Performance Improvements for the NIST 1 V Josephson Arbitrary Waveform Synthesizer

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***Abstract*—The performance of the NIST Josephson arbitrary waveform synthesizer has been improved such that it generates a root-mean-square (rms) output voltage of 1 V with an operating current range greater than 2 mA. Our previous 1 V JAWS circuit achieved this same maximum voltage over a current range of 0.4 mA by operating every Josephson junction in its *second* quantum state. The newest circuit synthesizes 1 V waveforms with the junctions operating in the *first* quantum state. The voltage per array is doubled because the number of junctions in each array was doubled through the use of improved microwave circuit designs that increased the bias uniformity to the junctions. We describe the circuit improvements and device operation, and we demonstrate the system capabilities by showing measured spectra of a 1 Hz sine wave and a dual-tone waveform. With only two arrays of the new circuit, we also synthesized a 128 mV sine wave without a compensation bias signal, which is one of the bias signals required for achieving 1 V. This is the same rms output voltage achieved with the previous circuit using four arrays.**

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

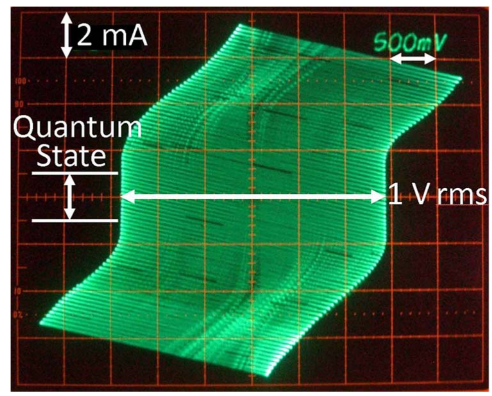

Fig. 1. Photograph of the analog scope measurement of the swept current-voltage characteristic that shows the 2 mA current range of the quantum state of the four-array circuit while synthesizing the 2 kHz sine wave with a 1 V rms output amplitude. The trace is produced by adding a triangle-shaped dither current across the circuit. The constant intensity region of the central rectangle (2 mA by 2.8 V peak-to-peak) indicates where the output signal has quantum accuracy such that every junction produces precisely one perfectly quantized voltage pulse for every input pulse as defined by the digital code.

I. Introduction

A Josephson arbitrary waveform synthesizer (JAWS) with a root-mean-square (rms) output voltage of 1 V was recently demonstrated [1]. This circuit consisted of four arrays of 6400 Josephson junctions each, all connected in series for a total of 25,600 junctions. To obtain this 1 V output voltage, each array was biased at a microwave frequency of 14.4 GHz such that every junction was operating in its second quantum state, producing two perfectly quantized pulses for every input pulse. This *second* quantum state was maintained over a current range of 0.4 mA. Similarly, the first quantum state, which produced 500 mV, or precisely half the voltage, was achieved under different bias amplitudes and remained quantized over a much larger current range of 3.0 mA. The magnitude of the current range of these quantum states depends on many factors, including electrical characteristics of the Josephson junctions, microwave frequency, microwave power, and amplitudes and relative phases of all the biases signals. Most importantly, the current range of each quantum-state depends on the uniformity of all these factors, especially the critical currents Ic's and resistances R's of all the junctions, as well as the uniformity of the microwave power and the amplitudes of other signals that bias all the junctions.

In this paper, we present a five-fold improvement in the current range (from 0.4 mA to 2.1 mA) over which all junctions in our JAWS circuit remain quantized while synthesizing a sine wave with a rms output voltage of 1 V (see Fig. 1). The current range was increased for synthesis of a sine wave with 1 V rms output by use of improved superconducting microwave elements in the circuit design, which allowed twice the number of junctions per array to operate in the *first* quantized state. Waveforms with peak amplitudes up to 1.5 V can now be synthesized with every junction operating in the *first* quantum state. In addition, we demonstrate that our JAWS system has useful system and application capabilities by presenting the fast Fourier trans-form (FFT) measurements of both a 1 Hz synthesized sine wave and a two-tone waveform that could be used for inter-modulation measurements. We also describe the results of new measurements of waveforms synthesized with the "zero-compensation" bias technique [1], [2].

