Circuit Precautions for Stable Operation of Josephson Junction Array Voltage Standard

Haruo Yoshida, Yasuhiko Sakamoto, *Member, IEEE*, and Tadashi Endo

***Abstract*—During the course of developing the Josephson junction array voltage standard at the ETL, the following precautions have been taken to improve its uncertainty; 1) New design and construction of a phase-lock circuit to obtain a stable millimeter wave frequency; 2) Optimum choice of a digital voltmeter for use as a suitable null detector; 3) Design and construction of line filters to reduce noise coming to the the Josephson junction array. These predictions are essential to a stable voltage calibration with an uncertainty of 1.3×10^{-8}.**

I. Introduction

The primary voltage standard of the Electrotechnical Laboratory (ETL) has been maintained by a new Josephson junction array voltage standard (JJAVS) of 1 V since January 1, 1990 [1]. In the course of developing the JJAVS, the configuration of which is illustrated in Fig. 2 of [1], we have taken particular care to obtain the stable performance of the JJAVS with an accuracy of 1.3×10^{-8}, in a usual laboratory without an electromagnetically shielded room. The key points for the precaution are as follows:

1) Design and construction of a phase-lock loop (PLL) circuit to drive a Gunn oscillator to obtain frequency stability of 1×10^{-10}.
2) Optimum choice of a digital voltmeter (DVM) for use as a null detector, comparing the following performances of several DVM's: resolution, zero-drift, and noise emission from input terminals to external circuits.
3) Design and construction of line filters to reduce noise coming to the Josephson junction array. Several JJAV's are working in other laboratories [2].

However, to the authors' knowledge, there are no publications on the details of the above points. We report here the particular precautions and resulting performance.

II. Design and Construction of a PLL to Drive Gunn Oscillator

A. Performance of a Conventional PLL Circuit

In the early stage of developing our JJAVS system, a conventional phase-locked millimeter wave source was used. The conventional source consists of the following components which are commercially available:

1) Gunn oscillator, 94 GHz, 60 mW . . . Millitech model GDM-10-4-18HM,

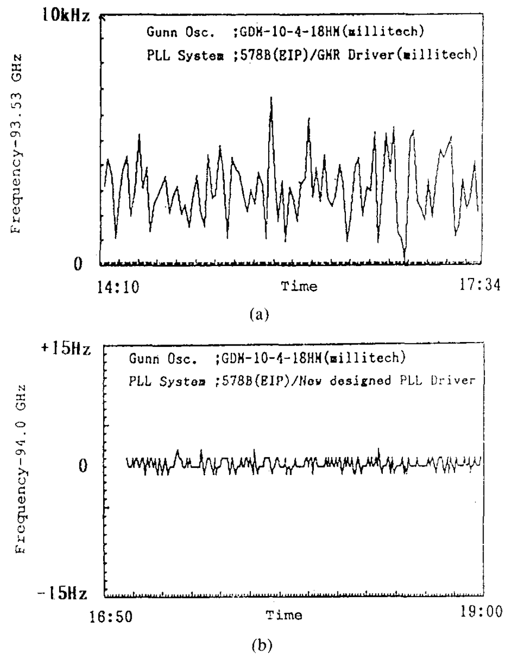

Fig. 1. Frequency stability of the Gunn oscillator. (a) Before and (b) after improvement of the PLL circuit.

2) Gunn oscillator driver . . . Millitech model GMR,
3) Source-lock counter . . . EIP model 578B,
4) Rubidium frequency standard . . . Tracor model 308A.

The frequency stability of this source for both short and long terms is about 5×10^{-8} as shown in Fig. 1(a). This frequency stability is insufficient for the JJAVS.

A Gunn oscillator driver is used to amplify the phase-lock signal from the source-lock counter and feed back it to the Gunn oscillator in a PLL circuit stabilizing the frequency. Two main functions are needed for the Gunn oscillator driver. One is to shift the level of the phase-lock signal up to the 10-V operating level of the Gunn oscillator. The other is to amplify the shifted phase-lock signal to produce a current amplitude enough to control the frequency of the Gunn oscillator. In the case of Millitech's model GMR, the phase-lock signal is input to the port of "fine-voltage adjustment" of the three-terminal voltage regulator in the driver.

