A Direct Comparison of a Cryocooler-based Automated 10 Volt Josephson Voltage Standard System

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***Abstract*— A commercially available, complete microprocessor controlled, fully automated 10 Volt Josephson voltage standard system with a liquid helium free cooling was developed in cooperation between the Institute of Photonic Technology and the Supracon AG. The system operates with an array of altogether 19,700 SIS Josephson tunnel junctions installed in a pulse tube cooler. The integration of the voltage standard circuit in the cryocooler as well as the properties of different cooling setups are discussed in terms of a stable operation. A direct comparison at a voltage level of 10 Volt between a cryocooled-based Josephson voltage standard system and a liquid-helium based system was performed with a result of 1.3 nV voltage difference and an uncertainty of 5×10^{-10}.**

***Index Terms*—cooling, cryogenic electronics, Josephson arrays, Josephson voltage standard**

I. INTRODUCTION

JOSEPHSON voltage standard systems on the basis of arrays of SIS tunnel junctions are commonly used as primary DC voltage standards. Applying them, secondary voltage standards as well as high precision digital voltmeters can be calibrated with the highest stage of accuracy.

Further developments are focused on a cryogenic-free operation [1, 2] and on programmable Josephson arrays [3, 4]. Because programmable Josephson arrays are difficult to manufacture at the 10 V level and in addition require an expensive control electronics SIS Josephson voltage standard systems are still an attractive alternative, in particular due to the advantage of the availability of zero current steps.

The system was developed to be easy to use and to avoid a manual control of the Shapiro steps. In the following we describe the performance of the cryocooler-based fully automated 10 Volt Josephson voltage standard system “supraVOLTcontrol” suitable for all DC voltage calibrations. Thereby we focus on the setup of the system installation and the results obtained by a direct comparison at the highest level of accuracy.

Fig. 1. Photograph of the cryocooler-based Josephson voltage standard system “supraVOLTcontrol” including the following components: 1: Pulse tube cooler with a SIS Josephson junction array and the 75 GHz microwave electronics installed in the 19” rack, 2: Control electronics, 3: EIP 578B source looking counter, 4: Keithley 2182A null detector, 5: 3-channel polarity reversal switch, 6: Sensors for temperature, pressure and humidity, 7: Laptop, 8: compressor unit with an input power of 2.5 kW.

Manuscript received June 9, 2008.

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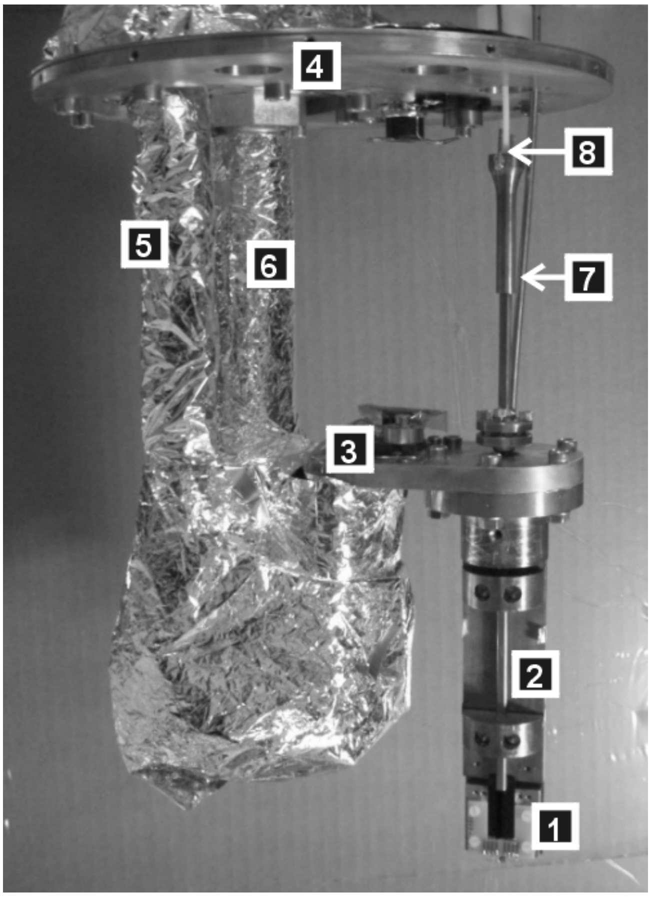

