Cryogenic Calibration of a Quantum-based Radio Frequency Source

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***Abstract*— We report on the calibration of quantum-based radio frequency waveforms generated by a Josephson arbitrary waveform synthesizer system. We measure these waveforms using a vector network analyzer and calibrate them at 4 K using a custom-designed cryogenic on-wafer multi-line thru-reflect-line calibration kit and a two-tier calibration procedure. The signals tested in this work can be used as reference signals to calibrate measurement instruments with potential benefits in terms of accuracy and flexibility compared to the conventional methods.**

***Keywords* — superconductive circuits, cryogenic microwave measurements, on-chip calibration, Josephson arbitrary waveform synthesizer, quantum-based voltage standards.**

I. Introduction

The Josephson arbitrary waveform synthesizer (JAWS) system has been used to generate voltage standards for metrology at audio frequencies [1]. We are currently extending the JAWS capability to the microwave frequency range for use in wireless communications metrology. While signal characterization and calibration are not required at audio frequencies, they are crucial if the JAWS system is to be used for metrology at microwave frequencies.

Although the RF signals generated by the JAWS system present quantum-based accuracy across the on-chip 4 K Josephson junction (JJ) circuit, the accuracy is lost off chip as the signals are conducted to room-temperature through long RF cables that introduce losses and phase offsets. Thus, traceable RF calibration is imperative to accurately translate the measurements made at room-temperature to the reference plane of the 4 K JJ circuit and retrieve the quantum on-chip accuracy.

The JAWS system exploits the voltage pulse quantization of cryo-cooled 4 K JJs to generate quantum-based waveforms with calculable amplitudes that are related to fundamental constants [1]-[3]. Driving an array of N JJs with a single current pulse yields a voltage pulse across the array with a time-averaged area equal to $N\Phi_0$, where Φ_0 is the magnetic flux quantum. To synthesize an arbitrary RF waveform, the JJ array is driven with a train of high-speed pulses whose separation is modulated with a delta-sigma algorithm to encode the desired waveform [4]. Typically, the driving pulse pattern is created by a room-temperature arbitrary waveform generator (AWG), and the pulse pattern produced by the array is low-pass filtered to get the quantized RF waveform.

The JAWS system has been used to synthesize waveforms up to 1 GHz [5], but those waveforms were not calibrated. In this work, we synthesize quantum-based RF waveforms using the JAWS system and calibrate them at 4 K using a vector network analyzer (VNA). For that, we add absolute amplitude and phase correction [6] to a scattering-parameter calibration [7] to provide a full wave-parameter calibration of the JAWS waveforms at the reference plane of the 4 K JJ circuit.

