Microvolt Josephson Voltage Standard Using a Dual-Channel Programmable Array Chip Developed at NIM

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Abstract – **Previously a differential programmable Josephson voltage standard (DPJVS) has been developed for precision ultra low-voltage measurement of microvolt (µV) level at NIM. In this paper we present an updated technology for microvolt Josephson voltage standard (MJVS) which uses a dual-channel Josephson array chip with NbSi barrier developed at NIM. It is a new type device to build two symmetric paths of microwave irradiation for differential frequencies applying to a pair of channels of Josephson junction array. This new approach can efficiently simplify the complicated DPJVS system, which has two cryogenic systems, more expensive devices and is more difficult to operate. Based on it, a series of quantum-accurate microvolt voltages are achieved with uncertainty less than 1 nV, tens of times more accurate than the conventional technique. And the relevant precision measurement system has been established for calibration purpose. For practical application, a nanovolt meter has been successfully measured under the 10 µV range. Besides this, an improved 10 V PJVS is in progress to be improved in range and resolution when combining with the new standard based on the new dual-channel Josephson array chip.**

Keywords –Josephson voltage standard, nanovoltmeter, voltage measurement, Josephson array.

I. INTRODUCTION

At present, the increasing need for precision low-voltage measurement makes it necessary to find a more accurate standard to be capable of covering broader ranges even down to ultra low voltages. Actually, low-voltage standard is a particular challenge because it is usually implemented by means of ratio dividers and amplifiers, resulting in worse SNR. For a sensitive measurement instrument e.g., nanovoltmeter, there still exist the limits of sensitivity determined by the noise of resistance in the measurement circuit [1], difficult to make the accurate low-voltage measurement.

Josephson array circuit is a perfect standard to generate quantum voltages [2] with tiny output resistance. But it still limited by its character. According to

Josephson effect, Josephson voltage $V = Mf/K_J$, where Josephson junction number M is an integer, f is the microwave frequency irradiated to the Josephson junctions. And K_J is Josephson constant. The lowest voltage value that quantized by the frequency is limited when the character of a Josephson chip is fixed. As K_{J-90}=483597.9 GHz/V, the minimum output is 31 µV when PJVS is applied by frequency of 15 GHz.

For that reason we have developed a differential programmable Josephson voltage standard (PJVS), which employed two PJVSs different from each other in driving frequency.[3][4] When they are in series opposite, one PJVS is compensated with the other to produce the differential voltages at microvolt level with quantum accuracy and stability. However, it is still faulty for its double cryogenic systems, complicated operation, and flux trapping more easily. In order to overcome these shortcomings, we have designed a chip consisting of a pair of series Josephson junction arrays. Each array is independent of the other with own microwave entrance and voltage terminal. Therefore, when microwaves are applied to arrays with different frequency at the same time, the chip can be used as a dual-channel circuit to output two different voltage values depending on their own frequency.

Base on that we simplified DPJVS and make the measurement of ultra-low voltage more reliable and practical. In addition, we also can expect it to act as a voltmeter with extended wider range when it in series with 10 V PJVS.

II. PRINCIPLE AND DEVELOPMENT OF DPJVS

As described before, a Josephson junction in the superconducting state (4.2 K) can generate quantized voltage as U

$$U = \frac{f}{K_J} \qquad (1)$$

The Josephson constant $K_J = 2e/h$, where e is the electron

charge and h is the Planck constant. For a programmable Josephson junction array (PJA), its output voltage V

$$V = NM\frac{f}{K_J} \quad (2)$$

Where M is the number of series junctions. And N, which presents polarity of voltage steps, is ± 1. If two Josephson arrays PJA1 and PJA2 are applied microwave frequency of f_1 and f_2 respectively, and synchronized to generate voltage steps in the positive polarity, their output voltages V_{PJA1} and V_{PJA2} are as follows.

$$V_{PJA1} = M_1 \times \frac{f_1}{K_J} \quad (3)$$

$$V_{PJA2} = M_2 \times \frac{f_2}{K_J} \quad (4)$$

Where M_1 and M_2 are the junctions number of two PJAs respectively. When we set the two Josephson arrays in reverse series, then the differential output voltage V_{diff} is

$$V_{diff} = M_1 \times \frac{f_1}{K_J} - M_2 \times \frac{f_2}{K_J} \quad (5)$$

If $\Delta f = f_1 - f_2$, and $M = M_1 = M_1$

$$V_{diff} = M \times \frac{\Delta f}{K_J} \quad (6)$$

Since the frequency is determined by the Josephson array characteristics, the current minimum Josephson voltage is limited. However, Δf can be free from the characteristics of the array. According to (6), we can obtain a series of quantized voltages of almost any resolution. Therefore we can make the ultra-low voltages reach direct traceability to the frequency and physics constant, to improve measurements accuracy by several orders.
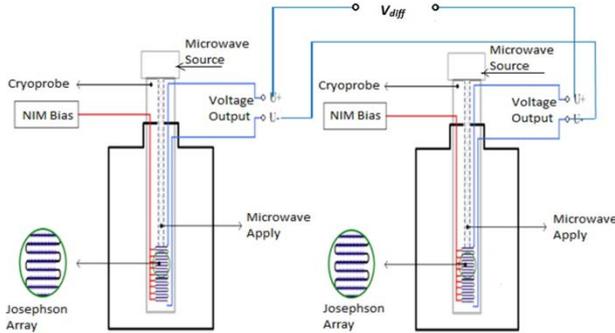

Fig.1 Differential programmable Josephson voltage standard.

