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Functional description of
Quantum Devices using Transmons

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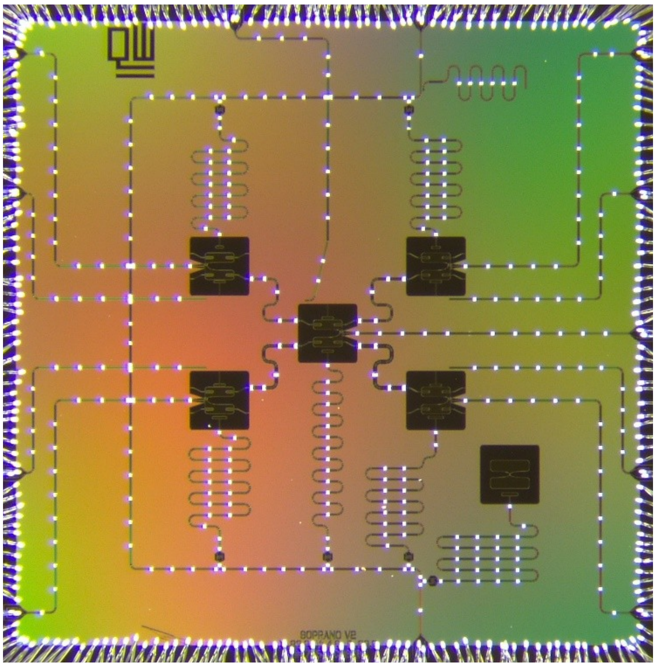
1. Abstract

This contribution is a literal text proposal for inclusion into the draft of "Cryogenic Solid State Quantum Computing".

2. Background information – how does a transmon-based QPU look like?



An optical image of a 6 qubit QPU device. Starting from the periphery, the wirebonds connecting the PCB to the QPU are visible. Most of the wirebonds are for grounding purpose, but the ones in correspondence to the on-chip CPW (black) lines are responsible to interconnect the various signals from the PCB to the QPU.

The control lines travel from the edge of the chip to transmons (dark squares in the central region)

Start of literal text proposal

5. Layer 1 – Quantum Devices

The quantum devices in hardware layer 1 are modules with qubits that are operating at cryogenic temperatures and may be implemented as chips and connected by PCBs (Printed Circuit Boards). Different solutions have been developed over time on how to implement the qubits in these devices, including transmons, flux qubits, semiconductor spin qubits topological qubits and NV centers in diamonds. Functional descriptions and functional requirements of these devices are described below.

5.1 Functional Description

5.1.1 Functional description of Transmons

A transmon is one implementation of the unit of quantum information. A number of transmons on a chip forms a superconducting quantum processor unit (QPU), which is typically controlled using microwave and DC signals. The microwave signals are used to initialize and manipulate the state of the qubit, to perform quantum operations and readout. The DC signals are typically used to change the qubit's working frequency.

A single transmon qubit is a nonlinear LC resonator with a narrow frequency in the bandwidth between 4 and 8 GHz. It has several input and output lines:

- A direct drive line that is used for injecting pulses modulated on a microwave carrier. These pulses are used to perform single qubit operations, such as initialize and manipulate the state of the qubit. The frequency of the pulse is at the same frequency of the corresponding qubit, so within the 4-8 GHz bandwidth, while their phase, amplitude and duration govern the amount of X and Y rotation that the qubit will acquire in the Bloch sphere.
  Typical values for the amplitude and duration of direct drive signals are -110 dBm (at PCB interface) and <30 ns, respectively.
- A flux line that is used to tune the individual qubit frequency to its desired value via a current. This DC current can be static (qubit at fixed frequency) or can be varied over time to move a qubit in or out of resonance with respect to other qubits, for example during 2 qubit gate operations. Moreover, a low frequency modulation can be over imposed to the DC current, to allow for a more accurate control of the trajectory of the qubit in its frequency and phase. The DC component of the flux signals have a maximum of around 2 mA, while the low frequency modulation might have a bandwidth up to 800 MHz and an amplitude of -110 dBm.
- A readout resonator (typically 6-7 GHz) is used to detect the state of the qubit. A readout tone at the frequency of the readout resonator is injected into resonator for a time between 300 ns up to a micro second depending on the desired read out fidelity. The

signal reflected from the resonator has a shift in frequency that depends on the state of the qubit.

A QPU, which consists of an array of transmon qubits may have additional input and output lines such as:

- A feedline, which is shared among a few qubits, to support frequency-multiplexed read out of multiple read-out resonators at the same time.
- An (optional) control line for tunable coupling, in QPUs where the qubit-qubit interaction is mediated by a controllable element. Similarly to the flux bias lines for qubits, the DC component of the tunable coupler signals have a maximum of around 2 mA, while the low frequency modulation might have a bandwidth up to 800 MHz and an amplitude of -110 dBm.
- The read-out signals at the feedline output are to be amplified first with dedicated ultra-low noise amplifiers operating at cryogenic temperatures. Commonly used solutions are Traveling Wave Power Amplifiers (TWPA). Typical TWPA-pump signals are narrowband tones with a power of around -40 dBm at around 8 GHz.

5.1.2 Functional description of Spin Qubits

Other experts are invited to contribute dedicated text for a functional description of Spin Qubits.

5.1.3 Functional description <other Qubit flavors>

Other experts are invited to contribute dedicated text for a functional description of other type of Qubits.