Fig. 2. Installation of the pulse tube cooler for Josephson voltage standard application. 1: 10 Volt Josephson voltage standard circuit, 2: cold finger, 3: 2nd stage at 4 K with temperature sensor and heater, 4: 1st stage at 55 K with temperature sensor and heater, 5: pulse tube of the 2nd stage, 6: regenerator of the 2nd stage, 7: copper wires shielded by a stainless steel tube, 8: dielectric waveguide with WR12 waveguide transition.

II. Setup of the System

The cryocooler-operated Josephson voltage standard system "supraVOLT-control" is shown in Fig. 1. The system is based on a 10 Volt SIS Josephson junction array cooled to a temperature of about 4 K with a two stage pulse tube cooler installed in a 19 inch rack, see Fig. 1. The cryocooler is driven by a compressor unit with an input power of 2.5 kW. The system is easy to handle and fully automated for all DC voltage calibrations. An user friendly operator interface was developed to ensure an easy handling of the system with several internal self tests. The microwave at a frequency of about 75 GHz is provided by a Gunn oscillator which is stabilized via a phase-locked-loop of the 578B EIP source locking microwave counter. The microwave power is adjusted automatically to its optimum by a voltage controlled attenuator in dependence of the required Josephson output voltage.

The SIS Josephson junction array (JJA) [5] is controlled by a µController electronics. A current source drives an AC current through the JJA and in parallel two 16 bit DACs as a voltage source adjust a course and fine voltage. In series to the voltage source a 100 Ω resistor is used for the step selection. By increasing the microwave power Shapiro steps appear with a step number given by the voltage of the DACs and the resistor characteristic. The operating point of the JJA is found if the voltage drop at the resistor becomes constant. This is only the case if the differential resistance of the array becomes zero, Shapiro steps appear, and the entire bias current flows through the array. The difference voltage of the JJA and a connected voltage standard is read out by a Keithley 2182A which acts as a null detector. In general the chosen voltage difference is smaller then 240 µV or 5 µV in the case of a direct comparison, respectively. A small difference voltage ensures a marginal influence of the gain error of the null detector. The JJA is disconnected from the bias electronics as well as from ground during the readout of the null detector.

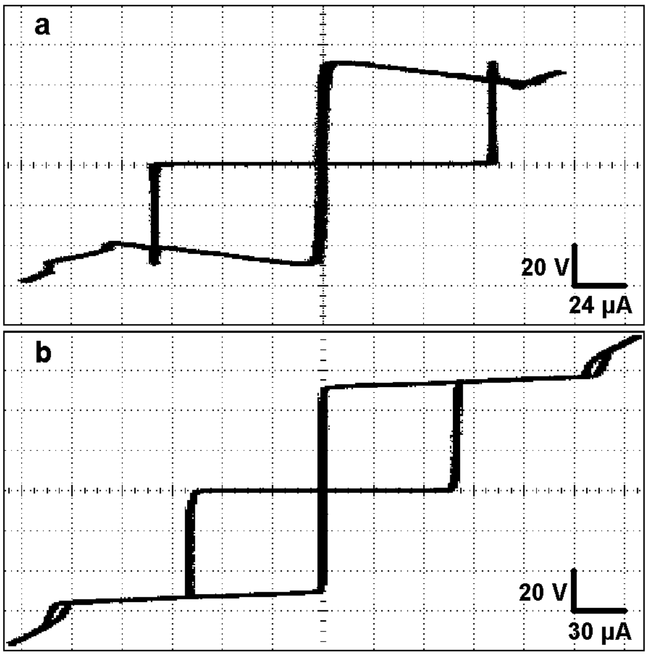

Fig. 3. Current voltage characteristics of a 10 Volt SIS Josephson voltage standard circuit with altogether 19700 junctions installed at the 2nd stage of the pulse tube cooler. a) Typical chip overheating behavior in the case of a bad thermal coupling between chip and cold stage. b) Characteristic with a good thermal coupling by using an indium-silicon interface.

