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Improvements in the Millimeter-wave System for Josephson Junction Array Voltage Standard Systems

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Abstract

Improvements in the millimeter-wave system have been accomplished in order to generate higher and more accurate Josephson voltages directly. The 94-GHz oscillator output power has been increased to 90 mW by incorporating a new InP Gunn diode, and a low-loss dielectric waveguide has been installed in liquid helium in order to increase the millimeter-wave power available at the input of the Josephson junction array chip. The stability of the millimeter-wave frequency has been improved to the order of 10^{-11}. The losses of the waveguide-to-microstrip transition have been investigated but remain a matter of further improvements.

I. Introduction

Josephson junction array voltage standard (JJAVS) systems have been serving not only the national standard laboratories but also industrial calibration laboratories as calibration standards, replacing conventional electro-chemical standard voltage cells. A photograph of an industrially used JJAVS system that automatically calibrates Zener diode based reference standards (ZDRS), and its block diagram are shown in Fig. 1 and Fig. 2, respectively. As follows from the ac Josephson effect, a macroscopic quantum effect, dc voltage steps are generated across a superconducting Nb/Al/Al-Oxide/Nb Josephson junction array (JJA) which is driven by an external millimeter-wave signal. The quantized dc Josephson voltage is simply given as a function of the millimeter-wave frequency by the well-known relation

$$V_n = n \frac{f}{K_{J\text{-}90}}, \qquad (1)$$

where

V_n : n-th quantized dc Josephson voltage,
n : total step number (integer),
$K_{J\text{-}90}$: Josephson constant [1],
f : millimeter-wave frequency.

Thus, the JJA can be regarded as an ideal frequency-to-voltage converter. The purpose of this paper is to describe the improvements in the millimeter-wave part of the JJAVS system that have been accomplished in order to drive larger arrays that generate higher Josephson voltages directly and therefore require higher millimeter-wave power, and to enhance the accuracy of the dc Josephson voltage by increasing the frequency stability.

