Improvements in the Millimeter-Wave Subsystem for Josephson Junction Array Voltage Standard Systems

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

Abstract—**Improvements in the millimeter-wave subsystem have been accomplished to provide higher millimeter-wave power to a Josephson junction array chip. The 94-GHz oscillator output power has been increased to 90 mW by incorporating an InP Gunn diode. The frequency stability of the InP Gunn oscillator is maintained at 10^{-10} of the center frequency. A low-loss dielectric waveguide has been installed in liquid helium to reduce the insertion losses of the millimeter waves to 3 dB/2.5 m. The improved millimeter-wave system has been confirmed to operate well in a Josephson junction array voltage standard system for voltage calibration at the 1-V level with the specified accuracy.**

I. Introduction

JOSEPHSON junction array voltage standard (JJAVS) systems [1] are operated at most industrialized nations' standard laboratories to maintain their voltage standards. JJAVS's can generate very precise reference voltages of 1 V, and recently up to 10 V. An increasing number of industrial calibration laboratories is lately using JJAVS systems to guarantee the accuracy of measured data of commercially available precision instruments. Increasing the working voltage range and improving the operation stability are therefore important developments for the routine operation of JJAVS systems.

The Josephson effect describes the tunneling of superconducting electron pairs in a weak link structure commonly called the Josephson junction. For voltage standard applications, the Josephson junction can be simply regarded as an ideal frequency-to-voltage converter. An externally applied high-frequency signal generates quantized dc voltages V_n across the superconducting electrodes of a Josephson junction device:

$$V_n = \frac{nf}{(2e/h)} = \frac{nf}{K_{J-90}} \tag{1}$$

where

f: frequency of the drive signal
n: integer
e: electron charge
h: Planck's constant
K_{J-90} = 483 597.9 GHz/V: conventional value of the Josephson constant [2].

The generated dc voltage V_n is only a function of the step number n and the drive frequency f which both can be accurately determined. Thus, the Josephson effect is ideal for the generation of very precise dc voltages.

Referring to (1), higher dc Josephson voltages can be generated by increasing the step number n and the drive frequency f. However, the step number n is practically limited by the millimeter-wave power coupled to the Josephson junction. The highest stable dc voltage generated by a single Josephson junction is roughly equal to the amplitude of the millimeter-wave voltage across the junction. A typical step number of $n = 2$ produces a dc voltage V_n of about 400 μV. Modern Josephson voltage standards increase the dc Josephson voltage by connecting many junctions in series and adding up the individual step numbers n to generate voltages higher than 1 V. Fig. 1 shows a photograph of a Josephson junction array (JJA) chip designed and fabricated at the Electrotechnical Laboratory for 1-V calibrations. The chip comprises an antipodal finline taper and a 127-mm-long, folded superconducting microstrip line incorporating 3000 Nb/AlO_x/Nb Josephson tunnel junctions. In order to adjust the total step number of the JJA, an external dc bias circuit is connected to the dc electrodes of the chip, and all junctions of the whole array are biased by this single dc source. The part of the chip with the antipodal finline taper has to be inserted into a standard waveguide to couple the millimeter waves from the waveguide to the microstrip line. Numerical simulations and experimental studies of high-frequency driven Josephson junctions have shown that the frequency of the driving signal should lie in the range of 70–100 GHz in order to drive this type of single-biased, many-junction Josephson array successfully [3]. Within this working frequency range, higher millimeter-wave power and higher frequency are advantageous for generating higher dc voltages under stable operation conditions of the JJAVS. These requirements are a challenging subject since with increasing frequency, the output power of an oscillator generally decreases and the insertion losses of the millimeter-wave components become larger. If higher millimeter-wave power can be fed to the JJA chip, the array will generate higher maximum dc voltages and

