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Cryogen-free Operation of AC Quantum Voltage Standards

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Abstract

We report on the recent and ongoing activities on helium-free operation with both types of Josephson standards: programmable SNIS arrays. Helium-free operation provides ease of use, a wider number of applications and users. Moreover, they allow to reduce cable loading thus are then crucial to overcome frequency-related limitations to their ultimate accuracy. Thermalization problems not faced with helium cooling are still challenging, in particular with programmable standards. The higher temperature operation capabilities of SNIS technology is advantageous to simplify cooling issues.

Some of our recent results indicate that a careful design of the setup allows operation with short cables without affecting the cooler effectiveness. If confirmed, cryogen-free SNIS Josephson standards will prove a benefit to speed up the synthesized quantum signal frequency rather than another obstacle to overcome.

Index Terms

Josephson Junctions, Voltage standards, Cryocoolers, Temperature effects, Metrology

I. INTRODUCTION

RESEARCH on Josephson quantum standards is foreseeing a fundamental change in the Metrology of the volt, for both AC and arbitrary waveforms. The aim is a direct link to the SI from DC up to operating frequencies in the MHz range, fulfilling the requirements set today by digital instrumentation. Programmable voltage standards converting a digital code into a quantum-accurate value are already available in primary laboratories. Even more advanced standards to convert sub-nanosecond binary coded pulses into any arbitrary signal with quantum accuracy [**?**] are now actively developed and tested. Yet, the most firmly established solution to control the output voltage so far are programmable arrays that use bias currents to activate/deactivate sub-sections with series connected junctions adding-up voltages following a power of two law, as in digital to analog converters of semiconductor electronics.

Despite a long standing interest **citare** in cryocoolers for application to Josephson voltage standards, liquid helium has been the only way to cool down voltage standard arrays for decades. In recent years a constant rise in interest in cryocooled quantum standards is shown by the number of papers on the subject. Reasons for that are many. Helium-free operation provides not only ease of use and, as such, a way to widen the application of quantum systems, but is now of compelling urgency owing to the increasing cost of liquid helium and rumors of shortages to be expected in the future. Furthermore, it is now clear that the foreseen increase in quantum standards operating frequency is ultimately limited by the loading effect of cables. As a way to reduce cable loading, cryocooler based standards are then crucial to overcome frequency-related limitations to their ultimate accuracy. Yet, thermalization problems not faced with helium cooling are still challenging, in particular when programmable arrays are considered.

SNIS Nb/Al-AlOx/Nb junction technology, based on low temperature superconductors but capable of operation above liquid helium temperature, is interesting for application to a cryocooled standard, allowing to set a compromise between device and refrigerator requirements. A further requirement for cryocoler operation is the temperature stability of the electrical parameters above 4.2 K. While SIS and SNS (Superconductor-Normalconductor-Superconductor) type junctions, show a reduced temperature dependence of the electrical parameters Vc and Ic below or above 4.2 K respectively, SNIS junctions can minimize it over an extended range, by optimizing some intrinsic properties 13. The high value of $V_\mathrm{c} = I_\mathrm{c} R_\mathrm{n}$ at 4.2 K is also advantageous for cryocooler operation, since the scaling of the electrical parameters with temperature, still allows to use them at higher temperatures.

II. CRYOGEN-FREE COOLING APPARATUS

Proper cryocooler operation of a voltage standard array relies on careful thermal design to overcome issues like minimization of gradients and heat transmission. All thermal links to the outer environment should be considered and reduced to a negligible level, to keep a suitable refrigerating effectiveness. Josephson voltage standard operation in particular requires a radio frequency

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signal transmission through a microwave guide (WR-12, 60-90 GHz) that can convey significant heat to the low temperature region. We adopted a stainless steel guide, with gold internal surface coating to reduce the dramatic signal attenuation and Joule heating on the stainless steel internal surface. Josephson standard for arbitrarily shaped quantum signals generation are irradiated with pulsed radio frequency currents, typically around $20\,\mathrm{GHz}$. A coaxial cable is used for the transmission of these harmonically rich signals. In our system we adopted a special rigid coaxial cable with stainless steel both inner and outer conductors, to reduce thermal conductance (see Fig. 2). It is quickly swappable with the waveguide setup, according to the requirements of the device under test. The negligible effect of this cable on the temperature of the experiment (provided thermal anchors are realized in the proper positions), is interesting because it relies on the low thermal conductance, that allow to keep the length close to $0.5\,\mathrm{m}$. If such a shorter cable is used for the transmission of the AC signal generated by the array, a significant effect of the frequency-related signal attenuation due to cable loading can be expected. In consideration of the square law dependence of the effect on cable length, a fourfold reduction can be expected. Tests of the cables on AC signal are underway.