The insufficient stability of the frequency (5×10^{-8}) is mainly caused by the following problems in the three-terminal voltage regulator:

Manuscript received June 12, 1990; revised October 9, 1990.
H. Yoshida is with ADVANTEST Corporation, Gumma 370-06, Japan.
Y. Sakamoto and T. Endo are with the Electrotechnical Laboratory, Ibaraki 305, Japan.
IEEE Log Number 9141636.

0018-9456/91/0400-0305$01.00 © 1991 IEEE

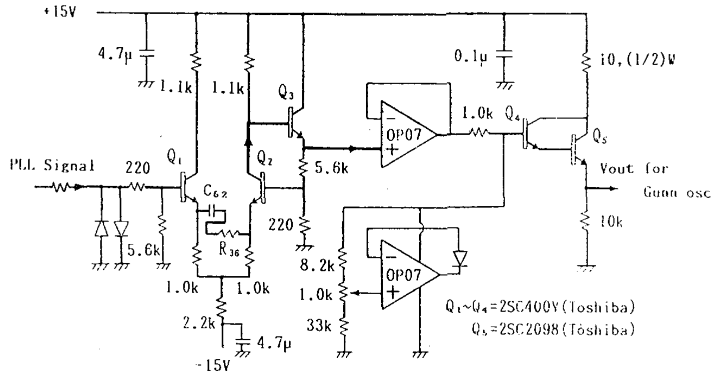

Fig. 2. Circuit diagram of the improved Gunn oscillator driver in the PLL circuit.

1) Slow response time of the regulator. That is, compensation for the rapid fluctuations of the frequency of the Gunn oscillator is not sufficient because the regulator is not designed for wide-band analog signal processing.
2) Large noise in the regulator. That is, inherent spectrum purity of the Gunn oscillator is degraded by noise generated in the regulator.

B. A New Design for the PLL Circuit

In order to remove those problems mentioned above, we designed and constructed our own PLL circuit. The circuit diagram is shown in Fig. 2. Improvement lies in the following two points:

1) Use of low noise and high frequency transistors in the circuit: 2SC400Y's (f_T = 300 MHz, Toshiba) for the level shifter and 2SC2098's (f_T > 100 MHz, Toshiba) for the Darlington type current booster for stabilizing the frequency of the Gunn oscillator.
2) The circuit C62–R36 between the emitters of transistors Q1 and Q2 is for the purpose of compensating gain and phase lag at high frequencies.

Open loop characteristics of the new Gunn oscillator driver for some sets of parameters (C62, R36) are shown in Fig. 3. We chose the case 2, C62 = 1000 pF and R36 = 680 Ω as an optimum set of parameters. The bandwidth of the circuit is 1.5 MHz which is 8 times wider than that for the Millitech's model GMR. As a result of this replacement from the GMR, the frequency stability has been improved to 3×10^{-11} from 5×10^{-8}.

The spectrum purity is also improved as follows: from −22 dBc (500 kHz off carrier) in the use of the model GMR to −37 dBc (500 kHz off carrier) in the use of our PLL circuit. This improvement contributes to reduce wide-band voltage fluctuations of Josephson voltage steps.

Fig. 1(b) shows the stability of frequency after the improvement.