5.2 Functional Requirements

5.2.1 Functional requirements of Transmons

The operation of superconducting qubits can easily be deteriorated by external disturbances from outside the device. Examples are disturbing quantities like temperature, static magnetic fields, EM-fields, vibrations, infrared stray photons, background radiation and cosmic activity. But there may be more issues of relevance that are to be specified, which may be less obvious. Their relevance is explained below.

5.2.1.1 Thermal requirements

Superconducting qubits typically operate at very low temperatures, typically a few milliKelvin, which is close to absolute zero. This is necessary to reduce thermal noise and decoherence in the qubits, which can cause errors in quantum computations.
The low temperatures are achieved using a cryogenic cooling system, which typically consists of a dilution refrigerator with a pulse-tube cryocooler. The cooling system cools the qubits and

their local control interconnections to very low temperatures (15 - 50mK), while also providing some level of electromagnetic and mechanical isolation.
Overall, the low temperature needed to operate superconducting qubits and the proper thermalization of all the components are critical factors that must be carefully managed in order to achieve reliable and accurate quantum computations.

5.2.1.2 Static Magnetic field requirements

Stray magnetic fields can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of magnetic interference in the cryostat.
One approach to reducing magnetic interference is to use shielding materials to block external magnetic fields from entering the cryostat. This can be achieved by using materials such as mu-metal or conductive foils to create a preferential magnetic path around the experimental volume. Additionally, careful placement of the cryostat and the orientation of the sample can help to minimize the amount of magnetic interference that arrives at the QPU.
Another approach is to use superconducting magnetic shields, based on the Meissner effect, that expels stray magnetic fields from the experimental volume below its superconducting transition temperature.
In general, the choice of non-magnetic materials in proximity of the QPU is to be avoided. Static magnetic fields can be compensated per qubit (by flux bias compensation) but is not a scalable solution and requires fully superconducting wiring to the QPU to avoid local dissipation.

5.2.1.3 EM field requirements

Electromagnetic interference can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of electromagnetic interference (EMI) in the cryostat.
One approach to reducing EMI is to use shielding materials to block external electromagnetic fields from entering the cryostat. This can be achieved by using materials such as mu-metal or conductive foils to create a Faraday cage around the cryostat. Additionally, careful placement of the cryostat and other equipment can help to minimize the amount of EMI that enters the cryostat.
Another approach is to use filters and other signal conditioning techniques to reduce the impact of EMI on the QPU. This can include using low-pass filters to remove high-frequency noise, or using notch filters to remove specific frequencies that are known to cause interference.
To ensure that the levels of EMI are within the required limits, it is important to measure and monitor the EMI levels in the cryostat using electromagnetic field sensors. This can help to identify any sources of EMI and enable corrective measures to be taken.

5.2.1.4 Vibration requirements

Cryostat vibration can be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the vibration levels in the cryostat.
One approach to reducing vibration is to use a mechanical support system that isolates the QPU from external vibrations. This can be achieved by using a combination of passive and active vibration isolation techniques. Passive isolation techniques include using rubber pads or

springs to decouple the QPU from the cryostat, while active isolation techniques use sensors and actuators to cancel out vibrations in real-time.
Another approach is to use a cryocooler that operates at a higher frequency than the natural frequency of the cryostat, which can help to reduce vibration levels. Additionally, careful placement of the cryocooler and other equipment in the cryostat can help to minimize vibration.
Vibrations in the cables have been shown to induce triboelectric noise in qubits.
To ensure that the vibration levels are within the required limits, it is important to measure and monitor the vibration levels in the cryostat using accelerometers or other sensors. This can help to identify any sources of vibration and enable corrective measures to be taken.

5.2.1.5 Infrared stray photon requirements

Stray photons in the infrared range can also be a significant source of noise and can cause decoherence in the qubits. Therefore, it is important to minimize the levels of infrared radiation that reach the qubits.
One approach to reducing infrared radiation is to use optical filters to block out infrared photons. This can be achieved by using filters that are designed to block out specific frequencies of infrared radiation. Additionally, careful placement of the qubits in light tight enclosure is necessary to minimize the amount of infrared radiation that reaches the qubits.
Another important consideration is that the waveguides used to interconnect the QPU typically also contain dielectrics that are transparent to IR radiation, therefore is essential to use IR filters or waveguides that are transparent to microwave frequencies but opaque to infrared radiation to create a shield around the qubits. This can be achieved by using dielectric materials such as copper or magnetic powders mixed in an epoxy matrix.
Overall, protecting the qubits from infrared stray photons is an important factor in achieving reliable and accurate quantum computations, and requires careful consideration of IR filtering and material selection.

5.2.1.6 Shielding requirements against background radiation and cosmic activity

Background radiation and cosmic activity can also be a significant source of noise and can cause decoherence in the qubits by the creation of phononic and quasiparticle excitations. Therefore, it is important to minimize the levels of background radiation and cosmic activity that reach the qubits.
One approach to reducing background radiation is to use shielding materials to block out radiation from the environment. This can be achieved by using materials such as lead or tungsten to create a radiation shield around the QPU to reduce the gamma ray component. With careful choice of radio pure materials in close proximity to the QPU, one can mitigate the amount of local radioactivity and the generation of induced secondary radioactivity.
Ultimately, to further reduce the impact of cosmic activity in the form of neutrons and muons, it is advisable to locate the cryostat in an underground facility under several tens of meters or more of ground.

5.2.2 Functional requirements of Spin Qubits

Other experts are invited to contribute dedicated text for functional requirements of Spin Qubits.

5.2.3 Functional requirements <other Qubit flavors>

Other experts are invited to contribute dedicated text for a functional requirements of other type of Qubits.

End of literal text proposal