Operating Margins for a Pulse-Driven Josephson Arbitrary Waveform Synthesizer Using a Ternary Bit-Stream Generator

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***Abstract*—We describe measurements with a pulse-driven Josephson arbitrary waveform synthesizer (JAWS) that uses a ternary arbitrary bit-stream generator as the bias source. This system is designed to be used as an ac Josephson voltage standard. From these measurements, we conclude that the system is operational for root-mean-square voltages of up to 220 mV. We measured the operating margins for different voltages synthesized with different numbers of junctions, waveforms, and bias conditions. We also present results on the influence of the critical current on the operating margins.**

***Index Terms*—AC voltage standard, digital-to-analog conversion, Josephson arrays, signal synthesis, superconductor–normal–superconductor devices, voltage measurement.**

I. Introduction

After B. D. Josephson first discovered the Josephson effect in 1962, techniques were developed to create a quantum-based dc voltage standard for electrical metrology applications. Thirty years later, interest arose in utilizing the Josephson effect to generate calculable quantum-accurate ac voltages. In conventional dc Josephson voltage standards, arrays of junctions are biased with a high-frequency continuous microwave (CW) current signal that causes the junctions to produce a constant stream of quantized voltage pulses (for an overview, see [1]). The result is a time-integrated voltage that is directly proportional to the CW frequency with a proportionality constant equal to $h/2e$, where h is Planck's constant, and e is the electron charge. The true quantum nature of the generated voltage must be ensured by determining the operating margins, i.e., the ranges over which bias parameters, such as the amplitude of the CW drive and a dc bias current, can be varied without changing the output signal.

In 1995, the National Institute of Standards and Technology (NIST) demonstrated the first pulse-driven Josephson circuits that were capable of producing quantum-accurate ac voltages [2]. A digitally programmed pulse pattern produces an arbitrary waveform whose time-dependent voltage varies in proportion to the pulse repetition rate. The operating margins for these pulse-driven circuits depend on the current amplitude of the drive, just as do the CW-driven arrays. Several methods have been developed to produce the high-speed current pulses that are required for synthesizing both unipolar and bipolar waveforms. For the highest-voltage applications, NIST uses a bipolar method that achieves a ternary-like code by combining a CW signal and a two-level digital signal [3]. The NMi Van Swinden Laboratorium (VSL) has developed an approach that uses a three-level current source with bipolar pulses [4]. This true ternary approach has the advantage of simplicity so that fewer bias parameters need to be adjusted [5].

The real challenge in making a useful ac Josephson voltage standard (ACJVS) is to achieve practical RMS output voltages of at least 100 mV. In previous work, this was accomplished by increasing the number of Josephson junctions and the repetition rate of the drive pulses. In this paper, we describe the results of a collaboration between NMi VSL and NIST to demonstrate an ACJVS that is biased with the ternary pulse drive. In the summary paper [6], we described the preliminary measurements that demonstrated the ternary operation of the ACJVS. In this paper, we study the effect on the operating margins by systematically changing the parameters.

II. Measurement Setup

The quantum ac waveform synthesizer consists of a Josephson array that is biased with high-speed current pulses through a semirigid coax cable. The Josephson array is cooled to 4 K in a liquid He Dewar. Low-speed four-point measurements can be performed on the array by using twisted-pair leads. Using the ac-coupling method to remove common-mode signals and allow multiple arrays to be connected in series [7], the low frequencies of the high-speed waveform are removed with a dc block and reapplied as a "compensation" signal through the current leads of each array. This is also useful to correct for the nonuniform attenuation of the high-frequency components. The array output voltage waveform is measured with a low-distortion high-dynamic-range spectrum analyzer. An oscilloscope, in combination with a sweep generator, is used to determine the current range of the dc operating margins by dynamically observing the current–voltage characteristics during signal generation. This dc current range, which describes the current that the array can provide to a load, is one parameter

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of the full set of "operating margins" for all bias parameters. Later in the paper, we use the operating margin of this particular parameter to characterize the system performance.

A. Array and Junction Characteristics

In our experiments, two superconducting integrated circuits were used, both of which were fabricated on 1 cm^2 Si chips, and each chip contains two nominally identical arrays. The arrays from different chips, however, contain different numbers of superconductor–normal metal–superconductor Josephson junctions, and the junctions have slightly different electrical parameters. On-chip inductive filters are added to the voltage and current taps so that the high-speed signals remain in the transmission line [8]. Both chips are flip-chip solder mounted on a microwave flex cryopackage that provides all the necessary high- and low-speed connections [9].

