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One-Volt Josephson Arbitrary Waveform Synthesizer

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***Abstract*—A quantum-accurate waveform with an rms output amplitude of 1 V has been synthesized for the first time. This fourfold increase in voltage over previous systems was achieved through developments and improvements in bias electronics, pulse-bias techniques, Josephson junction array circuit fabrication, and packaging. A recently described ac-coupled bipolar pulse-bias technique was used to bias a superconducting integrated circuit with 25 600 junctions, which are equally divided into four series-connected arrays, into the second quantum state. We describe these advancements and present the measured 1 V spectra for 2 Hz and 10 Hz sine waves that remained quantized over a 0.4 mA current range. We also demonstrate a 2 kHz sine wave produced with another bias technique that requires no compensation current and remains quantized at an rms voltage of 128 mV over a 1 mA current range. Increasing the clock frequency to 19 GHz also allowed us to achieve a maximum rms output voltage for a single array of 330 mV.**

***Index Terms*—Digital–analog conversion, Josephson arrays, quantization, signal synthesis, standards, superconducting device measurements, superconducting integrated circuits, voltage measurement.**

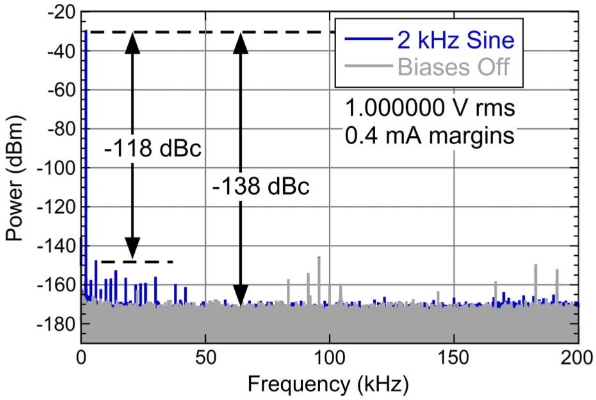

Fig. 1. Digitally sampled spectral measurement showing a −120 dBc [decibels below the fundamental (carrier)] low-distortion measurement of a 1 V rms 2 kHz signal synthesized with all four arrays of the ACJVS chip biased at the second quantum state ($n = 2$). The digitizer settings used were a 1 MΩ input impedance, a 10 V input range, a 10 Hz resolution bandwidth, no averaging, and a 500 kilosamples/s (kS/s) sampling rate. Gray data show the digitizer −138 dBc noise floor and the spurious signals with the bias signals turned off.

I. INTRODUCTION

AFTER nearly 19 years since the invention of the Josephson arbitrary waveform synthesizer (JAWS) [1], a quantum-accurate rms output voltage of 1 V has been synthesized for the first time. This voltage has been an important metrology goal because ac voltage calibrations are commonly referenced to primary ac standards (rms detectors such as thermal voltage converters and transfer standards) at a voltage of about 1 V, and most instruments used to measure the ac voltage are most accurate at 1 V [2], [3]. The JAWS systems, which are also called ac Josephson voltage standards (ACJVSs) when synthesizing sine waves and dc voltages, have been used to calibrate thermal voltage sensors in the 2 mV to 220 mV rms voltage range [4]–[7]. JAWS and ACJVS circuits are essentially perfect digital-to-analog converters whose operation in a quantum state allows them to produce perfect distortion-free waveforms with intrinsically accurate voltages.

Developing an intrinsically accurate 1 V source has been a particularly challenging technological goal because quantum-based voltage waveform synthesis requires large and series-connected Josephson junction arrays that are all biased into the same quantum state with complex bipolar digital pulse waveforms clocked at frequencies greater than 10 GHz. Nearly two decades of research and development by numerous technologists, metrologists, laboratories, and international research programs have been applied to this goal and to turning the devices into practical systems for calibrating ac voltage standards and other instruments [4]–[37]. In addition to enabling significant improvements in ac voltage metrology at rms voltages of 1 V and below, this system will act as a quantum-based reference for the entire parameter space of the National Institute of Standards and Technology (NIST)'s ac voltage calibrations [38]. Stepwise-approximated ac voltage waveforms can be generated by programmable Josephson voltage standards with a 7 V rms output. However, the nonquantum behavior of the transitions between the steps prevents these waveforms from having intrinsically accurate ac voltages ([13]–[15], [37]).

