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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 AlO_x as superconducting (S), normal (N) and insulating (I) elements, and the more recent SNS junctions with Nb_xSi_{1-x} barriers [8], and 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

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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