Operation of a NbN-Based Programmable Josephson Voltage Standard Chip With a Compact Refrigeration System

A. Shoji, H. Yamamori, M. Ishizaki, S. P. Benz, and P. D. Dresselhaus

***Abstract*—A refrigeration system was designed and constructed for realizing a liquid-He-free programmable Josephson voltage standard. The system is equipped with a two-stage Gifford-McMahon cooler, a thermal-radiation shield, a magnetic-field shield and semi-rigid coaxial cables to supply microwave power to a chip. The performance of the system was examined by use of a NbN-based 8-bit digital-to-analog converter (DAC) chip designed as a 1 V programmable voltage standard. When operated at 8.5 K on the cryocooler, constant-voltage steps with amplitudes greater than 1 mA were observed for every segment of junction arrays on the chip.**

***Index Terms*—Digital-to-analog converter, Josephson junction, NbN, refrigeration system, TiN, voltage standard.**

I. Introduction

A PROGRAMMABLE Josephson voltage standard (PJVS) is expected to serve as the next-generation voltage standard because it has practically useful properties, such as a programmable output voltage, a short voltage-settling time ($<$ 1 ms) and a large operating margin ($>$ 1 mA) [1]–[3]. The programmable and rapidly selectable output voltage of a PJVS enables measurement of the gain and linearity of a voltmeter in a short period of time. The large operating margins of a PJVS make it possible for us to stably maintain a generated constant voltage.

The National Institute of Advanced Industrial Science and Technology (AIST) and the National Institute of Standards and Technology (NIST) have cooperated in the development of NbN-based digital-to-analog converters (DAC's) for a PJVS [4]. NbN-based DAC's have the capability of operating at temperatures of around 10 K [4]. The main advantage of NbN-based DAC's is that they do not require liquid He, thus enabling their operation using simpler 10 K cryocoolers.

In this paper, we describe a refrigeration system designed for demonstrating a liquid-He-free PJVS and operation of an 8-bit DAC chip with the system.

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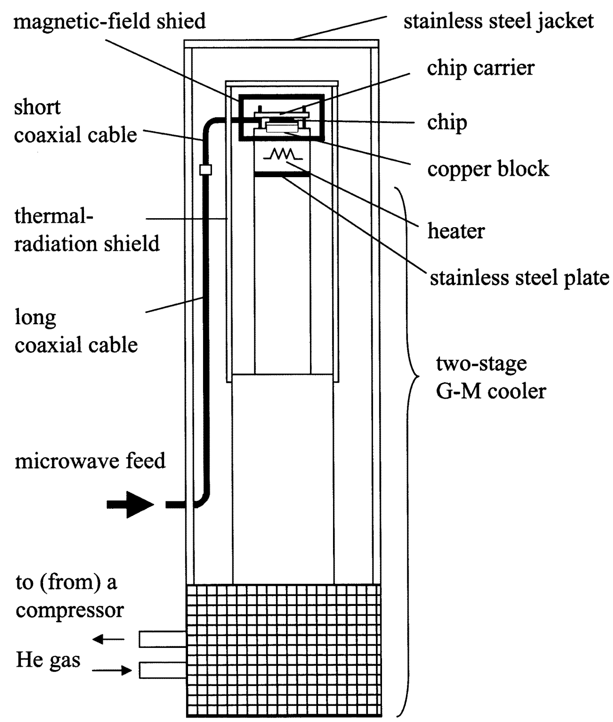

Fig. 1. A refrigeration system designed for a programmable Josephson voltage standard. The height of the system is about 500 mm. The diameter of the stainless steel jacket is 120 mm.

II. Refrigeration System

The structure of the refrigeration system is schematically shown in Fig. 1. The system consists of a two-stage Gifford-McMahon (G-M) cooler, a thermal-radiation shield, a magnetic-field shield, semi-rigid coaxial cables, a heater and a stainless-steel jacket to keep the inside of the system under vacuum. The height of the system is about 500 mm and the diameter of the jacket is 120 mm. The G-M cooler can cool a chip on its cold head to below 4 K and has a cooling power of 0.1 W at 4.2 K. The thermal-radiation shield, consisting of a cylindrical copper plate and a copper cap, both of which are covered with a gold film, prevents room temperature thermal radiation from heating the cold head of the cooler and the chip. The magnetic-field shield, consisting of a μ-metal can and a μ-metal cap, protects the chip from terrestrial and stray magnetic fields.

