Establishment of an Automated 10V Josephson Series Array Voltage Standard at National Physical Laboratory, India

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Abstract-In the present paper, we discuss the integration, characterization and operation of the recently established an automated 10 volt Josephson Series Array Voltage Standard (JSAVS) at National Physical Laboratory, India (NPLI). Furthermore, we discuss the precision calibration of the Zener reference standard alongwith the uncertainty budget. The combined standard uncertainty of the Zener reference standard calibration at 10V for a Single Point Measurement (SPM) [1] is ± 25 nV at k=1.

Keywords–10V JSAVS, quartz oscillator, microwave components, Zener reference standards, Gunn oscillator, nanovoltmeter, JVS bias controller, low thermal scanner, calibration, uncertainty, NISTVolt software.

I. Introduction

National Physical Laboratory, India (NPLI) is the National Metrology Institute (NMI) of India and is responsible for realization, maintenance and dissemination of the SI units in India. In the area of quantum electrical metrology, NPLI has established JSAVS at 1 volt level since 1997 [2] and 10 volt level since 2007. The JSAVS works on AC Josephson effect which state that if the two superconductors separated by a thin layer of insulator is irradiated with microwave frequency signal, it generates constant voltage steps whose values are given by the following equation:

$$V_n = n.f / K_J \qquad (1)$$

Where n is integer 0, ±1, ±2, ±3 ………..±n, V_n is the array output voltage at step no. n and K_J is the Josephson constant whose value depends on the fundamental constants of the nature i.e. e (electronic charge) and h (Planck's constant). The value of K_J has been internationally agreed as K_{J-90} = 483597.9 GHz/V since 1st January 1990.

In this paper, we describe in details; the integration, characterization and establishment of an automated 10 volt JSAVS for the calibration of Zener reference standards along with various sources of uncertainty and their evaluation.

II. Experimental Set-up

Figure 1 shows the block diagram of the automated 10V JSAVS system, integrated at NPLI where as Figure 2 shows its photograph. This system consists of the following five sub-systems namely:

A. Microwave Assembly

The microwave assembly consists of Gunn oscillator, isolator, coupler, mixer and attenuator. The Gunn oscillator in the present set up is from 'Quinn Star' which operates at 76 GHz. The frequency of the Gunn is measured and stabilized by means of a source locking microwave counter (EIP 578B) which in turn is stabilized by an external time base using 10 MHz of quartz oscillator. The long term stability of the quartz oscillator is controlled by NPLI's atomic clock. The accuracy and stability of 10 MHz reference signal are 4.42×10^{-10} and 1.45×10^{-10}/year.

B. Cryoprobe

The cryoprobe used is Model CP525 from 'High Precision Devices, USA'. The cryoprobe has waveguides which directs the microwave to the Josephson array. The waveguide has WR-12 launching horns on each end which has frequency range of 60-90 GHz. The cryoprobe is made from silver plated (inside) stainless steel tubes which results into low loss in the probe. The Josephson array chip is mounted inside a high permeability magnetic shield at the end of the probe which makes transition between a liquid helium dewar and the room temperature environment. The magnetic shield and waveguide are supported by fibre glass tube. The three pairs of copper wire are connected to the JVS array through Bendix connector of cryoprobe. One pair supplies bias current, a second pair for I-V curve monitoring in oscilloscope and the third pair delivers the array output voltage to the calibration system. All of the wires pass through multiple levels of radio frequency interference (RFI) filtering in a milled aluminum box at the top of the dewar to cut frequency below 100 MHz. Higher frequencies are blocked by conductive foam on the printed circuit board. The box, the filters and the Dewar itself form a shield that protects the Josephson array from electromagnetic interference that could cause step transitions. The attenuation of the waveguide is 0.9 dB.

