Compact DC Josephson Voltage Standard

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***Abstract* — This paper presents precision measurements with a prototype cryogen-liquid-free DC Josephson voltage standard that produces a 1 V maximum output. Its cryostat is sufficiently compact that it can be operated on a bench close to devices under test. Compared to the National Institute of Standards and Technology (NIST) programmable Josephson voltage standard (PJVS), this bench-top Josephson voltage standard (BJVS) has a smaller cryostat (only 25 % of the volume), the Josephson junction array circuit is less complex and has only 10 % as many junctions, simpler bias electronics, and reduced mechanical cooling requirements. Direct voltage comparison between the BJVS and the PJVS achieved a relative agreement of 5×10^{-10} at 1 V. With the recent redefinition of the International System of Units (SI), the BJVS becomes a primary realization the unit volt, requiring only access to a standard single-phase power outlet and a GPS signal (SI second).**

***Index Terms* — Digital-analog conversion, Josephson arrays, standards, superconducting integrated circuits, voltage measurement.**

I. Introduction

The dissemination of dc voltage from primary to secondary laboratories is nowadays exclusively dependent on the stability of Zener voltage standards. Although the uncertainty achieved with commercial Zener voltage standards is sufficient for most electrical instrument calibration, the intrinsic drift of Zener references requires their periodic calibration with a Josephson voltage standard (JVS) [1]. The Zener calibration with a PJVS is performed at a primary standards laboratory and requires shipping the Zener artifact. With the redefinition of International System of Units (SI), all Josephson voltage standards become a primary realization of the unit volt [2]. In this paper, we present a prototype of a simplified compact bench-top JVS (BJVS) designed to realize the unit volt. The maximum output voltage of the BJVS was chosen to be 1 V, but a small number of fixed voltages are realizable. The main advantages of the 1 V BJVS (Fig. 1) are the reduced complexity and cost of the bias electronics, higher fabrication yield of the BJVS array circuit (having fewer junctions than the 10 V programmable Josephson voltage standard (PJVS)), and the ability to run the cryogenic compressor from a standard single-phase power outlet. This more compact and easily deployable 1 V BJVS can realize the unit volt directly, such as at secondary standards laboratories, eliminating *de facto* multiple calibration measurements, typical of past traceability chains. The BJVS can also be implemented as a primary voltage reference for Kibble balances, which are now key instruments for the realization of the mass scale with the newly redefined SI, or as a traveling primary standard for interlaboratory comparisons.

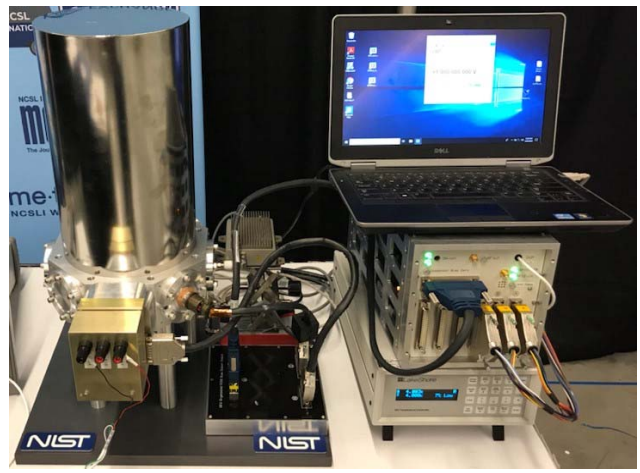

Fig. 1. Cryocooled 1 V bench-top Josephson voltage standard (air-cooled compressor not shown).

II. Bench-Top Josephson Voltage Standard

The BJVS circuit consists of 34 320 Josephson junctions (JJ) biased at a fixed microwave bias frequency of 14.090 8464 GHz. The JJ series array is subdivided into three subarrays of 3 432 JJs, 13 728 JJs, and 17 160 JJs, each generating, when biased on the n=±1 Shapiro step, ±0.1 V, ±0.4 V and ±0.5 V, respectively. The JJ array circuit is mounted on the 4 K cold stage of a Gifford-McMahon cryocooler. The cooling capacity of the cryogenic system is ~150 mW at 4 K, when operated with a single-phase-powered, air-cooled compressor. This cooling capacity is three-times the 50 mW cooling power required to operate the prototype circuit (JJ critical current: $I_c \cong 6.5$ mA at 4 K). A commercial temperature controller coupled to a 50 Ω heater is implemented to maintain the temperature of the device at 4 K. For the bias current sources, we used four channels of a low-cost compact commercial 16-bit digital-to-analog converter (±10 V), as well as four of the 24 current amplifier channels of our PJVS bias electronics amplifier board. A low-cost 24-bit (±0.5 V) analog-to-digital converter module is used to measure the chip output voltage, tune the bias-current operating range, and verify the

