Measurement Challenges for Scaling Superconductor-based Quantum Computers

P. F. Hopkins[1], M. A. Castellanos-Beltran[1], J. Biesecker[1], J. A. Brevik[1], P. D. Dresselhaus[1], A. E. Fox[1], L. Howe[1], D. Olaya[1,2], A. J. Sirois[1], A. S. Boaventura[1], D. F. Williams[1] and S. P. Benz[1]

[1]*Communications Technology Laboratory, National Institute of Standards and Technology, Boulder, CO 80305*
[2]*Physics Department, University of Colorado, Boulder, CO 80309*

INTRODUCTION

Global investment in the research and development of quantum information systems by industry, government, and academic institutions continues to accelerate and is expected to reach over $16B by 2027 [1]. Systems based on optical photons, atoms or ions, spins in semiconductors, and superconductor circuits are all being pursued. One of the most challenging technology hurdles for all these paradigms is scaling to the large number of qubits required to make a quantum computer (QC) capable of solving relevant problems that cannot be efficiently solved using a conventional computer. In the case of a QC using superconducting qubits with state-of-the-art gate error rates, it is estimated that greater than 1 million physical qubits will be required [2].

Scaling superconductor-based QCs to this size from the present ~ 10^2 qubits [3] will require designing, implementing, and testing large, cryogenic microwave systems for initialization, control of gate/entanglement operations, and readout of ~10^6 physical qubits using millions of low-power microwave signals. The goal of the NIST research highlighted below is to assist the nascent QC industry with making significant advances in 1) cryogenic microwave reference sources, 2) on-wafer microwave testing, and 3) on-wafer calibration standards that will be required for fabrication process control, design verification, and accurate modeling and simulation in the development of large-scale QCs.

Fabricated lithographically on silicon or sapphire wafers, superconductor-based "transmon" qubits consist of simple, cryogenic, non-linear *L-C* resonator circuits using superconducting tunnel junctions called Josephson junctions (JJs) to provide the nonlinear inductance (L). The resonators have a ground state (0) to first-excited state (1) energy separation E_{10} with a transition frequency $f_{10} = E_{10}/h$, where h is the Planck constant, typically in the 4 GHz - 8 GHz range. Because of the nonlinearity, the higher energy state separations (E_{21}, E_{32}, etc.) decrease, allowing the E_{10} transition to be isolated as a two-level system (TLS), i.e., a qubit. The qubit is cooled to the "quantum regime" in a dilution refrigerator (DR) to a temperature $T < 0.05$ K so that the thermal energy $k_B T << E_{10}$, where k_B is the Boltzmann constant. Low-power (~ -90 dBm =1 pW, as measured at the qubit) modulated microwave control signals are used to 1) initialize ("write") the qubit state, e.g., excite the qubit from the ground state to the first-exited state, and 2) perform gate operations, i.e., control the evolution of the qubit state and interactions with other qubits.

Readout of the qubit is a delicate measurement designed to interrogate but not upset the fragile quantum state. To do so, the qubit can be capacitively-coupled to a low-loss (high quality-factor) superconducting linear resonator with a resonant frequency f_r, typically chosen to be a few GHz higher than f_{10} (dispersively-coupled regime). Extremely low power (< -120 dBm = 1 fW) microwave signals are used to monitor f_r, which shifts depending on the qubit state. In multi-qubit systems fabricated on a single chip, each qubit is coupled to a different linear resonator with a unique f_r. Many resonators can be coupled to a single transmission line, allowing frequency-multiplexed readout [4]. Because the readout signals are so small, extremely sensitive, low-noise, cryogenic parametric amplifiers are located near the qubits and used as the first amplifier stage of the output chain; these "quantum-limited amplifiers," developed at NIST [5,6] and elsewhere, add only the minimum amount of noise dictated by quantum mechanics.

The microwave circuits and the modulated microwave signals they produce to initialize, control, and readout the qubits in a large-scale QC system will need to be fully characterized with calibrated measurements of signal power, phase, distortion, and noise. A programmable, self-calibrated microwave reference source is one tool that NIST is developing to enable these measurements.