A differential programmable Josephson voltage

standard consisting of two Josephson devices is shown in Figure 1. By setting up a multi-channel bias, developed at NIM, with very low noise and precision measurement system, we have produced the quantized ultra-low voltage at microvolt level with the uncertainty less than 1 nV. [3] Later on, based on it we have developed a calibration system for nanovoltmeter, shown as Fig.2.
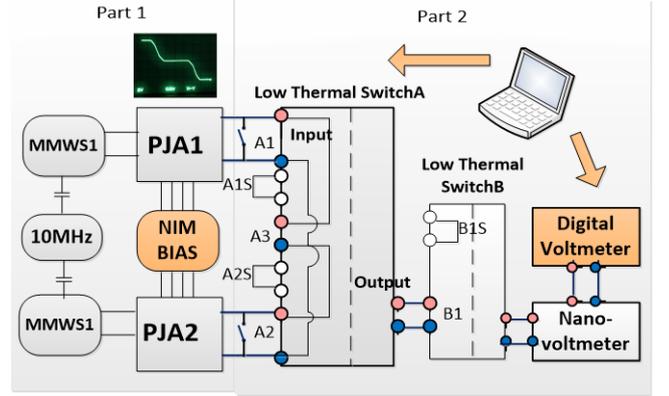

Fig.2 The system of nanovoltmeter calibration using DPJVS.

III. PROGRESS TOWARD TO A MICROVOLT JOSEPHSON VOLTAGE STANDARD USING A DUAL-CHANNEL PROGRAMMABLE ARRAY CHIP

The new design is a double channel Josephson array to simplify the 2 PJVS systems, shown as in Fig. 3. Thus differential voltages could be achieved base on one Josephson array standard.
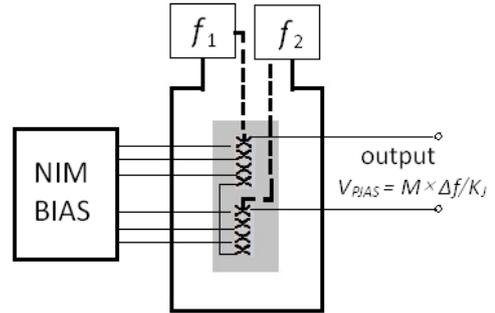

Fig. 3 The schematic of Microvolt Josephson voltage standard based on a double channel Josephson array.

A. Chip and circuit design

Two channels of Josephson junction array with NbSi barrier have been designed on a chip. Each array is segmented into nine parts, the number of junctions for each part is $2i$ ($i = 0,1,2…8$). The size of each junction is designed to be 8 μm × 8 μm. Both series arrays are located in a straight line with a length of about 8

millimeters. The size of the chip is 1 cm by 1 cm, placed on a thin copper sheet which is attached to a PCB board for the connection with bonding wires. And the chip holder is mounted at the bottom of a cryoprobe specially matched for it, in which there are two separated transmission lines for microwave irradiation, shown in Fig. 4.
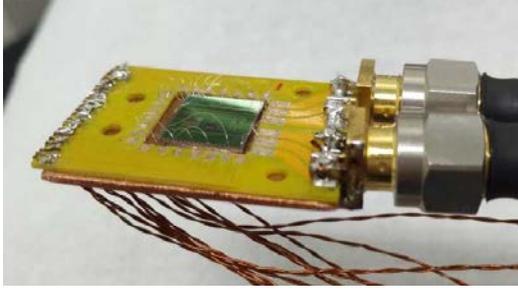

Fig. 4 Photo of a dual-channel circuit based on Josephson junction arrays.

We choose 4 parts of $2i$ ($i = 0,1,2,3$) for DC bias and observed their I-V characteristic, shown in Fig. 4. The critical current for total 15 junctions is about 2.7 mA for each channel. When irradiated by microwave frequency of 8 GHz, the I-V curves showed the step width more than 2 mA. In the graph, the data of square, circle, up triangle and down triangle shows characteristic of 1,2,4,8 junctions respectively.
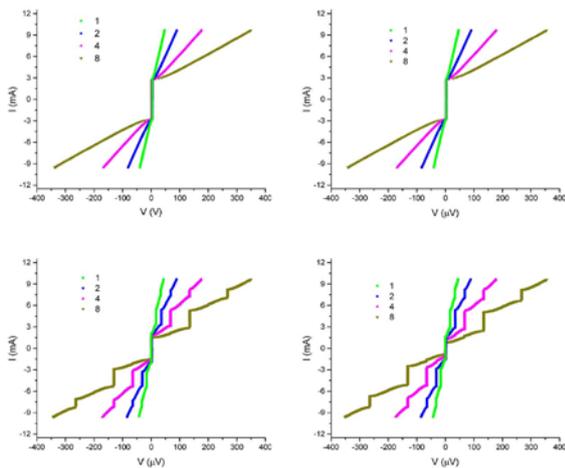

Fig. 5   I-V characteristic of dual-channel array. (a) I-V curve of channel 1 without microwave. (b) I-V curve of channel 2 without microwave. (c) I-V curve of channel 1 with microwave power. (d) I-V curve of channel 2 with microwave power.