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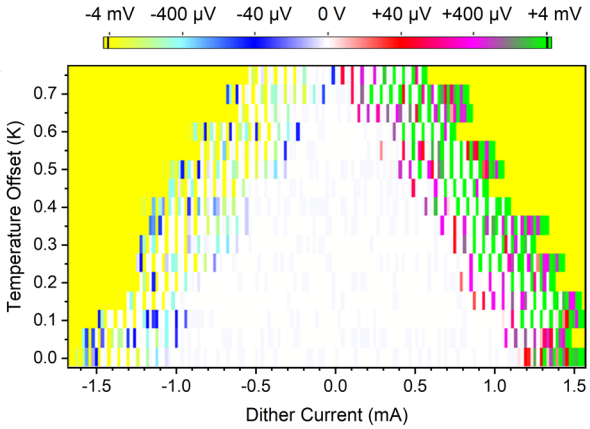

Fig. 2. Quantum locking range for the +0.5 V + (–0.4 V–0.1 V) subarray bias configuration as a function of the dither current and the temperature of the coldhead (referenced from 4 K).

quantum locking range of the BJVS. The microwave frequency is generated by a low-cost compact USB-powered synthesizer having a 100 Hz frequency resolution. The synthesizer is locked to an external 10 MHz reference (NIST primary frequency reference or GPS locked oscillator). The software was adapted to run the BJVS bias electronics while maintaining all the self-checks, diagnostic, and automatic tuning functions previously implemented with the NIST 10 V PJVS.

III. Quantum Locking Range

To measure the quantum locking range (QLR) with the best voltage resolution, the three subarrays are biased in the +0.5 V + (–0.4 V–0.1 V) = 0 V configuration. The white area (Fig. 2) shows the QLR domain as a function of both the dither current and the coldhead temperature. Unlike the 10 V PJVS system [3], the coldhead of BJVS is not fitted with a helium buffer tank, leading to an increase in the temperature oscillations (~240 mK), which are visible at the edges of the QLR by the band of successive voltage variations. Despite the correspondingly small ±0.5 mA bias current margin reduction associated with temperature oscillations, the QLR at 4 K remains larger than 2 mA.

IV. Direct JVS Comparison

We performed a direct comparison at 1 V between the BJVS and the PJVS. A digital nanovoltmeter (DNVM) measured the residual voltage difference. The low and high sides of the DNVM were connected respectively to the low side of the BJVS and the low side of the PJVS. The high sides of both JVS systems were connected in series. The low voltage tap of the BJVS was grounded on-chip through the current bias lead. In this configuration, only the leakage current contribution of the PJVS [4] contributed to a voltage error, but with an overall PJVS leakage resistance >150 GΩ [5], the leakage current-to-ground error contribution to this voltage comparison is insignificant. The measured leakage resistance of the BJVS was

Table I: Results of the BJVS-PJVS comparison at 1 V

Synthesizer Type	Synthesizer Resolution	Dataset size	Mean of ΔV (nV)	Type A Unc. k=1 (nV)
Compact	100 Hz	524	**–0.51**	0.37
Standard	1 mHz	357	**–0.14**	0.37

90 GΩ. A single dataset measurement of $\Delta V = V_{\mathrm{BJVS}} - V_{\mathrm{PJVS}}$ consisted of four groups of 15 DNVM readings, where the polarity of both arrays was reversed after every group to remove the thermal offset. All the comparison measurements were performed by applying a dither current sequence (0, +0.2, –0.2) mA in both JVS systems to verify the QLRs [4]. We measured ΔV with two different types of microwave frequency synthesizers on the BJVS system (Table I). If we assume that all the voltage error ($\Delta V = -0.51$ nV) is due to the finite frequency resolution of the compact synthesizer, then its frequency error is ~7 Hz at 14.090 8464 GHz, despite being locked to the same 10 MHz reference as the PJVS synthesizer. With the standard synthesizer replacing the compact synthesizer in the BJVS, this error does not appear and ΔV becomes comparable to the minimum voltage that a typical DNVM can resolve.

V. Conclusion

The 1 V BJVS is designed as a compact, cost-effective primary voltage standard, for use anywhere with access to a GPS signal needed to establish the traceability of the SI second. With lower complexity and cost compared to the PJVS systems, this BJVS may become a key instrument to disseminate DC voltage at secondary laboratories, shrinking or eliminating the existing traceability chain while improving measurement uncertainty (relative agreement of 5×10^{-10} at 1 V). Despite its reduced voltage output, programmability, and tunability (due to fixed frequency), the BJVS ability to generate 1 V and 100 mV enables calibration of a 10:1 voltage divider, which can be combined with the BJVS to extend the input range to 10 V and thereby also enable calibration of 10 V Zener outputs.

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