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DC VOLTAGE SYNTHESIS USING A PULSE-QUANTIZED JOSEPHSON VOLTAGE SOURCE

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Abstract

We have synthesized and measured dc voltages using a bipolar pulse-quantized Josephson voltage waveform synthesizer. Bias current ranges were determined for 101 equally spaced dc voltage steps between −18.6 and +18.6 mV. The flatness of a step at −7.444 mV was found to vary only 2.6 nV with a type A standard uncertainty of 1.6 nV. The linearity of a nanovoltmeter was investigated by synthesizing 11 different dc voltages.

Introduction

We are developing a Josephson voltage standard source capable of synthesizing both ac and dc voltages as well as arbitrary waveforms with multiple frequencies. In this paper, we present results of synthesized dc voltages using bipolar synthesis techniques in which the Josephson junctions generate perfectly quantized voltage pulses of both polarities. We determined the operating margins by measuring the bias current range of 101 voltage steps. We also measured the uncertainty and flatness of 11 voltage steps to evaluate the bipolar operation technique.

The original operating method for the pulse-driven Josephson voltage waveform synthesizer used a two-level input pulse drive that was capable of synthesizing only unipolar ac waveforms [1]-[3]. We recently demonstrated that bipolar waveforms could be synthesized by using a combined input drive consisting of a two-level bias representing the digital code and a sine wave [4]-[6]. This combined input drive provides a six-fold increase in output voltage compared to the original circuit using the same digital code generator. Bipolar ac generation is an important step toward achieving practical output voltages greater than 1 V.

DC Voltage Measurements

The operating range of the bipolar voltage synthesizer can be determined by measuring the current range of dc voltage steps that correspond to different digital codes. The range common to all codes is the total operating current range of the device. Any dc voltage $(p-q)Nnf\,[K_{J\text{-}90}\,(p+q)]^{-1}$ can be generated using a digital code with p 1's and q 0's, where N is the number of junctions, n is the harmonic step number, f is the sine wave frequency, and $K_{J\text{-}90}$ = 483 597.9 GHz/V is the Josephson constant.

We investigated a small set of 101 codes for a 100 bit pattern to demonstrate the functionality of the bipolar synthesizer. The code generator has an 8 megabit pattern memory capacity so that 8 million distinct dc voltages can be generated simply by changing the digital code. Additional voltages can also be generated by changing the drive frequencies, although for bipolar synthesis there is a constraint on the allowed relative values of the sine wave and code generator clock frequencies. In any case, the waveform synthesizer can generate voltages with over 22 bits of resolution for calibrating A/D converters.

Measurements were performed on an array of 1000 Nb-PdAu-Nb Josephson junctions distributed along a 7 mm length of 50 Ω Nb coplanar waveguide [5]. The critical current of each junction in the array was about 4.1 mA, and the resistance of each junction was about 3.8 mΩ. The transmission line was terminated with a 50 Ω PdAu resistor. Four-point measurements of the array were made using four bias taps. Each tap had a 50 Ω resistor close to the transmission line.

The array was driven with a 9 GHz sine wave, and the digital code generator was clocked at 2 GHz. The code generator's rise time was 30 ps, about 25 % of the sine period. The same values of sine wave amplitude, code generator amplitude and offset, and relative phase between the clock and sine wave were used for all codes. The voltages were measured with a high precision digital voltmeter on the 100 mV range.

We generated alternating positive and negative voltages starting with the maximum (all 1's) and minimum (all 0's) and decreasing toward 0 V (alternating 01 pattern). For each iteration, the positive and negative voltage patterns were changed by appending "01" to the right end of each 100 bit-long code (and deleting the two left-most bits). The resulting measurement sequence was +18.6, −18.6, +18.2, −18.2, ... , +0.4, −0.4, 0 mV. Each voltage can be generated using a number of different patterns; the 101 patterns measured here are only a subset of all possible patterns for these particular voltages, even within the set of 100 bit-long codes.