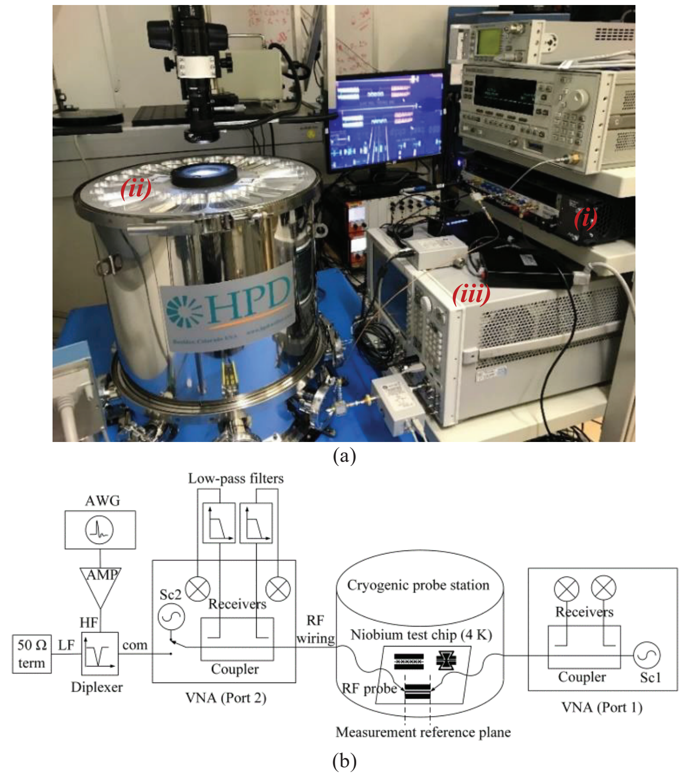

Fig. 1 a) Photograph of the cryogenic measurement setup including the room-temperature AWG that generates the driving patterns *(i)*, 4 K cryogenic probe station with test chip that contains the JJ circuit and calibration standards *(ii)*, and VNA apparatus to measure the JAWS signals *(iii)*. b) Simplified diagram of the measurement setup shown above. Low-pass filters are used at the input of the VNA receivers to improve the dynamic range of our measurements.

The quantum-based RF waveforms we test in this work can be used, for example, as reference signals to calibrate RF measurement instruments with potential benefits in terms of accuracy and flexibility compared to the conventional methods.

II. Measurement and Calibration Procedures

A. Measurement setup and quantum signal generation

The cryogenic measurement setup used in this work is shown in Fig.1. We use a high-speed arbitrary waveform generator (AWG) to create a delta-sigma-modulated current pulse pattern. This pulse pattern encodes the RF waveform to be quantized by the JJ circuit operating in the cryogenic probe station at 4 K [4].

We measure the JAWS signal in the frequency domain using a VNA (PNA-X[1]) that contacts the 4 K JAWS chip via cryogenic RF cables and movable RF probes installed on the 4 K stage of the cryogenic probe station. Internal switches allow us to route the VNA test ports to either the VNA internal

[1]We specify equipment models only to better explain the experiments. NIST does not endorse commercial products. Other products may perform as well or better.

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continuous wave (CW) sources (during the VNA calibration phase) or the external AWG driving pulse source (during the JAWS measurement phase).

To provide enough amplitude to properly drive the JJ circuit, we amplify the pulse driving pattern signal generated by the AWG using a broadband RF amplifier. We use a diplexer to isolate the JAWS output signal from the input pulse driving signal. In addition, the diplexer's low-frequency port is terminated with a 50 Ω load to avoid reflection of the JAWS signal towards the 4 K JJ circuit. We use a 16 GHz sine wave signal generated by an RF signal generator (not shown in Fig. 1b) as the primary phase reference for our measurements. This 16 GHz signal drives the AWG which in turn clocks the VNA with its 10 MHz output clock signal and drives the VNA comb generators with a 1 MHz square-wave signal that sets our measurement frequency grid.

We measured the frequency response of the JAWS output signal by measuring the power and phase at the fundamental of a single-tone signal that was synthesized in steps of 1 MHz from 10 MHz to 1 GHz. The 991 single-tone bipolar waveforms were each encoded into bias pulse patterns with a minimum of 10,000 waveform periods using a second-order, three-level [-1; 0; +1], bandpass delta-sigma modulator at a 64 gigapulse-per-second sample rate.

It is crucial that the driving pulse pattern has minimal power at the synthesis frequency. To reduce the signal level at the fundamental in the driving pulse pattern, the three-level codes were transformed into five-level codes so that each bias pulse had bracketing half-amplitude pulses with inverted amplitude and each pulse block had effectively zero average amplitude [3].

Each of the 991 pulse patterns was then sequentially programmed into the AWG, the VNA measurement frequency was set to the corresponding synthesis frequency, and the waveforms incident at and reflected from the JJ circuit were measured. For this experiment, quantum-locked operation of the JAWS system could be achieved across the entire synthesis frequency range only by reducing the amplitude of the waveforms to 2.5 % of the maximum pulse density of the input driving pulse train [4].

B. Measurement calibration procedure

The three-step procedure to calibrate the VNA measurements of the JAWS waveforms is illustrated in Fig. 2. This procedure allows us to operate our VNA with an external source and evaluate the calibrated forward propagating wave (AWG pulse driving signal) and backward propagating wave (JAWS output signal) at the 4 K on-chip reference plane.

1. First-tier calibration: we first operated the VNA in its default configuration (Fig. 2a), with the test ports routed to the internal CW sources, and performed a scattering-parameter, absolute amplitude, and absolute phase calibration at the coaxial reference plane in steps of 1 MHz from 10 MHz to 1 GHz [6].

