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Advancements in quantum voltage standards for time-dependent signals

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Abstract – **Quantum voltage standards based on ac Josephson effect are in use in metrology since just a few years after the discovery of the physical effect. The role of quantum standards is now crucial following the SI redefinition in 2019 [1]: electrical units are now defined in function of the fundamental constants e (elementary charge) and h (Planck's constant). The extremely low uncertainty in dc measurements, that can be below 1 nV/V at 10 V [2], is stimulating research to extend application to ac and signals arbitrarily changing with time. Approaching the dc accuracy is challenging, however. The two main technologies used for the generation of non-steady voltage signals are programmable and pulsed Josephson junction arrays. In the following we discuss the main advancements obtained with both technologies and the most recent developments, in particular the advantages of He-free device cooling techniques.**

I. INTRODUCTION

Josephson array voltage standards represent one of the most relevant achievement in superconducting integrated electronics and are fabricated only in few laboratories worldwide. Dc Josephson arrays with tunnel junctions operated at $4.2\,\mathrm{K}$ can generate steady voltages up to 10 V [3], but rapidly setting a voltage value and generating waveforms with quantum accuracy is very difficult. Josephson junctions in dc voltage standard applications are based on highly hysteretic Superconductor-Insulator-Superconductor (SIS) junctions with zero-crossing steps i.e. overlapping voltage steps with current range that spans positive and negative values, hence including the condition of zero dc bias. The current-voltage (IV) relationship is then not one-to-one [4] and it is not possible to control the voltage through electrical bias.

This is otherwise possible in Programmable Josephson Voltage Standards (PJVS) with junctions showing non-hysteretic behavior. Their IV curve under microwave irradiation is a staircase function, thus the output voltage is univocally defined by the current sent through the bias circuit. Such arrays are generally subdivided in sub-circuits with series-connected junctions generating voltages following a power-of-two rule: combining the voltage across all sections it is thus possible to source binary programmed voltages equivalent to the technique used in electronic digital-to-analog converters. Many approaches to junction fabrication have been developed, and several different technologies have proven successful in generating voltages up to 10 V, with good metrological properties: SINIS [5], SNIS [6], [7] with respectively Nb, Al and $\mathrm{AlO_x}$ as superconducting (S), normal (N) and insulating (I) elements, and the more recent SNS junctions with $\mathrm{Nb_xSi_{1\text{-}x}}$ barriers [8], and $\mathrm{NbN/TiN_x/NbN}$ junctions for higher temperature operation [9]. The most relevant limitation of PJVS devices is to be found in the time for step switching, when junctions are not operating in a quantized state. During these transients, the array voltage is not accurately known, thus programmable arrays can match primary metrology uncertainties requirements only for signals up to few hundreds Hz.

To get rid of the limitations of programmable standards, arrays operating with a pulsed, square wave, radiofrequency signal have been developed. Making use of short pulses in place of a continuous sinusoidal wave it is possible to suitably modulate the signal period spanning a wide range of frequencies. Fundamental accuracy follows from the control of the flux quanta associated to a single pulse going through a junctions. It follows that the output voltage of the array is exactly calculable in terms of fundamental constants if the number of the quanta per unit time, i.e. the pulse repetition rate, is known. Since the determination of the repetition rate is basically a frequency measurement, this can be done with extreme accuracy and the Josephson effect brings the accuracy of time and frequency measurement into voltage calibrations [10]. Pulsed standards can synthesize arbitrary waveforms with quantum accuracy, taking advantage of the $\Sigma\Delta$ technique for digital-to-analog conversion developed for semiconductor electronics, providing very high spectral purity. However, both operation and fabrication of pulsed standards set very challenging problems.

The extremely low temperatures required for the operation of superconducting devices is generally regarded as the major limitation to a widespread usage. To cool down ordinary superconductors at $4.2\,\mathrm{K}$ the standard technique is based on liquid helium refrigeration (LHe), where all the experiment is immersed, isothermally, in a helium bath. On the other side, more recent He-free systems are interesting because of ease of use, the savings over high costs of LHe, the absence of risk of shortages [11], and the negligible concerns for operators safety. Yet, proper cryocooler operation necessitates a very specific thermal design to face with problems that are not of concern with liquid coolants, e.g., minimization of thermal gradients to allow uniform operation of the chip. Moreover, the He-free refrigerator has reduced cooling power, thus the rf signal transmission to the chip must be carefully designed in order to limit the heat load on the low temperature stage of the cooler without compromising signal transmission. Additionally, cryocooled standards are particularly interesting for pulsed standard applications, where frequency dependent unwanted effects in the synthesized waveforms are due to the loading of voltage leads. It is possible to reduce these errors by using shorter cables, but this condition cannot be fully realized in LHe system, where cables are more than one meter long, while they can be more than halved in a mechanical cooler.