The largest rms output voltage achieved to date by a JAWS system is 275 mV, which was produced by summing the voltage of two separately biased Josephson arrays [29]. Recently presented results have doubled the maximum rms output voltage for a single array to 250 mV. This was done by using a new implementation of the ac-coupled bipolar bias technique and the development of new pulse-bias electronics that together

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allowed the junctions to be biased in their second quantum state [39]. In this paper, we describe how the rms output voltage was quadrupled to 1 V by using a four-array superconducting integrated circuit and with further improvements to the pulse-bias electronics and to the device packaging. These developments enabled a 1 V rms voltage to be achieved with a current margin of 0.4 mA by operating 25,600 Josephson junctions in the second quantum state. The measured spectrum of this waveform is shown in Fig. 1. We also describe in this paper our efforts to further increase the output voltage of a single array by increasing the microwave frequency to nearly 20 GHz.

II. Quantum States and Voltage Waveform Synthesis

In this section, we summarize how the zeroth, first, or second quantum state (and their opposite polarity states) of a Josephson junction is selected with pulses of appropriate amplitude (and polarity) by combining microwave and digital signals. This pulse-coding technique is described in detail elsewhere [39]. The intrinsic accuracy of JAWS quantum-based sources derives from the ac Josephson effect [40] and the ability of a Josephson junction to produce quantized voltage pulses whose time-integrated areas are precisely the value of the flux quantum $h/2e$, where h is Planck's constant, and e is the electron charge. If a Josephson junction is biased with a microwave signal or periodic pulses having a repetition frequency f, the junction's supercurrent oscillations can lock to this drive signal and produce quantized voltage steps $V_n = n(h/2e)f$, where integer n is the quantum number of the voltage step or the quantum state. Equivalently, quantum state n refers to the number of flux quanta traversing the junction barrier or the number of 2π phase slips of the junction phase propagation for each $1/f$ period of the drive signal.

Series arrays of junctions are used to increase the output voltage to the practical values necessary for precision measurement applications. However, junction dissipation attenuates the microwave bias signal and limits the number of junctions per array that can be uniformly biased. Thus, further increases in the total output voltage typically requires additional arrays connected in series, as shown in Fig. 2. For pulse-biased circuits containing N series-connected junctions, n is the net number of quantized output voltage pulses per input pulse, and the rms output voltage is $V = NV_n/\sqrt{2}$. Arbitrary voltage waveforms are produced by using analog-to-digital conversion techniques that define a digital code whose specific pattern and densities of ones and zeros precisely determine the presence (and polarity) or absence of a pulse. We define the operating margin of the circuit as the dc range over which the quantum state of a junction or an array of junctions remains locked to the ac drive signals.

For the 1 V results presented here, the frequency of our microwave bias is $f_m = 14.4$ GHz, and each array contains $N = 6400$ Josephson junctions. For metrological accuracy, we define the peak voltage of the array $V_A = Nnf_m/K_{J\text{-}90}$ in terms of $K_{J\text{-}90} = 483597.87$ GHz/V, which is the value of the Josephson constant defined in 1990. At this frequency, each junction generates about 30 μV on the $n = 1$ first quantized voltage step and about 60 μV on the $n = 2$ second quantum step. The peak voltage for each array on the second quantum step is 381.1431 mV. Thus, the entire series-connected four-array ACJVS circuit containing 25 600 junctions can produce a *peak* voltage of $4V_A = 1.5245724$ V. This corresponds to a potential maximum rms voltage of 1.0780355 V, depending on the limitations of the synthesis techniques. The dimensionless peak amplitude V_p of the digitally sampled waveform was defined to be $V_p = 0.9276133$ of V_A to precisely produce an rms of $V_p \bullet V_A/\sqrt{2} = 250.0000$ mV for each 6400-junction array when biased in the second quantum state and exactly 1 V rms for all four arrays. The digital waveforms were synthesized with a second-order delta–sigma modulator [41].