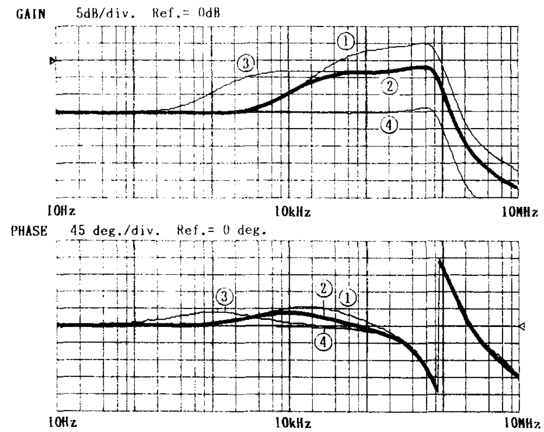

Fig. 3. Gain and phase characteristics of the improved Gunn oscillator driver. The curves numbered 1) through 4) are those for various values of C62 and R36: 1) 1000 pF 200 Ω; 2) 1000 pF, 680 Ω; 3) 10 000 pF, 680 Ω; 4) without C62 and R36. The curve 2 is of the optimum performance. (Note: +15 V and −15 V powers should be turned on/off simultaneously).

III. Choice of DVM for a Null Detector

In a low impedance range, e.g., below 10 Ω, some suspended wire type galvanometers of SQUID galvanometers are more sensitive null detecting devices than digital voltmeters. However, in order to operate the JJAVS under computer control, it would be very useful and practical if a DVM could be used as a null detector, with enough sensitivity in the higher impedance range.

The following characteristics are essential to a null detector that can be used in a JJAVS of 1-V level and controlled by a computer: (1) resolution of 10 nV or better, (2) high stability of zero, (3) very low noises emitted from the input terminals, and (4) leakage resistance higher than 10^{11} Ω.

In order to choose an optimum DVM, we tested six different models of DVM's with resolution of 10 nV. The DVM's were, ADVANTEST TR6561, ADVANTEST TR6871, Datron 1072, Keithley 181, Hewlett-Packard 3457A, and Hewlett-Packard 3458A. The best two of them screened, R6561 and 3458A, were examined in more detail on zero drift and noise emission. The DVM's under test were kept in a thermally steady state where the ambient temperature is 23 ± 1°C. The procedures and results were as follows:

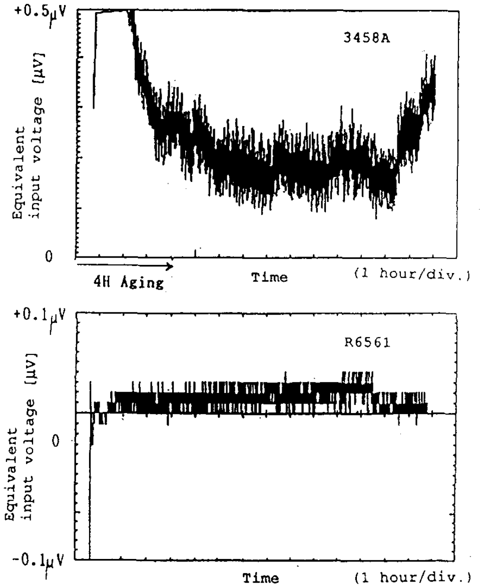

Fig. 4. Stability of zero for the DVMs, the models 3458A and R6561.

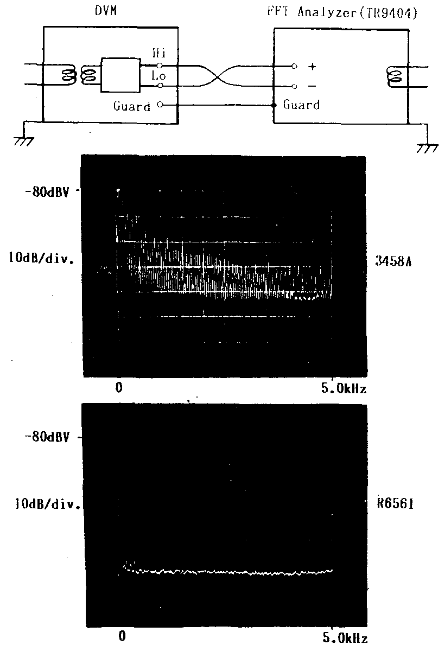

Fig. 5. Frequency spectrum of noise emitted from input terminals of the DVM's, models 3458A and R6561. The circuit connection for the measurement is shown at the top.