The system can automatically calibrate secondary voltage standards as well as the most common digital voltmeters, in a fast and highly accurate manner. For example the typical time for a calibration of a Fluke 732A with 20 points each in plus and minus polarity is only 30 s. A three channel polarity reversal switch with special latching relays ensures low thermal voltages below 5 nV. In the case of investigation of DVMs the gain factor and their nonlinearities can be measured with up to 100 data points. In this mode the nulldetector is used for determination the step number and the calculation of the exact Josephson voltage. The full functionality of the system in terms of critical current and the flatness of the Shapiro step of the Josephson junction array as well as thermal voltages and gain factor of the null detector can be checked automatically. The system includes sensors for

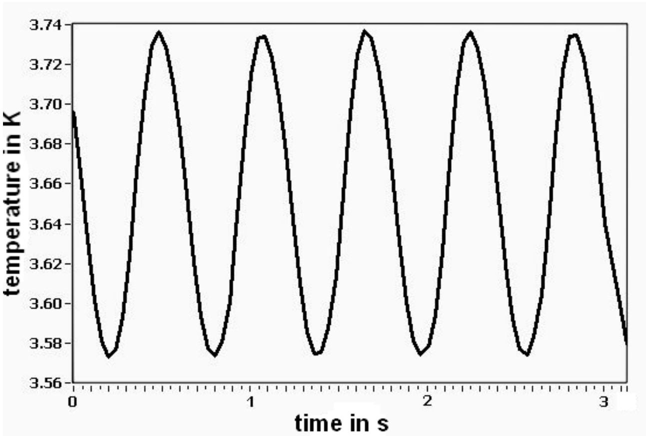

Fig. 4. Temperature measurement of the pulse tube cooler at the cold stage. A temperature oscillation of 150 mK in time of the cooler operation frequency of 1.7 Hz is clearly seen.

the environment temperature, cold stage temperature, humidity, barometric pressure and vacuum pressure of the Dewar.

III. Circuit Operation in the Cryocooler

A pulse tube cooler delivered from the Transmit GmbH Giessen was used in the system. The cryocooler has a cooling power of about 180 mW at a temperature of 4.2 K. Eight copper wires shielded by a tube of stainless steel and a 75 GHz dielectric waveguide [2] for microwave transmission were installed for chip operation, see Fig. 2. The available cooling power at 4.2 K was reduced to about 130 mW mainly due to the heat input of the cooper wires. The first and second stage of the cryocooler are thermal shielded and placed in a vacuum chamber. The chip itself is magnetically shielded by a cryoperm tube against earth magnetic field and disturbances of the magnetic phase transition material located in the regenerator of the cryocooler nearby the chip. A filter box on the top of the cryocooler with installed LC filters reduces the noise introduced by the device under test.

A good thermal coupling of the circuit to the cold stage is important to avoid chip overheating effects as seen in Fig. 3a. In the current voltage characteristic a temperature increasing is observed, if the critical current of the array is exceeded. In this case about 4 mW DC power is dissipated, which is sufficient to heat up the chip to a temperature of about 7 K, seen in the decrease of the gap voltage of the array. It is remarkable that the cold finger is still at a temperature of 3.7 K. By decreasing the current in the array the dissipated power decreases and the gap voltage increases as a result of a decreasing of temperature. The reason for the bad thermal contact is the strong different thermal expansion coefficients of silicon and copper and the used thermal contact material of the vacuum grease “Apiezon N”. Usually Apiezon N is very useful for cryogenic applications because of its high thermal conductivity, but here it becomes to hard to equalize the different expansions of copper and silicon during cool down.

