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# On the Synthesis of Stepwise Quantum Waves Using a SNIS Programmable Josephson Array in a Cryocooler

B. Trinchera, V. Lacquaniti, A. Sosso, M. Fretto, P. Durandetto, and E. Monticone

**Abstract**—This paper presents recent advances in the application of binary-divided 1 V array, consisting of 8192 intrinsically shunted SNIS overdamped Josephson junctions (JJs), for the synthesis of stepwise waves with quantum accuracy. The maximum output voltage is ensured by opportunely driving the subsections of the SNIS array by means of three states bias-current setpoints to the Shapiro steps  $n = 0, \pm 1$  or  $n = \pm 2$ , respectively. Reconfigurable digital modular electronics has been designed to bias individually each of the 13 subsections of the SNIS array. A two-stage closed cycle refrigerator equipped with LF and RF electrical lines is employed for cooling-down the SNIS array for temperatures ranging from 3.6 K to above 7 K. Stepwise sine waves with rms amplitude ranging from 1 V to 2 V using the first ( $n=1$ ) and second ( $n=2$ ) Shapiro steps, different temperatures and bias-current setpoints have been synthesized up to the kHz range. The synthesized waves have been recorded and analyzed by a high-precision differential sampling system. We report the results of the first characterizations carried out with the new multi-bit current source and an improved version of the sample holder designed to optimize the heat dissipation of the SNIS array for operation in cryocooler setups.

**Index Terms**—Josephson arrays, digital-analog conversion, voltage measurement, waveform synthesis, AC Josephson voltage standard.

## I. INTRODUCTION

SINCE the first ac programmable Josephson voltage standard (AC-PJVS) with fundamental accuracy was proposed [1], stepwise synthesized waveforms have been increasingly applied for ac voltage metrology in a wide range of amplitudes and frequencies. Conventional calorimetric methods based on ac-dc transfer standards are widely used for precision ac voltage metrology, but they are not intrinsically accurate. Synthesized ac waves by means of Josephson arrays allow, in principle, to compute the rms value and harmonic content with quantum accuracy through the well-known voltage-frequency Josephson relationship,  $V = n \cdot \Phi_0 \cdot \nu$ , which links the macroscopic physical quantity and the unit of volt to the assisted tunnelling of flux quanta  $\Phi_0 = h/2e$  through the JJs per time interval.

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In particular, AC-PJVS systems are used in many applications, e.g. characterization of thermal converters employed as ac-dc transfer standards or in instruments for precise rms measurements, electric power measurements, precision sampling measurements and characterization of metrological grade analog-to-digital converters [2]–[5] for low frequencies, i.e. ranging from sub-hertz to about 1 kHz. In contrast, pulse-driven Josephson Arbitrary Waveform Synthesizer (JAWS), offers an improved tool for calibrating of AC waveform instruments at higher frequencies, i.e. from a few kilohertz up to the megahertz range.

The transitions between the quantized voltages steps greatly influence the amplitude accuracy of the waves generated by the AC-PJVS synthesizer. Sampling strategies combined with AC-PJVS systems can detect and eliminate the undefined voltage during the transitions, thus allowing to improve the accuracy of the total rms voltage output of the AC-PJVS system [6–7]. Furthermore, it has been demonstrated that AC-PJVS operating in a conventional cryogenic setup is suitable to synthesise sine waves with known rms value at a level of  $1 \times 10^{-7}$  for frequencies below 200 Hz [8].

Recent trends for wide-spread use of programmable Josephson arrays concern the development of compact and user-friendly quantum voltage standards, operating in closed-cycle refrigerators, suitable for achieving output voltages ranging from 1 V to 10 V in a wide band of frequencies. Ensuring stable operating margins of a programmable Josephson array in cryogen-free system as close as possible to those obtained in conventional liquid helium is a fundamental prerequisite. In particular, practical operations of cryogen-free programmable Josephson voltage standards fabricated with different technologies were demonstrated only at few National Metrology Institutes (NMIs) [9]–[12].

In this paper, we present recent advances concerning the applications of a 13-bit programmable SNIS array for the synthesis of stepwise approximated sine waves operating in a closed-cycle refrigerator system.

The experimental setup is an improved version of the one proposed for characterization of programmable Josephson voltage standards [12]. The main changes concern the upgrading of the modular electronics for separate biasing of subsections of the array, and the redesign of the sample holder for thermal anchoring of the SNIS array.

The rest of the paper is organized as follows. In Section II, we describe the experimental setup and its main constituents, i.e. the control electronics and the cryocooler setup. Then we

briefly discuss the main features of the SNIS programmable Josephson array employed in these experiments and in Section IV the experimental results are reported, followed by conclusions.