A. Stability of Zero

The stability of zero (i.e., offset voltage when input voltage is zero) was measured by making a short circuit between the input terminals. The integration time was fixed to 2 s. The result is shown in Fig. 4. The short term fluctuations during a few minutes were 30 nV_{p-p} (one standard deviation = 5 nV) for R6561 and 180 nV_{p-p} (one standard deviation = 30 nV) for 3458A. This observation time of fluctuations corresponds to the time needed in the measurement of null voltage in an actual calibration procedure using the JJAVS.

Input leakage current of R6561 measured was +30 pA with fluctuations of 25 pA_{p-p} in the case of integration time of 2 s. The drift of the leakage current was 5 pA during 6 h.

B. Noise Emission from the Input Terminals

Most DVM's generate some electrical noise between the input terminals due to their modulation devices, usually FET choppers. If noise is too large, it will cause transitions among the Josephson voltage steps.

A FFT analyzer, ADVANTEST model TR9404, was used to measure the noise emitted from the input terminals of the DVM's. The frequency range of the measurement was from 10 Hz to 5 kHz. The circuit connection and the result of measurement are shown in Fig. 5. The maximum noise levels measured were −103 dBV for R6561, and −80 dBV for 3458A. Lower noise for R6561 is considered to be partly due to a built-in 2.2 μF capacitor shunted across the input terminals, which filters out the modulation noise from the FET choppers.

In consequence of the test, we have chosen R6561 for the null detecting DVM. Note that the results described here are of the particular units available at our laboratory, but not of the universal performance for all units of the same model.

C. Leakage Resistance of Input Circuit

The lowest leakage resistance of the JJAVS is between the input terminals and the guard of the DVM. The leakage resistance of the R6561 as received was 5×10^{10} Ω, which is not high enough. Because of this low leakage resistance, one of the input terminals should be connected to the ground (i.e., guard) and other measurement circuits are floated from the ground to eliminate the effect of ground loops. However, model 732A Zener voltage reference to be calibrated has also been found to be of pretty low leakage resistance, 1.5×10^{11} Ω. The leakage resistance contributes to an additional type B uncertainty of 7×10^{-9}, since the Zener voltage reference is about 1 kΩ in source resistance and cannot be grounded in this case.

In order to keep flexibility in many applications of the JJAVS, it is necessary that the grounding point of the JJAVS can be chosen at any point on the circuit (including the choice of completely floating from the guard). We increased the leakage resistance between the input terminals of DVM and the guard to 5×10^{11} Ω by using a specially manufactured power transformer. Through this modification the uncertainty associated leakage resistance can be improved to as low as 2×10^{-9}.

IV. Line Filters

A transition of current-bias point between neighboring quantized voltage steps occurs when a single "spike-like" current noise with an amplitude large enough gets into the Josephson junction array. We have found that the Zener voltage reference (to be calibrated) generates noise comparable to that of the DVM. For both devices, the noise looks "spike-like" superimposed on wideband noise. Occasionally, considerable noise

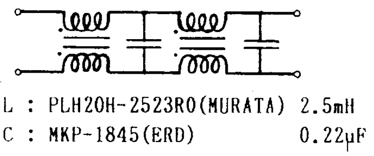

Fig. 6. Line filter inserted into the pair of dc leads of the Josephson junction array. $C = 0.22\ \mu F$, $L = 2.5$ mH.

TABLE I
COMPARISON OF CHARACTERISTICS

DC characteristics	DC resistance	0.12 Ω
	Inductance	5 mH
	Capacitance	0.44 μF
Leakage resistance	Wire to wire resistance	1.5×10^{12} Ω
	Wire to guard resistance	2.0×10^{14} Ω
Low pass filter characteristics	−3 dB cut off frequency	53 kHz
	Attenuation at 150 kHz	−60 dB
	1 MHz	−80 dB
	10 MHz	−80 dB

can be caused by a dc bias supply source for the Josephson junction array or electromagnetic inteference from an environment.