The scattering-parameter calibration was performed using a 2.4 mm short-open-load-thru (SOLT) calibration kit, the phase was calibrated using a frequency comb generator that is traceable to the NIST electro-optic sampling system, and the amplitude calibration was done with a power sensor that is traceable to the NIST calorimetric power reference. By performing the first-tier calibration, we effectively set the calibration reference plane at the coaxial plane of the VNA test ports.

2. Second-tier calibration: in the second calibration step (Fig. 2b), we connected the VNA (still in its default configuration) to the cryogenic probe station and performed a 4 K scattering-parameter calibration at the reference plane of the JJ circuit [7]. For that, we used a custom-designed cryogenic multi-line TRL calibration kit fabricated on the same chip as the JJ circuit. This kit comprises two coplanar waveguide (CPW) reflect standards (open and short), six CPW lines with lengths ranging from 70 μm to 9 mm, and a 0-length CPW thru line that sets the reference plane of our TRL calibration exactly at the terminals of the JJ circuit. Additionally, to allow simple on-wafer SOLT calibrations, we included 50 Ω load standards in the kit. By performing the second-tier calibration, we move the reference plane from the VNA coaxial plane to the on-chip reference plane of the JJ circuit. Our calibration procedure has a 50 GHz bandwidth capability, which allows to support future frequency scaleup of the JAWS system.

3. Measurement: for the JAWS measurements, we routed the switching circuitry of the VNA test port 2 to the AWG connected to the back-panel of the VNA (see Fig. 2c), and measured the JAWS signal that was generated as described in section II.A. Note that changing the VNA source configuration does not affect the calibration performed in steps 1 and 2, because the full wave-parameter calibration matrix is source-independent. To correct the measured data, we used the NIST Microwave Uncertainty Framework (MUF) software [8].

III. Measurement Results

A. Control experiment

In order to help verify our calibration, we used the setup depicted in Fig. 3 to mimic the JAWS measurements. For that, we created a swept-sine signal from 10 MHz to 1 GHz in steps of 1 MHz using an RF signal generator, fed this signal into the cryogenic probe station port 1 and measured it at the VNA test port 2 via the on-chip thru standard.

We calibrated the measured data of this swept-sine at the TRL reference plane like we did for the JAWS waveforms and de-embedded the cable of port 1 to reference the measurements to the coaxial connector of the signal generator (see Fig. 3). The measured results presented in Table 1 agree with the nominal power levels generated by the signal generator within the manufacturer margins. Although this measurement setup is simpler than the JAWS setup as there are no broadband pulse signals involved and no linearity issues, it gives a good indication that our amplitude calibration is correct.

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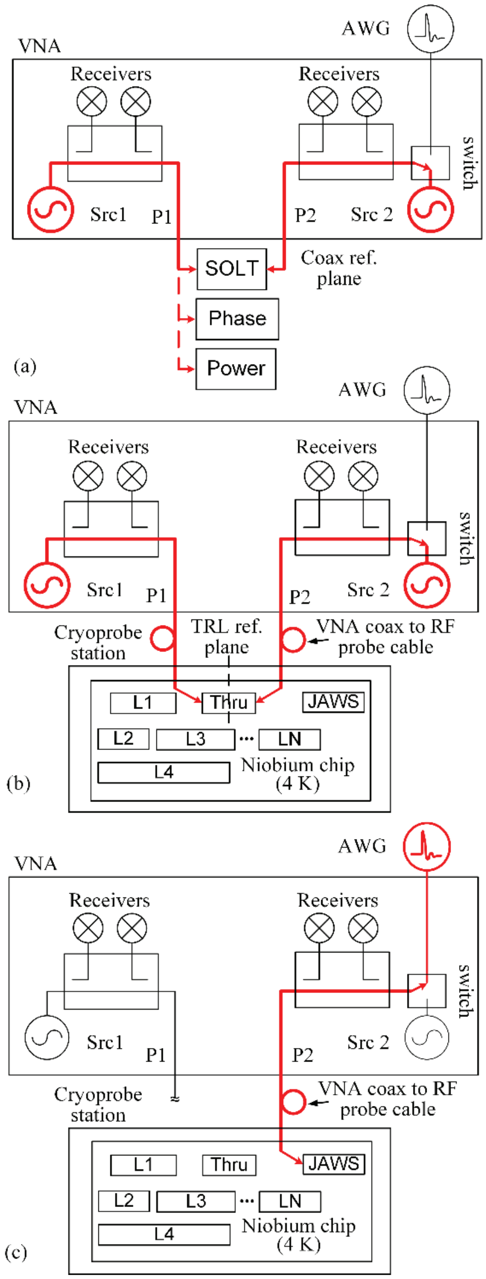