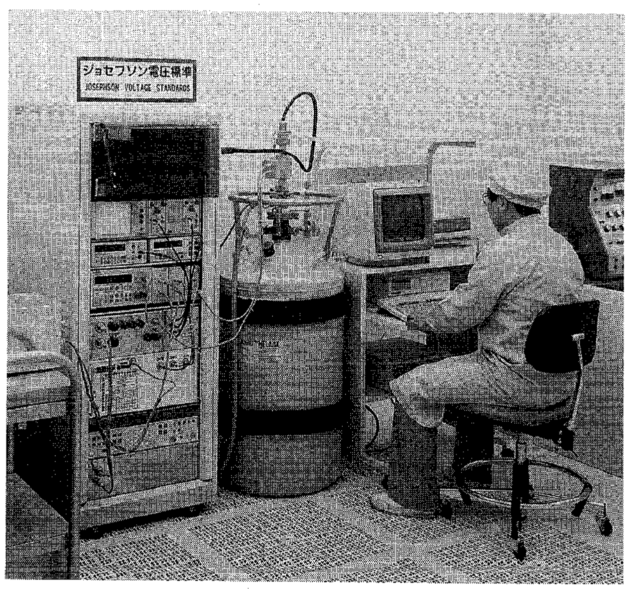

Fig.1 Photo of an industrially used JJAVS system

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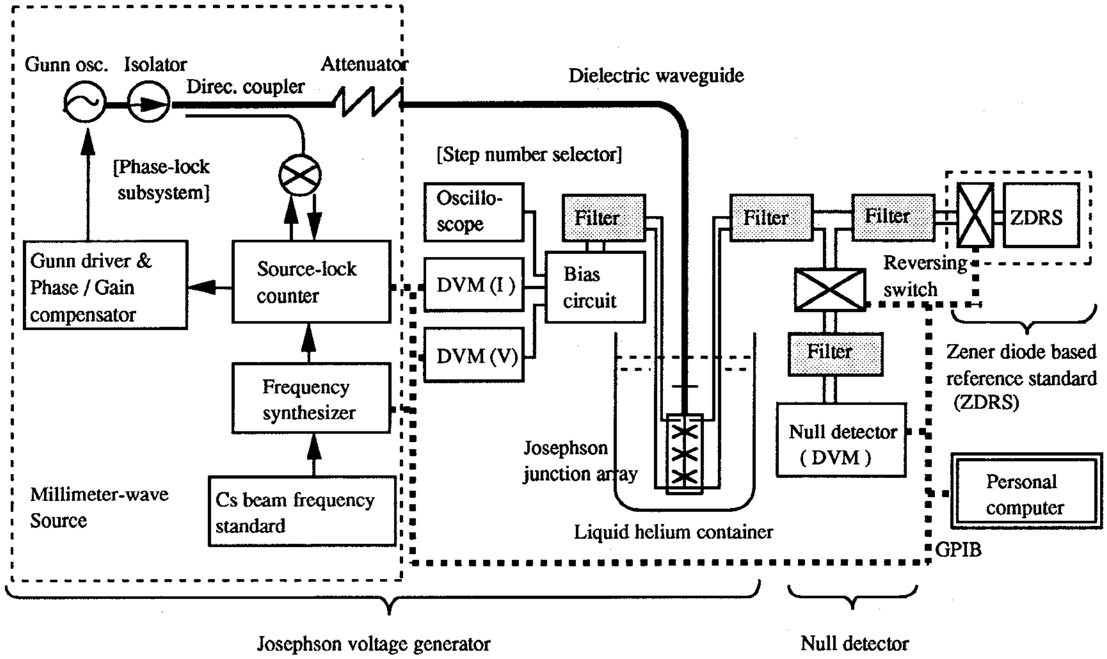

Fig. 2 Circuit configuration of an automated JJAVS system. The dotted-line box encloses the millimeter-wave source subsystem.

II. Millimeter-wave source

2-1 Improvement in the Gunn oscillator power

For the JJAVS system in practical use, a solid-state Gunn oscillator has been used as the millimeter-wave source instead of a Klystron which requires a bulky high-voltage power supply and water cooling [2]. A recently developed InP Gunn diode provides an oscillator output power of 90 mW at a frequency of 94 GHz [3].

The new diode has 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 and the dead space region in the active layer across which the Gunn domain transits is reduced. The output power of the newly designed Gunn oscillator is more than 1.5 times higher compared with a conventional GaAs Gunn oscillator. The characteristics of oscillation frequency and output power of the InP Gunn oscillator are shown in Fig. 3 as a function of bias voltage.

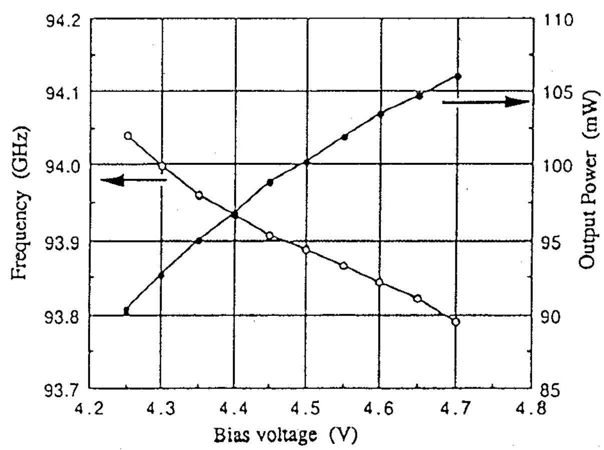

Fig.3 Characteristics of the new InP Gunn oscillator (Oscillation frequency and output power vs bias voltage)

2-2 Stabilization of the millimeter-wave frequency

According to equation (1), the accuracy of the Josephson voltage depends directly on the accuracy of the millimeter-wave frequency. Improvements in the frequency stabilization of the Gunn oscillator that contribute to a higher frequency accuracy by using an appropriate phase and gain compensation in the phase-locked circuit were proposed by the authors in 1990 [4]. The improved behavior of frequency fluctuations is shown in Fig. 4, resulting in a frequency stability of 3 $\times 10^{-11}$ which is three orders of magnitude better compared to using a commercial Gunn driver. The stabilization circuit developed for the JJAVS system as the national standard at the Electrotechnical Laboratory (ETL) has been used since then at the Bureau International des Poids et Mesures (BIPM) [5] and a number of other laboratories.

