ACJVS Operating Margins using a Ternary Arbitrary Bitstream Generator*

Ernest Houtzager [1], Samuel P. Benz [2], Helko E.van den Brom [1]

[1] NMi Van Swinden Laboratorium (NMi VSL)

[2] National Institute of Standards and Technology (NIST)

Abstract

We describe measurements with a pulse-driven AC Josephson voltage standard (ACJVS) that uses a ternary arbitrary bitstream generator as the bias source. From these measurements we conclude that the circuit is operational for voltages up to 220 mV rms. We present a measured spectrum and operating margins for different voltages.

Introduction

After Brian 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 to utilize 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 Ref. [1]). The result is a time-integrated voltage that is directly proportional to the frequency, whereas the amplitude of the CW drive affects the operating margins. In 1995, NIST demonstrated the first pulse-driven Josephson circuits that were capable of producing AC voltages [2]. The operating margins of the pulse-driven circuits dependent upon the current amplitude of the drive, just like the CW-driven arrays. However, arbitrary waveforms and AC signals are possible with pulse-driven circuits. Digitally programmed pulse patterns produce arbitrary waveforms whose time-dependent voltage varies in proportion to the pulse rate.

Several methods have been developed to produce the high-speed current pulses that are required for the synthesis of both unipolar and bipolar waveforms. For the highest voltage applications NIST uses a bipolar method that achieves a ternary-like code by combining CW and a two-level digital signal [3]. NMi 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 of making a useful ACJVS is to achieve practical output voltages of at least 100 mV rms (root-mean-square). In previous work this was accomplished by increasing the number of Josephson junctions and by increasing the repetition rate of the drive pulses. In this paper we describe an ACJVS based on a ternary pulse drive and present the results of a collaboration between NMi VSL and NIST.

Measurement Set-up

The quantum AC waveform synthesizer consists of a Josephson array that is biased with high-speed current pulses through a semi-rigid 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 use of twisted pair leads. The array's output voltage waveform is measured with a low-distortion, high-dynamic-range spectrum analyzer. An oscilloscope is also used to determine the current range of the operating margins by dynamically observing the current-voltage characteristics during signal generation. The operating margins are obtained by determining the range of pulse amplitude and DC current offset over which no change is observed above the noise floor of the measured spectrum.

The chip used in this experiment contains two arrays, each having 5120 SNS junctions [6]. The Josephson junctions are distributed in a tapered coplanar waveguide that is terminated with a characteristic impedance of 32 Ω [7]. The resistance per junction is about 3.5 mΩ. For a directly coupled bias, this would result in a common-mode voltage. By AC coupling the drive current it is possible to remove the common-mode signal on the termination and define the reference ground of the array output independently from the pulse-drive electronics [8]. Furthermore, AC coupling allows the output of both arrays to be connected in series in order to double the rms output voltage. The pulse generator produces bipolar positive and negative pulses (each returning to zero) at a rate of up to 15 Gpulse/s. At this pulse rate, the combined maximum DC output voltage for both arrays is 318 mV. Bipolar AC waveforms can be synthesized with peak amplitude up to 98 % of this voltage, or 220 mV rms.

The pulse patterns used to generate these waveforms are programmed in an 8 Mbyte memory that can be subdivided into four separate memory blocks for fast switching between waveforms. This feature can be used, for example, for AC-DC comparisons. The pulse patterns used to excite the Josephson array are generated with a delta-sigma modulation algorithm [1].

The large bandwidth of the pulse waveforms requires low loss cables and broadband microwave components. For example, lossy cables produce uneven attenuation between the high- and low-frequency components of the broadband pulse waveform. The operating margins are reduced for any degradation of the pulse waveform uniformity, which can be caused by frequency-dependent response or nonlinearities from the pulse generator, cabling, or circuit design.

A disadvantage of the ternary pulse generator is the low output current of its output driver. The current is insufficient to drive Josephson junctions with critical

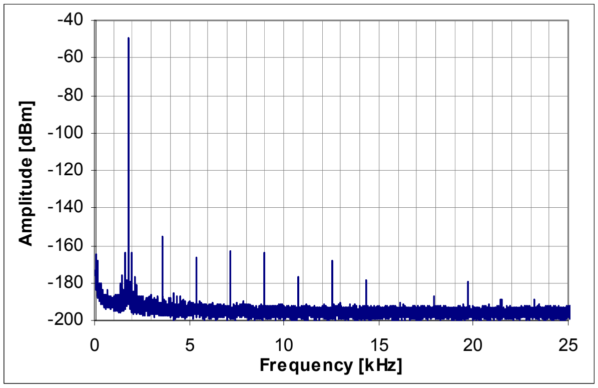

Figure 1: *Spectrum of a 100 mV 1.8 kHz signal showing intrinsic low distortion from the digitizer at -110 dBc (10 averages, 2 Hz resolution bandwidth, 1 MΩ input impedance, 2 V input range).*

currents larger than about 3 mA. In order to match the pulse drive signal with the Josephson circuit, we increased the output current with an amplifier and reduced the 8.8 mA junction critical current (at 4 K) to around 3 mA by operating the junctions at higher temperature by raising the cryoprobe in the Dewar so the circuits were above the liquid He level.

