Superconducting Qubits: The Best Approach to Quantum Computing?

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Introduction

A new type of computer based on the theory of quantum mechanics, a quantum computer, is currently in development by researchers around the globe. The theory of quantum mechanics describes nature at the atomic and subatomic level. Quantum technology has the potential to build powerful tools that process information using the properties of atoms, photons, and electrons. These quantum computers could also address challenges of much greater complexity than what today's computers can solve, and help further advancements in science, technology, medicine, and more.

With countries spending billions of dollars, the race for who can produce the first practical, commercialized quantum computer is on. There are currently several approaches to build this sort of computer, and this all begins with creating and initializing quantum bits, also known as qubits.

What is a Qubit?

A qubit is the basic unit of quantum information, similar to how the bit is the basic unit of information in classical computing. The difference here is that bits only exist in a state of 0 or 1, while a qubit can exist in a combination of all possible states. Known as superposition, this means that any two or more quantum states can be added together and result in another quantum state.

There are many competing hardware approaches to quantum computing, with the three most common being ion trap, silicon quantum dot, and superconducting circuit. This white paper introduces all three, with a focus on superconducting circuits.

Approaches to Quantum Computing

Ion Trap

One way to devise a large-scale quantum computer is with the trapped ion approach. Ions are electrically charged atomic particles that can be suspended in free space using electromagnetic fields, with the qubits stored in the electronic states of each ion. Because of the stability of the electronic states, quantum information passes through the collective quantized motion of the ions in a shared trap.

Qubits initialize through a process called optical pumping, when light raises electrons from a lower energy level in an atom or molecule to a higher one. During this process, a laser couples an ion to excited states that will eventually decay to one state that is not coupled to the laser. For a single qubit, lasers induce coupling between internal qubit states. For entanglement between qubits, lasers are applied between the qubit states and external motional states.

These lasers must be at precise wavelengths to match the resonance frequency of the atom. For this to occur, two laser technologies are needed. The first cools and reduces the kinetic energy at a fixed trap condition and atom number, while the second repumps when the atom decays to the wrong ground state. For this process, there are eight total laser wavelengths used for cooling, trapping, gating, and readout. An optical spectrum analyzer measures the amplified spontaneous emission background after amplification of the laser source.

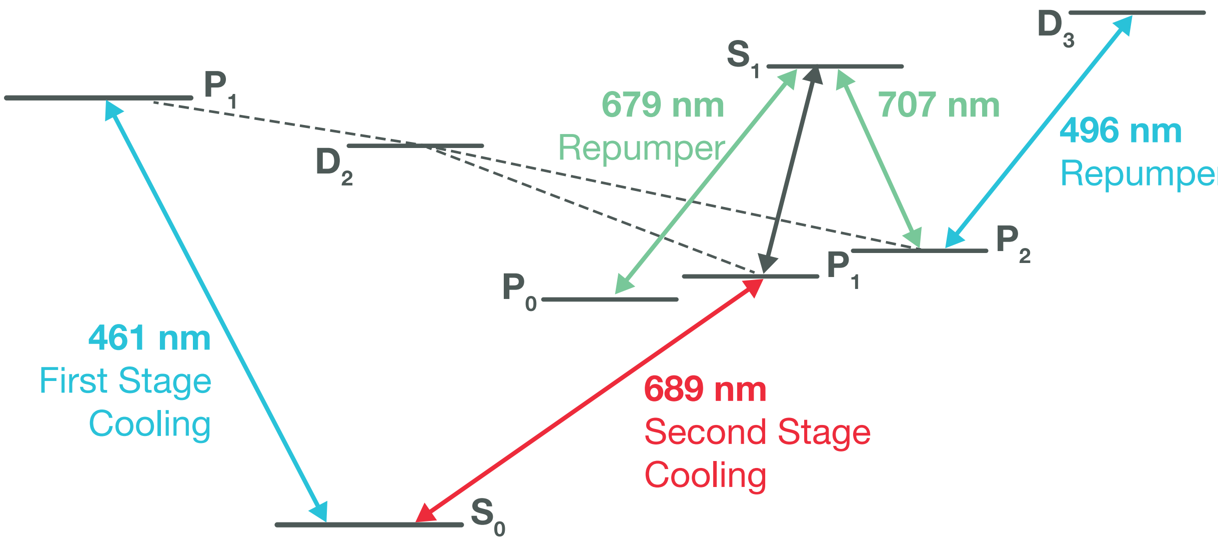

Figure 1. Example laser wavelengths used for quantum cooling

Plans in development for scaling the number of qubits in the system include transporting ions in an array of ion traps to distinct locations, building large, entangled states from photonic networks of remotely entangled ion chains that transmit information as optical signals using light, and combinations of these ideas. Because of this, the ion trap method shows promise in the actualization of a large-scale, usable quantum computer.