A much better performance could be achieved by using a

TABLE I
Performance of the Pulse Tube Cooler for Different Setups

	Cooling power @ 4.2 K	Temperature oscillation
Initial state of the cryocooler	180 mW	150 mK
With the Josephson voltage standard setup without stabilization	130 mW	150 mK
Passive stabilization with a plate of Nickel-Erbium	60 mW	30 mK
Additional active stabilization by anti-phase heating	0 mW	10 mK

special thermal interface. Fig. 3b shows the hysteretic current voltage characteristic of the Nb/AlO_X/Nb tunnel junctions for this arrangement. A typical characteristic is observed as also seen by measurements in liquid helium. A thin plate of silicon which is cold welded with indium to the copper cold finger acts as a perfect thermal coupling interface. Now the chip itself can be pasted with Apiezon N to the silicon plate.

One important parameter for operation of the system is the temperature stability of the 4 Kelvin cryocooler. In fact, all available types of cryocoolers show an intrinsic temperature variation in time of their operation cycle. In particular for our pulse tube cooler an oscillation of 150 mK at a temperature of 3.7 K was found in time of 1.7 Hz, the operation cycle of the cooler, see Fig. 4. This is in a good agreement with theory [6]. Such a temperature oscillation reduces the stability of the Shapiro steps and an operation of the system seems to be difficult. This is in contrast to programmable Josephson voltage standard circuit on the base of nonhysteretic junctions which have a much larger step widths [7]. To overcome this problem we investigate two configurations. First, we added a thin plate of Nickel-Erbium between the second stage at 3.7 K and the chip holder. Because Ni-Er is a material with a relatively high thermal capacitance at 4.2 K with a bad thermal conductivity a slight thermal decoupling form the cold stage could be obtained. Of course the cooling power is reduced too, about 60 mW at a temperature of 4.2 K, but at the same time the temperature oscillation could be decreased by a factor of 5 to be about 30 mK. The experiments show that a stable operation of the JJA is now possible. The direct comparison experiments described in the next chapter are performed in this configuration.

For other cryocooler applications, for example bolometer detectors for THz radiation [8] it is necessary to minimize the temperature oscillations furthermore. This could be possible by an anti phase heating. An integrated 100 Ω resistor installed at the cold finger is used as heater, driven by a matched signal from the temperature sensor similar like that shown in Fig. 4, but amplified and dc shifted. The measured time constant of the cold finger is in the same range as the operation frequency of the cooler, so the temperature oscillation could be decreased further. In the experiments we could realize a minimal temperature oscillation of about 10 mK, which was limited by the fact to operate not at higher temperatures then 4.2 K. That means the available cooling power was zero and a further reducing of the oscillations

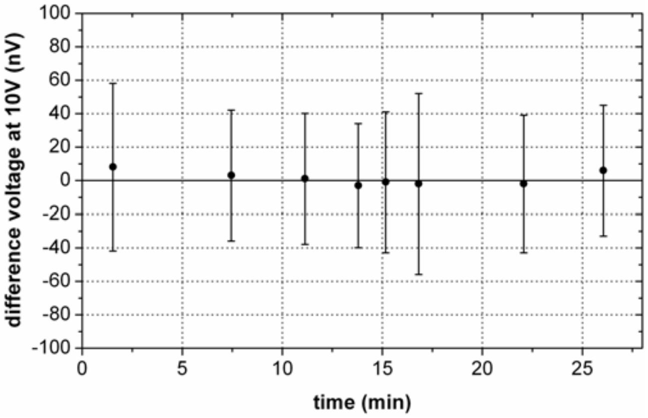

Fig. 5. Measurements of the direct comparison between a liquid-helium-based and a cryocooler-based Josephson voltage standard system at a voltage level of 10 Volt. The difference of the voltages was $V_{PTCS} - V_{LHeS} = 1.3$ nV.

requires a higher cooling power. The amplitude of the heater voltage was 4 V. The cooler properties for different setups are summarized in table I.