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II. Quantum Accurate Waveform Synthesis

We recently described advances for NIST JAWS systems including a new implementation of the ac-coupled bipolar bias technique and a zero-compensation bias technique that produces waveforms without any bias at the desired signal frequency [2]. We are working to improve the performance of our circuits with both bias techniques, and with a particular focus on the zero-compensation bias technique because it may have fewer systematic errors for signals synthesized at frequencies above 100 kHz.

All JAWS systems take advantage of the AC Josephson effect [3] 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. When current biased to a non-zero voltage, a junction's supercurrent oscillates at a frequency that is directly proportional to the voltage. When a junction is biased with either a microwave signal or periodic sequence of pulses having a repetition frequency f, this supercurrent can lock to this external 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 quantum state. For circuits containing N series-connected junctions, n is the net number of quantized voltage pulses per input pulse, and $V(n, N) = Nn(h/2e)f$ is the output voltage for the quantum states of an N-junction array [4]. The voltage can therefore be changed by modulating the pulse repetition frequency, and arbitrary waveforms can be synthesized by use of digital synthesis techniques [5]–[9]. A JAWS circuit is essentially a perfect digital-to-analog converter whose operation in quantum states allows it to synthesize distortion-free arbitrary waveforms with a voltage amplitude that has quantum accuracy [10]–[19].

The maximum amplitude that can be synthesized with a JAWS circuit and the maximum current range over which the waveform has quantum accuracy depend on whether its high-speed bias amplitudes are tuned to optimize the quantum states that are accessed by the waveform. All the codes are generated with a delta-sigma modulator algorithm [5]. For all waveforms demonstrated in this paper, the first quantum state $(n = 1)$ is used to define the maximum voltage. The waveforms generated with the ac-coupled bias technique used a three-level digital code to access either the $-n$, 0 or $+n$ quantum states (or -1, 0 or $+1$, for this paper) [2]. The waveforms synthesized with the zero-compensation bias technique used a two-level digital code to toggle each junction between its 0 and $+1$ quantum states [2]. The biases that produce these quantum states are generated by combining a microwave bias frequency $f_{CW} = 14.4$ GHz with a two-level digital signal that is non-return-to-zero (NRZ) clocked at $f_S = 28.8$ GHz. The microwave frequency is chosen to be precisely one-half that of the NRZ clock frequency, such that $f_{CW}(m = 1) = (m/2)f_S$, with $m = 1$.

Fig. 2 shows each of these individual waveforms and their combined waveform. Four unique bit pairs define the different bias configurations (plus, minus, zero, and alt zero) that are used to generate the desired quantum states of each junction. The bias conditions used in the ac-coupled bias technique are "minus", "zero", and "plus" to toggle the junction between the -1, 0 or $+1$ quantum states. The zero-compensation bias technique uses the "zero" and "alt zero" bias conditions to toggle between the 0 and $+1$, states, but with an additional dc bias added that causes the "alt zero" configuration to yield only a single pulse of just one polarity instead of two pulses having opposite polarity [2].

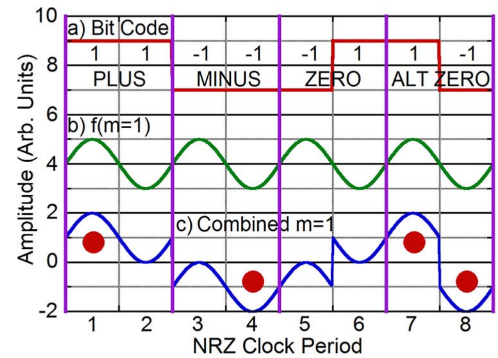

Fig. 2. Idealized bias waveforms for the ac-coupled and zero-compensation bias techniques. (Waveforms are consecutively offset vertically from origin by 4 units). (a) Digital bit code signal showing 4 pairs of bits aligned to the NRZ Clock f_S, identified as PLUS, MINUS, ZERO, and ALT ZERO pairs. (b) Microwave bias with $f_{CW}(m = 1) = f_S/2$. (c) Combined high-speed biases. PLUS (periods 1 and 2) and MINUS (periods 3 and 4) bias conditions each generate one input pulse, but of opposite polarity. Filled circles indicate when junctions would pulse. The ZERO bias condition generates no pulses, while the ALT ZERO (NRZ clock periods 5 thru 8) condition generates pulses of both polarity (unless dc bias is also applied, as is the case for the zero-compensation bias condition).