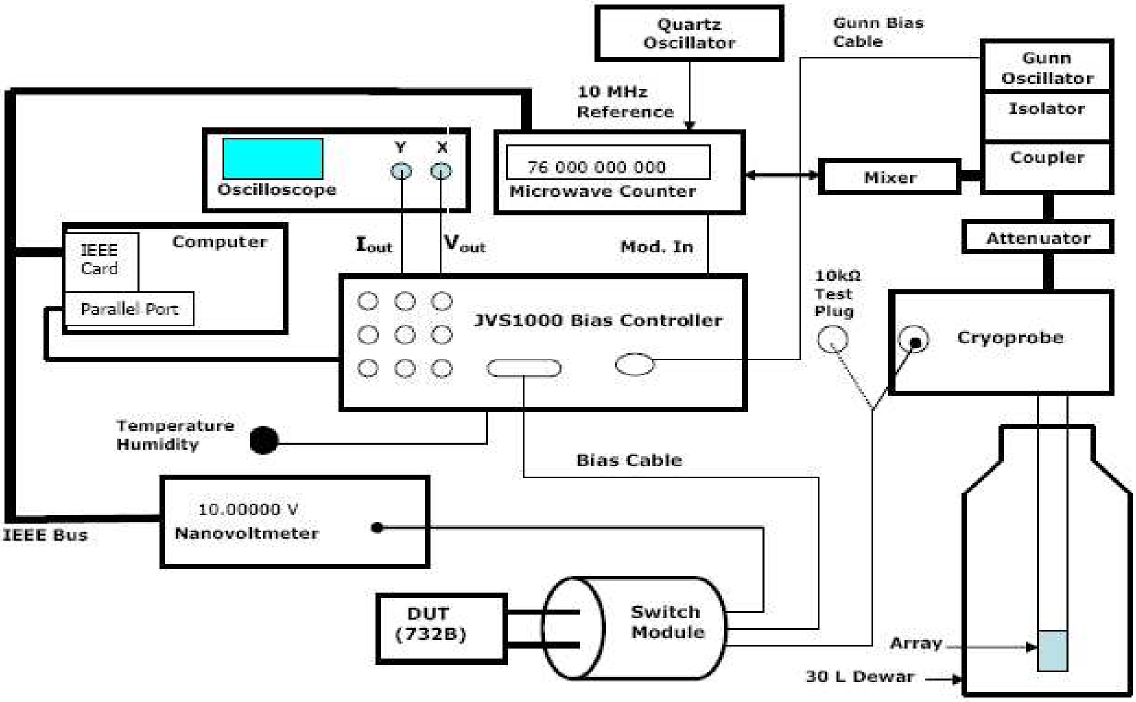


Figure 1.Block diagram of automated 10V Josephson series array voltage standard system at NPLI

Figure 2. Photograph of automated 10V Josephson series array voltage standard system at NPLI

C. Bias controller

The bias controller in the present set up is JVS1000 bias controller from ‘VMetrix, USA’. This is used to bias the array and supply the power to Gunn oscillator. The controller has output/ connections for display of I-V curve of the array on the oscilloscope. The controller has facility for both manual and automatic biasing of the array. In automatic mode, the computer uses 16 bit Digital to Analog Converter (DAC) for setting bias and controlling it. The controller has provision for attachment of temperature, humidity and pressure sensor which is read by NISTVolt software in automatic mode. The controller has also one channel low thermal scanner (i.e. switch module) which is used for reversing the polarity of Device Under Test (DUT).

D. Josephson array chip

The JVS array chip is commercially available from ‘Hypress, USA’. This 10V chip has about 20,000 $Nb/Al_2O_3/Nb$ junctions which give zero crossing steps up to ±12V. The best performance of this chip is at 76.12 GHz as tested and recommended by Hypress. The critical current of the array is 70 μA.

E. Measuring instruments

These consist of nanovoltmeter model Agilent 34420A and a Zener reference standard. The Zener reference standard is used as a secondary standard. The nanovoltmeter is used for reading the array and DUT voltage and also the difference voltage between them. To minimize noise coupling due to 50 Hz power supply to the Zener, it is used in battery mode during measurement.