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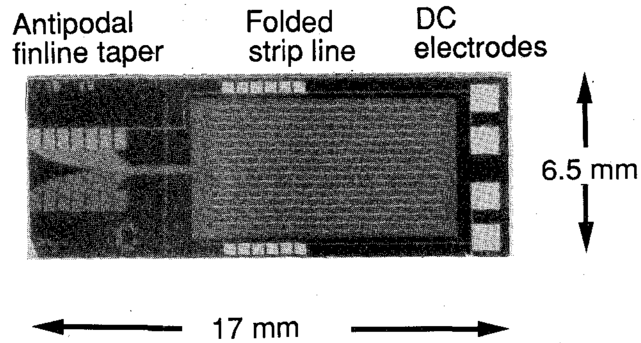


Fig. 1. A Josephson junction array chip incorporating 3000 $Nb/AlO_x/Nb$ Josephson tunnel junctions.

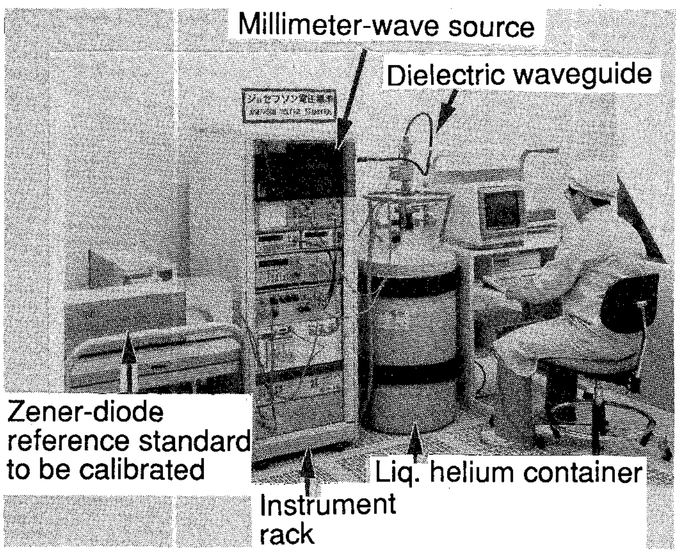


Fig. 2. Photograph of a JJAVS system.

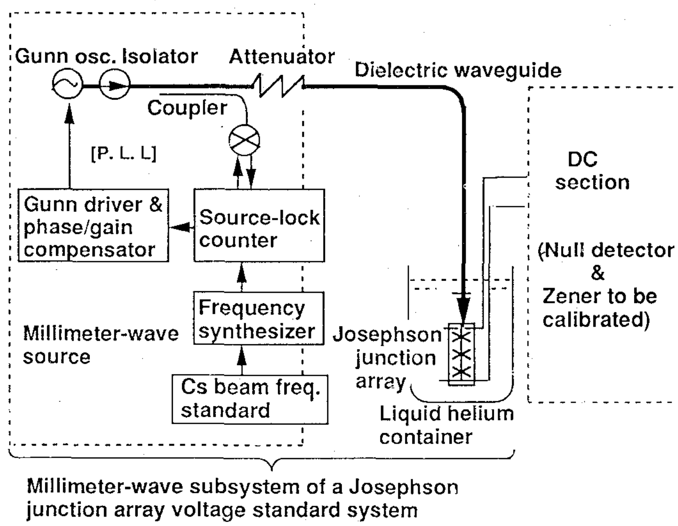


Fig. 3. Block diagram of the JJAVS system. Millimeter-wave subsystem is composed of phase-locked millimeter-wave source installed in the instrument rack (drawn inside of the dotted-line box) and a dielectric waveguide.

operate with higher stability at the lower working voltage. The purpose of the study presented in this paper is to improve the performance of the millimeter-wave subsystem of the JJAVS in order to feed higher millimeter-wave power to the JJA chip.

Fig. 2 shows a photograph of an industrially used 1-V JJAVS system that automatically calibrates the output voltage of Zener diode reference standards [4]. The block diagram of the system is shown in Fig. 3. The millimeter-wave source consists of a Gunn oscillator driven in a phase-locked loop. Although klystrons are able to provide higher output power, they are not suited for the industrial use of JJAVS systems since they require bulky high-voltage power supplies and water cooling. Therefore, the purpose of this work was to increase the available output power of the millimeter-wave solid-state oscillator. A detailed description of the new Gunn oscillator and its characteristics are presented in Section II.