After several attempts, we developed a custom packaging for measuring arrays, with the chip inserted between two printed circuit boards. The copper sheet of both boards acts as thermal conductor to provide a good contact to cold finger on both the lower and upper sides of the chip. A suitable window allows chip bonding to the board pads, without damage. The cryocooler we used for measurements is a Gifford-McMahon type with 1 W cooling power at $4.2\,\mathrm{K}$, $8\,\mathrm{kW}$ compressor input power. The cold finger top was fitted with an additional disk retaining inside a deep-set thermometer that, along with a heater wire wound around it, allows fine temperature monitoring and control. A second thermometer close to the chip was used to better estimate the array operating conditions and detect unwanted thermal gradients.

III. MEASUREMENTS

IV. INTRODUCTION

Voltage metrology is several decades old, yet it still represents one of the most complex and successful achievement in superconducting electronics. Hysteretic Superconductor-Insulator-Superconductor (SIS) technology has proved successful to fabricate arrays with tens of thousands of very uniform junctions, generating up to 10 V, so that primary DC voltage calibrations now attain relative uncertainties as low as 10^{-11} [1]. Currently [2], voltage standard research is focused on the application of Josephson arrays to AC (programmable) and arbitrary signals (pulsed) [3]. So far, the most successful solution to control the output voltage are programmable Josephson arrays that use bias currents to activate/deactivate sub-sections with series connected junctions adding-up voltages following a power of two law, as in digital to analog converters of semiconductor electronics. Cryogen-free operation of superconducting devices is becoming crucial for a wider application of superconductivity [4] and bears a particular interest for Josephson standards [5], owing to the foreseeable impact of instrumentation with integrated quantum accuracy. The quest for helium-free systems is becoming more urgent, owing to the expectations of shortages in the future. Yet, presently cryocoolers for low temperature superconductors are still quite expensive and cannot provide the ease of use required for operation without specific skills. Large arrays fabricated with high critical temperature superconductors, like YBCO or the more recent MgB2 [6], are not available up to now. The most interesting results so far have been achieved using YBCO bi-crystal shunted junctions, with quantized steps above 100 mV measured near 77 K [7]. Operation above 4.2 K of junctions based on low temperature superconductors is consequently a compelling issue. Among these, NbN/TiN/NbN have demonstrated operation at these temperatures, achieving a sound result such as a 11 bit DAC with 20 V output at 10 K [8]. However, they require temperature stabilization within 0.1 K and have a strong demand on power and fabrication process. The temperature stability needs can be relaxed if temperature effects on junction behavior are reduced. This is of interest in all applications such as RSFQ and voltage standards [9]. The SNIS junction technology, based on low temperature superconductors but capable of operation above liquid helium temperature, is interesting for application to a cryocooled standard, allowing to set a compromise between device and refrigerator requirements.

