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Verification of thermal converters by means of a pulsed Josephson standard

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Abstract – **Starting from 2019 a new central role is played by quantum standards, owing to the redefined SI [1], where electrical units are directly linked to the fundamental constants e (elementary charge) and h (Planck constant). Thus, metrologists are nowadays trying to extend the astonishing accuracy attainable in dc measurements to ac and beyond, moving from sinusoidal toward quantum calibrations of arbitrary signals. Programmable Josephson Voltage Standards are nowadays capable of fulfilling primary metrology requirements only for signals up to few hundreds Hz. Pulsed Josephson standard are instead capable of generating arbitrary waveforms at higher frequencies, so are generally called Josephson Arbitrary Waveform Standards (JAWS). In particular, the capability of generating high spectral purity signals allows high accuracy measurements of the ac-dc difference of thermal converters. We report in the following about our setup for quantum calibrations of thermal converters, first results obtained and open issues.**

I. INTRODUCTION

The impressive improvement in accuracy of dc voltage calibrations attained with Josephson junction arrays is one of the most relevant success of superconductive electronics. Dc Josephson Voltage Standards (JVSs) can generate stable voltages up to 10 V with uncertainties below 1 nV/V [2]. Unfortunately, the generation of ac voltages of similar accuracy is difficult because the output voltage cannot change unless at relatively low rate. Instead, the one-to-one current-voltage (IV) relationship [3] in Programmable Josephson Voltage Standards (PJVS) under microwave irradiation makes it possible to suitably control the voltage by setting the junction bias current. They are realized with many Josephson junctions, connected in series and subdivided in sub-circuits following a power-of-two rule: the total voltage across all sections can thus be binary programmed, equivalently to the technique used in electronic digital-to-analog converters. Among the different technologies proposed for PJVS, we mention SNIS junctions with respectively Nb, Al and AlO_x as superconducting (S), normal (N) and insulating (I) elements, developed at INRiM [4], that proved particularly interesting for operation with He-free systems [5].

However, the step switching speed of PJVS is also limited, thus PJVS are suited to primary metrology generating ac voltages at frequencies up to few hundreds Hz. The resulting transients between consecutive waveform steps deteriorate the accuracy of the rms value calculated from quantum-accurate dc voltages of these steps. To get rid of PJVS limitations, arrays operating with a pulsed, ideally-square wave, microwave bias were developed. The use short pulses rather than a continuous sinusoidal wave allows to suitably modulate the signal frequency over a wide range of frequencies. Exploiting the $\Sigma\Delta$ technique developed for semiconductor electronics, pulsed standards can synthesize arbitrary waveforms with quantum accuracy and guarantee very high spectral purity in signals from digital-to-analog conversion. Quantum-traceable sinewaves of high purity are currently considered to estimate the ac-dc conversion error of thermal converters with unparalleled accuracy, for primary ac voltage metrology [6].

For evaluating the ac-dc transfer difference of a Fluke 792A[1] thermal voltage converter (TVC) we used our cryocooled JAWS system to generate quantum accurate dc and ac signals applied to the input of the TVC.

II. MEASUREMENT METHOD

The highest accuracy in ac voltage measurements are generally attained by means of thermal voltage converters (TVCs), where ac and dc voltages are compared and the rms value is determined from the heating effect of both.

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[1] Brand names are used for identification purposes and such use implies neither endorsement by INRiM nor assurance that the equipment is the best available in the market.

However, due to thermoelectric and electromagnetic effects, the TVC is affected by a residual difference of its response to ac and dc, that depends on both the applied voltage and frequency.

The ac-dc transfer difference with its uncertainty, apart from the sensitivity, is one of the most relevant characteristics of the TVC [7]. It is usually calculable by the mathematical model of the construction, depending on its geometrical dimensions, material properties, and physical phenomena. The ac-dc transfer difference depends strictly on the frequency. At the frequency of typically below 100 Hz, the main reasons of the transfer difference are the nonlinear thermal phenomena and insufficient averaging of the temperature of the heater and thermoelectric junctions. In the frequency range of 100 Hz to 10 kHz, the transfer difference is mostly due to thermoelectric effects, which do not occur with the ac voltage provided. At the level of 10 kHz to 1 MHz, the skin effect in the heater and microwave circuits start to be the most essential factors of enlarging of the transfer difference. Finally, above 1 MHz, the microwave phenomena such as reflection, interference, characteristic impedance mismatching, and standing waves as well as residual parameters of the heater determinate the ac-dc transfer difference of the TVC.

In the TVC quantum-based calibration method, the TVC input is connected to the JAWS output, then a proper sequence of different calculable and quantum-defined voltage signals are applied to TVC input. Finally, the TVC output is measured with a high-resolution dc nanovoltmeter. Since the pulsed Josephson standard can generate signals with any arbitrary shape, a wide range of possibilities are available to analyze the TVC behaviour. The typical test follows the sequence dc-ac-dc: by comparing the response in ac with the average of values for dc of opposite polarities, the ac-dc difference can be accurately obtained with drifts and offsets reduction. In some cases, it can be preferable to observe difference in the response to signals at different frequencies, to determine the, so called, ac-ac difference. Sometimes, to eliminate the dc reversal error and other electrothermal phenomena, more sophisticated procedures are used to determine the ac-dc transfer such as ac/dc+/ac/dc-/ac, where dc+ and dc- denote the dc voltages with opposite polarities [8].