Figure 1 shows the current range of the flat step generated by each pattern as a function of the measured voltage. The step edges were determined using a search criterion of 6 standard deviations. The voltmeter averaged each voltage measurement over 20 power line cycles. The current range for all 101 patterns is greater than 1.1 mA. The smallest current range occurs for the pattern corresponding to about 3 mV. Although the current range of all steps is greater than 1.1 mA, the combined operating range for all 101

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This work was supported in part by the Office of Naval Research and The International Science and Technology Linkages Fund (99-CSP-25-CHRI).

patterns is only 0.66 mA, as indicated by the dashed box in Fig. 1.

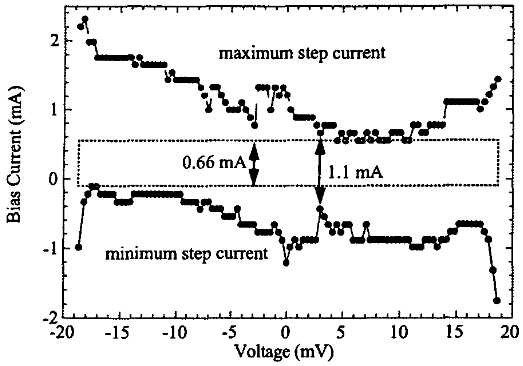

Fig. 1. Bias current margins vs. voltage showing the current range for 101 digitally synthesized patterns of a 100 bit code. The dashed box indicates the common operating current range of all 101 patterns.

The flatness of the −7.4442 mV constant voltage step was determined by repeatedly measuring the voltage for this particular code at different bias currents on the step. The bias current was varied over a range of 1 mA. The difference in average voltages obtained over many interleaved low, optimum, and high bias current measurements was 2.6 nV with a type A standard uncertainty of 1.6 nV. Over the measured current range, the step is flat to within 7 µV/V at a 95% level of confidence (k=2).

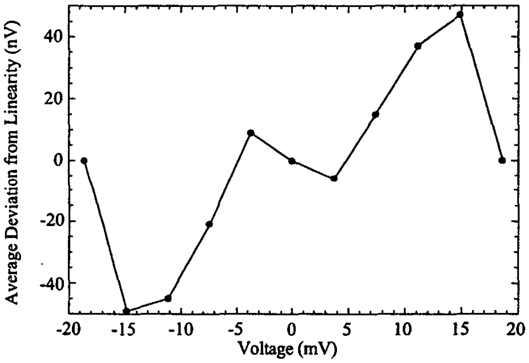

Fig. 2. Linearity measurement for a 10 bit code. Each measured voltage has the offset voltage drift removed and is then scaled by the ratio of the maximum applied voltage to the maximum measured voltage. The differences between these scaled and applied voltages are plotted in nanovolts.

The linearity of the 100 mV range of the digital voltmeter was investigated by applying 11 different dc voltages ranging from +18.610527 mV to -18.610527 mV. These voltages were generated by combining a 10 bit-long code with the same digital clock and sine wave frequencies as before. Again, the same values of sine wave amplitude, code generator amplitude and offset, and relative phase between the clock and sine wave were used for all codes. The sequence of measurements chosen was +V1, −V1, 0, −V1, +V1, +V2, −V2, 0, −V2, +V2, etc. The data recorded for each voltage was the average of 25 readings each with 20 power line cycles. A linear fit to the resulting five 0 V measurements was used to remove the offset voltage drift (including thermal) from the measured voltages.

Figure 2 shows the average of the offset and gain corrected results from 8 linearity runs made over a period of 8 days. A gain correction for each polarity was calculated from the ratio of the maximum applied voltage to the maximum offset corrected voltage. The two gain corrections were then applied with the effect of forcing the difference between the corrected voltages and the applied voltages through zero at the maximum voltages. While the resulting linearity curve is within the manufacturer's 55 to 66 nV analog-to-digital linearity specifications, other measurements made with a conventional dc Josephson array voltage standard indicate that the linearity curve shape shown may not be due entirely to the digital voltmeter.

Conclusion

We have made progress towards establishing the dc accuracy of a bipolar pulse-driven Josephson array chip. This is an important step in verifying the accuracy of the bipolar technique for generating ac voltages and arbitrary waveforms. In addition, the circuit has demonstrated capability as a high-resolution voltage source.

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