IV. Direct comparison

A direct comparison between two Josephson voltage standard systems was carried out at a voltage level of 10 V in order to verify the accuracy of the cryocooler-based system. The second system was cooled by liquid helium. Both systems operated with a SIS tunnel junction array. The liquid-helium-based system, called LHeS, provided the Josephson voltage at 10 V, whereas the pulse-tube-cooler-based system (PTCS) measured this voltage. The system LHeS was driven with a frequency of 74.70 GHz, and the PTCS operated at 74.76005 GHz, respectively. At those frequencies the JJAs were most stable and the difference voltage at the 10 V level is close to zero. Both systems were stabilized and phase locked to the same GPS synchronized 10 MHz reference frequency. Its accuracy is better then 10^{-10}. In order to avoid unwanted interferences of the systems during the adjustment of the Shapiro steps only one JJA was connected to its bias electronics and to ground, the other JJA was floating. Nevertheless it was necessary to find a good common grounding point for both systems in order to avoid large jumps of the Shapiro steps at the time of connecting the voltages together.

The procedure was started with the adjustment of a Shapiro step at 10 V with system LHeS, which is done automatically by the matched user interface implemented in the supraVOLTcontrol software. Its step voltage is always measured by the Keithley 2182A of LHeS from which value the absolute Josephson voltage was calculated. Afterwards the system PTCS was connected to its bias electronics and a Shapiro step near 10 V was chosen, too. The Keithley 2182A of system PTCS act as null detector and measured the difference voltage of both systems. System PTCS was searching a Josephson voltage close to that voltage adjusted by the other system in order to minimize the voltage difference and thereby the gain error effect of the null detector. In the experiments the maximum difference voltage was below 4 µV, so we estimated a typ B uncertainty of the null detector of about 0.2 nV. The null detector read out 20 points with 20 ms integration time without using filter functions. It is important to note, that during this time both systems were floating from the ground, and they were not connected to their bias electronics. During connection and disconnection of the systems it could happen that the Josephson voltage of LHeS jumps to a neighboring step, but if the difference to 10 V was smaller than 5 mV, the comparison was continued at this voltage level. During adjustments of the Josephson voltages the null detector is shorted in order to avoid an offset shift.

TABLE II
Estimated uncertainties of the direct comparison at 10 Volt for both Josephson volatge standard systems.

	Type	Uncertainty
	A	3.4 nV (k=2.37)
Frequency	B	1.0 nV
Leakage current	B	1.0 nV
Null detector	B	0.2 nV
Total (RRS)	A and B	4.9 nV

The thermal voltages in the wires of both systems were eliminated by repeating the procedure at minus polarity by a reversal of the output voltages. The total thermal EMF and offset voltages were around 800 nV. The polarity reversal switch was always in the same position during the measurements.

The results of the measurements of the direct comparison are shown in Fig. 5. Altogether eight measurements were made in about 25 minutes. The error bars denote the standard deviation of the mean value of a single plus-minus-measurement with 20 points for each polarity. The standard deviation for one data point was in the range of 40 nV, which is higher by a factor of two or three than in previous comparisons with two liquid helium based systems [9]. The reason for that behavior takes further investigations, but it seems to be connected with interferences on the ground. The difference voltage of the comparison is $V_{PTCS} - V_{LHeS} = +1.3$ nV with an uncertainty of 4.9×10^{-10}.

The type A uncertainty is 3.4 nV, calculated with a k-factor of 2.37, which conform to a level of confidence of 95% for the 8 data points. The uncertainty for the leakage current was estimated by the measured isolation resistance of the systems and the total resistance of the wiring loop. The combined standard uncertainties are 4.9×10^{-10} and include type A and type B components from both Josephson systems and are listed in table II.

V. Conclusion

The cryocooler-based Josephson voltage standard system supraVOLTcontrol ensures a stable operation of a 10 Volt SIS tunnel junction array in spite of temperature oscillation in the range of 30 mK caused by the operation cycle of the pulse tube cooler. A thermal interface between the chip and the cold stage is used to avoid a chip overheating. The experiments demonstrate an accuracy of the cryocooler-based system to be better than 5×10^{-10}. The direct comparison shows a difference of 1.3 nV at a voltage level of 10 Volt.

Acknowledgment

Many thank to R. Behr from the Physikalisch-Technische-Bundesanstalt (PTB), Braunschweig for many helpful discussions and to G. Thummes for his assistance in providing and installing the cryocooler.

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