## II. EXPERIMENTAL SETUP

### A. Reconfigurable digital electronics

The control electronics employed in the experimental setup is a high-channel-density system, e.g. a PXI chassis with bandwidth up to 1 GS/s per slot, suitable for high-speed measurements, which has been previously proposed for dynamic  $I$ - $V$  characterization of Josephson arrays [13].

Fig. 1 shows the schematic diagram of the measurement setup employed for the synthesis of stepwise sine waves.

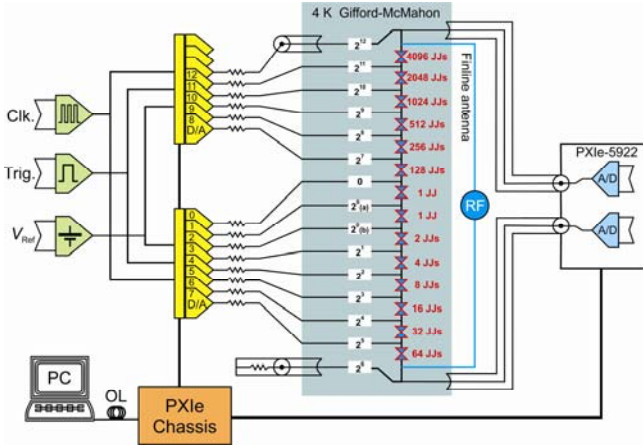


Fig. 1. Schematic of the experimental setup employed for the stepwise synthesis of sine waves. A synchronized wideband precision differential digitizer samples continuously the output of the AC-PJVS synthesizer.

It has been enhanced to allow direct digital synthesis of stepwise waveforms by using all available subsections of a 13-bit SNIS Josephson array. Two digital-to-analog boards were combined, each one containing up to 8-output channels and 16-bit of vertical resolution. The signals necessary for synchronization, triggering and clocking of the DAC boards may be provided internally by routing the digital signals path through the backplane of the PXI chassis or externally to dedicated digital ports. Up to now, the most prominent solution in terms of RF noise immunity is the one in which the DAC boards are clocked internally to the same clock pattern generator and the trigger signal is provided externally by an additional DAC. Three state digital patterns are stored in the memory of DAC boards. Each bit can be set to  $(-n, 0, +n)$  quantum voltage steps. For a 13-bit 1 V SNIS array up to 16384 levels are available for the synthesis of unipolar waveforms. The last-significant-bit (LSB) corresponds to the voltage provided by a single Josephson junction when it is biased on the  $n = 1$  or  $n = 2$  Shapiro steps, respectively. A peculiar characteristic of the DAC boards is the presence of a circulating memory, which enables the uploading of new digital patterns without stopping the generation process, so the final synthesized waveforms result uninterrupted.

The longest time staying on a Shapiro step is inversely proportional to the update frequency clock of the DAC converters, i.e.  $\Delta t = 1/f_{\text{clk}}$ . The bias current of individual subsections can be set in the range  $-20$  mA to  $+20$  mA and the current resolution may be scaled down by varying the external voltage reference of the DAC. Typically for bias-current setpoints ranging from  $-10$  mA to  $+10$  mA the current resolution is lower than  $10$   $\mu$ A. The current resolution and intrinsic current noise of the bias source are sufficiently lower than the variations of the critical current of subsections,  $\Delta I_C$ , due to various noise contributions, e.g. electromagnetic interferences and mechanical vibrations, low-frequency oscillations of the cold finger temperature of the closed-cycle refrigerator,  $\Delta T_{\text{CCP}}$ , self-heating of the subsections during the on/off switching and the microwave power applied at the finline antenna. In particular, the ratio  $\Delta I_C/\Delta T_{\text{CCP}}$  was measured to be about  $1.25$  mA/K at  $4.7 \pm 0.1$  K, for sections containing a large number of JJs, i.e. greater than 2048 junctions.

### B. Cryocooler setup

The constraints coming from combining heating effect due to the Joule heating and microwave irradiation power are less stringent when the programmable Josephson array operates in conventional cryogenic setup based on liquid helium. In contrast, Josephson arrays fitted in cryogenic setups based on closed cycle refrigerators are still challenging to ensure proper functionality at 1 V level or beyond for primary ac voltage metrology.