V. HIGH TEMPERATURE OPERATION OF SNIS JUNCTIONS

SNIS Nb/Al-AlOx/Nb junction technology [10] derives from the known SIS process with significant modifications in the metal Al layer thickness that ranges from 30 to 100 nm and in the oxide layer exposure, between 100 and 400 Pa·s. A specific feature is the possibility of obtaining values of current density as high as 0.5 mA/µm2 and characteristic voltages up to 0.7 mV at 4.2 K. The specific normal resistance of these devices ranges from 150 to 300 ncm2 hence is of the same order of magnitude as that in high-current-density single-barrier Josephson junctions [11]. In SNIS junctions the subgap resistance Rsg at 4.2 K and very low voltages is of the order of 0.3 , i.e. comparable with the normal state resistance RN [12]. The very transparent oxide produces reproducible barriers free from pinholes or other leakage mechanism [12]. The high value of Vc= IcRn at 4.2 K is also advantageous for cryocooler operation, since the scaling of the electrical parameters with temperature, still allows to use them at higher temperatures. A further requirement is the temperature stability of the electrical parameters above 4.2 K. While SIS and SNS (Superconductor-Normal conductor-Superconductor) type junctions, show a reduced temperature dependence of the electrical parameters Vc and Ic below or above 4.2 K respectively, SNIS junctions can minimize it over an extended range, by optimizing some intrinsic properties [13]. In fact, the temperature dependence of Ic (which coincides with that of Vc, since RN is almost constant from low temperatures up to Tc) can be described following a model firstly developed in [14]. In this model two length scales parameters, the electron mean free path l and the coherence length x, are used to derive some dimensionless quantities dealing with the proximity interactions inside the junctions eff S/N dAl /x*Al, where S/N RNb/Al/rAl x*Al, x*Al=xAl(TcAl/TcNb), RNb/Al is the product of the Nb/Al interface resistance with the area, rAl and xAl are the normal-state resistivity and the superconducting coherence length of Al, respectively dAl is the thickness of the aluminum normal layer and TcAl and Tc Nb are the respective critical temperature of these layers. We applied these calculations to SNIS junctions and obtained different curves of temperature dependence of Ic and Vc for different values of the aluminum thickness. In particular, it has been found that by properly choosing the eff parameter, the temperature derivative of Ic and Vc can be minimized in different ranges of temperatures [11]. For example, for eff=20, corresponding to an aluminum thickness of 100 nm, the absolute value of this normalized derivative is 0.6 from 0.5 T/TC up to the transition, compared to a value from 1.1 up to 1.25 for SNS junctions and even larger values for SIS junctions in the same temperature range (see Fig.7 [11]).

Fig. 1. Relationship between Al-Nb thickness, eff and Vc

In general, it is possible for SNIS to engineer the junction structure in order to optimize the operation at a certain temperature [13], by selecting a eff value and then determining a value of dAl and at the same time a Vc value as shown in Fig. 1, where the univocal relation between these parameters is shown at a temperature of 0.5 T/TC (4.5 K). III. cryogen-free cooling apparatus We measured junctions in a Gifford-McMahon refrigerator with 1 W cooling power at 4.2 K, 8 kW compressor input power. The cold finger top was fitted with an additional disk retaining inside a deep-set thermometer that, along with a heater wire wound around it, allows fine temperature monitoring and control. A second thermometer close to the chip was used to better estimate the array operating conditions and detect unwanted thermal gradients. Reliable cryocooler operation of a voltage standard array requires a careful thermal design to solve problems like minimization of gradients and heat transmission. Even small thermal links to the outer environment can compromise the refrigerating effectiveness. Conduction of the RF signal for AC biasing the junctions requires a microwave guide (WR-12, 60-90 GHz) that is difficult to thermalise, then a stainless steel guide was adopted, with gold plated internal surface to reduce the dramatic signal attenuation of stainless steel and unnecessary Joule heating on the guide internal surface. Owing to the higher thermal conductivity of gold with respect to stainless steel, the thermal conduction of the plating layer is, however, non negligible. A similar setup will soon be used with a special coaxial line, for tests at lower RF frequencies. It will be quickly swappable with the waveguide setup, according to the test requirements. After several tests we developed a custom packaging for measuring arrays, with the chip inserted between two printed circuit boards. The copper sheet of both boards acts as thermal conductor to provide a good contact to cold finger on both the lower and upper sides of the chip. A suitable window allows chip bonding to the board pads, without damage (see Fig. 2).

Fig. 2. Chip sample holder for cryocooler measurements.

IV. Fast data acquisition assembly

A new experimental setup has been introduced recently for fast recording of current voltage characteristics of SNIS and SNS Josephson arrays. It is built around a multi-bus wideband PXI Express chassis that provides the interconnection layer to every high precision and fast front-end electronic units: digital to analog converter (DAC), analog to digital converters (ADC) and synchronization board. All boards can be synchronized internally either by means of dedicated lines routed through the backplane chassis, or applying timing signals from an external reference oscillator, for higher accuracy. The bandwidth in both cases is up to 1 GS/s. IV curves are obtained running two synchronized tasks. First, the synthesis of isofrequential bias signals, coming from DAC board. The second task is related to the digitization process, which allows a continuous stream of data from on-board memory to local host memory. To maintain a high rate of data collection from the ADC boards, configured for differential measurements, the computation task mainly involves a fast deserialization and differentiation process. Single ended lines like coaxial cables are adopted for bias current transmission up to the audiofrequency band. The measuring system has been calibrated against a low-value resistance standard of 20 W. The resistance of the standards was measured with the digital system and the value was computed. A relative difference of about 300 ppm was found. Our estimate for the accuracy of IV curves obtained with this system is 0.1 A schematic diagram for the measuring system is reported in Fig. 3.