To feed microwave power to the chip, we employ a combination of a long semi-rigid coaxial cable (440 mm) with center and outer conductors of silver-painted cupronickel and a short

TABLE I
TECHNICAL SPECIFICATIONS OF THE REFRIGERATION SYSTEM

Cryocooler	
Type	**Two-stage Gifford-McMahon cooler**
Cooling power	**0.1 W at 4.2 K**
Required power	**1.2 kW (AC 100 V)**
Dimension	
Cold head	**about 400 mm (height)**
Compressor unit	**380 mm × 453 mm × 451 mm**
Weight	
Cold head	**9 kg**
Compressor unit	**45 kg**
Coaxial cables	
CuNi coaxial cable	
Diameter	**0.5 mm (center conductor), 2.2 mm (outer conductor)**
Length	**440 mm**
Attenuation	**7.6 dB/m at 16 GHz**
Cu coaxial cable	
Diameter	**0.5 mm (center conductor), 2.2 mm (outer conductor)**
Length	**100 mm**
Attenuation	**2.9 dB/m at 16 GHz**
Connectors	**SMA (0.1 dB at 16 GHz)**

one (100 mm) with copper conductors. Cupronickel is selected for the long coaxial cable because it has a thermal conductivity less than one hundredth that of copper. However, the attenuation of microwave power of the silver-painted cupronickel coaxial cable is twice as large per unit length as the copper cable.

In Table I, we summarize the technical specifications of the refrigeration system. ¿From the attenuation values in the table, we estimate that the total attenuation of the coaxial cable and connectors in the system is about 3 dB.

Fig. 2(a) and (b) show a schematic cross-sectional view of the sample-holding section and its top view, respectively. Electrical contact between the chip and the chip carrier is established by use of InSn-solder bumps [5]. Thermal contact between the chip and the copper block beneath the chip is established through an In film 0.1 mm thick. The temperature of the chip is indirectly measured with a Si diode in the block. We control the temperature of the chip by supplying a dc current to a heater buried in the copper block so as to achieve an optimum I_cR_n product for the junctions, where I_c is the critical current of a junction and R_n is the normal-state resistance. However, due to the motion of a piston in the G-M cooler, the measured temperature fluctuated with an amplitude of 0.4 K, which was too large for stable operation of the DAC. In order to suppress the temperature fluctuation, we inserted a stainless steel plate 2 mm thick between the copper block and the cold head, as shown in Fig. 1. This decreased the temperature fluctuation to 0.1 K, which is sufficiently small for stable operation of the DAC.

III. DAC CHIP AND ITS OPERATION

A photograph of an 8-bit DAC chip that was fabricated at AIST is shown in Fig. 3. The size of the chip is 20 mm × 4.7 mm. The DAC chip is designed to use one tap to feed microwave power to all junctions in the chip. The microwave power was fed uniformly to the 8 junction arrays through a coplanar network circuit and dc blocking capacitors. Each array

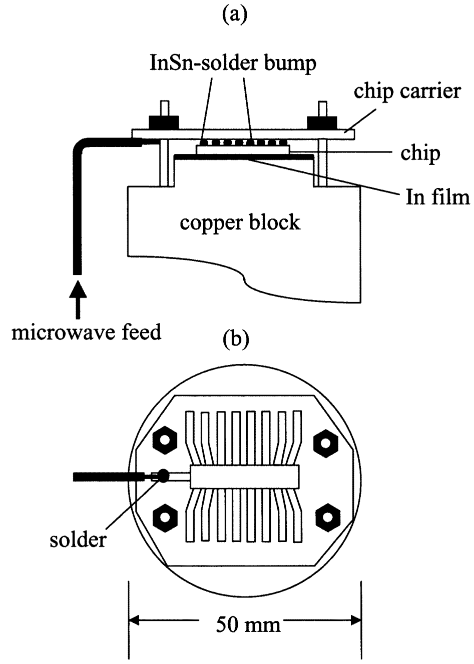

Fig. 2. Layout of the sample-holding section composed of an 8-bit digital-to-analog converter chip, a chip carrier, a copper block and a coaxial cable. (a) a cross-sectional view, (b) a top view.

