Three Volt Pulse-Driven Josephson Arbitrary Waveform Synthesizer

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***Abstract* — We describe a new generation of Josephson Arbitrary Waveform Synthesizers that generate programmable ac waveforms with an rms amplitude of 3 V and, at 1 kHz, have a quantum locking range greater than 1 mA. This system has two chips with a total of 204 960 Josephson junctions (JJs) co-located on a cryocooler. To test for systematic errors, we phase-shift by 180° the waveform generated by half the JJs (102 480 JJs) to produce an approximate null. The measured residual of 51 nV rms implies a relative agreement of 3 parts in 10^8 between the two halves of the system.**

***Index Terms* — Digital-analog conversion, Josephson junction arrays, measurement standards, signal synthesis, superconducting integrated circuits, voltage measurement.**

I. Introduction

Over the past two decades, there has been steady improvement in the magnitude of the output voltage of the pulse-biased ac Josephson voltage standard, also known as the Josephson Arbitrary Waveform Synthesizers (JAWS) [1]. These continued improvements have resulted in the JAWS becoming a more practical tool over a larger amplitude range for ac calibrations and useful for applications such as impedance metrology [2]. Increasing the JAWS output voltage also increases the signal-to-noise ratio in measurements of systematic errors. Finally, the system improvements that were implemented to produce larger voltages have also led to simplified lower voltage systems with better understood sources of error.

In this paper, we further increase the JAWS output voltage by 50 % and measure the system performance. We use a cryocooled system to generate a 1 kHz waveform with a 3 V rms amplitude that is quantum-accurate over a dc current offset "locking" range of over ±0.5 mA. In Section II we describe the new chip and simplified electronics. In Section III we show measurements of the quantum locking range. We also begin an investigation of systematic errors by comparing two halves of the system using a null measurement and demonstrate a relative agreement of 3 parts in 10^8.

II. JAWS System Characteristics

This 3 V JAWS system combines two newly designed chips on a 4.6 K cryocooler (Fig. 1) with new bias electronics. The new chip design builds on advances demonstrated in [1]. The new bias electronics are based on a commercial pulse generator introduced in [3] and custom battery-powered isolation amplifiers that provide low-frequency compensation currents.

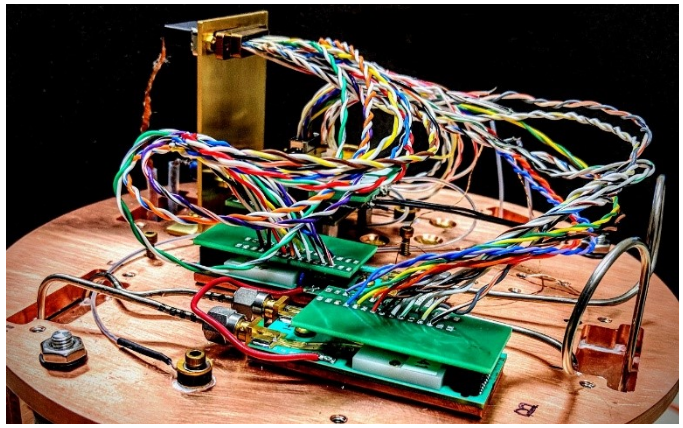

Fig. 1. Two JAWS chips mounted on a cryocooler.

The new chip design features eight arrays of Josephson junction (JJs); each array has 12 810 JJs that are embedded in series in the center conductor of a coplanar waveguide [1]. The JJs are self-shunted with a niobium-silicide barrier and niobium wiring. The JJ arrays have a critical current in liquid helium of 10 mA and a characteristic frequency of 20 GHz. In this paper, we demonstrate waveforms with an rms output of 1.5 V per chip.

Fast pulses are applied to the JJ arrays through two layers of Wilkinson dividers [1], so each chip requires only two RF inputs to drive all eight arrays. Each of the JJ arrays has an inside-outside DC block between the array and the Wilkinson dividers, with a 3 dB corner frequency of about 150 MHz to isolate the arrays at low-frequencies from each other and the RF input.

The fast pulses are provided by a commercial arbitrary waveform generator (Keysight M8195A*) at a rate of 14.4×10^9 pulses per second. An integrated finite impulse response filter is used to optimize the shape of the pulses so that every input current pulse causes each JJ to output exactly one quantized voltage pulse. The output of this generator is amplified with a commercial 50 GHz amplifier.

We use two different configurations for the low-frequency wiring of the chips. First, there is a "2 V" configuration where all the JJ arrays are connected in series with superconducting

*Commercial instruments are identified to specify the experimental procedure. NIST does not endorse commercial products. Other products may perform as well or better.