Fig. 3 Block diagram of the measuring system employed for real-time characterization of array of Josephson junctions operating in cryocooler.

The system is designed for fast testing the arrays as AC quantum voltage sources, but it proved useful for observing IV curves with reduced thermal effects from dissipated electrical power. V. Results To verify that SNIS junctions are adequate for cryocooler operation at temperatures well above 4.2 K, we performed both tests in helium gas and experiments with a cryocooler. We measured segments from 1 to 8192 junctions of SNIS arrays fabricated in cooperation with the Physikalisch Technische Bundesanstalt (PTB) [14]. For testing purposes chips were fabricated with different parameters. In our test we selected a device with eff20 for optimal temperature stability, according to the previously explained theory. Results are compared with measurements in helium gas above liquid on devices with eff ranging from 10 to 25, corresponding to Vc values from 0.25 to 0.55mV at 4.2 K.

A. Temperature dependence of electrical parameters

Since our study is specifically aimed at the application to voltage standard, we focused on the temperature dependence of IcRn product, whose value sets the frequency corresponding to maximum step width. As already observed [10], in SNIS junctions the normal resistance Rn does not change with temperature. The dependence of critical current Ic with temperature, displayed in Fig. 4, shows no significant difference between cryocooler and liquid helium measurements.

Fig. 4. The critical current of an array of SNIS junctions measured in liquid helium and with a cryocooler at: 8.3 K (pink/dash-dotdot), 6.6 K (blue/dash-dot), 5.0 K (green/dot), and 4.2 K (red/dash: LHe, black/solid:cryocoooler)).

B. RF step properties The values of relevant electrical parameters show that SNIS junctions can be used at temperature above 4.2 K in a closed-cycle refrigerator. Previous calculations and measurements [13] have verified that the dependence of Cooper pairs current on Josephson phase I() in the four-layered structure of these junctions, with a thick aluminum normal layer, has no meaningful deviation from the sinusoidal shape. As a consequence, the step amplitude has a fairly regular Shapiro dependence. The temperature dependence of the step width for different arrays of SNIS junctions was known from measurements in helium cold gas. Metrological evaluation of the step profile with microvolt resolution was also performed [17] up to 1.25 V at 6.5 K. The behavior of SNIS devices has been thus investigated, under RF irradiation also in cryocooler. Steps of SNIS arrays have been measured when irradiated by a gunn diode with frequencies from 70 to 75 GHz and 1 to 30 mW power at the input flange. Measurements in cryocooler are reported in Figure 5 for an array with 4096 junctions, where they are plotted with results obtained in He gas at 6-7 K.

Fig. 5. RF steps across 4096 junctions SNIS array observed at 73.8 GHz with increasing temperatures: at 6.1 K in He (red/square), at 6.7 K in He (blue/triangle) and at 6.0 K in cryocooler (black/circle). The inset shows a higher resolution plot of a subsegment with 64 junctions in cryocooler at the same temperature.

When comparing helium gas with cryocooler data [18], one can see that the step is reduced in the latter case from approximately 0.5 mA to about 0.2 mA. In the inset a higher resolution plot of the step profile is shown for a lower order array segment. In this experiment we observed in general a reduction of the step amplitude while increasing the number of junctions. VI. Conclusions Experiments on SNIS arrays have been carried out in liquid helium and cryocooler. Devices under test were selected for fabrication parameters that provide, according to our theory, maximal temperature stability above liquid helium temperatures. From the measurement of the electrical properties and direct step observation, operation of the SNIS junction technology at temperatures above 4.2 K in cryocooler was confirmed, but with steps that are in general narrower than those observed in helium gas at the same temperature. We explain this behavior as a consequence of the limitations in conveying to the cold head the heat generated by the electrical power dissipated into the chip. We thus expect that further refinements in sample holder design and better chip thermalization will significantly reduce these discrepancies.

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