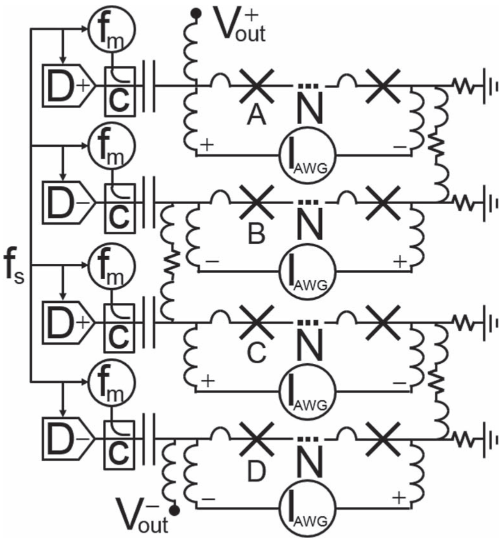

Fig. 2. Simplified circuit schematic showing the four (A–D) series-connected arrays, each biased using the ac-coupled bipolar pulse technique. Each N-junction array has three biases, digital bit code D (data + or data complement −), the microwave bias of frequency f_m, and the arbitrary waveform generator (AWG) compensation [12], [39]. Coupler C combines the two high-speed signals. Microwave termination resistors are shown at the end of each array.

We use the ac-coupled bipolar pulse-bias technique [9], [17], which requires three biases for each array, including a low-speed compensation bias current I_{AWG} whose frequency is the same as that of the synthesis frequency and two high-speed signals, a microwave signal of frequency f_m, and a two-level digital data signal D that is nonreturn to zero (NRZ) clocked at the pattern's sampling frequency, which is twice that of the microwave frequency, $f_s = 2f_m$ [39].

The four-array circuit and its simplified bias signal schematic are shown in Fig. 2. The bias circuitry is essentially the same as in [39], apart from there being four arrays instead of one, and there are two synchronized synthesizers that each provide a pair of complementary digital data signals, i.e., data D+ and data complement D−, to pairs of consecutive arrays. The high-speed signals for each array are combined with a directional coupler (C), ac coupled through an alternating series of two dc blocking capacitors (one capacitor shown) with a 250 MHz cutoff frequency and a 1 dB attenuator (not shown), and applied via a semirigid coax and a normal metal grounded-coplanar-waveguide interface board to each N-junction Josephson array (symbolically represented by $X \bullet\bullet\bullet X$). Each synthesizer also generates a pair of compensation bias current signals (I_{AWG}) that is synchronized to the data signal and that biases two of the four arrays.

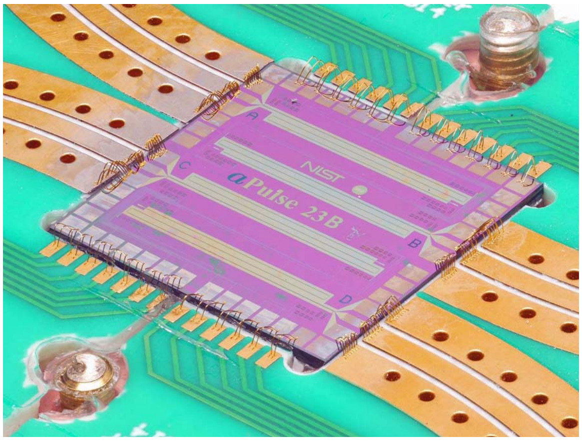

Fig. 3. Photograph of the NIST 1 V rms JAWS chip mounted on a copper block, showing the wire bond connections to the interface circuit board. Two coplanar lines on two opposite sides of the chip bias the four arrays with high-speed signal biases. Low-speed connections on the adjacent sides provide current compensation bias signals and the voltage output leads. (Photo compliments of Dan Schmidt).

III. JAWS CIRCUIT AND SYNTHESIZER IMPROVEMENTS

The design of the four-array superconducting integrated circuit is essentially identical to previous circuits [29], except that the number of arrays is doubled, and the second pair of arrays has its coplanar waveguide (CPW) launch pads located on the opposite edge of the chip. Details of the array fabrication and the microwave circuit design are presented elsewhere [42]–[45]. The minimum critical current for all junctions on the *four-array* chip is $I_c = 8.7$ mA, the average junction resistance is $R = 4.3$ mΩ, and the impedance-tapered CPWs are terminated with 26.5 Ω resistors [44], [45].