The JJA chip has to be immersed in liquid helium in order to be cooled below its superconducting transition temperature. As seen in Fig. 2, the length of the millimeter-wave transmission line measures more than 2 m from the millimeter-wave oscillator located in an instrument rack at room temperature to the JJA chip at the bottom of the liquid helium container. As conventional metal waveguides show considerable insertion losses in the frequency range of the driving millimeter wave, a low-insertion-loss dielectric waveguide has been installed between the low-temperature and the room temperature parts of the millimeter-wave subsystem. Details of the dielectric waveguide are described in Section III.

Section IV summarizes the characteristics of the JJAVS system utilizing the improved millimeter-wave subsystem.

II. Millimeter-Wave Source

The millimeter-wave source of the JJAVS system has to provide sufficiently high output power for the stable operation of the JJA at the desired voltage level, as well as high-frequency stability to ensure the required accuracy for calibration services.

The maximum available millimeter-wave power imposes rigid limitations on the design and fabrication technology of JJA devices. As the output power of currently available, commercial solid-state oscillators is only marginally higher than the minimum power needed for Josephson voltage standard applications, the single junctions in modern Josephson arrays are commonly operated at low dc Josephson voltages that require a rather low HF voltage amplitude of the driving millimeter wave. Any increase in available output power therefore results directly in higher dc Josephson voltages generated by the JJA in practical use, in more stable operation conditions, and in design rules for JJA chips that are easier to meet by the established fabrication technologies.

The desired uncertainty for voltage calibration services is on the order of one part in 10^8. In order to guarantee the required accuracy of the JJAVS system, the frequency stability of the millimeter-wave source has to be at least on the order of 10^{-9}, but preferably higher.

Up to now, a commercially available 94-GHz GaAs Gunn oscillator with an available output power of 60 mW has been used as the millimeter-wave source in the 1-V JJAVS system at ETL. In order to increase the millimeter-wave power, a newly developed InP Gunn diode [5] has been tested in the JJAVS system. Generally speaking, the use of InP material for Gunn effect mode oscillation in the millimeter wave region has been predicted to be efficient compared with GaAs material because of the high peak-to-valley ratio of the electron velocity as a function of applied electron field.

The new InP diode features a special doping profile of the active layer with a linearly increasing impurity density from cathode to anode. As a consequence of the graded doping profile, the electric field strength is raised near the cathode, thus reducing the dead space region in the active layer across which the Gunn domain transits, and increasing the efficiency of the device. The epitaxial n–n^+ layers of the diode are grown by low-pressure organometallic chemical vapor deposition (MOCVD) on a highly S-doped (n^+) InP substrate, and the 1-μm-thick active n-layer has an average doping density of 1.8×10^{16} cm^{-3}. Such a structure allows fundamental mode oscillation at 94 GHz with 3.0% efficiency. These features are different from the conventional InP Gunn diode which has a flat doping profile [6].

The packaged Gunn diode has been mounted in a standard WR-10 waveguide cavity. As a structural part of the dc bias post, a disk resonator is placed between the Gunn diode and a waveguide section of reduced height. The disk resonator has a $\lambda/4$ diameter and serves as an impedance matching device between the low-ohmic diode and the waveguide. With a Q-factor of 50, the disk resonator also determines the mechanical tuning range of the oscillator from 92 to 94.5 GHz.