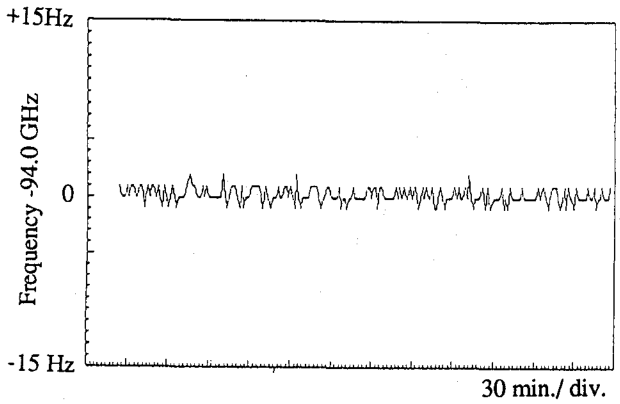

Fig. 4 Frequency fluctuation of the stabilized Gunn oscillator that drives the Josephson junction array [4] .

III. Improvements in insertion losses of the millimeter-wave transmission line

3-1 Dielectric waveguide

The length of the transmission line from the millimeter-wave source installed in an instrument rack, to the top of the cryoprobe at the bottom of a liquid helium container measures at least 2 m. The power transmission losses along a 2-m standard WR-10 metallic waveguide (75 - 110 GHz) are typically 9.0 dB at 94 GHz which makes it difficult to drive even a 1-V JJA of 3,000 Josephson junctions. After improvements in the mechanical structure of the propagation mode transformer of commercially available dielectric waveguides have rectified strain relief problems in liquid helium, the metallic waveguide has been replaced by the modified dielectric waveguide.

The structure of the dielectric waveguide is similar to that of an optical fiber. It is composed of a porous polytetrafluro-ethylene (PTFE) core which has a relatively high dielectric constant ($\varepsilon_r = 1.70$) and a surrounding cladding of a low permittivity PTFE ($\varepsilon_r = 1.26$). In addition, the outer circumference is covered by a copper foil for electromagnetic shielding. Power transmission losses of the improved dielectric waveguide has been reduced to 3.0 dB for the total length of 2.5 m.

3-2 Evaluation of a transition loss of the finline antenna in liquid helium

The millimeter wave that propagates along the waveguide is coupled to the microstrip line comprising the JJA by a finline antenna. The finline antenna can be regarded as an impedance and mode transformer from waveguide (Z_0=377 Ω) to microstrip line (Z_0=8 Ω).

As the transition (or transmission) losses of the finline antenna fabricated on the same wafer with the Josephson array and immersed in liquid helium is difficult to be measured directly, we have estimated its value by measuring reflection coefficient S_{11} in the frequency domain. The reflection coefficient s_{11} in the time domain can be obtained by applying an inverse Fourier transform to the frequency domain data. The calculated s_{11} in the time domain are shown in Fig. 5 and the according s_{11} value of the finline antenna is 2.0 dB. This corresponds to an estimated transmission loss of 4.3 dB which is equal to a power transmission of 36.9%.

The insertion losses and corresponding output powers of each part of the improved millimeter-wave transmission line are listed in Table-1. Thus, the power available at the input of the JJA is approximately 5 mW.