REFERENCE SOURCES FOR MICROWAVE SIGNALS

The primary standards developed at NIST for dc and ac voltage used around the world are based on superconductor circuits consisting of series arrays of $N = 10^3$-10^5 JJs [7,8]. When an array of JJs is driven with a current pulse of appropriate amplitude, it will emit a voltage pulse with a quantized time-integrated area exactly equal to $N\Phi_0$, where N is the number of JJs and $\Phi_0 = h/2e$ is the magnetic flux quantum defined by two fundamental constants, h and the unit of elementary charge e. Programmable, arbitrary waveforms can be generated by driving the JJ array with encoded pulse patterns using pulse density modulation [8]. The quantized output pulse areas are identical for every device, traceable to fundamental constants, and immune to variations in operational and environmental parameters. NIST is extending this technology to develop RF waveform synthesizers as reference sources for telecommunications metrology [9,10]. Waveform synthesis at 1 GHz with up to -28 dBm output power [11] and a 4-tone multi-sine signal [12] with programmable amplitudes and phases have been demonstrated.

NIST is also developing these quantum-based synthesizers for quantum information applications [13]. QC laboratory demonstrations typically route signals through coaxial cables from racks of room temperature microwave electronics into the cryostat to perform the initialization, control, and readout of qubits; this “rat’s nest” configuration is not scalable. The scaling of cryogenic QCs will require closer integration of the qubits with compatible cryogenic, energy-efficient, electronics for qubit control and readout [14,15]. Several research groups worldwide are working on cryogenic semiconductor (cryo-CMOS) control solutions [15]. NIST is investigating the use of energy-efficient superconductor pulse generators for in-situ, extremely stable, self-calibrating, reproducible, digital qubit control that is scalable and has potential for standardizing the testing of qubits [16]. These superconducting qubit “drivers” could be combined with cryo-CMOS electronics at the classical-quantum interface of the QC [14].

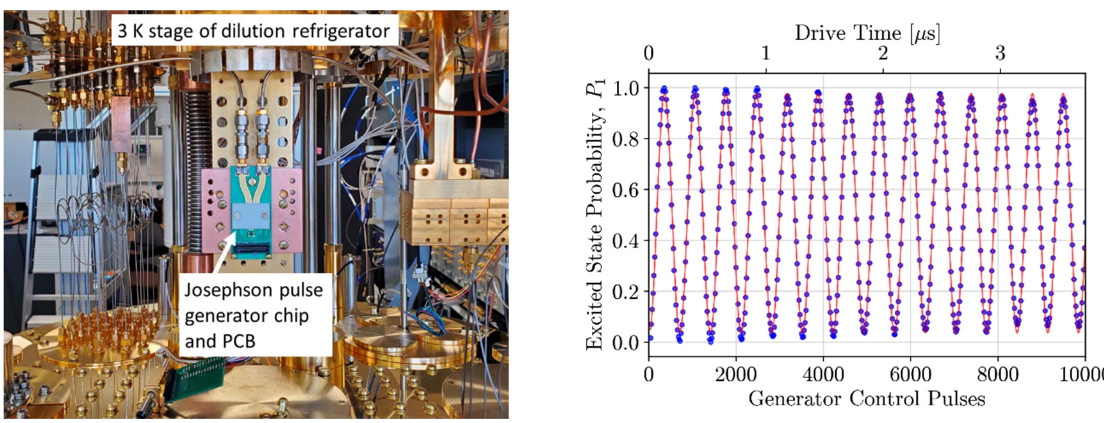

FIGURE 1. Left: A “Josephson pulse generator” located at the 3 K stage of a dilution refrigerator used to digitally control a superconductor qubit at the 10 mK stage (electromagnetic shielding has been removed). Every quantized pulse sent by the generator is identical and causes a discrete change in the qubit state. Right: A Rabi oscillation plot, showing data (blue points) and fit (red line) of the probability that the qubit is observed in the excited state (P1) versus the number of control pulses.