An appropriate bias voltage at 94 GHz is 4.3 V, and the dc current saturates at about 900 mA. The characteristics of oscillation frequency and output power, as well as the tuning sensitivity of the InP Gunn oscillator are shown as a function of bias voltage in Figs. 4 and 5, respectively. The output power of the newly designed Gunn oscillator is more than 90 mW, or more than 1.5 times higher compared with the conventional GaAs Gunn oscillator. The output power of the InP Gunn oscillator is limited by the heating of the Gunn diode. The InP Gunn diode is able to supply an output power higher than 100 mW by increasing the bias voltage and improving the heat conduction away from the diode. The single-sideband AM carrier-to-noise ratio of the InP Gunn oscillator has been found to be better than 70 dB in the frequency range from 93.5 to 94.5 GHz, measured in a 1-kHz bandwidth at 100 kHz from the carrier. As for the higher power solid-state millimeter-wave source, a continuous wave IMPATT oscillator is also commercially available, but it cannot be used as a millimeter-wave source for JJAVS system because of its inferior spectrum purity.

The frequency of the Gunn oscillator has to be stabilized in a phase-locked loop (PLL) in order to meet the specifications for its use in the JJAVS system. With an optimized Gunn oscillator driver that was proposed by the authors, a frequency stability of the GaAs oscillator of 3×10^{-11} (peak to peak) has been established with counter reading [7]. The GaAs Gunn oscillator requires a 10-V bias voltage at a dc current of 200 mA. The circuit diagram of the Gunn driver is shown in Fig. 6. The circuit can be adjusted to provide different dc bias voltages to the Gunn oscillator by simply changing the value of the level shifter. In order to optimize the frequency regulation of the PLL, the phase and gain lag compensations at high frequencies ($R13$–$C21$ and $R11$) have to be individually matched to the specific characteristics of the Gunn oscillator. Fig. 7 shows the frequency stability of the InP Gunn oscillator for (a) the free-running oscillator, and (b) the oscillator in the PLL with the Gunn driver circuit adjusted to the 4.3 V bias voltage of the InP diode. The frequency fluctuation shows a standard deviation of 0.9 Hz, and the mean of the measured oscillation frequency has an 0.4-Hz

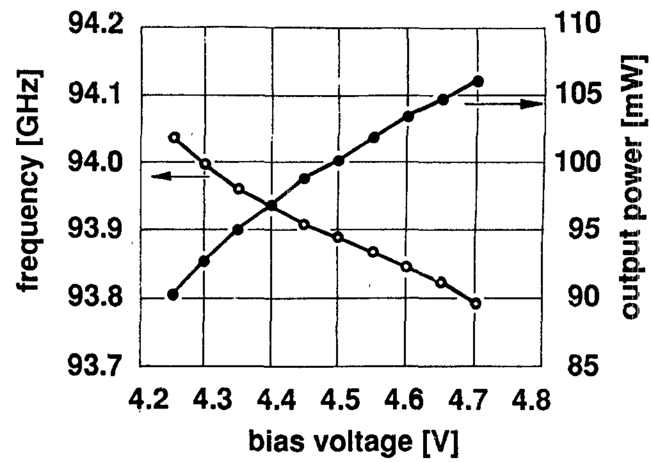


Fig. 4. Frequency and output power versus bias voltage of the InP Gunn oscillator.