The cryocooler setup is an improved version of that reported in [14], which was used to test both programmable SNIS array and pulse driven SNS array. It is based on a Gifford-McMahon closed-cycle refrigerator with top loading sample assembly, a minimum temperature near 2.9 K (no thermal load), and nominal cooling power of 1 W at 4.2 K. The cold finger top was fitted with an additional copper disk (cold plate) which contains a thermometer and a heater for temperature monitoring and control. A second thermometer close to the chip was added to monitor thermal gradients and precisely estimate the array operating conditions and detect thermal gradients related to power dissipation inside the chip.

A sample holder, made of Oxygen-free (OFHC) copper was designed to optimize thermal conduction. In particular, in order to guarantee a more efficient thermal contact between the chip and the cold plate, a special sandwiched structure was used. Electrical insulation is kept by interposing a thin sapphire substrate between copper and chip, without a substantial reduction of thermal conduction.

Conduction of the RF signal for AC biasing the junctions requires a microwave guide (WR-12, 60-90 GHz) that is difficult to thermalize, therefore a stainless steel guide was adopted, gold plated internally. This reduces the extremely high signal attenuation of stainless steel and the unnecessary Joule heating on the guide internal surface.

To keep vacuum tight operation a WR-12 flange with mica windows was used for the cryocooler chamber feedthrough. Thermal conduction is further reduced by careful anchoring

the microwave guide on the first stage of the cryocooler.

The digital pattern is sent to the SNIS array through low-frequency (LF) single ended lines thermally anchored on the second stage of the cryocooler.

However, the overall cryogenic setup is quickly swappable with RF coaxial cable for use with pulse-driven Josephson arrays aimed at the synthesis of high purity waveforms [15].

Fig.2 shows a photo of the experimental setup employed for the synthesis of stepwise sine waves.



Fig. 2. Photo of the experimental setup based on a reconfigurable electronics for direct synthesis of current-bias setpoints of PJVS SNIS chip and high precision sampler (on the left) and a 3.6 K two-stage cryocooler system (on the right).

### III. SNIS PROGRAMMABLE JOSEPHSON ARRAY

Superconductor – Normal – Insulator – Superconductor Nb/Al–AlO<sub>x</sub>/Nb (SNIS) as an alternative intrinsically shunted junction technology compared to SNS and SINIS junctions, have been proposed for applications in quantum voltage metrology [16], [17]. In particular, the four-layered structure with a comparatively thick ( $\sim 100$  nm) Al film and a highly transparent but uniform [18] oxide layer allow the trimming of the electrical parameters in a wide range and enables improved temperature stability. This parameter, expressed as the temperature derivative of  $I_C$  or  $V_C$  as function of the temperature of the device, is minimized with respect to other families of junctions, especially above 4.2 K [19]. Programmable binary divided Josephson arrays containing up to 8192 series connections of JJs, with trimmable behavior between hysteretic and non-hysteretic  $I$ – $V$  characteristic by varying the temperature, were intensively investigated in DC as well as under RF irradiation, both in liquid helium [20] and in helium-free environment [12]. The sections contain series connections of JJs arranged according to the powers of two, namely binary divided.

The device tested in these experiments was fabricated with a niobium base electrode of 120 nm and an aluminum layer of 80 nm. The oxidation exposure of the barrier (oxygen pressure per oxidation time) was 400 Pa s.

At 4.2 K the measured current densities were around 10 kA/cm<sup>2</sup> and the characteristic voltages were 420  $\mu$ V.

The high values of characteristic voltage attainable from

these junctions made it possible in the experiments in cryocooler to have all the sections of the array optimized on the  $n = 2$  step at  $T$  around 4.2 K, and to use them on the  $n = 1$  step at  $T$  slightly higher than 6.5 K.

### IV. EXPERIMENTAL RESULTS

The main measurements concern the determination of suitable ranges of temperature, current biasing, power and frequency of the microwave radiation, within which it is possible to ensure stable and flat quantized voltage step. In particular, the investigation was focused on the optimization of operating margins on the first and second Shapiro step by finely trimming the cryocooler temperature and microwave input power. After this, the control electronics was switched-on in the synthesis mode for generation of stepwise sine waves at different amplitudes and frequencies.

#### A. Tests for the flatness of quantum voltage step

The flatness of the steps generated by each subsection was verified under microwave irradiation by recording the  $I$ – $V$  characteristic. Since the cold finger temperature of the cryocooler oscillates at the operational frequency of about 1.5 Hz, we recorded the temperature variations by sampling the output of the thermometer installed close to the SNIS array. The peak-to-peak temperature oscillations of the sample holder were measured to be within 0.2 K at 4.5 K and rise up to 0.7 K at around 7 K. These temperature oscillations lead to a variation of current and voltage in the  $I$ – $V$  characteristic of the SNIS subsections, which become most pronounced at higher temperatures. The  $I$ – $V$  characteristics were tracked by using a bias current of triangular shape, whose frequency was set typically to one order of magnitude higher than the cold finger temperature oscillations. The sampling frequency of the high precision digitizers employed was set to 100 kS/s and their aperture time was set to  $t_A = 100$  ms. The frame recording of  $I$ – $V$  characteristics bunches was  $\sim 1/t_A$ .