Silicon Quantum Dot

Another method of initializing a quantum computer is through the use of silicon quantum dots. Quantum dots are semiconductor nanoparticles that are so small their electronic properties differ from larger particles. Their electrical properties are governed by quantum mechanics, and when paired, quantum dots can be used as a single qubit.

These silicon qubits can hold one or a few electrons. To determine whether the qubit is in a 1 or 0 state, the spin of electrons is measured. Since many elements have an inherent nuclear spin which interferes with the ability to read and manipulate the spin of the electron, most quantum dots are made from silicon-28, a naturally spin-free isotope. A burst of microwaves is used to flip the spins.

Silicon quantum dots operate at higher temperatures than competing methods and are on the same size scale as transistors. Because temperatures are above one-degree kelvin and quantum dots are made in a similar way to transistor, they can be placed together with no cabling and may be able to use the same technology as computer chips. These advantages make the silicon quantum dot method a feasible approach to making a high qubit count quantum computer.

Superconducting Circuit

One of the most popular and successful approaches for developing a quantum computer uses superconducting electrical circuits. This approach has been adopted by Google, IBM, and several well-known startups including Rigetti Computing. Superconducting circuits are specially designed microwave resonators, similar to LC tank circuits. When cooled to millikelvin temperatures, these circuits exhibit quantum mechanical properties that make them great qubits.

Superconducting circuits can be manipulated with microwave pulses and DC biasing. They are designed such that their resonant frequencies are strongly dependent on the magnetic flux traveling through the circuit (DC current sources engineer this magnetic flux).

These circuits must be frequency-tunable to park at a specific frequency, which varies from qubit to qubit. The magnetic field requires fine-tuning so that quantized energy levels can smoothly transform, crucial for initializing a quantum computer.