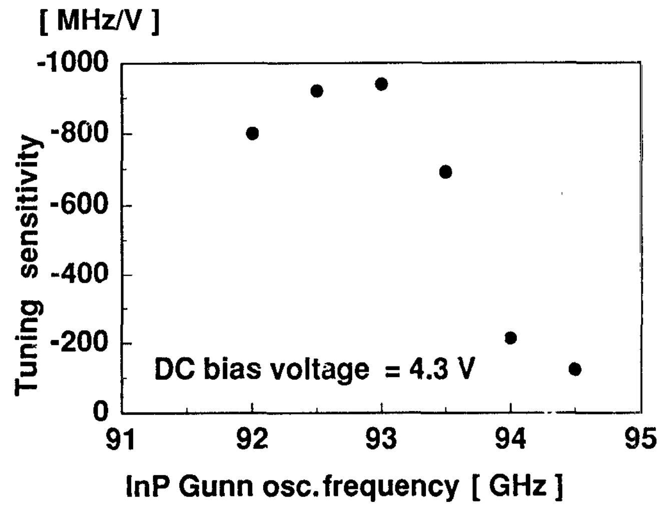
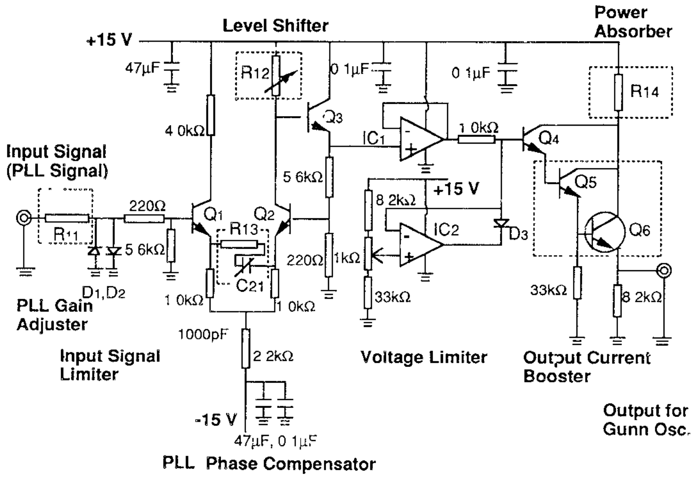


Fig. 5. Tuning sensitivity of the InP Gunn oscillator. This diagram is used for the design of the Gunn oscillator driver to realize stable phase-lock operation.



Active devices	D1~D3 1S953 (NEC) IC1,IC2 : OP07 (TI) Q1~Q4 · 2SC4C0Y(Toshiba) , Ic=100mA, Pc=250mW Q5 . 2SC2098(Toshiba) , Ic=6A, Pc=20 W Q6 . 2SC2681(NEC) , Ic=10A, Pc=100W Q6 only for InP Gunn oscillator
Adjustable devices	R11 · 3.3 kΩ Trimmer R12 4 0 kΩ + 100 Ω (Variable Resistance) R13 : 680 Ω Trimmer C21 : 1000 pF Trimmer R14 : 10 Ω (10 W) (Variable Resistance)

Fig. 6. Circuit diagram of the Gunn oscillator driver.