Fig. 3 is a photograph of the chip mounted in its cryopackage showing gold wire bond connections to the circuit board interface [46]. The arrays are connected in series on the interface board with copper jumper wires (not shown in the photograph but represented by small resistor symbols in Fig. 2). Since the digitizer has a high input impedance and no currents flow between the arrays, these nonsuperconducting connections have no effect on the measurements presented in this paper. The cryopackage was mounted on a liquid helium cryoprobe, and the device was measured in a 100 L liquid helium storage Dewar at 4.0 K. High-speed signals are provided to the package via a semirigid coax and coax-to-printed-circuit-board connectors. The low-speed compensation biases are provided by twisted-pair leads soldered to pads on the interface board of the cryopackage. This cryopackage was modified for the four-array circuit from a new cryocooler-compatible package that was designed for two-array ACJVS systems.

The cryopackage and the two-channel arbitrary bitstream generator ABG-2 bias electronics from High Speed Circuit Consultants were both developed in 2013 and optimized for two-array ACJVS systems.[1] This development included automation software for the two-array systems that is capable of optimizing the operating margins for each array and performing ac–dc difference calibrations.

In January and February 2014, we installed two of these automated two-array ACJVS systems at the ac voltage calibration laboratory at NIST, Gaithersburg, MD, USA, and at the U.S. Army Primary Standards Laboratory, Huntsville, AL, USA. In March 2014, the ABG-2 electronics were delivered and used to bias NIST ACJVS chips at both the National Institute of Measurement, Changping, Beijing, China, and the National Research Council, Ottawa, ON, Canada. These systems were all able to synthesize 250 mV rms voltages for each array of their two-array circuits. The ABG-2 design delivered to these laboratories is essentially the completed two-channel version of the electronics presented in [39], which used a 28 Gb/s output multiplexer (MUX) and Picosecond Pulse Labs 5882 amplifiers for the data signals.

During the testing of these multiple ABG-2 units, we discovered that the newer output MUX circuits were not able to be overclocked to 30 GHz, as we found in the original prototype circuit that enabled the results in [39]. Thus, depending on the MUX performance, these units are clocked either at the recommended 28 GHz or up to a maximum frequency of 28.8 GHz, as is used for the results presented in this paper. Furthermore, it was found that the operating margins at 250 mV for each array with these systems were very small, typically only a few hundred microamperes, such that only two of the five ACJVS systems successfully synthesized 2 kHz waveforms at an rms voltage of 500 mV with operating margins of at least 0.1 mA.

For the results presented in this paper, two ABG-2 units were used, one of which had been modified to have a faster 45 Gb/s MUX. The trigger output from one unit, which is aligned with the start of the waveform, was used as the trigger input for the second unit, and the software trigger delay of the second unit was adjusted to correct for cable delays and to align the data outputs of the two units. We disabled the internal microwave synthesizer in one unit and used the microwave synthesizer output from the second unit to clock both units. Without this modification, the relative phase jitter of the microwaves from the two units prevented effective compensation for the crosstalk between the arrays.

Both ABG-2 units were also modified in order to reliably yield larger operating margins by installing new amplifiers that produce an 8 V peak-to-peak data amplitude, which is three times greater than the 2.7 V peak-to-peak maximum output amplitude of the original amplifiers. These new amplifiers allowed us to achieve operating margins as large as 0.8 mA for the 250 mV rms voltage waveforms for some single arrays and some data channels. This larger output amplitude enabled larger operating margins to be achieved in the second quantum state for arrays that have critical currents larger than 7 mA.

IV. MEASURED OPERATING MARGINS AND SPECTRA

While optimizing the performance of the second ABG-2 unit with the faster MUX, we first investigated whether higher operating frequencies (f_m and f_s) could produce larger output voltages for a single array. For these measurements, we used the same 6400-junction array of the *two-array* chip that was used

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[1] Commercial instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the equipment identified is necessarily the best available for the purpose.

