (n). Other experiments[14] have been performed which used two different rf sources of known detuning ($\Delta\omega$) to bias the junctions and thus to generate an increasing i_S consistent with Eq. 1 and the

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prediction that $\Delta V = \Delta V_0 = nh\Delta\omega/4\pi e$, where h is Planck's constant, and e is the magnitude of the charge of the electron. This method of measurement may provide a powerful new method of detecting very tiny frequency differences generated in gravity wave detectors and Sagnac-effect gyroscopes [6].

Referring to Eq. 1, it is clear that an arbitrarily precise measurement of ΔV may be made by either decreasing L, increasing the length of the measurement interval, or both. The value of the self-inductance (L) of the MQC need not be limited by the SQUID's input inductance [13]. Due to the interaction of the two Josephson devices via the superconductive loop, the measured ΔV is not simply equal to $\Delta V_0 = nh\Delta\omega/4\pi e$. Rather there exists a correction which depends on the value of L, and which becomes large as L approaches the Josephson inductance $L_J = h/2eI_c$, where I_c is the junction's critical current. These corrections, which have been calculated within the framework of the Steward-McCumber model [4] in the absence of external noise, are detailed in the proceedings of ISEC '91 [5].

These JAVS may be used as an ultra-stable voltage source provided that the load is very quiet and that the compliance current never exceeds the voltage state's critical current (which is on the order of 100 μA). In such applications (which may include ultra-accurate drift tube measurements at cryogenic temperatures) the voltage resolution and stability is directly determined by the linewidth and center-frequency stability of the biasing oscillator. Conventional microwave locker/counters can servo the center frequency of Gunn diode oscillators to within a few Hertz out of 75 - 95 GHz. Superconductive cavity oscillators have been developed which have $Q > 10^6$ over their full tuning range [15]. This cavity oscillator may be tuned with a proposed ultra-stable superconductive positioner [16] in order to obtain about a factor of one thousand improvement over conventional center-frequency stability.

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