Fig. 2a) First-tier VNA calibration using SOLT, power and phase standards. b) Second-tier VNA calibration using broadband on-wafer multiline TRL kit. c) JAWS measurements, with AWG driving signal passed through the VNA.

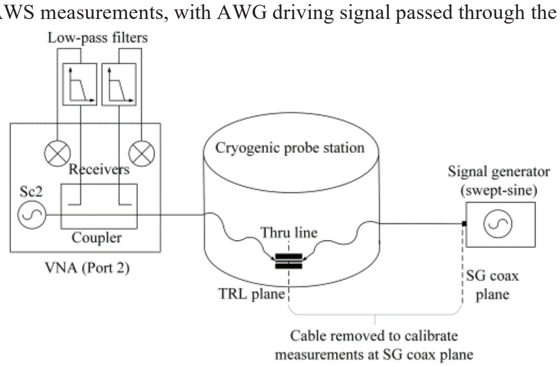

Fig. 3 Simple control experiment used to verify the calibration.

Table 1 Calibrated signal generator amplitude. The average and standard deviation are taken over the 1 GHz bandwidth measurements.

Nominal output power level (dBm)	Calibrated mean	Standard deviation
0 ± 0.5	-0.07	0.05
-30 ± 0.7	-30.07	0.05

B. Optimizing the VNA dynamic range

To generate a signal amplitude high enough to properly drive the JJ circuit, we amplified the pulse pattern signal using a broadband RF amplifier prior to sending it through the VNA test set. The grey curve in Fig. 4a shows the 50 GHz spectrum measured by the VNA for a delta-sigma pulse pattern used in our experiments. This signal has frequency components that are much larger than the low-frequency JAWS output signal of interest.

Due to non-linear intermodulation distortion in the VNA receivers, large high-frequency components of the driving pulse pattern (which effectively is a broadband multi-tone signal) can be down-converted and lead to erroneous measurement and calibration of the low-frequency JAWS signal of interest. To overcome this problem, which is simplistically illustrated in the inset in Fig. 4b and detailed in [9], we used low-pass filters with 1 GHz cut-off frequency at the input of the VNA port 2 receivers (see filtered signal in Fig. 4a). This produced measurement results more consistent with the expected JAWS frequency response predicted in [4] (dashed lines in Fig. 4 and Fig. 5).

C. Calibrated JAWS frequency response

Preliminary calibrated measurements of the JAWS amplitude frequency response are presented in Fig. 5. The solid and dotted curves in Fig. 5a correspond to calibrated measurements with and without low-pass filters on the VNA port 2 receivers, respectively. For the case where no filters were used, a ripple of 9 dB was observed in the calibrated data (Fig. 5a). This ripple is caused by calibration artifacts because of a strong distortion in the receiver for the forward wave on port 2. Filtering only this receiver substantially improved the calibrated results, but these results still presented spurs consistent with distortion in the receiver for the backward wave. By low-pass filtering both receivers, we improved the VNA dynamic range and improved the calibrated measurements of the JAWS frequency response. The closeup in Fig. 5b shows a 0.9 dB roll-off and a small ripple. The ripple, which presents a defined oscillating frequency, is believed to be caused by an impedance mismatch between the JJ circuit and the VNA measurement setup.

IV. Conclusions

We have produced the first calibrated measurement of a JAWS system up to 1 GHz. We achieved a calibrated JAWS amplitude frequency response measurement that is within 0.9 dB of the expected amplitude level predicted in [4]. The roll-off is believed to be caused by distortion of the pulse driving signal throughout the radio channel and the remaining ripple is attributed to impedance mismatch between the JJ circuit and our VNA measurement setup.