TABLE I
SINGLE-ARRAY OPERATING MARGINS AND RMS OUTPUT VOLTAGE FOR DIFFERENT QUANTUM STATES, WAVEFORM AMPLITUDES, AND FREQUENCIES

f_m (GHz)	V_p	Current Margins (mA)		RMS Output Voltage (mV)	
		n=1	n=2	n=1	n=2
15.0	0.89051	2.9	0.9	125.0000	250.0000
19.0	0.92761	2.9	0.35	164.9306	**329.8611**
19.5	0.37105	4.5	1.0	67.7083	135.4167
19.5	0.74209	3.2	0.6	135.4167	270.8333
19.5	0.92761	2.7	0.0	169.2708	

in [39] because we wanted to compare the results with that of the previous work. The junctions on this array had a minimum critical current of $I_c = 7.2$ mA, an average junction resistance of 5.1 mΩ, and the CPW was terminated with a 22.4 Ω resistance. We operated this modified ABG-2 with NRZ clock frequencies up to 39.8 Gb/s and the corresponding microwave frequencies up to 19.9 GHz. As described previously [39], we found that the operating margins depended on the amplitude of the waveform being synthesized and the microwave frequency.

For comparison, we list the margins that were previously achieved with this same array when biased at 15 GHz [39]. The highest frequency results are shown in Table I for waveforms with different peak amplitudes. The largest voltages were achieved for the second quantum state. Although the $V_p = 0.927613$ pattern did not yield margins at 19.5 GHz for $n = 2$, margins of 0.35 mA were achieved at 19.0 GHz, which produced a new record rms output voltage of 329.8611 mV for a *single* array. Surprisingly, operating margins greater than 1 mA (not shown in Table I) were also achieved for the $n = 3$ *third* quantum state at 14.5 GHz for the smaller amplitude $V_p = 0.371045$ pattern, which yielded an rms voltage of 151.0147 mV (not shown in the table). Since only one of our ABG-2 units had this faster MUX, we were unable to bias four arrays to achieve voltages greater than 1 V rms for this chip.

For the 1 V operation with all four arrays, the frequencies of both ABG-2 units were set to $f_m = 14.4$ GHz and $f_s = 28.8$ Gb/s because that was the fastest data rate available from the unmodified MUX in the first ABG-2. Fig. 1 shows the spectrum for the 2 kHz synthesized waveform as measured with a National Instruments 5922A digitizer. The 2 kHz tone is seen at -30 dBm, with the noise floor at -138 dBc [decibels below the fundamental (carrier)].

The noise floor and the electromagnetic interference (EMI) were measured with all biases to all four arrays turned off, and this trace is plotted together with the sine-wave measurement, effectively obscuring these features of the sine-wave measurement. The few spurious tones that remain, which are around 100 kHz and above 165 kHz, are attributed to the EMI. These signals remained even after all bias cables were disconnected and only the voltage output coax remained connected between the cryoprobe and the digitizer. These signals indicate that shielding could be improved, which will be addressed in the future.

The harmonic tones at frequencies less than 45 kHz that are all less than -118 dBc are produced by the digitizer and are not intrinsic to the JAWS-synthesized waveform. These harmonic tones were found to change their relative amplitudes when measured with the other channel of the digitizer and when either channel's internal calibration procedure was performed. These signals also did not modulate when a dither bias current oscillating at tens of hertz was applied across all four arrays.

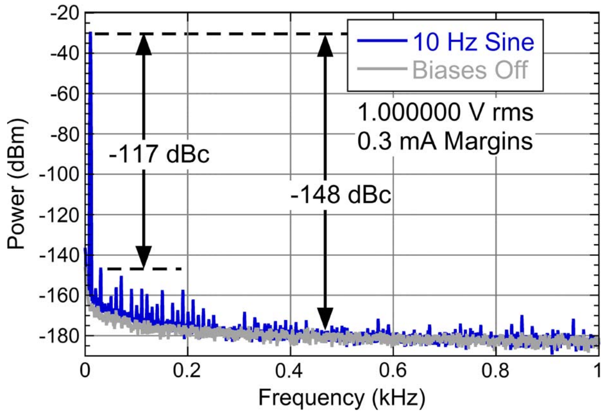

Fig. 4. Digitally sampled spectral measurement of a 1 V rms 10 Hz synthesized waveform in the second quantum state ($n = 2$). The digitizer settings were as follows: a 1 MΩ input impedance, a 10 V input range, a 1 Hz resolution bandwidth, 10 averages, and a 100 kS/s sampling rate. Gray data show the digitizer -148 dBc noise floor with the bias signals off.