The JAWS capability to generate pure signals over a wide range of frequency allows to perform this test in a straightforward manner, the measurement accuracy is in any case guaranteed by JAWS principle of operation. However, it is widely recognized that, for increasing frequencies, the most relevant uncertainty contribution in JAWS standards is due to the loading effect of voltage leads [9]. One way to reduce these errors is to use a short voltage cable, though this condition cannot be fully realized in a LHe system, where the cable is more than one meter long. In our cryocooler the cable length is more than halved with respect to a liquid Helium cryostat (typical cryoprobe length > 1 m).

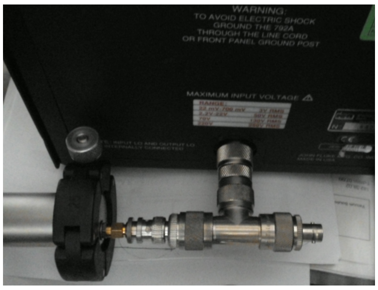

Fig. 1. Short connection of the TVC to the JAWS inside the pulse-tube cryocooler through the vacuum-tight SMA feedthrough.

III. CALIBRATION SYSTEM

The setup is realized around a “flexible” cryogen-free refrigeration system [10] that we built to operate both programmable and pulsed standards. The arrays of Josephson junctions we used were realized by PTB with $\mathrm{Nb}_x\mathrm{Si}_{1-x}$ as barrier material [11]), where Nb and Si relative content (x) is suitably adjusted to get characteristic frequencies around 10-15 GHz at 4.2 K. Our JAWS sample consists of two arrays, with 5000 junctions each, integrated on a $10\,\mathrm{mm}\times 10\,\mathrm{mm}$ silicon chip. For each array, junctions are arranged in double stacks and are embedded into the center line of a 50 Ω coplanar waveguide, which ensures a suitable propagation of pulses. The JAWS chip is mounted in a special thermally-conductive cryopackage similar to that described in Ref. [12], designed to enhance heat dissipation in the cryocooler vacuum environment. The copper coldplate that refrigerates the cryopackage hosts a thermometer and a heater to finely monitor and control its temperature. A second thermometer is installed onto the cryopackage, in proximity of the Josephson chip. Transmission of the quantized signal through the probe is generally done with either a coaxial cable or twisted pair, with length around $1.5\,\mathrm{m}$ in liquid He experiments, or even longer in cryocoolers since thermalization requires suitable thermal anchors windings. In this setup we instead used a cryogenic coaxial cable that allowed us to reduce the total length from chip to outer connector down to $0.5\,\mathrm{m}$, a value even lower than in special short He probes. A special SMA vacuum-tight feedthrough is installed onto a flange of the cryocooler vacuum chamber to pick up the Josephson voltage. Figure 1 shows the straight connection from cryocooler output to TVS.

IV. RESULTS

At first, the dc current-voltage (IV) characteristics of the arrays, hence with no pulsed rf-bias, are observed. These have been properly analysed to evaluate the junc-

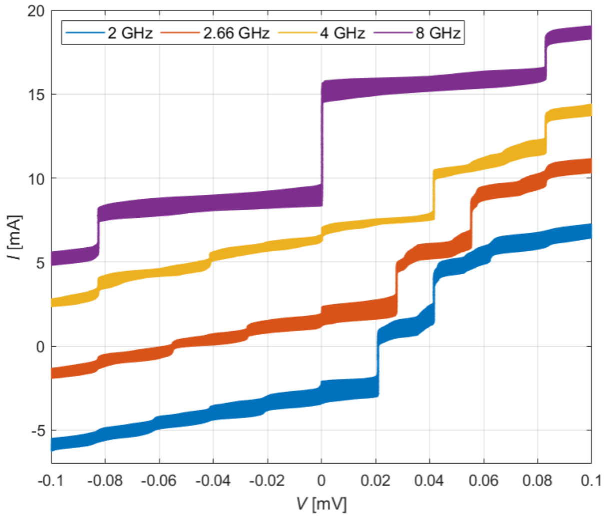

Fig. 2. IV curves of the Josephson array radiated with unipolar pulses of amplitude 1 V, at different repetition frequencies, at 4.5 K.

tions electrical parameters, namely critical current I_c, normal resistance R_n and characteristic frequency $f_c = K_J\, I_c\, R_n$, with K_J the Josephson constant. This characterization is necessary to determine the optimal temperature setpoint, which is related to highest pulses repetition frequency and width as well as to the cryopackage thermal performances. Indeed, optimal pulse amplitude and frequency for wide quantum range depend on critical current and characteristic frequency, which in turn depend on the operating temperature.

In addition, one of the two available JAWS array was investigated as on-chip temperature sensor, in a similar way as described in Ref. [13]. This would ensure the stabilization of the actual chip temperature even when microwave pulses are applied to the junctions, which is particularly critical at lower temperatures, owing to the reduced thermal conduction.

Next, the Josephson array has been microwave-radiated with pulses at different repetition frequencies, but same pulse width, in order to verify the array quantum behavior in the same experimental conditions that will be reproduced for the sinusoidal quantum-based waveform synthesis needed for the TVC calibration. IV curves of the Josephson array at the constant temperature of 4.5 K, radiated with pulses of amplitude 1 V, at different repetition frequencies are plotted in Fig. 2. Wide first-order quantum voltage steps have been obtained for this large frequency range. The effect of the cryocooler-induced temperature fluctuations are visible in the IV characteristics, causing the reduction of the useful quantum step current-amplitude.

V. CONCLUSION

A cryocooled pulse-driven Josephson standard setup for the analysis of TVC properties by means of quantized pure sinewaves was presented. Very small cable loading effect were obtained, thanks to a special short coax. In particular, the preparation of the measurement apparatus and the optimization of operating parameters for the generation of verified quantum signals were discussed. Quantum operation of the standard was demonstrated for both sinusoidal and pulsed rf excitation.

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