B.   *System and measurement results*

The system was set up as Fig. 6. Two Agilent 8257D signal generators provide microwave drive to the arrays of channel 1 and channel, with the frequency f_1 and f_2 respectively. A multi-channel current bias was improved to offer DC bias separately for dual-channel array. It is powered by battery to depress the noise in the circuit. It is believed to be important for the accurate ultra-low voltage measurement. A low-emf switch system was used to investigate the step flatness of each channel array and achieve the differential voltages.

Fig. 6   The set-up of microvolt Josephson voltage standard

The I-V character of one of the subarrays, as shown in Fig. 7, was measured to demonstrate the step margin of the array is more than 1.5 mA with 8 GHz. It is enough for the stability of the differential voltages. And the measurement of the step flatness shows the slope of steps is less than 3 nV/mA, good enough for the voltage accuracy.
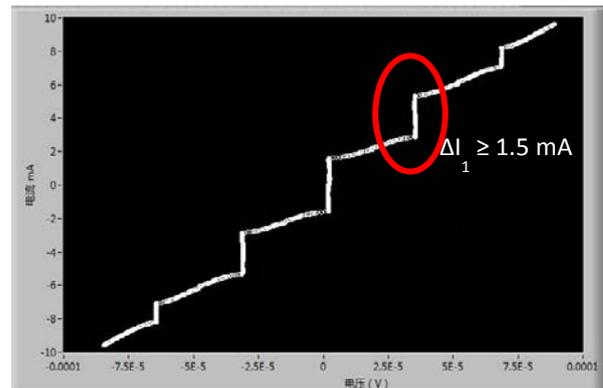

Fig. 7 The I-V character of one subarray with microwave irradiation.

When setting frequency f_1 and f_2 with 8.03 GHz and 8.5136 GHz respectively, quantum voltages of 1 µV to 8 µV were obtained by 1 to 8 junctions of 2 channels. A nanovoltmeter Agilent 34420A was used for measurement. The results are shown in Table 1. The uncertainty is determined by standard deviation since it is

Table *1 Microvolt measurement results based on the dual-channel array, Vm is the measurement result, V$_{nom}$ is the nominal value.*

V_{nom}	1 µV	2 µV	3 µV	4 µV	8 µV
$\Delta V = V_m - V_{nom}$ (nV)	-0.016	0.8	-0.4	-0.6	-1.3
Relative difference (µV/µV）	0.16×10^{-4}	3.9×10^{-4}	-1.4×10^{-4}	-1.6×10^{-4}	-1.6×10^{-4}
Standard deviation	0.7　nV	1.1　nV	1.2 nV	1.2 nV	1.2 nV

the main source of type A.

The result of shows that at 1 µV, the difference between the measured values V_m and the nominal value is less than is 0.02 nV with the standard deviation of 0.7 nV. And the relative differences at levels from 1 to 8 µV all are less than 1.6×10^{-4}. That can meet the demand of the precision measurement for ultra-low voltage measurement.

IV. CONCLUSION AND DISCUSSION

We have developed a microvolt Josephson voltage standard using a dual-channel array chip. The chip is designed particularly with two channel microwave injection for the differential Josephson voltage output. The purpose is to replace the complicated dual PJVS system with a simple dual-channel array chip, making it to be a practical quantum standard for precision low-voltage measurement. The satisfactory results have been obtained at the microvolt level with the uncertainty around 1 nV. Furthermore, the application combined with a normal 10 V PJVS can be expected to be an extension to lower voltage range at microvolt level. be used as an ideal quantum voltmeter [5] which can measure voltages from 100 nV to 10 V, show as Fig. 8.
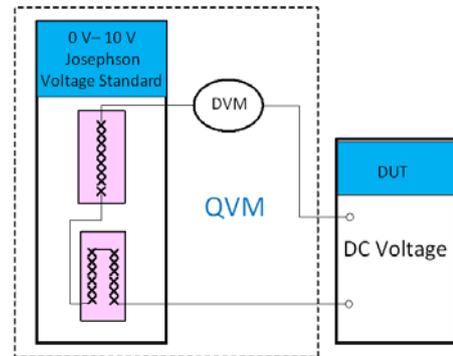
ACKNOWLEDGMENT

Fig. 8 Quantum voltmeter for measuring DC voltages from 100 nV to 10 V.

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