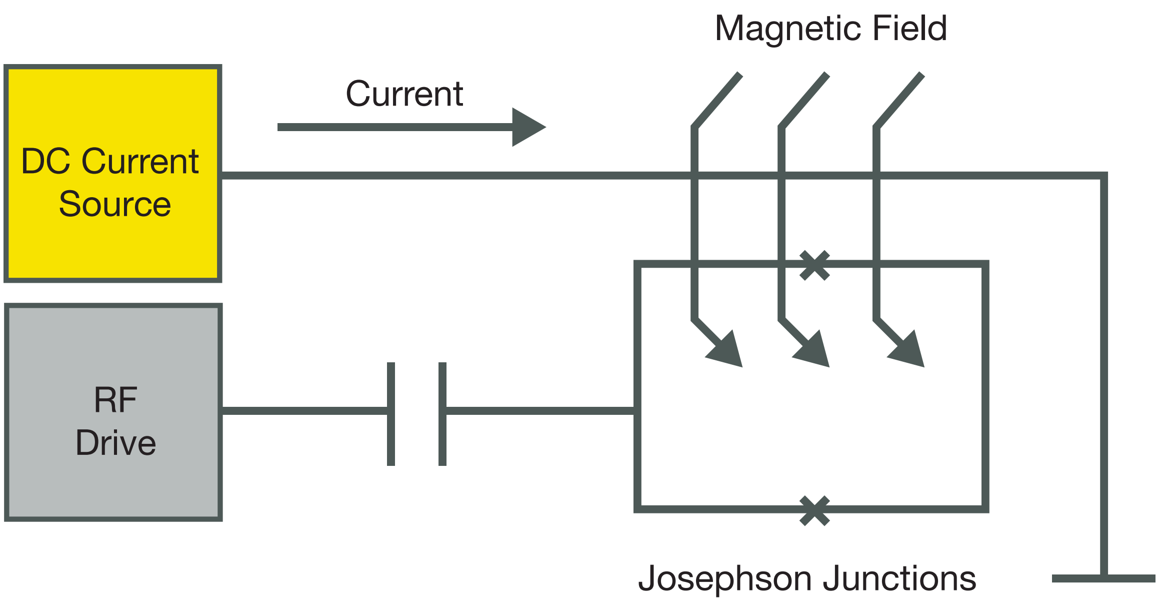

Figure 2. A DC current source creates a magnetic flux through the circuit

Setup and Instrumentation

Instrumentation for quantum experiments often includes a DC current source, RF stimulus, and microwave engineering tools in the 1-10 GHz range including vector network analyzers, arbitrary waveform generators, spectrum analyzers, filters, and amplifiers.

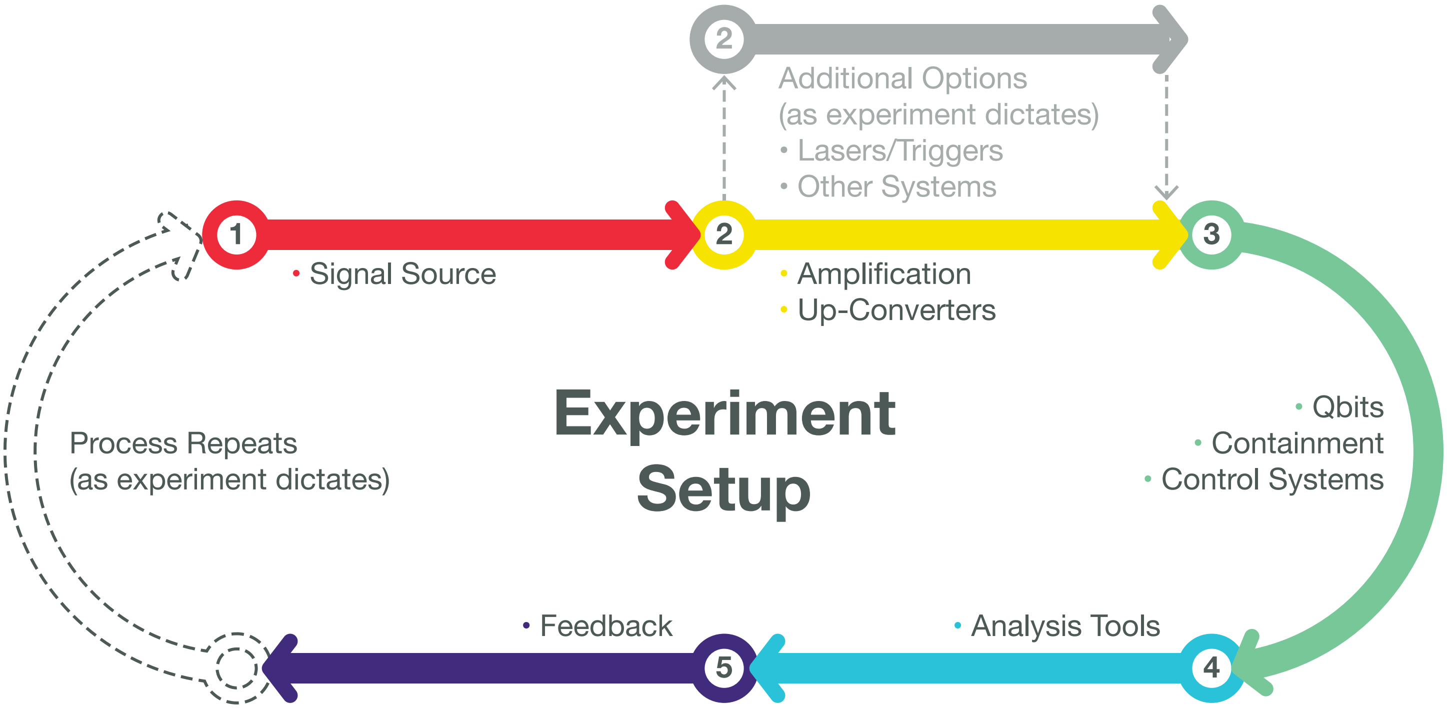

Figure 3. Typical setup for a quantum computing experiment

The typical setup for quantum computing experiments includes a base signal source to generate IQ, followed by an amplifier or up-converter. Other system types, like a control system, can run in parallel, depending on the experiment of choice. Because of the complexity of these quantum experiments, digital channels that trigger or activate other devices may also be needed. These sorts of experiments are typically undertaken at cryogenic temperatures, which often begets challenges for the signal source and triggers the potential for predistortion and pre-compensation to adjust for losses. Analysis tools and feedback mechanisms are needed to analyze data, make adjustments, and run the experiment multiple times.