Chip I had 5120 junctions per array, so both arrays in series could produce a 220 mV RMS sine wave when driven by a digital code at a 15 GHz pulse rate [10]. These junctions were distributed in a tapered coplanar waveguide that is terminated with a characteristic impedance of 32 Ω [11]. Each junction has a normal-state resistance of about $R_n = 2.8$ mΩ and a critical current of $I_c = 12.8$ mA, which yields a 35.8 μV I_cR_n product that corresponds to a characteristic frequency of 17.3 GHz for the junctions.

Each array on Chip II contained 2560 junctions, so the chip produced a maximum RMS voltage of 110 mV with both arrays. Each junction had a 4.3 mΩ resistance and a 10 mA critical current, which yielded a 43 μV I_cR_n product that corresponds to a 20.8 GHz characteristic frequency. These arrays were series distributed in a straight coplanar waveguide that was terminated with 50 Ω.

B. Ternary Pulse Generator

The pulse generator produces dc-coupled bipolar positive and negative pulses (each returning to zero) at a rate of up to 15 Gpulse/s (see Fig. 1). The sample frequency can be locked to an external reference, such as an atomic clock. The pulse patterns that are used to generate waveforms are programmed in a memory and can be a maximum length of 33 554 432 *digits*, where a *digit* is a positive pulse, a zero, or a negative pulse. Internal to the pulse generator, there are two bit-stream generators with differential outputs that are combined in the opposite phase to produce the positive and negative pulses. The positive and negative amplitudes can independently be set.

A computer calculates the desired waveform and fills the entire memory of the pulse generator using General Purpose Interface Bus. This procedure takes a few seconds.

The pulse patterns used to excite the Josephson array are generated with a delta–sigma modulation algorithm [1]. The delta–sigma modulation behaves like a pulsewidth modulation, but it pushes the quantization noise out of the band of interest and uses an integer number of discrete pulses. The intended waveform is decoded from the pulse pattern by low-frequency filtering.

The lowest frequency that can be synthesized, which is called the pattern repetition frequency $f_1 = f_s/M$, is determined by the memory length M of the code and the pulse repetition rate f_s. At the maximum clock frequency, it is possible to generate an arbitrary waveform with a lowest frequency of 447 Hz, which corresponds to a single cycle filling the entire memory. One could go lower in frequency by decreasing the pulse repetition rate, but this is undesirable because it decreases the maximum output voltage as well as the operating margins since the arrays are designed to operate at higher frequencies. The highest frequency is limited by the accuracy of the waveform to be generated: For higher frequency waveforms, fewer digits per cycle are available, which results in a higher ratio of the signal to the digitization harmonics. At the maximum pulse rate of 15 Gpulse/s, the combined maximum dc output voltage for both arrays is 318 mV for Chip I and 159 mV for Chip II. The bipolar ac waveforms can be synthesized with a peak amplitude of up to 98 % of this voltage or 220 mV RMS (in case of a sine wave) for Chip I.

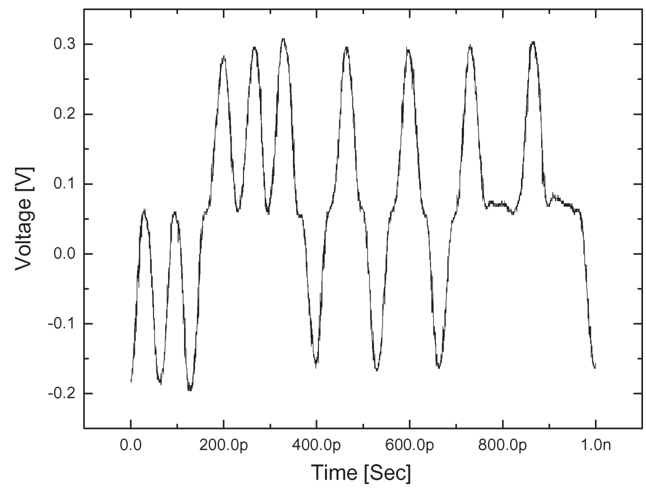

Fig. 1. Typical pulse shapes from the pattern generator showing different pulse shapes and amplitudes depending on their location in the pulse pattern.

The large bandwidth of the pulse waveforms requires low-loss cables and broadband microwave components. For example, the lossy cables have an attenuation that increases with frequency, which monotonically attenuates the higher-frequency components of the broadband pulse waveform. The operating margins are reduced for any degradation of the pulse waveform, which can be caused by frequency-dependent response or nonlinearities from the pulse generator, cabling, or circuit design.