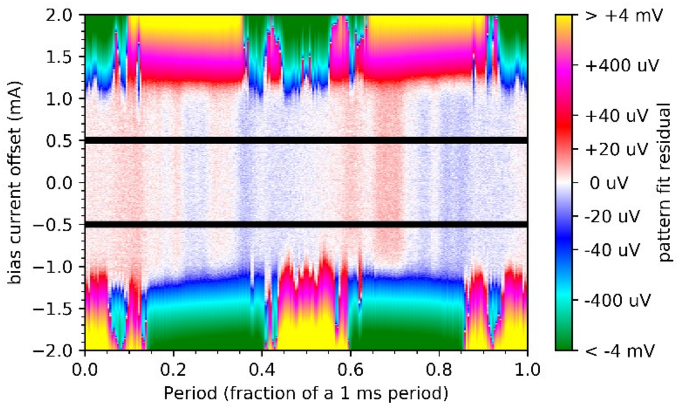

Fig. 2. Voltage residuals of a fit to a sinusoid of the digitally sampled waveform with an rms amplitude of 3 V versus dither offset current (*y*-axis) and waveform period (*x*-axis). The quantum locking range is greater than 1 mA (black lines).

wire. Second, in the "1 V + 1 V" configuration there are two pairs of outputs with the JJ arrays driven by each RF input separately connected in series. For this paper, we connect the two outputs of a "1 V + 1 V" chip and the output of a "2 V" chip in series on the cold stage of the cryocooler using short copper jumper wires.

As in earlier systems, we individually apply a low-frequency current to each JJ array through separate leads to compensate for the AC coupling of the fast input pulses by the inside-outside DC blocks [1]. The current to the arrays on each chip is provided by a pair of custom 4-channel battery-powered isolation amplifiers. The amplifier is driven by a function generator and the gain of each isolated output is controlled using an RS-485 interface on the amplifier.

For this experiment, we use one M8195A per chip. The two pulse generators are synchronized using a Keysight M8197A* synchronization module, and the instruments are synchronized to the same 10 MHz reference clock. The function generators are triggered from a M8195A marker channel.

III. 3 V and Null Measurements

We determine that we have successfully generated a 1 kHz waveform with a quantum-accurate rms magnitude of 3 V by measuring the output waveform as a function of dc bias current using a NI PXI-5922* digitizer. This measurement of the "quantum locking range" demonstrates that the system is operating correctly, with each JJ generating one output pulse for every input pulse, despite changes in the electrical or physical environment [1].

As is shown in Fig. 2, the quantum locking range is greater than 1 mA. During this measurement, the digitizer was set to its 10 V peak-to-peak range with a 1 MΩ input impedance and 1 MHz sampling rate. An additional factor-of-three resistive divider was inserted at the digitizer input (10 kΩ across the digitizer input in series with 20 kΩ) to reduce the effect of digitizer nonlinearities. The digitizer nonlinearities create vertical red/blue stripes that are independent of the offset current in Fig. 2 and create harmonics in the separately measured spectrum (Fig. 3).

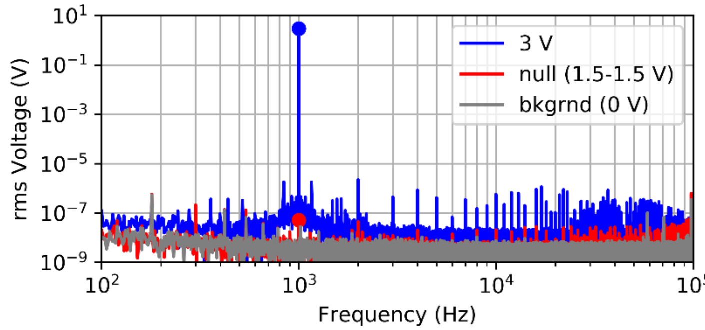

Fig. 3. Digitally sampled spectral measurement of a low distortion 1 kHz (dots) JAWS waveform with an rms magnitude of 3 V (blue), null measurement of 1.5 - 1.5 V (red), and 0 V background (grey).

As a first step in the investigation of systematic errors in this JAWS system, we measure the agreement between the different halves of the system. Each pulse generator is loaded with waveforms that are 180° out of phase. An additional delay is then applied in each pulse generator and between the pulse generators to minimize the combined amplitudes, resulting in an attempted null with an rms magnitude of 51 nV (Fig. 3). The magnitude of the attempted null depends on which JJ arrays and bias channels are generating in-phase/out-of-phase voltages. This is likely due to leakage current from the compensation electronics and will need to be investigated in more detail, along with other sources of systematic error.

VI. Conclusion

We demonstrate a cryocooled JAWS system that generates ac waveforms with an rms magnitude of 3 V and a quantum locking range at 1 kHz that is greater than 1 mA. A null measurement indicates that the two halves of the system agree to within 3 parts in 10^8, with each half generating a 1 kHz waveform with an rms magnitude of 1.5 V. More extensive measurements are in progress to better understand the systematic errors of this system.

References

[1] N. E. Flowers-Jacobs *et. al.*, "Josephson arbitrary waveform synthesizer with two layers of Wilkinson dividers and an FIR filter," *IEEE Trans. Appl. Supercond.,* vol. 26, no. 6, 143007, Sep 2016.

[2] F. Overney, N. E. Flowers-Jacobs, B. Jeanneret, A. Rüfenacht, A. E. Fox, J. M. Underwood, A. D. Koffman, and S. P. Benz, "Josephson-based full digital bridge for high-accuracy impedance comparisons," *Metrologia,* vol. 53, no. 4, pp. 1045-1053, Aug 2016.

[3] J. A. Brevik, N. E. Flowers-Jacobs, A. E. Fox, E. B. Golden, P. D. Dresselhaus, and S. P. Benz, "Josephson arbitrary waveform synthesis with multilevel pulse biasing," *IEEE Trans. Appl. Supercond.,* vol. 27, no. 3, 1301707, Apr 2017.