III. Four-Array Jaws Circuit

The waveforms presented in this paper were synthesized with a four-array circuit having a total of 51,200 junctions, *twice* as many junctions as the previous circuit [1], such that each array contains 12,800 junctions. Fig. 3 shows the circuit schematic, which is identical to the previous circuit apart from the number of junctions. The figure also shows the three bias signals that are required for each array, namely the high-speed bias consisting of the microwave signal (of frequency $f = f_{CW}$) and the two-level digital signal (D), and the "low-speed" "compensation" bias (I_{AWG}), whose frequency is the same as that of the synthesized output signal. Four arrays (A through D) are required because junction dissipation, and the resulting attenuation of the high-speed signals, limits the number of junctions that can be uniformly biased with the high-speed signals. The arrays are connected in series to maximize the output voltage produced by the entire circuit.

We were able to double the number of junctions per array by improving the high-speed bias uniformity through the use of on-chip microwave components that were designed for the NIST programmable Josephson voltage standard (PJVS) circuits as well as JAWS. The microwave components, namely coplanar waveguide (CPW) bias-tee interconnects, terminations, and corners, were optimized for continuous-wave microwave signals with frequencies up to 22 GHz [20]–[23]. The design of the tapered transmission lines [22], [23], which are used to partially compensate for the junction dissipation, was adapted from the PJVS circuits that have 8400 junctions per array to account for

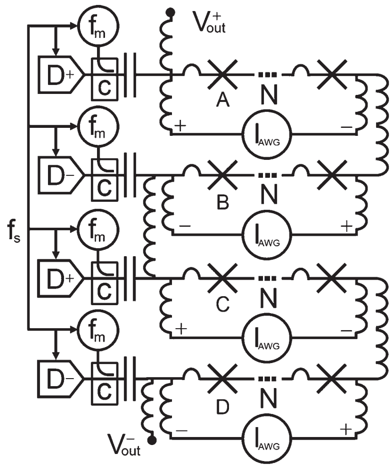

Fig. 3. Simplified circuit schematic showing the four (A through D) series-connected arrays each biased using the ac-coupled bipolar-pulse technique. Each N-junction array has three biases: digital bit code D (data D+, and data complement D−), microwave bias of frequency f_m, and compensation AWG [2], [8]. Coupler C combines the two high-speed signals.

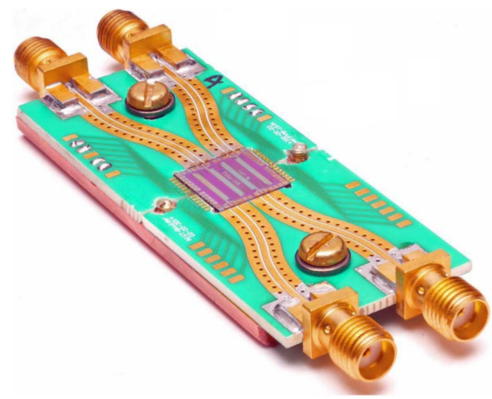

Fig. 4. Photograph showing the cryopackage for the 1 cm × 1 cm NIST 1 V JAWS chip (25,600-JJ circuit used in [1]) mounted on a copper block. Pads on the chip are wire-bonded to two interface circuit boards. Coplanar lines on opposite edges of the chip provide the high-speed biases to the four arrays, while the low-speed-bias and output voltage leads for each array are accessed by circuit-board pads on the adjacent sides. (Photo compliments of Dan Schmidt, NIST).

the ∼50% larger number of junctions (12,800) per array in the new JAWS circuit.

The Josephson junctions are double-stacked junctions made with niobium superconducting leads and amorphous-niobium-silicon barriers. Details of the stacked-junction fabrication have been presented elsewhere [23], [24]. The minimum critical current for all junctions on the *four-array* chip is $I_c = 7.3$ mA, the average junction resistance is $R = 4.1$ mΩ, and the impedance-tapered coplanar waveguides are terminated with 26.7 Ω resistors.

The peak voltage of each array is $V_n^A = Nnf_m/K_{J-90}$ in terms of $K_{J-90} = 483597.9$ GHz/V. For this work at microwave frequency 14.4 GHz and biased on the first quantum step $V_1^A = 381.1431$ mV. The entire series-connected four-array JAWS circuit containing 51,200 junctions can potentially produce a peak voltage of $4V_1^A = 1.5245724$ V and a synthesized sine wave with a maximum rms voltage of 1.0780355 V, depending on limitations of the synthesis techniques. A second-order delta-sigma modulator [5]–[9] was used to produce the digital code that generates the two-level digital signal. The dimensionless peak amplitude V_p of the digitally sampled waveform was defined to be $V_p = 0.9276133$ of V_1^A so as to precisely produce an rms voltage of $4V_p \bullet V_1^A/\sqrt{2} = 1.000000$ V rms.

