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Preliminary Comparison of a 10 V Programmable Josephson Voltage Standard and a Hysteretic Josephson Voltage Standard

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Abstract—A 10 V programmable Josephson voltage standard system has been installed at the National Research Council Canada. The current margins for the first Josephson step at either current polarity are greater than 1 mA. A preliminary direct comparison of this programmable system with a hysteretic Josephson voltage standard is performed at 10 V.

Index Terms—DC voltage, DC voltage calibration, Josephson junctions, programmable Josephson voltage standard, hysteretic Josephson voltage standard, Josephson system comparison, voltage measurements.

I. INTRODUCTION

Josephson junction arrays have been widely used as voltage standards, especially since the adoption of the Josephson constant KJ_{90} [1]. A conventional Hysteretic Josephson Voltage Standard (HNS) has been used at the National Research Council Canada (NRC) for many years to calibrate DC reference standards and digital voltmeters [2]. Recently, the National Institute of Standards and Technology (NIST) in Boulder has commercialized its Programmable Josephson Voltage Standard (PNS). NRC purchased a system capable of achieving 2.5 V for research purposes back in 2008. In 2013, the system was upgraded to 10 V with the eventual aim of providing DC voltage calibrations. Here, we report on the optimization of the new 10 V PNS system at NRC and on its comparison with the NRC HNS system, where the output voltage of the PNS is directly used to bias the HNS to the desired quantized voltage step.

II. PJVS SYSTEM OPTIMIZATION

The NIST 10 V PNS chip at NRC contains a total of 265,110 Josephson junctions arranged in stacks of 3 junctions and distributed in a total of 32 coplanar waveguides into 23 subarrays. Nodes connected to 24 independent current sources allow current to flow through 7 "least significant bit" subarrays (where the number of junctions grows in a ternary sequence from 6 to 4374) and 16 large subarrays (where the number of junctions in each one lies between 8400 and 16800).

The main task when tuning the PNS parameters is to optimize the current range (called "margin") that allows all the Josephson junctions in a given subarray to stay on quantized voltage step n (where $n=0$, $+1$, or -1) within $3JtV$. The process is automated and repeated for all the subarrays. Changing the microwave generator output power setting (before amplification) reveals dependences such as those shown in Fig. 1a. The margins for the first step are larger than 1 mA as long as the power setting is larger than -1.4 dBm. The discontinuity

Fig. 1. (a) Microwave power setting dependence of the margins for the $n=0$ (upper two curves) and $n=1$ steps (lower two curves) at 18.7 GHz for subarray 7 (blue lines) and subarray 17 (orange lines). On this chip, subarray 7 has the largest margins, while subarray 17 has the smallest ones. (b) Dither current flatspot showing the dither current width of the quantized voltage step. All subarrays up to subarray 15 are biased at $n=1$ and all the others, at $n=-1$. The calculated quantized voltage is the Josephson voltage $V_J = 232.0109 \mu\text{V}$, and the difference between the measured voltage and V_J is plotted along the vertical axis. The power is 2.2 dBm, and the frequency is 18.7 GHz. Data points are measured in random order.

in the curves from Fig. 1a at 3 dBm arises when the power becomes so large that an on-chip superconducting microwave splitter becomes normal. The system is therefore operated at a 2.2 dBm power setting.

Once the margins are known for the 23 subarrays, a verification of quantized voltage stability against dither current flowing through the entire array is performed. This test is commonly referred to as a "dither current flatspot" test. It must be performed before and after any calibration work to confirm that the output voltage of the array corresponds to the expected value. An example of dither current flatspot measurement is provided in Fig. 1b, where all subarrays up to subarray 15 are biased to the $n=1$ step, while all subarrays beyond that are biased on the $n=-1$ step. The width of the flat region along the dither current axis is 1.24 mA in the example, indicating that, during any calibrations using this particular table of margins, the voltage quantization survives dither (and noise) currents of 0.62 mA of either polarity.

III. COMPARISON WITH HYSTERETIC JOSEPHSON VOLTAGE STANDARD

The PJVS is first optimized using the PJVS core computer as described in the previous section with a digital nanovoltmeter connected in parallel with its output voltage terminals (not shown). The nanovoltmeter is then removed from the circuit. The 10 V PNS system is compared to the 10 V HNS system by connecting the two in series opposition and by using

Fig. 2. Circuit diagram for the HJVS-PJVS comparison. The switch is controlled by the HJVS computer.

a digital nanovoltmeter as a null detector. The schematic in Fig. 2 shows the resulting circuit used for the comparison.

For practical reasons, a second computer, *PNS* remote, is connected to the *PNS* core computer via a local network in order to send the relevant voltage (and dither current) settings via DataSocket. The *PNS* remote computer simply reads these settings in a command file and sends the appropriate command to the *PNS* core, which in turn controls the current bias sources and microwave frequency. The *PNS* core computer can change the microwave frequency by up to ± 10 MHz from the operating 18.7 GHz to allow for the fine tuning of the PJVS output voltage.

The HJVS computer generates the command files passed to the *PNS* remote computer. The *HNS* computer also controls a relay switch connected across the null detector (see Fig. 2 and Ref. [2]). A HJVS bias source is not used in this comparison, as the bias comes from the *PNS* output voltage [3], which prevents ground-loop problems that often arise when using multiple bias sources. The relay switch is closed by the *HNS* computer whenever the voltage on the *PNS* is changed in order to allow the *HNS* to reach the appropriate quantized voltage step. The *HNS* computer toggles the relay switch a few times until the *HNS* settles on the exact step required. The expected voltage difference for 10 V on both systems is only 0.01 nV, so the nanovoltmeter is used as a null detector. Data points are only acquired once the nanovoltmeter reading is on the expected step. If for some reason the *HNS* jumps to a different step during data acquisition, the data are discarded and the relay is closed and opened until the hysteretic system settles back on the correct step. Fortunately, this is an infrequent event.

Measurements of the voltage difference, D.HNS-PJVS, are acquired with the (+,-,+) polarity sequence for a total of 20 iterations. The standard deviation of the mean is used as the type A uncertainty. We find D.HNS-PJVS = (2.2 ± 0.6) nV. As mentioned above, the *HNS* software controls the hysteretic array so that it remains on the correct voltage step. Voltage quantization of the *PNS* is ensured by applying a dither current of either polarity through the entire *PNS* array. The results of measurements of D.HNS-PJVS with (0, 0.3, -0.3) nA dither current in the *PNS* array are summarized in

TABLE I
VOLTAGE DIFFERENCE HJVS-PJVS AT 10 V

PJVS Dither current (nA)	HJVS-PJVS (nV)	Type A uncertainty (nV)
0	2.2	0.6
0.3	2.2	0.5
-0.3	1.9	0.5

Table I. Within the uncertainties, D.HNS-PJVS is independent of dither current, and the difference between the two systems at 10 V is only 2 parts in 10^{10} .

IV. CONCLUSION

In summary, a 10 V programmable Josephson voltage standard has been setup and compared to the NRC hysteretic Josephson voltage standard. The margins for the first Josephson step of each subarray of the programmable system are greater than 1 nA. The output voltage of the programmable system has been used to bias the hysteretic one. The preliminary comparison at 10 V has revealed a difference D.HNS-PJVS = (2.2 ± 0.6) nV. After the type B uncertainty components have been evaluated, the new 10 V programmable Josephson voltage standard will be used to calibrate digital voltmeters and DC reference standards.

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