III. Integration, characterization and operation of 10V JSAVS

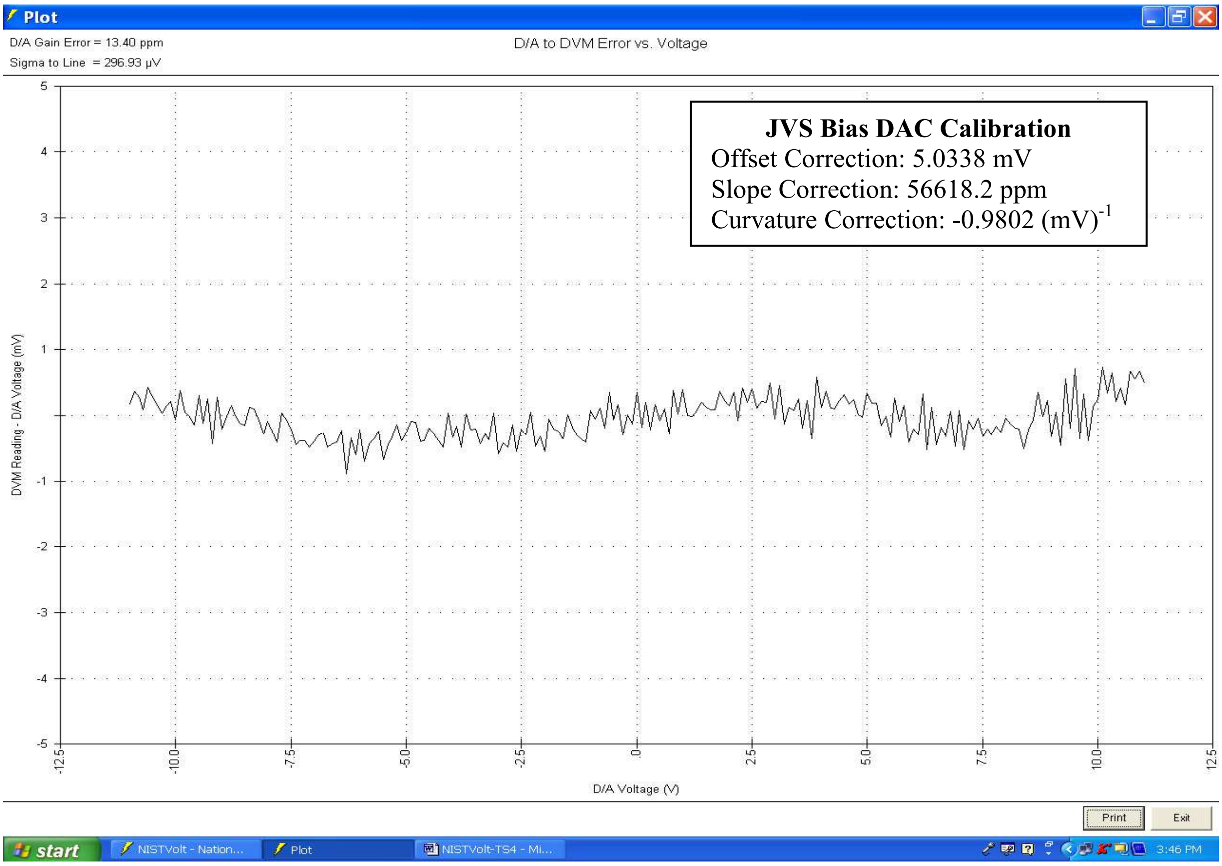
All the instruments of the sub-systems were individually tested for their operation and were integrated as shown in Figure 1. Josephson array chip was mounted on a sample holder of the cryoprobe and it was covered with a cryoperm shield. It was lowered slowly inside liquid helium dewar without any electrical connection to the cryoprobe. Then connections were made.

For the automated precision calibration of the Zener reference standards, first, the 16 bit DAC of the JVS1000 bias controller was calibrated using ”NISTVolt” software which has been developed by NIST, USA. Figure 3 shows the calibration of 16 bit DAC of JVS1000 array bias controller. With 16 bits covering a range of ±12V, the resolution is 366 μV which is very close to the one sigma error of the plot. By using the three calibration constants namely offset correction, slope correction and curvature correction; the DAC error can be driven to zero at three points which “NISTVolt” software chooses as +9, 0 and -9 V. After that,”Self -Test” was run as per the procedure depicted in the”NISTVolt” software. The ”Self-Test” measures 15 system parameters (e.g. JVS1000 internal temperature, external probe temperature, humidity, atmospheric pressure, D/A converter gain error, zero intercept, zero offset, array current sense circuit, array bias impedance, normal null loop resistance, reverse null loop resistance, scanner short voltage, zero step null voltage, array minimum critical current, array critical current at 5 V, array return current at 4 V and stability at 1V and set power) and displays the measured values together with upper and lower limits. The values were within the normal limit. The nanovoltmeter was calibrated for zero offset and 10 V range.

The dc I-V characteristics were observed as shown in Figure 4a. We observed that there was no trapped magnetic flux. Next, ac I-V characteristics were observed by adjusting microwave power and frequency. The large numbers of Shapiro steps were obtained. The current amplitude of these Shapiro steps was more than ±10 μA. Figure 4b shows characteristics of the chip with microwave irradiation at 76 GHz.

After its optimization, the Zener reference standard was connected to the JVS system. The “NISTVolt” software was used to make automatic calibration of Zener reference standards. The detailed algorithm of the “NISTVolt” software has been discussed elsewhere [3-4]. The single point measurement (SPM) of the Zener reference standards takes about 5 minutes. The algorithm of the “NISTVolt” software also collects data during step transitions. Thus it takes care of step jumps. The “NISTVolt software” uses “+ – + – “measurement sequence to minimize the thermal emf errors. In this process, the software collects 10 data in each polarity. Thus for the above measurement sequence, it collects 40 data. Based on this 40 data, a three parameter least-square curve fitting is done to calculate the value of DUT output voltage, offset voltage and thermal emf drift rate. The software was validated before using for calibration of other Zener reference standards. The details of the validation of the software will be reported elsewhere.