The major limitation of the ternary pulse generator is the low-output currents of its output drivers. The current is insufficient to directly drive Josephson junctions that have critical currents larger than 3 mA. To match the pulse-drive signal amplitude with the Josephson circuit, we increased the output current with a broadband amplifier and decreased the junction critical current by raising the cryoprobe so the chip was above the liquid He, thereby raising its temperature.

C. Compensation Signal

When an ac-coupled amplifier is used to increase the current drive or dc blocks for the ac coupling method, the low-frequency components of the generated signal are removed. These missing frequency components need to be reapplied to the arrays. When using delta–sigma modulation, the only signal present in the low-frequency band is the intended output waveform. The low-frequency reinjection is done using an arbitrary waveform generator that is frequency locked to the pulse-generator clock and synchronized with the digital code pattern. By ac coupling the drive current, it is possible to remove the common-mode signal on the microwave termination and independently define the reference ground of the array output from the pulse-drive electronics. The ac coupling also enables the possibility of connecting multiple arrays in series [7]. When the voltage of the Josephson arbitrary waveform synthesizer (JAWS) is measured with a low-impedance instrument, the Josephson arrays must supply a load current. Normally, the pulse generator has to deliver the current needed to drive the load. However, in the ac-coupled system, the compensation signal can supply the load current. This is useful for the calibration of low-impedance thermal converters.

D. Margins

When practical measurements are being made with an ACJVS, the system should be able to drive various load impedances. Small variations in the impedance should not influence the Josephson array output voltage. Therefore, it is desirable to have operating margins of at least 1 mA. The operating margins are determined by deliberately adding an error current to the compensation signal and determining the range over which the error current can be varied without any change being observed above the noise floor of the measured spectrum; such a change might be the appearance of harmonic distortion that would indicate that the array is not producing the correct quantized signals. The margins can be reduced by many different effects, such as the shape of the current pulses, the bandwidth of the high-frequency components (amplifiers, output drivers, microwave connectors, and transmission lines), and the characteristic frequency, critical current, and uniformity of the junctions. The effects of the characteristic frequency and the critical current have been investigated in [12].

III. Results

We investigated the effect of different parameters on the margins, such as the bandwidth of the high-frequency components and the effect of changing the critical current. The measurements were performed with different combinations of amplifiers, bias settings, pulse-repetition frequencies, numbers of junctions (one or two arrays in series and arrays from the different chips), and critical currents. Different amplitudes were also obtained by using waveforms with different fractions of peak voltage (which are defined through the delta–sigma algorithm). When the arrays were on operating margins, the only distortion harmonics observed were those caused by the spectrum analyzer's nonlinearities and were the same as those described in [10]. In this paper, we address operating margins only through measurements of the harmonic distortion. Experiments that measure the RMS voltage of the synthesized waveforms, such as those using transfer standards and thermal converters, are required to ensure the absolute voltage accuracy of the synthesized waveform [13], [14].

A. Decreasing the Critical Current

Even with amplification, we were unable to achieve operating margins for these junctions when the critical currents were larger than 10 mA. The arrays on Chip I had a 12.8 mA critical current at liquid helium temperature. By operating at a higher temperature, the critical currents could be decreased to the range of 2 mA to 10 mA. This was done by lifting the cryoprobe such that the array was above the helium level. This is not a favorable situation for a calibration setup since it is not stable over long periods. However, the results of such measurements gave us important insight about the optimum critical current that is required to match the different configurations of the amplifier and output driver.

Two different amplifiers produced useful operating margins with the ternary bias: Amplifier A1 had a bandwidth of 9 kHz to 40 GHz, whereas amplifier A2 had a bandwidth of 10 MHz to 20 GHz. Both amplifiers had similar gain ripple, but A2 had additional attenuation of 0.2 dB every 1 GHz, whereas A1 had a flat response. The main difference between the amplifiers is that A1 has twice the bandwidth, which is important for transmitting the higher frequency content of the pulse waveforms.

One might expect that the operating margins would linearly increase with the critical current, because the wider the Shapiro step, the more variation in drive amplitude can be tolerated without affecting the output voltage. However, changing I_c also changes the I_cR_n product and, consequently, the characteristic frequency. Hence, at a higher critical current, the Josephson array performs better for higher pulse frequencies. Since the maximum pulse generator frequency is 15 GHz, optimizing the system performance requires optimizing the junction's electrical parameters and matching them to this maximum frequency. The other complicating factor that affects margins is that the amplifier saturates at high power, creating distortion that reduces the operating margins at higher critical currents.