ON-WAFER CRYOGENIC MEASUREMENTS AND STANDARDS

Previously, NIST demonstrated scattering-parameter microwave calibrations at millikelvin temperatures [17] and is now working to combine a commercial room-temperature vector network analyzer with a NIST-developed cryogenic front-end with unprecedented sensitivity to accurately characterize the very low power microwave control and readout signals present at the qubits [18]. Challenges include designing and implementing the front-end to measure modulated microwave signals that are several orders of magnitude weaker than possible with state-of-the-art network analyzers while operating at millikelvin temperatures inside the DR; power, phase and noise-parameter standards are also being developed to reach the lowest power levels. If successful, this instrument will be able to make direct, on-wafer, calibrated measurements of scattering parameters, impedances, voltage and current waveforms, nonlinear distortion, and noise and will be indispensable for design verification and developing the accurate models of microwave systems required for designing large-scale cryogenic, microwave-based QCs.

In related work, NIST has developed a 4 K cryogenic microwave probe station with 3-axis translation for accurately characterizing on-wafer superconductor devices up to 40 GHz. This measurement system is being used to develop the quantum-based waveform sources mentioned above as microwave power standards. The two-tier calibration procedure includes a custom cryogenic through-reflect-line (TRL) microwave calibration kit co-located on-chip with the superconducting devices under test. Loss and dispersion in the input/output signals due to the RF cables and interconnects are de-embedded (subtracted out), enabling accurate measurements of the microwave signals using a vector network analyzer [19].

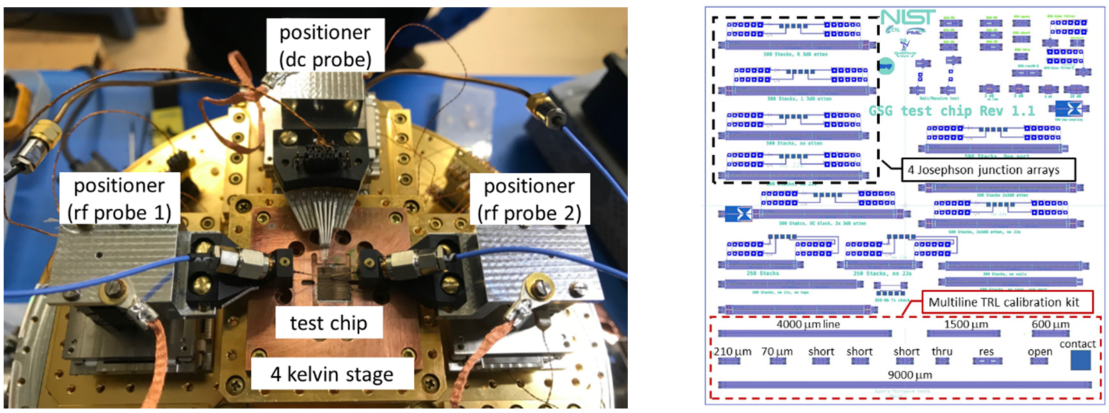

FIGURE 2. Left: Sample stage of NIST's cryogenic microwave probe station. Right: Layout of a 1 cm x 1 cm chip, designed and fabricated at NIST, that includes the cryogenic superconductor-based TRL microwave calibration kit (dashed red box at bottom)) and several superconducting circuits with arrays of Josephson junctions (dashed black box indicates four examples).

Ultrasensitive, calibrated cryogenic microwave measurements and standards for understanding, designing, testing, and scaling the microwave circuits that initialize, control, and readout the qubits are key to enabling the commercialization of large-scale microwave-based cryogenic QCs. NIST's research on cryogenic microwave reference sources, a new cryogenic vector network analyzer with unprecedented capability, and superconducting on-wafer microwave calibration standards should provide assistance towards this challenging endeavor.

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KEYWORDS

Quantum computing, superconductor qubits, qubit control, qubit readout, microwave calibrations