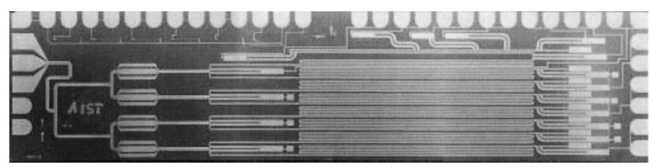

Fig. 3. Photograph of a NbN-based 8-bit digital-to-analog converter chip for a programmable voltage standard. 32 768 NbN/TiN_x/NbN junctions are included in the chip.

is composed of 4,096 NbN/TiN_x/NbN junctions with wiring made from NbN films [4]. For DAC operation, the total array containing 32 768 junctions is divided into 9 segments with 10 bias taps. The number of junctions in each of the 9 segments is: 128, 128, 256, 512, 1024, 2048, 4096, 8192 and 16 384. The 10 bias taps are connected to the array through quarter-wave-length transformers for rf blocking. Typical resistance of the Pd termination resistors is 50 Ω. The size of the junctions is $4\ \mu$m × $4\ \mu$m and the critical current density is 25 kA/cm^2.

After a sample was mounted in the refrigeration system, gases inside the system were evacuated with a turbo-molecular pump and then the G-M cooler was turned on. The temperature of the chip cooled to approximately 10 K in 4 hr. During this cooling process, flux was occasionally trapped in the junction arrays. However, the flux was readily de-trapped by raising the temperature of the chip above the critical temperature of the NbN films using a heater.

Fig. 4 shows constant-voltage steps at 8.5 K for the 8-bit DAC chip when biased with 16 GHz microwaves at 306 mW. The microwave power is measured at the output terminal of the microwave source. The step indicated by "n" in Fig. 4 corresponds to the segment containing $128 \times 2^{(n-1)}$ junctions. For example, the $n = 9$ step appearing at 1,000 mV corresponds to the junction array containing all 32 768 NbN/TiN_x/NbN junctions. As

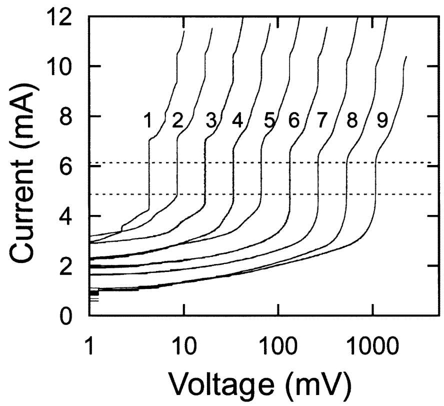

Fig. 4. Constant-voltage steps measured for 9 junction arrays in the DAC chip coupled to 16 GHz microwave power at 8.5 K. The step denoted by "n" corresponds to a junction array containing $128 \times 2^{(n-1)}$ junctions. The $n = 9$ junction array contains 32 768 junctions.

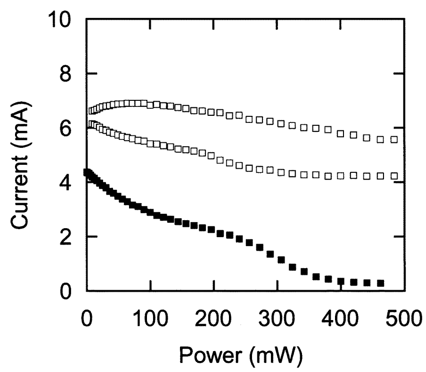

Fig. 5. Dependence of the constant-voltage step amplitude on applied microwave power for an array containing 32 768 NbN/TiN$_x$/NbN junctions. Open squares denote the maximum and minimum current values corresponding to the first constant-voltage steps and solid squares denote the zero-voltage critical currents.

seen in Fig. 4, constant-voltage steps with amplitudes greater than 1mA are observed for all of the 9 segments in the DAC.

In Fig. 5, we plot the maximum and minimum current values for the first constant-voltage step as well as the maximum current for the zero-voltage step for the $n = 9$ junction array in Fig. 4 as a function of the microwave power. While the microwave power increased up to 480 mW, the DAC chip operated normally, indicating that the temperature of the chip is not greatly changed by the largest microwave power.

IV. Summary

We have designed a refrigeration system for a programmable Josephson voltage standard. The system is equipped with a 2-stage G-M cooler, a thermal-radiation shield, a magnetic-field shield and semi-rigid coaxial cables. As a sample for evaluating the performance of the system, an 8-bit DAC chip containing 32 768 NbN/TiN$_x$/NbN junctions was fabricated. With application of 16 GHz microwave power to the chip, constant-voltage steps with amplitudes greater than 1 mA were observed for 9 junction arrays included in the chip. This result suggests that the refrigeration system constructed in this study is usable for voltage standard applications.

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