In Zener reference standards calibration using JSAVS; there are various sources of uncertainty in measurement as mentioned in Table 1 in which the contribution from the DUT has been excluded [1]. The uncertainty components at (1) and (2) depend on DUT output voltage. The other components from (3) to (9) are evaluated as a Type A uncertainty that is determined from a set of short circuit measurement. This Type A uncertainty is called the zero-offset uncertainty. The combined uncertainty (evaluated by Type A and Type B methods) of a single point measurement (SPM) is estimated as ±25 nV at k=1. Table 2 gives the uncertainty budget of Zener reference standards calibration for a single point measurement (SPM). The SPM is not the true reflection of the uncertainty of the Zener reference standards. For getting the true reflection of the uncertainty for Zener reference standards, its noise should be also included in the uncertainty budget which is in the range of 50 to 200 nV. Table 3 shows the result of the calibration of the bank of Zener reference standards having 4 nos. of 732B Zener reference standards in which the noise of the Zener reference standards has been included.



D/A Gain Error = 13.40 ppm

Sigma to Line = 296.93 μV

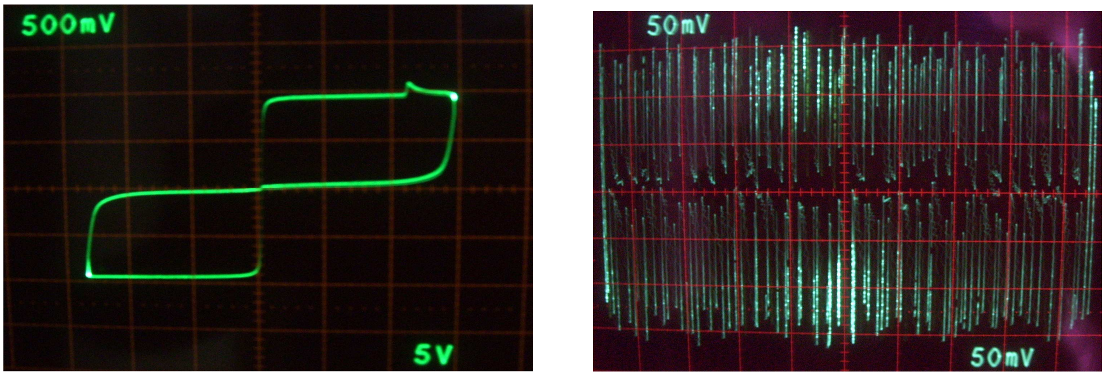
JVS Bias DAC Calibration

Offset Correction: 5.0338 mV

Slope Correction: 56618.2 ppm

Curvature Correction: -0.9802 $(\mathrm{mV})^{-1}$

Figure 3. Plot of 16 bit DAC calibration of JVS1000 Bias controller



(a) dc I-V Characteristic (i.e with microwave OFF)
horizontal: 5 V/div. , vertical: 50 μA/div.

(b) ac I-V characteristic with microwave irradiation (frequency 76 GHz).
horizontal: 50 mV/ div. , vertical: 5μA/ div.

Figure 4. I-V characteristics of the Josephson array chip with and without microwave irradiation.

Table 1. Sources of uncertainty for a Josephson voltage standard

1. Reference frequency offset and noise
2. Leakage currents in the measurement loop
3. Detector gain error
4. Detector bias current
5. Detector offset, input impedance, nonlinearity and noise
6. Uncorrected thermal voltages in the measurement loop
7. Offset owing to rectification of the reference frequency current
8. Any effect of electromagnetic interference (EMI)
9. Sloped steps resulting in bias dependent Josephson voltage

Table 2. Uncertainty budget of Zener reference standards calibration for a single point measurement (SPM)

Sources of uncertainty	Type	standard uncertainty/nV	Degree of freedom
Repeatability	A	19.6	37
Zero-offset	A	15.0	22
Frequency	B	4.6	∞
Leakage	B	1.2	∞
Combined		25.2 (rss)	63 (ν_{eff})*

* ν_{eff} = effective degree of freedom

Table 3. Result of calibration of Bank of Zener reference standards (at k=2 for 95% confidence level)

Zener standards	Nominal value	Measured value along with expanded uncertainty
S/N 9130701	10.0 V	10.000 026 704 V ± 350 nV
S/N 9130702	10.0 V	10.000 030 049 V ± 350 nV
S/N 8099001	10.0 V	9.999 993 985 V ± 350 nV
S/N 7899006	10.0 V	9.999 972 367 V ± 350 nV

IV. Conclusions

In this paper, we have discussed about the establishment of the automated 10V JSAVS alongwith the evaluation of uncertainty in measurement of the calibration of the Zener reference standards. The combined standard uncertainty at 10V for a SPM is ± 25 nV. Now NPL-India has an automated 10V Josephson series array voltage standard for dissemination of the unit 'volt' to meet the present requirement of our industries and various other users at par to international level.

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