These two competing phenomena are observable in Fig. 2, where the operating margins appear to peak for a critical current of around 5 mA. For these measurements, we used a single array of Chip I that is driven to its first Shapiro step, which means an output voltage of 100 mV for a 90 % fraction of peak voltage. The operating margins linearly increase with critical current, as expected for the increasing critical current for low critical currents. For higher critical currents, the operating margins decrease because of either junction dynamics (larger I_cR_n mismatches with pulse frequency) or greater amplifier nonlinearites for the larger pulse amplitudes that are required. For amplifier A2, which has lower bandwidth, the optimum operating margin occurs at a lower critical current, which corresponds to a lower pulse amplitude. For this amplifier, the higher 0.98 fractional peak voltage also has lower margins, which again suggests amplifier nonlinearities.

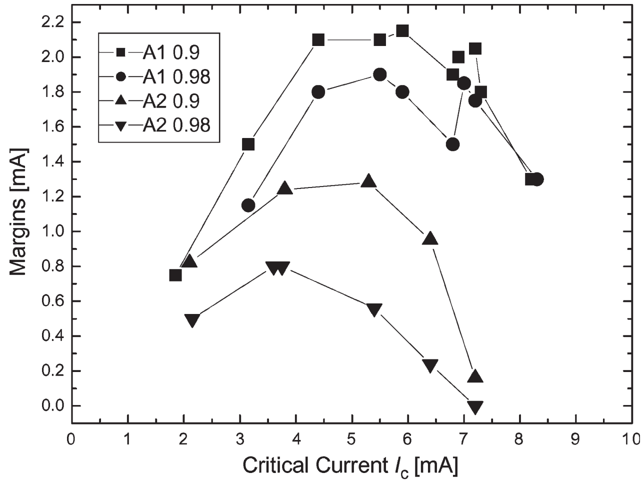

Fig. 2. Operating margins versus critical current of a single array from Chip I for two different output voltages and two different amplifiers. The amplifiers (A1 and A2) with different gain and bandwidth were used to amplify the ternary pulse signal. Waveforms with two different peak amplitudes (0.9 and 0.98) generated voltages at either 100 mV or 110 mV.

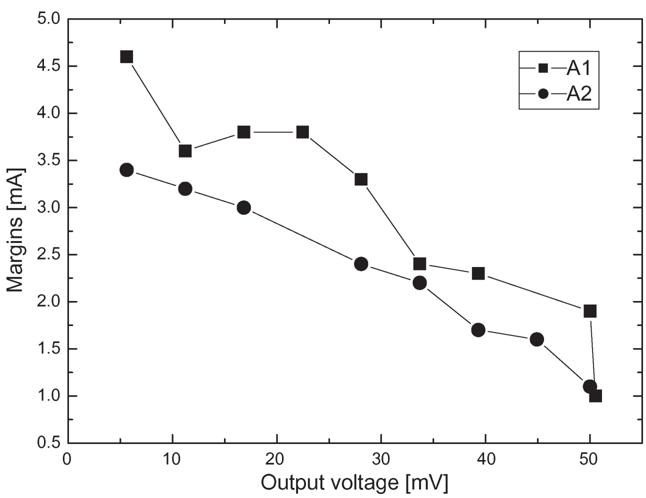

Fig. 3. Operating margins as a function of the output voltage for two different broadband amplifiers (A1 and A2). The output voltage is chosen by setting the fraction of peak amplitude between 10 % and 90 % by means of the delta–sigma algorithm. Measurements were done with Chip II using one array.

B. Margins Versus Voltage

In an ideal situation, the margins should not depend on the output voltage. We investigated the operating margins as a function of the fraction of peak voltage for a single array of Chip II with a reduced critical current of 7 mA. When driven on its first Shapiro step ($n = 1$, where the junctions produce one output pulse for every input pulse), this array produces 50 mV RMS voltage at 15 GHz for a 90 % fraction of the peak voltage. In Fig. 3, we can see that the operating margins decrease when the output voltage is increased. Fig. 3 also shows that the amplifier with a lower bandwidth (A2) produces lower operating margins for the same voltage.