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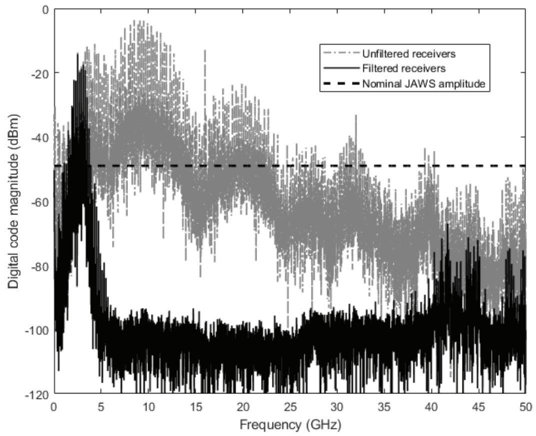
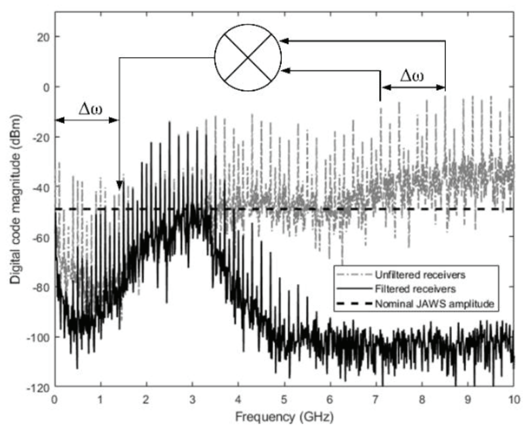
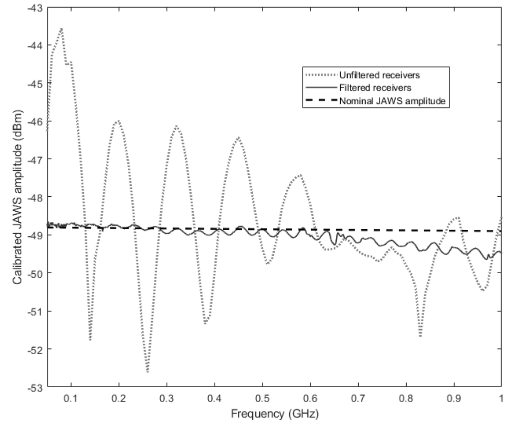


(a)

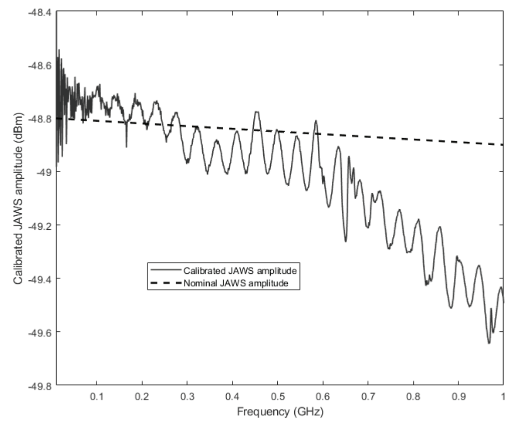


(b)

Fig. 4a) 50 GHz bandwidth measurement of the spectra of a delta-sigma-modulated pattern corresponding to a synthesis frequency of 500 MHz with and without low-pass filters on the VNA port 2 receivers. b) First 10 GHz of the spectrum shown in Fig. 5a. The inset illustrates the intermodulation distortion mechanism in the VNA receivers.



(a)



(b)

Fig. 5a) Preliminary results of calibrated JAWS amplitude frequency response. b) Closeup of the frequency response.

Preliminary load-pull measurements [9] have shown promise for helping to accurately model the JJ circuit (including its frequency-dependent amplitude and impedance). This will allow us to apply mismatch correction to our measurements and resolve the ripple issue. Calibrated broadband measurements of the input bias and quantized output pulses will be of interest to investigate the roll-off in the JAWS frequency response. Future work will also focus on scaling up the frequency and power capabilities of our JAWS system.

V. Acknowledgments

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