Results

Measurements were performed with different combinations of amplifiers, bias settings, pulse repetition frequencies, numbers of junctions (one or both arrays), and junction 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 dominant distortion harmonics ranged between -95 dBc and -110 dBc, which is typical for the nonlinear distortion of the spectrum analyzer. The spectrum of a 110 mV rms signal from a single array is shown in Figure 1.

We present the most promising results in Table 1. The operating margins clearly decrease for both higher frequencies and higher fractions of peak voltage. Both observations suggest that bandwidth of the high-speed current drive is being degraded either in the pulse generator, the amplifiers, or elsewhere in the transmission path. The operating margins increase linearly with critical current, as expected.

Conclusions

In this work we measured the operating margins for an AC Josephson voltage standard biased with a ternary arbitrary bitstream generator in the AC coupled mode. These operating margins were not as large as those obtained using the NIST setup for this same chip, which were 1.5 mA and 1.9 mA for the two arrays at 4 K (where I_c = 8.8 mA) at 220 mV rms.

From the measurements presented here we conclude that the ternary-pulse-biased Josephson array system successfully yielded operating margins and produced accurate and low-distortion waveforms. However,

Table 1: Margins for different settings of bias parameters.

Fraction of peak voltage (%)	Critical current (mA)	Pulse repetition rate (GHz)	Generated voltage (mV)	Generated frequency (kHz)	Operating margins (mA)
90	3.8	8.4	56.5	1.0	1.7
98	3.8	8.4	61.6	1.0	1.4
60	5.0	15.0	67.4	1.8	1.5
90	5.0	15.0	100	1.8	1.1
98	6.2	15.0	110	1.8	0.9
98	4.0	15.0	220	1.8	0.4

broader-band amplifiers and/or arrays with lower critical current need to be implemented in order for the system to operate as an ACJVS with practical operating margins. Operating margins of at least 1 mA are desirable for practical applications and are usually hardest to achieve for the largest waveform amplitudes. We plan to fabricate new arrays that we hope can be directly biased with the lower current amplitude of the ternary drive, with no external amplification. In the near future, AC/DC comparisons are planned between the ACJVS systems at NIST and NMi VSL.

Acknowledgements

We appreciate the superconducting circuit fabrication and system integration expertise of Paul Dresselhaus, Norm Bergren and Charlie Burroughs.

References

[1] S.P. Benz and C.A. Hamilton, "Application of the Josephson effect to voltage metrology," *Proc. of the IEEE*, vol. 92, pp. 1617-1629, October 2004.

[2] S.P. Benz and C.A. Hamilton, "*A pulse-driven Programmable Josephson voltage standard*," Appl. Phys. Lett., vol. 68, pp. 3171-3173, May 1996.

[3] S. P. Benz, C. J. Burroughs, T. E. Harvey, and C. A. Hamilton, "Operating conditions for a pulse-quantized AC and DC bipolar voltage source," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 3306-3309, June 1999.

[4] H.E. van den Brom, E. Houtzager, B.E.R. Brinkmeier, and O.A. Chevtchenko, "Bipolar pulse-drive electronics for a Josephson arbitrary waveform synthesizer" *IEEE Trans. Instrum. Meas.,* vol. 57, in print (2008).

[5] H.E. van den Brom, E. Houtzager, O. Chevtchenko, G. Wende, M. Schubert, T. May, H.-G. Meyer, O. Kieler, and J. Kohlmann, "Synthesis of sinusoidal signals with a Josephson arbitrary waveform synthesizer", *Supercond. Sci. Techn*., vol. 20, pp. 413-417 (2007)

[6] P. D. Dresselhaus, Y. Chong, and S. P. Benz, "Stacked Nb-$MoSi_2$-Nb Josephson Junctions for ac Voltage Standards," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 449-452, June 2005.

[7] P. D. Dresselhaus, S. P. Benz, C. J. Burroughs, N. F. Bergren, and Y. Chong, "Design of SNS Josephson arrays for high voltage applications," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 173-176, June 2007.

[8] S. P. Benz, C. J. Burroughs, and P. D. Dresselhaus, "AC coupling technique for Josephson waveform synthesis," IEEE Transactions on Applied Superconductivity, vol. 11, no. 1, pp. 612-616, March 2001.