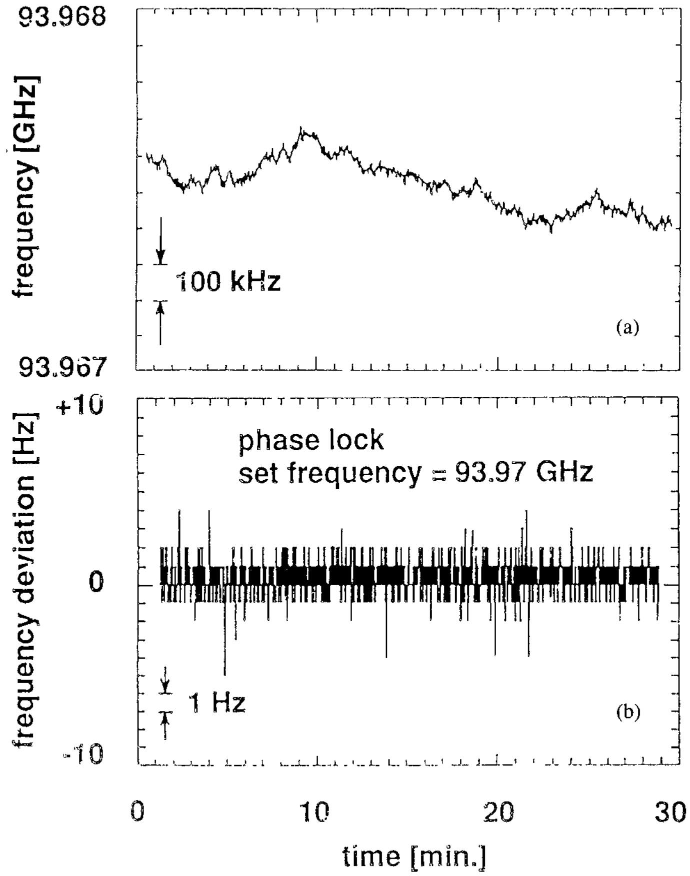


Fig. 7. Record of frequency fluctuation of (a) free-running and (b) phase-locked InP Gunn oscillator. The frequency is measured by a frequency counter with 1-Hz resolution and the gate time was set to 1 s. (a) Free-running data were taken 5 h after switching on the power supply. (b) Phase-lock set frequency is 93.97 GHz. The mean frequency has an offset of 0.4 Hz from the set frequency. The frequency distribution shows a standard deviation of 0.9 Hz.

offset from the set frequency of 93.97 GHz. The achieved frequency stability is about 1×10^{-10} (peak to peak), which is about ten times better than the required minimum stability. It is expected that the frequency stability of the InP Gunn oscillator can be improved by trimming the phase and gain compensation and by employing the modified output current booster ($Q5$–$Q6$) that allows for the four–five times higher dc current in the InP diode. The power spectrum of the frequency-stabilized InP Gunn oscillator as it is used in the JJAVS system is shown in Fig. 8.

III. Millimeter-Wave Transmission Line

A. Dielectric Waveguide

The length of the millimeter-wave transmission line, from the millimeter-wave oscillator located at room temperature to the JJA chip at the bottom of the liquid helium container, measures more than 2 m. A 2.5-m-long standard WR-10 copper waveguide (75–110 GHz) has insertion losses as high as 11.3 dB at 94 GHz. Significant improvements in the power transmission have been realized by using a dielectric waveguide instead of a metal waveguide. Fig. 9 shows the structure of the dielectric waveguide, which is similar to that of an optical fiber. It is composed of a porous polytetrafluoroethylene (PTFE) core with a relatively high dielectric constant ($\epsilon_r = 1.70$) and a surrounding cladding of a low dielectric constant PTFE ($\epsilon_r = 1.26$). The outer circumference of the dielectric waveguide is covered by a copper foil for electromagnetic shielding. Insertion losses of the dielectric waveguide are typically as low as 0.9 dB/m. Critical parts

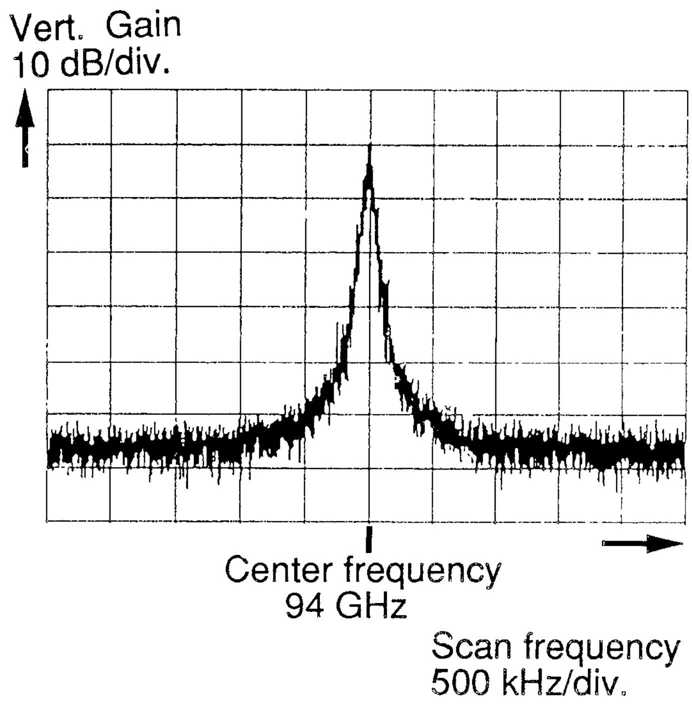


Fig. 8. Power spectrum of phase-locked InP Gunn oscillator at 94 GHz.

