RF Josephson Arbitrary Waveform Synthesizer: JAWS up to 3 GHz and beyond

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Quantum-Based Signal Sources

**Goal:** Create a programmable quantum-based RF source for signal & power metrology

**Points of emphasis:**
- Calculable, quantum-based SI-traceable signal accuracy
- Quantum Locking Range: stable, reproducible, location-independent
- Arbitrary waveform synthesis using “3-level DAC” → calculable out-of-band signal
- Typical -48 dBm at cryogenic reference plane; demonstrated up to -28 dBm
Federal role established in the U.S. Constitution

JAWS Quantum Source: pulse-driven JJs

Basis of JAWS* Voltage Standard!

- Only 20 µV/JJ for 10 Gpulses/sec → need long JJ arrays & fast pulses
- Sequence of pulses generates ac waveform
  - determine sequence using delta-sigma algorithm
  - quantized area → calculable spectrum

*Co-invented by Przybysz, Worsham, Hamilton and Benz in 1995
Practical Voltages Require Series Arrays

- Common bias requires
  - Uniform junctions
  - Uniform microwave power
  - Excellent microwave designs

\[ V_{n,N} = \frac{h}{2e} nNf \]
Example calculated spectrum

- Delta-sigma algorithm
  - feedback with loop filter
  - RF-JAWS uses bandpass loop filter
- Very small background
  - In filter bandwidth
- Calculation assumes:
  - $\delta$-function JJ pulse shape
  - no feedthrough of bias pulses

- Synthesizing 5 kHz tone
- Digitization “noise” shaped by feedback loop

$$V(t)dt = \frac{h}{2e}$$

- 14.4 GHz pulse repetition rate

**Graph:**
- Power (dB relative to 5 kHz tone) vs. Frequency (Hz)
- Power values range from -200 to 0 dB
- Frequency range from $10^3$ Hz to $10^{10}$ Hz

**Legend:**
- Synthesizing 5 kHz tone
- Digitization “noise” shaped by feedback loop
Cryogenic Probe Station

- Optical window & camera
- 4 K cryocooled cryostat
- RF ports
- Piezoelectric probe control system
4 K Stage with JJ Devices & Standards

- RF probe port 1
- RF probe port 2
- Attocube 3-axis positioners
- Device & standards chip
- DC probe
- 25 cm dia.
Single Chip: JAWS and RF Standards

Calibration standards
Calibrated RF measurement of JJ voltage

**Two-stage LSNA calibration:**
- 300 K coaxial reference planes
- SOLR calibration
- Absolute power & phase

**4 K cryogenic reference planes**
- SOLR standards & multiline TRL standards
- JJ devices

Measure:
- Pulsing JJs generate \( a \) and \( b \) waves
- Low-power scattering parameters \( S \)

Determine measured JJ waves $b_{JJ,1}$ and $b_{JJ,2}$ from measured $a$ and $b$ waves and $S$ scattering parameters

$$b_{JJ,1} = b_1 - a_2 * S_{12} - a_1 * S_{11}$$
$$b_{JJ,2} = b_2 - a_1 * S_{21} - a_2 * S_{22}$$

Compare measured/calibrated value to quantum-based calculation (FFT of pulse pattern)
Preliminary Two Port Results

- 0.1 dB low-frequency offset
  - Origin under investigation

- High-frequency roll-off:
  - $b_{JJ,2} \rightarrow$ finite JJ pulse width
  - $b_{JJ,1} \rightarrow$ additional time-of-flight broadening of JJ pulse width
RF-JAWS Quantum Locking Range

Single Frequency QLR Sweep

Preliminary QLR measurements
Low-pass and Band-pass delta-sigma modulators can be combined – NTFs are multiplied

Conclusion

- JAWS is a quantum-based voltage source
  - Uses Josephson junctions to convert frequency -> voltage
  - Mature quantum-based DC voltage source (PJVS)
  - Young quantum-based low-frequency voltage source
  - We disseminate PJVS & LF-JAWS as NIST Standard Reference Instruments (SRI)

- Recently started RF-JAWS program: GHz quantum-based arbitrary signal source
  - Generate single-sines for power/phase calibrations
  - Generate multi-tones and pulses for measuring DUT non-linearities
  - Pulsed qubit control
  - Applications increase with frequency and power

- Currently focusing on step 1: Cryogenic probe station measurements
  - Comparing LSNA calibrated measurement to calculated value
  - 0.1 dB agreement at low frequencies and -48 dBm
    - qualitatively understood deviations <0.5 dB up to 3 GHz

- Working on faster JJs and faster pulses, higher frequencies and higher powers

\[ \int V(t)dt = \frac{h}{2e} \]