In order to prevent noise from producing instability and consequently large uncertainties in voltage calibration, we designed a line filter based on the following considerations.

A. Design Parameters of the Line Filter

1) DC Resistance: Allowable maximum dc resistance of the filter, R_F, is determined from a voltage drop developed by an input leakage current of the null detecting DVM flowing though the filter. We characterized the voltage drop less than 0.1 nV, i.e., 1/100 of one digit resolution of the DVM. As the drift of the input leakage current is 5 pA, which cannot be cancelled out simply by reversing the high and low of the DVM input, R_F should be less than 20 Ω (= 0.1 nV/5 pA).

2) Leakage Resistance: Since the output resistance of the model 732A Zener voltage reference is about 1 kΩ, it is necessary to keep the leakage resistance of overall JJAVS at least 10^{11} Ω in order to obtain the uncertainty less than 10^{-8}. For the filter itself, the leakage resistance is preferably more than 10^{12} Ω.

3) Low-Pass Filtering Characteristics: This depends on the character of noise coming from the environment around JJAVS and noise generated inside the JJAVS circuit including the Zener voltage reference and the null detecting DVM. The best result in our case has been as described in Table I.

B. Realization of The Line Filter

We have realized the line filter by using two sections of *LC* circuit as shown in Fig. 6. The components are common mode chokecoils with ferrite cores, 2.5 mH, PLH20H-2523RO (Murata) and polypropylene capacitors, 0.22 μF, MKP-1845 (ERO). Filtering characteristics are shown in Fig. 7 and summarized in Table I with other parameters.

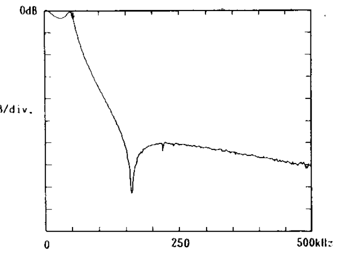

Fig. 7. Low-pass filtering characteristics of the line filter shown in Fig. 6.

As a result of filtering, we can keep a Josephson junction array on a constant (and arbitrarily chosen) Josephson voltage step for 10 min or more. We can complete a series of voltage differences measurements for the calibration of a Zener voltage standard in 30 min, with an uncertainty of 1.3×10^{-8} [1].

In the use of the filter, we are influenced by the paper of Clarke *et al.* [3].

V. Conclusion

Considerable modification of the PLL circuit system has been carried out to make the frequency stability high enough for a commercially available PLL Gunn oscillator. A low-pass filter has been designed and inserted into the outside dc circuit of a Josephson junction array to minimize unintentional voltage transitions between Josephson steps. These techniques, together with optimum selection of the digital voltmeter for null detection, are essential to successful operation of the Josephson junction array voltage standard system with a sufficient stability and the uncertainty of 1.3×10^{-8} as reported in [1].

Acknowledgment

The authors would like to thank K. Yoshihiro and C. Yamanouchi for their kind discussions. They wish to thank T. Sakuraba and A. Odawara for their technical assistance.

References

[1] Y. Sakamoto, H. Yoshida, T. Sakuraba, A. Odawara, V. Murayama, and T. Endo, "Josephson junction array voltage standard at the ETL," *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 312-316, this issue.

[2] See, for example, J. Niemeyer and L. Grimm, "The present status of the PTB voltage standard with Josephson series arrays," CCE/86-53, 1986. R. L. Steiner and B. F. Field, "Josephson array voltage calibration system: Operational use and verification," *IEEE Trans. Instrum. Meas.*, vol. 38, pp. 296–301, Apr. 1989.

[3] J. Clarke, A. N. Clealand, M. H. Devort, D. Esteve, and J. M. Martinis, "Quantum mechanics of a macroscopic variable: The phase difference of a Josephson junction," *Science*, vol. 239, pp. 992–997, Feb. 1988.