There are two reasons for this behavior. First, there is a dynamic effect of the pulse repetition frequency such that the current margins increase when the pulse frequency is slower than the junction characteristic frequency [12]. For lower voltages, the pulse frequency is proportionally lower. When the fraction of the peak voltage is increased, the number of zeros between pulses decreases, and the pulses in the bit stream get closer to each other. Second, reflections and bandwidth limitations change the shape of consecutive pulses, as shown in Fig. 1. For example, at the highest frequencies, the pulses no longer return all the way to zero because of the asymmetric attenuation between the low- and high-frequency parts. This causes the pulses to be less uniform in amplitude, and consequently, the Josephson array becomes more sensitive to changes in the operating parameters. Both effects reduce the margins for higher voltages, where the pulse density increases.

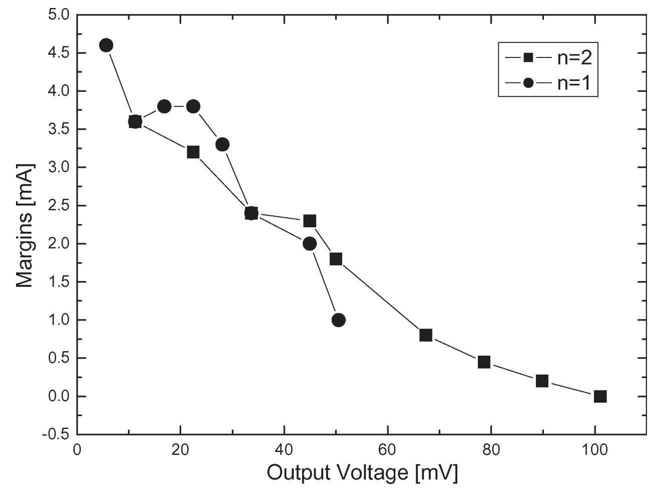

Fig. 4. Operating margins as a function of output voltage for the first ($n = 1$) and second ($n = 2$) Shapiro steps for the same range of fractions of peak voltage (10 % to 90 %). The output voltage is changed by means of the delta–sigma algorithm. Measurements were done with Chip II using one array. Amplifier A1 was used for these measurements.

Note that for the highest output voltage of this array, i.e., with a peak fraction of 90 %, we still have margins. To further increase the output voltage, we increased the pulse amplitude to drive the array on its second Shapiro step ($n = 2$). By comparing the data in Fig. 4 for both $n = 1$ and $n = 2$ data, the trend of decreasing margins continues for the higher output voltage of $n = 2$. Since the margins practically overlap for the lowest voltages (less than 45 mV), the data suggest that the performance is not limited by bandwidth but is primarily limited by junction dynamics for this amplifier.

C. Operating Multiple Arrays

As discussed earlier, the ac coupling technique makes it possible to connect multiple arrays in series. Our most demanding measurements were performed when both 5120 junction arrays from Chip I were connected in series. The challenge lies in the fact that bias signals to both arrays are not identical due to the differences in the pulse generator output drivers, amplifiers, and transmission lines to the arrays. Both of the arrays also have slightly different critical currents and high-frequency responses due to the fabrication process. All of these effects force us to independently tune the bias signals to both arrays to maximize the operating margins. The pulse generator has two outputs (data and data complement) that are used

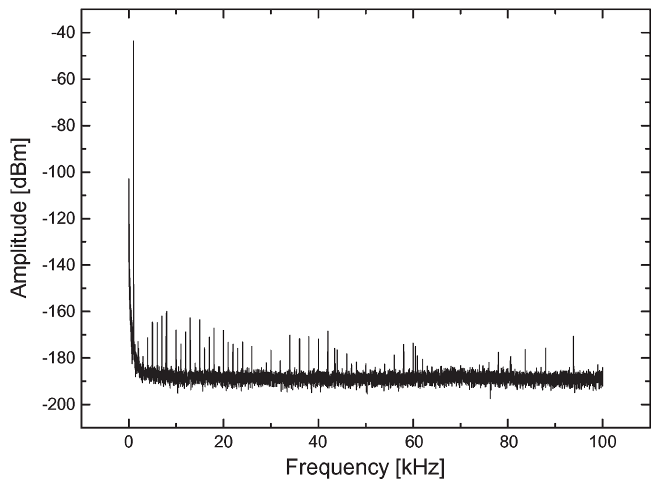

Fig. 5. Spectrum of a 200 mV, 1 kHz signal showing the intrinsic low distortion from the digitizer at -110 dBc (ten averages, 2 Hz resolution bandwidth, 1 MΩ input impedance, 2 V input range). The residual peaks are from the distortion created by the digitizer.

