Radio-Frequency Waveform Synthesis with the Josephson Arbitrary Waveform Synthesizer

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***Abstract* — We have measured the output power versus synthesis frequency (transfer function), up to 100 MHz, of a modified Josephson arbitrary waveform synthesizer. A 50 Ω resistor was integrated within the Josephson junction array circuit to match the nominally zero array impedance to a 50 Ω transmission line and load. The resistor significantly reduces ripple in the transfer function due to reflections from impedance mismatches, but it reduces the output voltage by a factor of two. The measured power is constant within 0.01 dB up to 10 MHz, above which it deviates by no more than 0.15 dB.**

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

I. INTRODUCTION

The Josephson arbitrary waveform synthesizer (JAWS) has been used to generate quantum-accurate waveforms with fundamental frequencies up to 1 MHz [1]. We have recently begun developing a JAWS system that can synthesize waveforms at frequencies ranging from the kilohertz to the gigahertz range and drive 50 Ω loads. Ideally, this system would be able to do so while providing a quantum-accurate output voltage at room temperature over the frequency range of interest. As a first step toward gigahertz-frequency waveforms, we have synthesized single-tone sinusoids with frequencies up to 100 MHz.

Although it is possible to measure a quantum-accurate voltage across the Josephson junction (JJ) array – with each junction producing a quantized voltage pulse for every bias pulse – the accuracy of the output voltage is degraded by the circuit that connects the array to the room temperature load, and by the load itself. The main sources of voltage error are: (1) impedance mismatches between the superconducting circuit, cabling and the load, which lead to standing-wave voltage deviations [2]; (2) loss in the cables that connect the superconducting circuit to room temperature circuits; and (3) a frequency-dependent inductive voltage error [1].

In order to drive 50 Ω loads, two modifications must be made to the standard audio-frequency JAWS circuit so that it is properly matched to those loads. In the audio-frequency JAWS circuit, a pair of filtered taps that connect to twisted-pair leads are used to measure the voltage generated across the array. The taps separate the desired low-frequency signal from the high-frequency pulse bias. The filters and twisted-pair leads have insufficient bandwidth for waveform synthesis up to 100 MHz, and do not have 50 Ω impedance. We have replaced the filtered, twisted-pair lines with a 50 Ω coaxial transmission line. For this first design, the filters have been omitted, so there is no on-chip separation of the output signal and pulse bias.

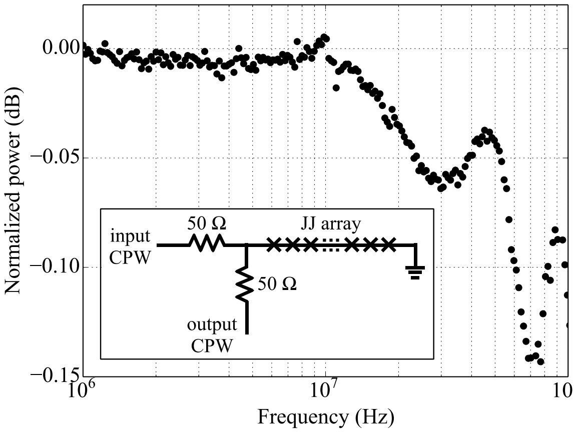

Fig. 1. Measured output power versus synthesis frequency, normalized to the power at 1 MHz. *Inset:* The modified superconducting circuit used in this version of the JAWS system.

Josephson junction arrays have an output impedance of roughly 0 Ω. This means the audio-frequency JAWS circuit is not properly impedance-matched to any finite load. When low-frequency waveforms (≲ 100 kHz) are synthesized, this impedance mismatch has a negligible effect on the voltage accuracy. However, for synthesis frequencies above a few megahertz, the standing waves created by reflections between the array and load lead to ripple in the output power versus synthesis frequency (transfer function). One solution, which we explore in this work, is to add a 50 Ω impedance-matching resistor to the JJ array circuit. Although this method significantly improves the accuracy at high-frequency by reducing the transfer function ripple, the voltage drop across the resistor reduces the output voltage by a factor of approximately two. Even with this improvement, there may be residual standing waves due to impedance mismatches between the matching resistor, cabling to room temperature, and the load, as well as parasitic impedances in the load and throughout the measurement circuit. There will also be loss of accuracy in the output voltage with frequency due to the frequency-dependence of the load and the loss in the output cables.