II. QUANTUM STANDARDS FOR AUDIOFREQENCIES

In Josephson junctions where dissipative effect dominates, the junction capacitance can be neglected. These show non hysteretic behavior in the IV curve that allows changing the output voltage through control of the bias current. In other words, the IV curve under irradiation is a one to one staircase, thus the output voltage is univocally defined by the current fed through the controlling circuit. This is totally different from the case of hysteretic junctions used in dc standards, were steps are overlapping and all share approximately the same interval of currents. This property is exploited in the so-called programmable standards, where the junctions bias currents are used to activate/deactivate array sections. Programmable arrays are subdivided in sections with series connected junctions generating voltages following a power of two sequence. Combining the sections it is then possible to source binary programmed voltages in a way that is very similar to the technique used in electronic digital to analog converters [12] Programmable Josephson arrays are so far the most effective result extending metrological applications of Josephson standards beyond dc, have been used for several applications and provide output voltages up exceeding 10 V [13] In programmable standards, a crucial role is played by the measurement program that controls the bias of array sections, undertakes first data processing (e.g. step verification), and evaluates data validity. The high complexity of quantum based devices, places software in a fundamental role. We developed a Python package for automated measurements with a modular and expandable structure [14] suited to different calibration and testing purposes. The open source approach adopted offers a well known and tested framework for these needs, based on a collaborative effort and improved by shared information and the updates contributed by the community.

INRiM started developing a custom technology for fabrication several years ago. Low hysteresis (overdamped) junctions developed at INRiM can be derived from hysteretic Nb/Al-AlO$_x$/Nb SIS junctions technology, but the thickness of the Al layer is significantly higher. These junctions can be described as SNIS, since the thick aluminum film is a normal metal at liquid helium temperature. An essential feature is that, at $4.2\,\mathrm{K}$, a transition from the hysteretic to the non-hysteretic state can be induced by changing AlO$_x$ exposure. An interesting feature of SNIS junctions for metrological applications and quantum computing is the high value of current densities achievable and, consequently, of characteristic voltage. This makes SNIS junctions advantageous with respect to other technologies, facilitating the operation of PJVS arrays above $4.2\,\mathrm{K}$ in compact cryocoolers, in the view of the future substitution of expensive and complex LHe refrigeration systems and the consequent diffusion of voltage standards to the private companies. Indeed, present Josephson junctions technologies with high temperature superconductors, like YBCO or MgB_2, are not yet proven effective in providing the integration levels required for large array fabrication [15]. On the other side, the use of SNIS junctions at temperatures close to $4.2\,\mathrm{K}$ is favorable for the generation of wide high order steps, again thanks to the large characteristic voltages [16].

We deeply investigated the development of programmable standards operating at step orders above the first one, making it possible to synthesize stepwise quantum voltage waveforms with fewer bias lines and fewer Josephson junctions, without losses in terms of performances [17]. In particular, we proposed to simultaneously exploit zero, first and second Shapiro steps to reduce junctions and bias lines by two.

III. PULSED STANDARDS TOWARD RF

Pulse-driven arrays of Josephson junctions has proven successful in generating ac voltage waveforms with very pure frequency spectra. They are the basis for the Josephson Arbitrary Waveform Synthesizer (JAWS). Compared to PJVS, JAWS is capable of synthesizing waveforms at much higher frequencies (up to the MHz range) and with rms output voltages up to 2 V [18, 19]. JAWS principle of operation is based on the irradiation of arrays with a train of sub-nanosecond pulses with rise-time of few tens of picoseconds: fundamental accuracy follows from the control of the flux quanta transferred through the junctions in each pulse. The output voltage is then exactly calculable from fundamental constants from:

$$V_n = \Phi_0 \cdot N \cdot n \cdot f_{rep} \tag{1}$$

where $\Phi_0 = h/2e \simeq 2.07 \cdot 10^{-15}$ Wb is the magnetic flux quantum, N is the number of junctions in the array and n is the Shapiro step number, i.e. the number of flux quanta transferred for each current pulse. N and n being fixed, the voltage depends only on the instantaneous pulse repetition frequency f_{rep}. It is possible then to synthesize arbitrary waveforms with quantum accuracy by continuously varying this frequency, which is generally in the range of microwaves. The waveform to be synthesized is encoded into a 0/1 or 1/0/-1 bitstream by means of $\Sigma\Delta$ modulation techniques. In our setup, schematically represented in Fig. 1, the $\Sigma\Delta$ code is generated with a program written in Python and then loaded into the circulating memory of two pulse generators, one for positive and one for negative pulses, properly phased and sharing the same reference clock.