Challenges

There are several challenges for superconducting circuits specifically and creating a quantum computer in general. These circuits are fabricated in the same way that complementary metal-oxide-semiconductor (CMOS) is fabricated, which is a straight-forward process. Therefore, it's easy to print many of these circuits on a chip to create a many-qubit system. The challenge comes when one tries to control those individual circuits to ensure certain circuits talk to each other and avoid crosstalk between undesirable circuits, as well as ensure each circuit has a good lifetime.

As the number of qubits and quantum experiments grow, more challenges arise. For example, when channel counts increase, additional and larger equipment is necessary. Each qubit can require multiple independent signals, and each of those signals may require its own up-conversion, pre-distortion, and conditioning. This leads to further issues with the cabling required for each of these signals, such as delays, multiple tangled wires, difficulty in characterization, and losses. These channels also require synchronization, as timing is critical for accurate results.

Environmental challenges must also be considered. Because superconducting circuits are highly sensitive to even the smallest changes, they require thermal, mechanical, and electrical isolation and must be kept at slightly over zero degrees kelvin. This necessitates complex cooling systems and makes it more difficult to set up the instrumentation for these experiments.

Solutions

DC Current Source

Qubits are built up from non-linear Josephson junctions that are sensitive to changes in the magnetic field. A small current from a DC current source produces and fine-tunes that magnetic field, which makes the DC current source a critical part of superconducting circuit experiments.

It is critical that DC current sources be extremely stable and have low noise. If the current fluctuates or the noise is too high, the experiment is affected because of the frequency's dependence on that current value.

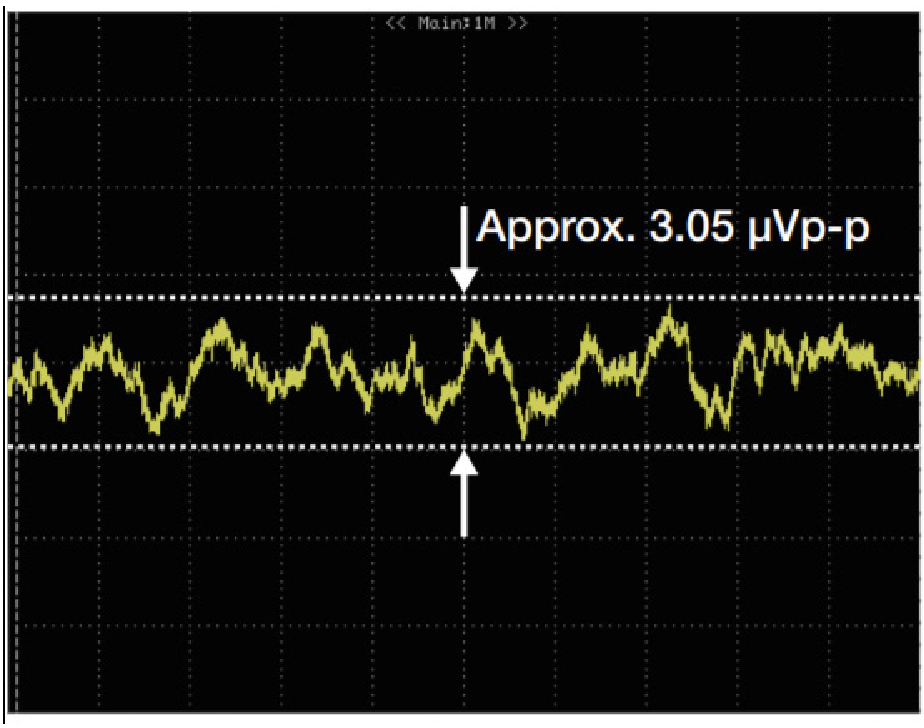

Figure 4. A noise waveform example at 0V output in 10V output range (observed using a 1000 times amplifier with a 10 kHz band-limiting filter)

When the frequency jitters, the magnetic field noise increases, which shortens the lifetime of the resonators. If the source isn't stable, the frequency drifts and the quality of the device degrades.