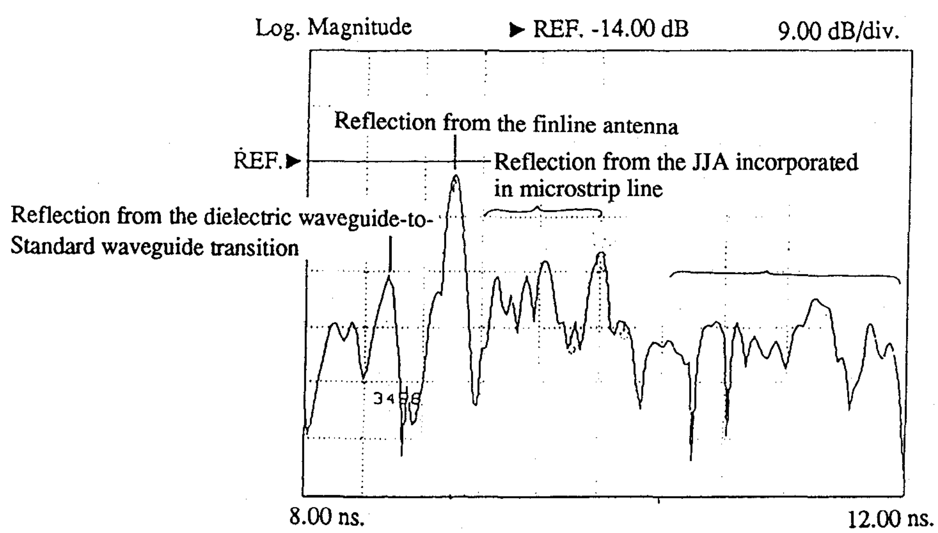

Fig. 5 Time domain reflection coefficient s_{11} of the finline antenna and the Josephson junction array

Table-1

Millimeter-wave device	Transmission loss (dB)	Output power (mW)
(1) Gunn oscillator		90.0
(2) Isolator	2.3	53.0
(3) Directional coupler	1.3	39.3
(4) Attenuator	1.0	31.2
(5) Standard waveguide	0.5	27.8
(6)Dielectric waveguide	3.0	13.9
(7) Coupling waveguide	0.3	13.0
(8) Finline antenna	4.3	4.8
(9) Josephson junction array	3.8	

Insertion loss and corresponding power at the output of each component of the millimeter-wave system which is shown in Fig. 2.
Large insertion loss of a metallic waveguide is replaced by the low-loss dielectric waveguide (6).

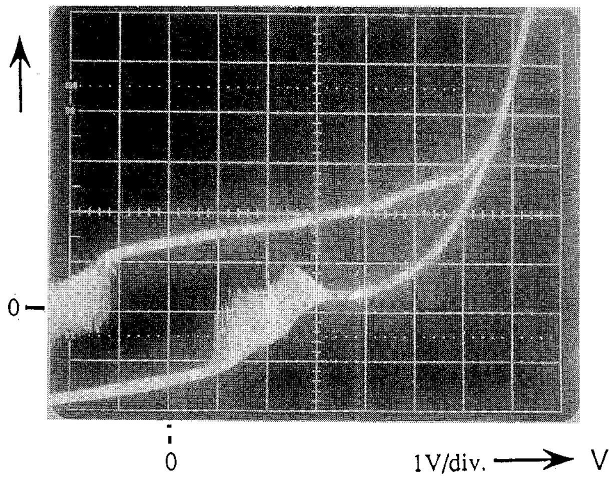

Fig.6 Josephson voltage steps obtained with 3,000 junctions in series and employing the improved millimeter-wave system

IV. Result and Discussion

A maximum dc Josephson voltage of 3.1 V has been obtained by introducing the above described improvements in the millimeter-wave system and the use of a new JJA device that has been designed and fabricated at the ETL. The new JJA design comprises a total number of 3,000 Josephson junctions. The dc characteristics obtained with the improved millimeter - wave system and showing Josephson voltage steps up to 3.1 V is shown in Fig. 6.

In order to obtain dc Josephson voltages of more than 10 V, it is important to investigate both the Josephson array and the millimeter-wave system. As regards the millimeter-wave system, improvements in the output power of the InP Gunn oscillator and in the transmission losses by employing a low-loss dielectric waveguide have been achieved, but the large transition losses of the finline antenna still remain a matter of further improvements.

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