Fig. 3(a) shows an example of the  $I$ – $V$  characteristic of 1 V SNIS array under stationary microwave irradiation. The characterization was performed at  $6.5 \pm 0.1$  K and only one half of the array is active. We measured a peak-to-peak voltage noise  $V_{pp} \sim 30$   $\mu$ V on  $n = 1$  step and current margins width up to 500  $\mu$ A. These current margins are almost identical to all subsections of SNIS array under characterization.

The opposite case, in which the temperature oscillations are lowered by switching-off the helium compressor, is shown in Fig. 3(b). The voltage and current oscillations are reduced and JJs electrical parameters improved, i.e. operating current margins increased more than 20 %. The results obtained are comparable with those obtained in liquid helium.

The same characterization approach was applied on the same array but at lower temperature. We measured stable  $n = 2$  Shapiro step at  $T$  around  $4.5 \pm 0.1$  K. The  $I$ – $V$  characteristic of subsections optimized for operation on  $n = 2$  step is shown in Fig. 4. The current range over which the step  $n = 2$  shows an acceptable flatness is around 200  $\mu$ A.



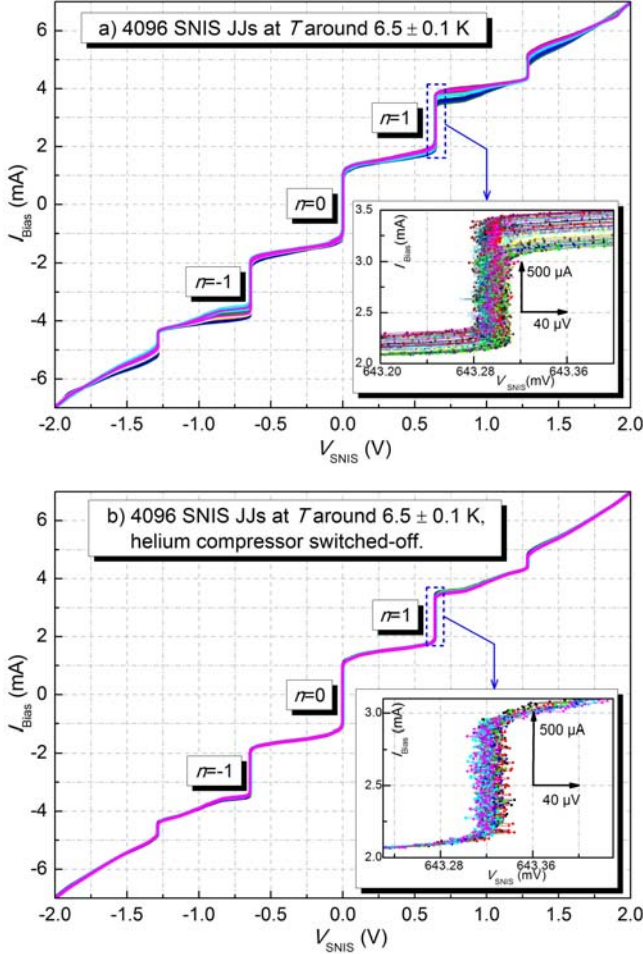


Fig. 3.  $I$ - $V$  characteristic of a half SNIS array under microwave irradiation. Current range over which the  $n=1$  step is constant when the helium compressor is: a) switched-on; b) switched-off.

The flatness of the quantized voltage was determined by a linear fit using the  $I$ - $V$  characteristic of individual subsections. The voltage flatness for almost all subsections was verified to be within  $0.3 \mu\text{V}/\text{mA}$ .

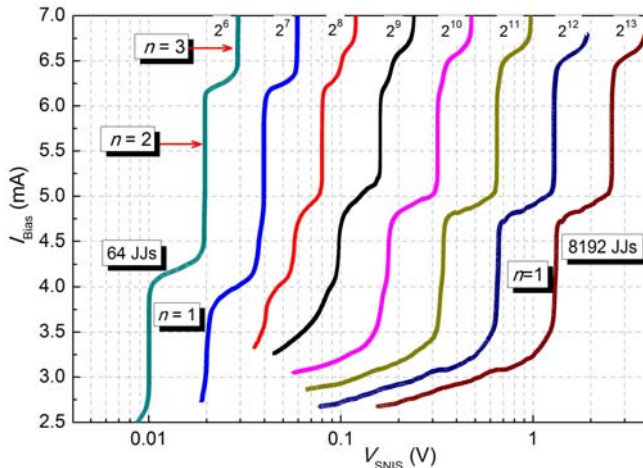


Fig. 4.  $I$ - $V$  characteristic of SNIS subsections at  $4.7 \text{ K} \pm 0.1 \text{ K}$  optimized for operation on  $n=2$  step, by keeping constant the power and frequency of the microwave radiation.