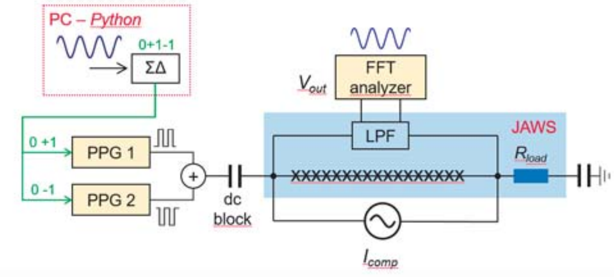

Fig. 1. Schematic representation of JAWS setup.

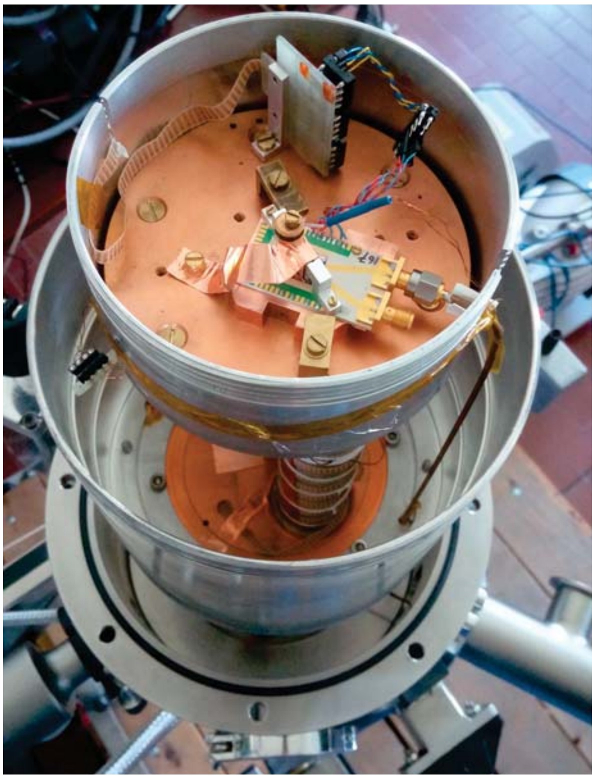

Fig. 2. JAWS standard installed on the coldplate of a pulse-tube cryocooler.

It is widely recognized that, approaching the MHz-range, the most relevant uncertainty contribution in JAWS standards is due to frequency-dependent errors originated by the loading effect of voltage leads [20, 21]. One way to reduce these erros is to use shorter cables, though this condition cannot be fully realized in LHe system, where cables are more than one meter long. Using compact cryocooler, the cable length can be at least halved.

We developed and tested thoroughly a cryogen-free refrigeration system capable of operating a pulsed standard were cable length is halved with respect to helium cooled setups [22].

IV. CRYOCOOLER OPERATION

In the last decade, we have set up two flexible cryogen-free refrigeration systems suited for operation of both programmable and pulsed standards. These are built on two-stage cryocoolers with 1 W cooling power at 4 K and minimum temperature below 3 K (without thermal loads). The second stage of the coolers is fitted with an additional disk (the coldplate) made of oxygen-free copper. In both systems, the coldplate hosts a thermometer and a heater to finely monitor and control its temperature. A second thermometer is free to be installed wherever is necessary, as onto the carrier, in proximity of the Josephson chip. Either a stainless-steel WR-12 waveguide, for PJVS 70 GHz rf transmission, or a low thermal conductivity coaxial cable made of beryllium-copper, for JAWS pulsed bias up to 30 GHz (see Fig. 2), can be installed to reduce the thermal link between the cold region and the outer stages of the cryocooler and the laboratory environment. The apparatus can be easily switched between the two available ac Josephson voltage standards.

As described previously, junctions fabricated with SNIS technology lend themselves as a good option for operation at temperatures above 4.2 K. In particular they show some specific properties with regard to temperature stability of its electrical parameters, measured as the temperature derivative of I_c and V_c vs. temperature [23–28]. SNIS arrays are interesting candidates for a cryocooled standard, providing a compromise between device and refrigerator requirements [29].

Proper operation of a Josephson standard in cryocooler is always a challenging task, owing to the tight thermalization requirements [30, 31] alongside the need of supplying non negligible dc and rf power for proper operation. We addressed the issue of designing an optimized cryopackage for maximizing the thermal contact between the chip and the cooling surface [32]. It takes advantage of a soft indium foil with a corrugate surface for optimal transmission, achieved by filling the voids between rough surfaces. This approach avoids soldering the parts, a solution that is prone to cracks and surface damage with thermal cycling. Moreover, a highly-conductive, electrical insulating, sapphire lamina is placed on the top of the chip, thus further contributing to the total heat conduction. Thorough tests of thermal conduction, using some junctions as temperature sensors, showed better performance than different methods reported in literature. A specially designed structure guarantees the reproducibility of results and strict control of mechanical parameters.

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