Fig. 4 shows a photograph of a wire-bonded chip (of the previous design having 6400 junctions per array) and the cryopackage consisting of a chip soldered to a copper pedestal on a copper block and wire bonded to gold-plated traces on two PCB interface boards. The photograph shows the bias connections to the PCB interface board, including the coax-to-PCB connectors and the pads used to make the array-to-array connections and the compensation bias leads. The arrays were connected in series by use of copper jumper wires (not shown) between the PCB pads.[1] The cryopackage was mounted in a liquid-helium cryoprobe by use of four semi-rigid coaxial cables for the high-speed biases and twisted pair copper leads for the compensation bias and output voltage signals. The device was measured in a 100 L liquid-helium storage Dewar at 4.0 K. This four-array cryopackage was based on previously optimized designs [25] and on a cryocooler-compatible PJVS cryopackage [26] that was originally designed for two-array JAWS systems [1].

The bias electronics, consisting of two arbitrary bitstream generators ABG-2 from High Speed Circuit Consultants, were developed in 2013 and optimized for two-array JAWS systems.[2] Each generator is designed to bias two arrays and has separate high-speed and low speed outputs for each array. The generators are frequency referenced to each other by the use of the same 14.4 GHz microwave clock, and the synthesized output signals are synchronized with a trigger signal.

IV. Measurements of Synthesized Waveforms

To ensure JAWS synthesized waveforms maintain their quantum accuracy, they must *be shown* to preserve both their voltage accuracy and signal purity over a finite range of every bias parameter. As a simplified figure of merit for comparing the performance of these devices, we define the JAWS "operating margin" as the dither current range over which the circuit maintains quantum accuracy. We determine the operating margin by adjusting either the dc level or the amplitude of a triangle sweep with a frequency of about 300 Hz. The output voltage must remain constant and the distortion must not increase above the noise floor. We typically use a National Instruments 5922A digitizer and measure a 2 kHz synthesized sine wave for comparing circuit performance. With our new circuit, we achieved a 2.1 mA operating margin

[1]Since a digitizer with a high input impedance is used for the measurement and no currents flow between the arrays, these non-superconducting connections have no effect on the measurements presented in this paper.

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

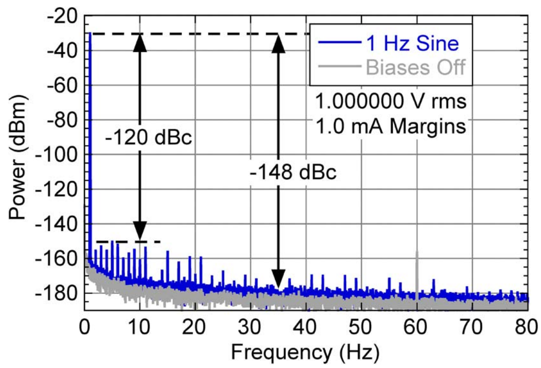

Fig. 5. Digitally sampled spectral measurement showing −120 dBc [dB below the fundamental (carrier)] low-distortion measurement of a 1 V rms 1 Hz signal synthesized with all four arrays of the JAWS biased at the first quantum state ($n = 1$). The digitizer settings used were 1 MΩ input impedance, 10 V input range, 0.1 Hz resolution bandwidth, five averages, and 100 kS/s sampling rate. Grey data show the digitizer −148 dBc noise floor and 60 Hz pickup with the bias signals turned off.