The obtained results seem promising to use both first and second Shapiro steps for the synthesis of stepwise sine waves.

#### B. Synthesis of stepwise sine waves at $n=1$ and $n=2$ Shapiro steps

Two further experiments were performed on the synthesis of stepwise sine waves. By finely trimming the cryocooler temperature to around  $6.5 \pm 0.1 \text{ K}$  we synthesized sine waves of about  $1 \text{ V}_{\text{rms}}$  amplitude using  $n=1$  step. While, at  $T$  around  $4.7 \pm 0.1 \text{ K}$  the use of the  $n=2$  step for waveform synthesis leads to most promising results, in terms of noise induced on the quantized voltage steps of subsections, because the intrinsic temperature oscillations of the cold finger are much lower at these low temperatures. The great advantage is that the amplitude of the stepwise sine wave synthesized using the second step reaches its maximum value at around  $2 \text{ V}_{\text{rms}}$  by varying the cryocooler temperature, the power of the microwave radiation and by loading appropriate biasing codes.

The output frequency of the stepwise synthesized sine waves depends on the number of points per period and the frequency update of the DAC boards. Stepwise  $1 \text{ kHz}$  single-tone sine waves synthesized at maximum amplitude using  $n=1$  and  $n=2$  step are shown in Fig. 5.

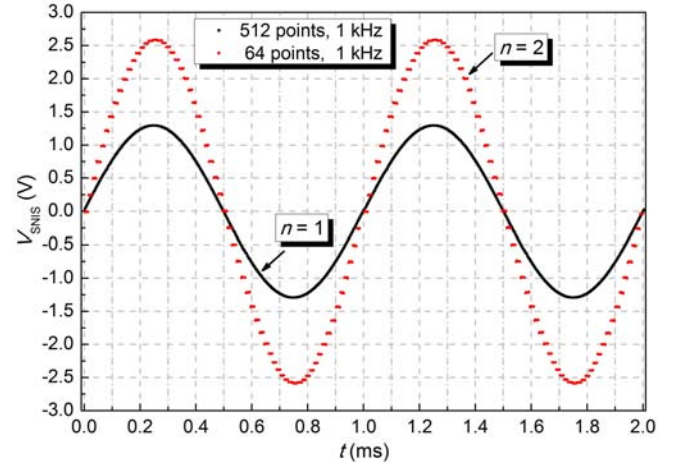


Fig. 5. Stepwise sine waves synthesized on  $n=1$  and  $n=2$  Shapiro steps with the AC-PJVS system based on a 13-bit SNIS binary divided JJs array operating in a closed cycle refrigeration system.

As a clarification, the stepwise waveform synthesized on  $n=2$  step contains only 64 samples, whereas those synthesized on  $n=1$  step contain 512 samples. The staying time of each voltage step is  $\Delta t = N_P / f_{\text{clk}}$ .

The synthesized waves are digitized with a high precision differential sampler at a sampling frequency of  $512 \text{ kS/s}$  and 24-bit of vertical resolution.

#### V. CONCLUSION

We have demonstrated the feasibility of synthesizing stepwise sine waves using of a binary divided SNIS array operating in a closed-cycle refrigerator and a new control electronics specially designed for this application. Sine waves with rms amplitude ranging from  $1 \text{ V}$  up to  $2 \text{ V}$  and frequencies in the  $\text{kHz}$  range have been synthesized. For

amplitudes up to 1 V<sub>rms</sub> the subsections of the SNIS array were biased on the  $n = 1$  step. Particularly promising were the results obtained by biasing the subsections of the SNIS array on the second Shapiro step ( $n = 2$ ) and the maximum peak-to-peak voltage amplitude obtained was about 5 V.

Preliminary characterizations show that the quantized amplitude of the stepwise synthesized sine waves is mainly affected by temperature fluctuations, which become more pronounced above 6 K, and intrinsic vibration of the two-stage cryocooler setup. The use of temperature compensation technique and low-vibration cryocooler systems will further improve the overall performance of the AC-PJVS synthesizer proposed.

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