Another source of error that must be addressed is the frequency-dependent inductive error signal. The high-frequency current bias in a zero-compensation pulse bias has some remaining signal at the fundamental synthesis frequency that drives the distributed inductance of the coplanar waveguide (CPW) in the JJ array [1]. This creates a voltage error signal at the synthesis frequency, with a magnitude that is proportional to that frequency. For high-frequency waveform synthesis this error, which adds in quadrature to the desired output voltage, is expected to dominate.

II. OUTPUT POWER VERSUS FREQUENCY MEASUREMENT

We measured the output power versus synthesis frequency of the simple JJ array circuit shown in the inset of Fig. 1. In this circuit, a CPW routes the high-frequency bias signal to an array of 102 JJs embedded in the CPW, in 34 stacks with three JJs each. The end of the JJ array is terminated to the ground plane. A 50 Ω resistor is embedded in the input CPW leading to the array to absorb unwanted reflections of the pulse bias from the short at the end of the array. Another 50 Ω resistor is embedded in the output CPW tap, thereby placing an impedance-matched resistor in series with the JJ array.

The pulse-bias input and voltage output CPWs were ribbon-bonded to a controlled-impedance circuit board, which routed those channels through two 1.3 m, 40 GHz coaxial cables to room temperature. All of the above hardware was housed in a cryoprobe, which was submerged in liquid helium for the measurements. From the top of the cryoprobe, the input channel was connected to a series of inner-only dc blocks, two 3 dB attenuators, and a bias tee. The pulse-bias signal was provided by a commercial 65 gigasamples-per-second, 8-bit arbitrary waveform generator (RF-AWG) and amplified by a commercial 50 GHz modulator driver. The cryoprobe output channel was connected to a spectrum analyzer (SA) through a 20 GHz coaxial cable, with the shortest possible length of 10 cm. The SA had an input impedance of 50 Ω.

The frequency-dependence of the system output power was measured by synthesizing single-tone waveforms ranging in frequency from 1 MHz to 100 MHz. For each measurement, the sinusoidal waveform was converted into a three-level delta-sigma modulated pulse bias, which in turn was converted to a five-level zero-compensation code using the method described in [1]. The amplitude of the compensation pulses in the five-level code was then optimized by measuring the feedthrough signal versus amplitude at several frequencies across the range, as explained in [1]. A quantum locking range of 3.5 mA was first obtained for a 1 kHz waveform. The locking ranges were then verified over the entire synthesis frequency range, to ensure that the output voltage across the array was quantum-accurate and that any deviations were generated between the array and load. An automated program was used to program the RF-AWG with the desired single-tone pulse bias, set the SA to the proper center frequency, and acquire a trace for each frequency step with 1 kHz video and resolution bandwidths. The measurement was repeated with a 6 dB attenuator on the pulse-bias input to the array to quantify the inductive error signal versus synthesis frequency, as explained in [1].

The relative transfer function measurement, spanning 1–100 MHz, is shown in Fig. 1. The transfer function has been normalized to the power at 1 MHz, because no absolute calibration of the SA was performed and the impedance of the matching resistor had not been characterized. The frequency response of the output power is constant within 0.01 dB up to ~10 MHz, but begins to decrease and oscillate with increasing frequency. The transfer function shows a ~0.15 dB decrease in output power from 10 MHz to 100 MHz. When the 10 cm coaxial cable connecting the cryoprobe to the SA was replaced with a similar 1 m cable, the power dropped by ~0.25 dB over the range 7–100 MHz, suggesting this deviation was caused by frequency-dependent loss in the cable. The transfer function ripple, which is ~0.1 dB peak-to-peak, showed a shift in frequency periodicity with cable length. This is consistent with a standing wave between the superconducting circuit and the SA. The measurement of the inductive error signal versus synthesis frequency (not shown) increased with synthesis frequency as expected and reached a level of -37 dB relative to the fundamental tone at 100 MHz.

VI. CONCLUSION

A simple, impedance-matching JJ circuit has been used to measure the frequency dependence of the output power of a high-frequency replacement to the standard audio-frequency JAWS circuit. The transfer function shows flat frequency response up to 10 MHz, and a deviation of roughly 0.15 dB from 10 MHz to 100 MHz. We expect that the inductive error signal will become the dominant source of error at synthesis frequencies above 10 MHz. An upcoming circuit revision will include an on-chip superconducting block on the bias input that will decrease the inductive error signal by reducing the feedthrough of the drive signal to the output measurement.

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