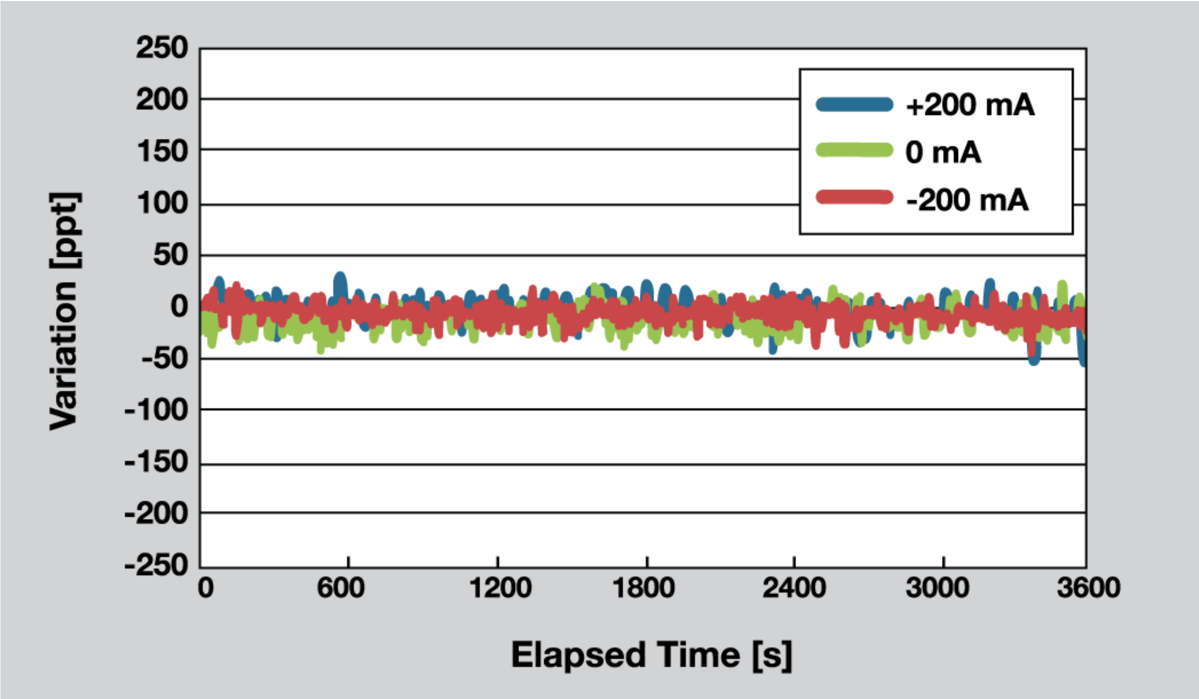

Figure 5. Example of one hour stability in output 200 mA range (as reference data)

Because of the previously mentioned challenges with space and channel count, it is important to find a DC source that is small, reasonably priced, and allows for synchronization with multiple units. However, the noise and stability specifications are still most important when selecting a source to ensure quality experiments.

Optical Spectrum Analyzers

The ion trap approach to quantum computing utilizes several lasers at varying wavelengths for cooling, repump, trapping, gating, and readout. Precise laser wavelengths are needed for each of these. An optical spectrum analyzer displays the power distribution over a specified wavelength span and measures and ensures the lasers are tuned to the correct wavelength so that the qubits maintain their quality.

Conclusion

While the superconducting circuit approach is the most widely used method for creating a quantum computer, there are arguments for and advantages to the ion trap and silicon quantum dot approaches as well. There are still many challenges in all these methods, with the primary one being how to scale the number of qubits up while maintaining the qubits integrity and limiting the amount of space taken up by instruments. But given the potential benefits, researchers are working to overcome these obstacles and determine the best approach to swiftly bring quantum computers to the market.