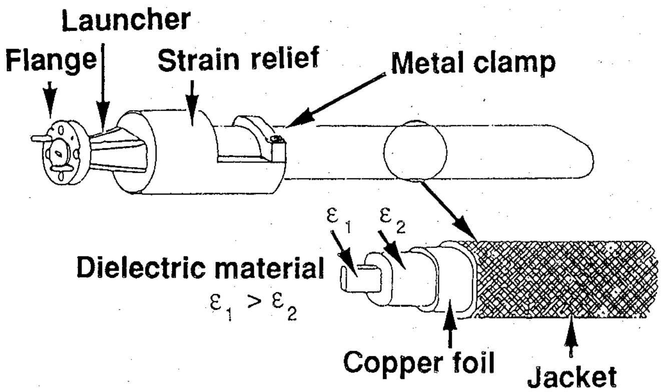


Fig. 9. Configuration of dielectric waveguide. Launcher is a transitional part between metal and dielectric waveguide. Strain relief part fixes the launcher to the dielectric waveguide mechanically.

for the overall performance of the dielectric waveguide are the launchers at both ends of the dielectric waveguide that act as transitions between the dielectric waveguide and a standard metal waveguide. By carefully assembling these launchers to the dielectric waveguide, the mismatch loss of each launcher can be kept as low as 0.38 dB. Thus, the total insertion loss (summing of the mismatch losses of in/output launcher and transmission line loss) of a 2.5-m-long dielectric waveguide with launchers assembled at both ends is only about 3 dB.

The use of the dielectric waveguide in a voltage standard system requires that one end of the dielectric waveguide is immersed in liquid helium. Any change in the insertion loss at low temperatures is therefore of interest. In order to investigate the low-temperature performance of the dielectric waveguide, the following experimental measurements were performed. The S parameter S_{11} at the room temperature end of the waveguide was determined after shorting the far end with a blind flange. The far end was then cooled down from room temperature to liquid helium temperature by immersing the shorted waveguide end into a liquid helium bath. The S parameter S_{11} was continuously monitored, but did not indicate any difference. Hence, it can be concluded that the temperature variation from room temperature to liquid helium temperature does not cause any significant changes in the insertion loss of the dielectric waveguide.

The launchers are mechanically attached to the dielectric waveguide by a strain relief gadget (see Fig. 9). For commercially available standard dielectric waveguides, this strain relief part is made of plastic that cannot stand very low temperatures. The low-temperature end of the dielectric waveguide thus had to be modified by employing a metal clamp as shown in Fig. 9. The modified version of the dielectric waveguide has now been working in a JJAVS system without a problem for more than three years.

IV. Results and Conclusion

The InP Gunn oscillator provides an output power of 90 mW at 94 GHz. Other components in the millimeter-wave subsystem (isolator, directional coupler, attenuator, and a 15-cm-long metal waveguide) have a total insertion loss of 5.1 dB. Using the 2.5-m-long dielectric waveguide with 3 dB insertion loss, the millimeter-wave power at the input flange of the Josephson junction array holder in liquid helium has been increased to 14 mW before propagating through the finline antenna. Fig. 10 shows the dc current–voltage characteristics of the 1-V JJA chip shown in Fig. 1. The improved millimeter-wave subsystem was used to drive the Josephson junction array, and the dc characteristics display quantized dc Josephson voltages up to 2.7 V. The GaAs Gunn oscillator, which has 60 mW output power at 94 GHz, produces Josephson voltages up to 2.2 V on the same Josephson junction array. A JJAVS system incorporating the improved millimeter-wave subsystem was tested for voltage calibrations at the 1-V level and worked successfully within its specified accuracy of 0.013 ppm. The system has been confirmed as a useful voltage standard.