This dither current is also used to determine the current range (the operating margin) over which the quantum state of the waveform is preserved. Nonquantum behavior is indicated by the presence of harmonic tones (not present and not shown) that appear above the measured noise floor. These harmonic tones are also distinguished from those caused by digitizer nonlinearities and the EMI because they will show a finite width in the frequency that modulates with the dither current. The 2 kHz waveform with an rms output voltage of 1 V had an operating margin of 0.4 mA, whereas the margins of the four individual arrays ranged from 0.5 mA to 0.8 mA. This decrease in the operating margin with all arrays biased is an indication of crosstalk between the arrays.

Sine-wave synthesis at lower frequencies is useful for ac calibrations, particularly at 50 Hz and 60 Hz power line frequencies. Fig. 4 shows the measured spectrum of a 10 Hz synthesized waveform, also having an rms output voltage of 1 V. This measurement shows similar behavior and performance to that of the 2 kHz waveform described earlier. Fortunately, the smaller sampling frequency, the resolution bandwidth, and the use of averaging allowed us to reduce the measured noise floor to -148 dBc. The digitizer distortion is practically the same at around -117 dBc, whereas the lower noise floor allows us to observe the digitizer's distortion up to 1 kHz. We note that the synthesis of this 10 Hz waveform with a 28.8 GHz clock frequency is only possible because of the large memory available in the ABG-2 electronics. The ABG-2 synthesizer has 32 Gb of memory, which will allow the synthesis of waveforms longer than 1 s (0.9 Hz at $f_s = 28.8$ GHz). The pattern repetition frequency of a synthesized waveform, i.e., $f = f_s/M$, where M is the length of the digital waveform in bits, determines the minimum frequency that can be synthesized with that pattern length and the frequency resolution of single-tone and

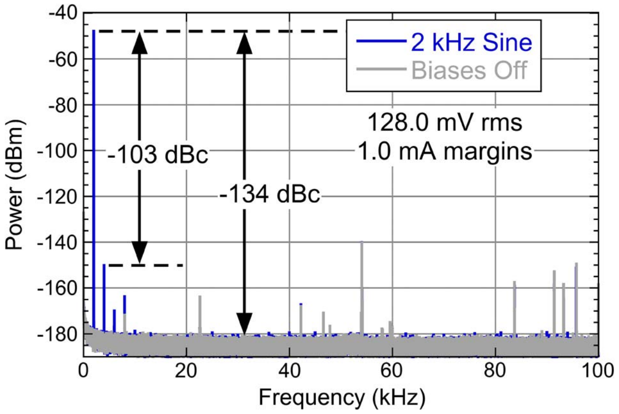

Fig. 5. Digitally sampled spectral measurement of the 2 kHz 128 mV rms signal synthesized with all four arrays of the ACJVS with the "zero-compensation" bias technique when biased at the first quantum state $(n = 1)$. The digitizer settings used were a 1 MΩ input impedance, a 10 V input range, a 2 Hz resolution bandwidth, 10 averages, and a 500 kS/s sampling rate. Gray data show the digitizer -134 dBc noise floor and the spurious signals with the bias signals off.

multitone harmonic waveforms that can be synthesized with patterns of this same length. The pattern length for the 10 Hz waveform is $M = 2\,880\,000\,000$ bits. Note that the code length for the 2 kHz pattern is 28 800 000 bits because it is synthesized as a second harmonic of the 1 kHz pattern repetition frequency for that code length. Synthesizing the fifth and sixth harmonics of this pattern repetition frequency with the 2.88 Gb code length enables the direct synthesis of the power line frequencies.