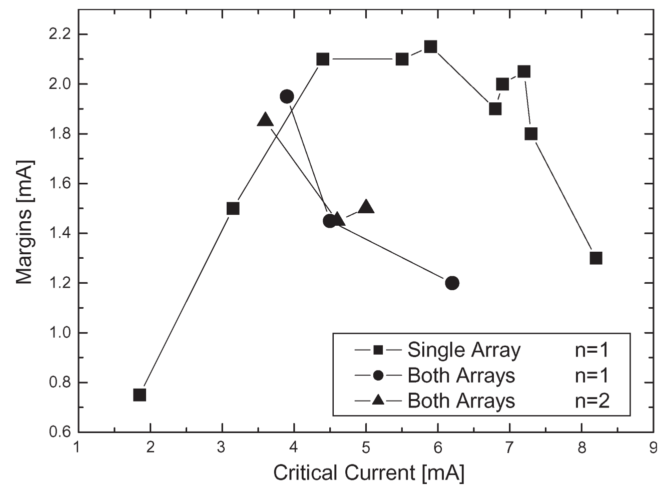

Fig. 6. Operating margins as a function of the critical current for the two array combined of Chip I as compared with the results for a single array (taken from Fig. 2). Measurements at $n = 2$ are done with 45 % fraction of the peak voltage.

to drive the two arrays. Unfortunately, their pulse amplitudes cannot independently be tuned; therefore, the fine bias signal to one array must be accomplished with manual attenuators, which is difficult. Nevertheless, we simultaneously achieved operating margins for both arrays for a combined RMS output voltage of 200 mV, and the resulting power spectrum is shown in Fig. 5. The observed distortion harmonics are produced by the nonlinearities of the digitizer used to measure the signal and imperfect quantization at the maximum output voltage of the array at 200 mV. The distortion of the digitizer is determined by inserting an attenuator on the input of the digitizer. The distortion signals that are generated outside the digitizer decrease with the attenuation. The signals that do not scale with the inserted attenuation are from the nonlinear distortion within the digitizer.

For the combination of the two arrays, we also investigated the optimum critical current. The RMS output voltage of 200 mV was obtained in two different ways: 1) by driving both arrays on the first Shapiro step $(n = 1)$ with 90 % fraction of peak voltage and 2) by driving both arrays on the second Shapiro step $(n = 2)$ with 45 % fraction of the peak voltage. Unfortunately, we were not able to find margins for the even higher-voltage combination (400 mV), where both arrays were driven on the second Shapiro step with 90 % fraction of peak voltage. Fig. 6 shows the results of this investigation, plotted together with the result taken from Fig. 2 for a single array. Although it is clear that we obtained good margins for the double array with A1 amplifier bias, we note that optimizing the operating parameters in this case was extremely difficult for the reasons previously described.

IV. Summary of Results

In this paper, we have investigated the operating margins for an ACJVS biased with a ternary arbitrary bit-stream generator in the ac-coupled mode. We note that this same chip and the same 200 mV RMS output voltage resulted in 2.4 mA operating margins with the NIST bipolar bias scheme at 4 K (where $I_c = 12.8$ mA) [10]. The ternary-biased arrays produced operating margins of 2.1 mA for a much lower critical current (i.e., 4.4 mA). The NIST bipolar scheme produced margins that were 19 % of the critical current, whereas the ternary-biased scheme produced margins that were more than 50 % of the critical current. This is a very impressive and positive result for the ternary-biased scheme and probably results from a number of factors relating to the differences in the bipolar bias schemes and the junction dynamics for the different operating temperatures of the two measurements. In any case, we can conclude that there may be significant performance advantages in using a ternary-biased scheme.

From the measurements presented here, we conclude that the ternary-pulse-biased Josephson array system successfully yielded operating margins and produced accurate low-distortion waveforms. The operating margins clearly decrease for both higher frequencies and higher fractions of the peak voltage. Both observations suggest that the bandwidth of the high-speed current drive is being degraded in either the pulse generator, the amplifiers, or elsewhere in the transmission path. The operating margins linearly increase with critical current, as expected, until the amplifier nonlinearities reduce the margins at higher currents.

Operating margins that are greater than 1 mA for the largest waveform amplitudes can be achieved with commercially available amplifiers, which are more than sufficient for the practical operation of the system as an ACJVS. Broader bandwidth amplifiers need to be implemented to further increase the operating margins. To further improve the performance of the ternary-biased JAWS/ACJVS system, we plan to design and fabricate new arrays with lower critical current that are optimized for operation with the A1 amplifiers.

In the near future, ac/dc comparisons are planned between the ACJVS systems at NIST and NMi VSL.

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