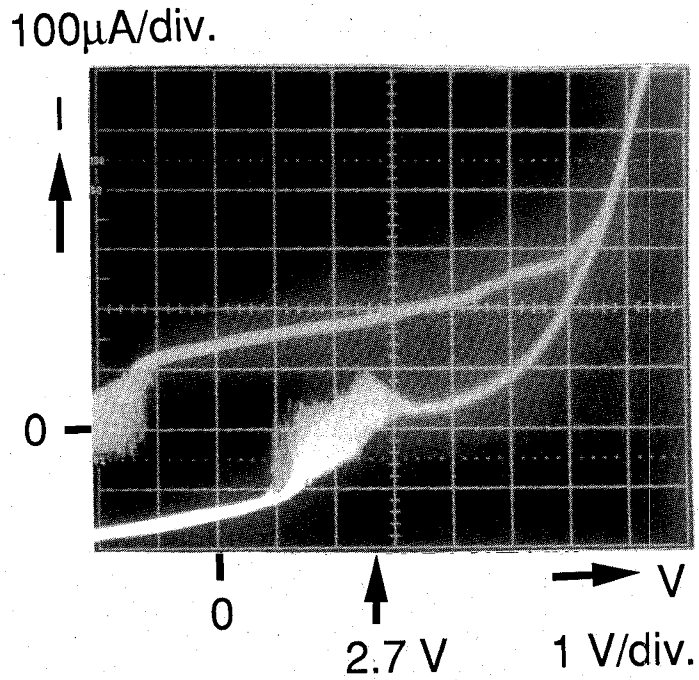


Fig. 10. Current–voltage characteristics of the Josephson junction array shown in Fig. 1 and driven by the improved millimeter-wave subsystem. The white area seen at the voltage range between 1 and 3 V is a trace of many vertical lines 194 μV apart (quantized Josephson voltage steps). Highest voltage of the zero crossing steps (i.e., Josephson voltage steps that cross the voltage axis) is 2.7 V. The JJAVS system can be used for the calibration of dc voltages up to this value.

Besides the comfortable safety margin for stable operation conditions of the 1-V JJAVS system that has been achieved by the improved millimeter-wave subsystem, the increase of the available millimeter-wave power is also important for the future design and operation of easy-to-use Josephson voltage standards at considerably higher voltages. The accomplished improvements therefore present a practically important part of the development of more advanced JJAVS systems for the calibration service in national standard laboratories, as well as in industrial calibration laboratories.

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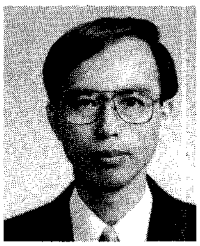
REFERENCES

[1] R. Pöpel, "The Josephson effect and voltage standards," *Metrologia*, vol. 29, pp. 153–174, May 1992.
[2] B. N. Taylor and T. J. Witt, "New international electrical reference standards based on the Josephson and quantum Hall effects," *Metrologia*, vol. 26, pp. 47–62, Mar. 1989.
[3] R. L. Kautz, C. A. Hamilton, and F. L. Lloyd, "Series-array Josephson voltage standards," *IEEE Trans. Magn.*, vol. MAG-23, pp. 883–890, Mar. 1987.
[4] Y. Sakamoto, H. Yoshida, T. Sakuraba, A. Odawara, Y. Murayama, and T. Endo, "Josephson junction array voltage standard at the ETL," *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 312–316, Apr. 1991.
[5] A. Yokohata, K. Suga, A. Kodama, S. Kato, H. Kurita, and M. Ohmori, "Millimeter-wave InP Gunn diodes with linearly graded profiles grown by low pressure MOCVD," in *3rd Asia-Pacific Microwave Conf. Proc.*, Tokyo, 1990.
[6] F. B. Frank, J. D. Crowlay, M. C. Buswall, C. Hang, P. H. Wolfart, D. Tringali, and L. Y. Ching, "High efficiency millimetre wave oscillators and amplifiers," *Electron. Eng.*, pp. 39–42, June 1985.
[7] H. Yoshida, Y. Sakamoto, and T. Endo, "Circuit precautions for stable operation of Josephson junction array voltage standard," *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 305–308, Apr. 1991.



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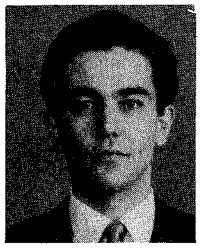

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