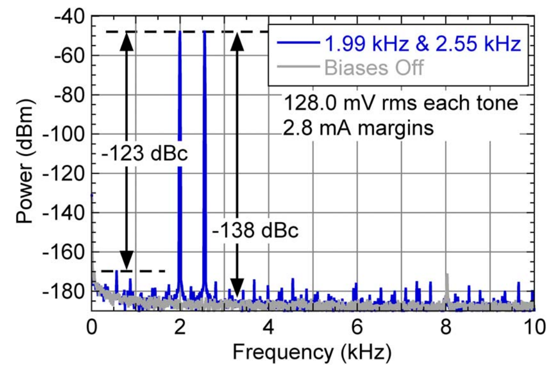

Fig. 6. Digitally sampled spectral measurement of a two-tone waveform with frequencies of 1.99 kHz and 2.55 kHz and synthesized with one array of the JAWS circuit biased at the first quantum state ($n = 1$). Each tone has a rms amplitude of 128 mV. The digitizer settings used were 1 MΩ input impedance, 2 V input range, 10 Hz resolution bandwidth, 10 averages, and a 500 kS/s sampling rate. Grey colored data show the digitizer −138 dBc noise floor and spurious signals with the bias signals turned off.

for the 2 kHz waveform with 1 V rms output voltage. This is five-times larger than the 0.4 mA operating margin measured for the previous circuit that used the second quantum state [1].

Fig. 1 shows the analog-oscilloscope image. A dither current is applied that modulates the signal beyond its operating state. The operating margins were determined with the digitizer and a dc dither current instead of the oscilloscope, and the current range is marked in Fig. 1. This current margin is related to the current range of quantization for a constant-voltage Shapiro step of a Josephson junction with an applied microwave frequency. But in this case, the voltage along the horizontal axis is continuously sweeping in time the sinusoidal output voltage.

One can consider this image to be a collection of constant voltage steps that are produced at every voltage of the sine wave. The non-quantized regions at current biases outside the quantum state show intensity variations, which indicate where some of the junctions are not generating exactly one output pulse for every input pulse. We show this image as a point of interest, not as a method for accurately determining operating margins; digitizer measurements of the non-linearities are far more sensitive than oscilloscope measurements for determining the quantum accuracy. (See [1] and [2] for discussion of measurement techniques, such as use of a dither current, to determine margins.)

The measured FFT of the 2 kHz, 1 V rms sine wave synthesized with this new circuit was comparable to the one shown previously [1]. So instead, we present in Fig. 5 a measurement of a 1 Hz synthesized waveform that also has an rms amplitude of 1 V. This low frequency can be directly synthesized because there is sufficient memory for a pattern of length 28.8 Gbits. These data show digitizer non-linearities that are less than −120 dBc [dB below the fundamental (carrier)], which is comparable to the 60 Hz pickup, and the performance is similar to that observed for this instrument on its other channels and at other voltages and frequencies. The noise floor of the waveform measurement is a few decibels larger than the digitizer noise floor measured with the JAWS biases turned off. Both noise floors appear non-white, indicating jitter inherent to the digitizer measurement and perhaps also from the JAWS source.

In Fig. 6 we show the FFT of a two-tone waveform that is synthesized with a single array, and that may be used for evaluating intermodulation distortion of the digitizer or other instruments. The tones have frequencies of 1.990 kHz and 2.550 kHz and identical 128.000 mV rms amplitudes. The peak amplitude of the time-dependent voltage of this beat waveform is 362.04 mV. The distortion harmonic with the largest (−123 dBc) amplitude intermodulation product is at 560 Hz frequency, which is at the expected difference frequency of the two tones and comparable in magnitude to the single tone nonlinearities of the digitizer. The operating margin for this waveform was 2.8 mA.

Finally, we describe measurements of 2 kHz sine waves synthesized with the zero-compensation bias technique. With one array, we achieved an operating margin of 1 mA at an rms amplitude of 64 mV. With two arrays synthesizing a 128 mV rms amplitude, we achieved 0.75 mA operating margins. By biasing each array with different codes having opposite dc polarities, the synthesized dc voltages of each array exactly cancelled, which is necessary for future rms measurements. While making these measurements, we observed significant coupling between the arrays, which prevented simultaneous operation of all four arrays. We plan to investigate and resolve this problem to use all four arrays to synthesize an uncompensated waveform with an rms amplitude of 256 mV.

V. Conclusion

In conclusion, we demonstrated improved performance of the NIST JAWS system, namely a five-fold increase in the operating margin (to a current range of 2.1 mA) when synthesizing a 2 kHz sine wave at 1 V rms. We also demonstrated a 1 Hz, 1 V rms sine wave with quantum accuracy and a two-tone waveform that is useful for characterizing intermodulation of analog-to-digital converters. We reduced from four to two the number of arrays required to synthesize a 128 mV rms sine wave without compensation bias.

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