V. WAVEFORM SYNTHESIS WITH ZERO-COMPENSATION BIAS TECHNIQUE

Finally, we show in Fig. 5 a waveform with an rms amplitude of 128 mV that was synthesized with the zero-compensation bias technique [39]. This technique allows waveforms to be synthesized without a compensation bias current by maintaining a nearly zero average voltage from the high-speed digital drive signal. Such waveforms may become useful for evaluating systematic errors generated by inductances inherent in the JAWS circuit, such as those produced by the compensation bias currents or by other undesirable signals and parasitic elements in the bias and measurement circuits. This technique may be particularly useful for generating sine waves and arbitrary waveforms at frequencies greater than 100 kHz. The maximum rms voltage per array $V_p V_A/(\sqrt{2})$ is achieved with this technique when $V_p = 0.25$. For this waveform, we chose $V_p = 0.2374690$ as the fraction of the full scale of the first quantum step to exactly produce $4V_p \bullet V_A/(\sqrt{2}) = 128.0000$ mV for the four-array circuit.

The zero-compensation bias technique requires a smaller pulse amplitude than the 1 V waveforms because it toggles between the 0 and +1 quantum states instead of the −2, 0, and +2 states. Thus, we installed an additional 3 dB attenuator on all four ABG-2 high-speed output lines to set the pulse amplitude to an appropriate range for the electronics.

Each array produces an rms voltage of precisely 32.00000 mV and a dc offset of 47.6 mV (0.2496327 fraction of the $n = 1$ step voltage). The operating margins for the waveforms generated by each array ranged from 1.0 mA to 1.8 mA, whereas the operating margin of the 128 mV waveform for all four arrays was 1.0 mA, equaling the smallest margin of the four separate arrays.

As discussed previously [39], this method to synthesize arbitrary waveforms and sine waves has significant operating margins and can also eliminate inductive voltage errors due to the compensation bias and other signals. A dc bias is still required nevertheless. One disadvantage of this technique is that the maximum amplitude that can be synthesized is one-fourth that of the $n = 1$ Shapiro step voltage. The most challenging drawback of the zero-compensation bias technique is the inherent dc offset of the output waveform because it prevents the practical implementation of rms measurements. For the aforementioned synthesized waveform, we perfectly eliminated the dc offset by loading waveforms with opposite polarity dc offsets in the two ABG-2 synthesizers. The arrays generated their expected dc offsets when biased separately, but when biased simultaneously, we were able to perfectly cancel the dc voltage.

As a point of interest, by inverting the code and the relative phase in one of the two synthesizers, we also succeeded in canceling the 2 kHz signal to only produce a 269 mV dc output signal. We also successfully canceled either dc or ac signals by loading different waveforms having sine waves and dc offsets of opposite polarities. This may be a useful technique in such multiple-array systems for ensuring the quantum accuracy of the individual arrays and uncovering systematic errors and undesirable coupling between the circuits. Similar methods are used in the NIST programmable Josephson voltage standard systems to ensure quantum accuracy of dc voltages for its circuit containing 23 subarrays [47], [48]. This voltage-cancelling technique can be also used with the higher voltage waveforms produced with the ac-coupled bipolar bias technique.

VI. CONCLUSION

In this paper, we have demonstrated a fourfold increase in rms voltage over previous ACJVS systems to 1 V by using improved pulse-bias electronics that enabled operation in the second quantum state and by doubling the number of junctions with a newly developed four-array JAWS circuit. By operating one of the bitstream generators with a faster MUX clocked at 39.8 GHz, we demonstrated a new record rms output voltage for a single array of nearly 330 mV. For the first time, we also demonstrated quantum-accurate waveforms synthesized at 10 Hz and a 1 V rms output, as well as a 2 kHz sine wave synthesized with the third quantum state that produced an rms output voltage of 151 mV. Finally, we demonstrated a 128 mV rms voltage waveform using the zero-compensation bias technique and demonstrated the perfect cancelation of the inherent dc offsets by using waveforms with intentionally different polarities for the ac and dc voltages.

Future development of this NIST system will include the construction of four-channel bias electronics, improvement in shielding, and automation to optimize the 12 separate biases required to synthesize quantum-accurate waveforms with four-array circuits. If we succeed in achieving operation margins on four arrays with the faster MUX clocked at 39.8 Gb/s (or faster), we should be able to synthesize sine waves with a 1.32 V rms output voltage with this chip. Additionally, since the first quantum state produced such large operating margins, we will fabricate a new chip design containing twice as many junctions in order to see if we can further increase the output voltage per array, as well as the operating margins for 1 V rms waveforms.

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