अतिचालक क्यूबिट्स

14

अतिचालक क्यूबिट्स के लिए नियंत्रण एवं मापन प्रणाली

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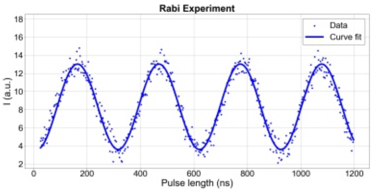
टाटा मूलभूत अनुसंधान संस्थान (टामूअसं), मुंबई



राबी प्रयोग

सारांश

अति-चालक क्यूबिट्स के नियंत्रण और माप की प्रक्रिया क्वांटम कंप्यूटिंग अनुसंधान के महत्वपूर्ण पहलू हैं, जो क्वांटम प्रणाली से जानकारी को संचालित और प्राप्त करने के लिए आवश्यक हैं। त्वरक नियंत्रण प्रभाग, भाभा परमाणु अनुसंधान केंद्र, क्यू. एम. सी., टाटा मूलभूत अनुसंधान संस्थान के सहयोग से सामान्य तापमान पर संचालित इलेक्ट्रॉनिक प्रणाली के विकास की दिशा में काम कर रहे हैं, जो अति-चालक क्यूबिट्स के नियंत्रण और माप के लिए है। इस लेख में प्रोटोटाइप क्यूबिट कंट्रोलर के साथ किए गए क्यूबिट अभिलक्षण प्रयोगों के परिणाम प्रस्तुत किए गए हैं।

Superconducting Qubits

14

Control and Measurement System for Superconducting Qubits

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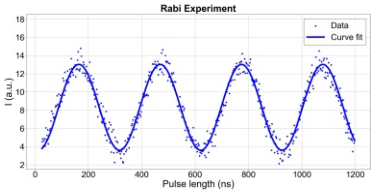

Rabi experimnet

ABSTRACT

The control and measurement of superconducting qubits are critical aspects of quantum computing research, essential for manipulating and extracting information from quantum systems. Accelerator Control Division, Bhabha Atomic Research Centre, in collaboration with QuMaC, Tata Institute of Fundamental Research is pursuing development of room-temperature electronic system for control and measurement of superconducting qubits. This article presents the test results from qubit characterization experiments conducted with the prototype qubit controller.

KEYWORDS: *Quantum system, Qubits, Superconducting qubits.*

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Introduction

Quantum computing is a revolutionary approach to computation that harnesses the principles of quantum mechanics to process information. In quantum computing, a control and measurement system plays an important role in manipulating the state of qubits by applying quantum gates, and determining their state. A control and measurement system for superconducting qubits is being developed to conduct qubit characterization experiments, and execute high-fidelity quantum gate operations. The controller is designed to support a diverse range of experiments, including the capability to perform resonator spectroscopy, qubit spectroscopy, Rabi experiment, XY gate operations, and measurements of qubit relaxation and de-phasing times.

Control and Measurement of State of a Qubit

A quantum bit or qubit is the fundamental unit of information in quantum computing, analogous to the classical bit [1]. A superconducting qubit is one of the many physical realizations possible for building a qubit [2]. It is built around a Josephson junction, which is formed by two superconductors separated by a thin insulating barrier. Its fabrication process aligns well with established semiconductor manufacturing techniques, making it conducive to scalability.

Controlling the state of a qubit involves manipulating its quantum state to perform desired operations. This manipulation typically involves applying sequence of quantum gates [3], which are analogous to classical logic gates but operate on quantum states [4]. These gates can deterministically change the state of qubits, allowing for the creation of superposition and entanglement, as well as other quantum operations required for computation. Measuring the state of a qubit involves determining its quantum state at a specific moment in time. Qubits are coupled to microwave resonators located in close physical proximity to them. It is through these resonators that qubit state is determined or "readout". One common technique for determining the state of a qubit is the dispersive readout method [5]. This method utilizes the fact that the state of a qubit has a direct influence on certain macroscopic parameter of the readout resonator such as its resonant frequency.

Qubit Control and Measurement System

Architecture of the qubit controller

The qubit controller consists of an FPGA, a microprocessor, and data converters, and provides precise control and fast data acquisition essential for quantum state manipulation and measurement.

Fig.1 depicts the architecture of the qubit controller. The controller consists of an arbitrary waveform generator and a data acquisition block implemented in the FPGA. The arbitrary waveform generator utilizes digital up-conversion and interpolation operations to synthesize microwave pulses of specified frequency, shape and duration for both control and readout operations. The output of the generator connects to a DAC. During the measurement of the qubit state, the data acquisition block acquires samples from the ADC and performs digital down-conversion, decimation, and averaging operations. The microprocessor oversees overall operations, while the FPGA-based sequencer manages data acquisition and pulse generation, and is programmed to execute specific experiments.

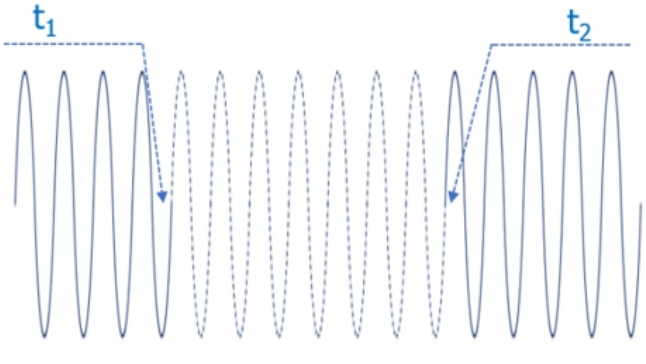


Fig.2: A continuous sinusoidal waveform depicting phase coherence.

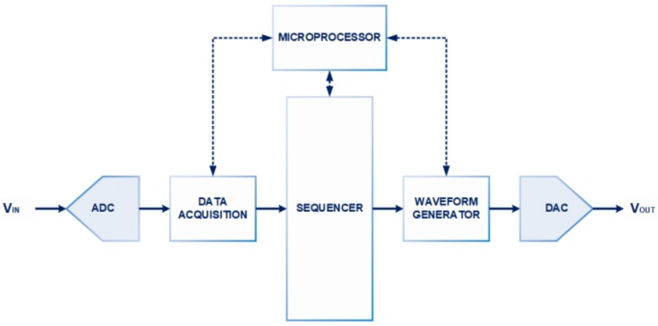


Fig.1: Architecture of Qubit controller.

Both digital up-conversion and digital down-conversion operations utilize a common time base to preserve phase coherence. Fig.2 illustrates the concept of phase coherency using a continuous sinusoidal waveform. This continuous sinusoid can be conceptualized as two pulsed sinusoids separated in time, with the first one ceasing at time 't1' and the second one commencing at time 't2'. The initial phase of the second pulsed sinusoid matches the phase of the continuous sinusoid at time 't2'. Phase coherence in control and measurement signals ensures accurate qubit manipulation.

Application software

An application software, which enables performing a set of experiments, namely, resonator spectroscopy, qubit spectroscopy, Rabi experiment, decoherence time and dephasing time measurements, has been developed and deployed on the qubit controller.

Additionally, a graphical-user-interface (GUI) has been created to facilitate user interaction, allowing for configuration settings, experiment monitoring, and result analysis, thus enhancing the overall user experience. Fig.3 provides a screenshot of the GUI of the control and measurement system.

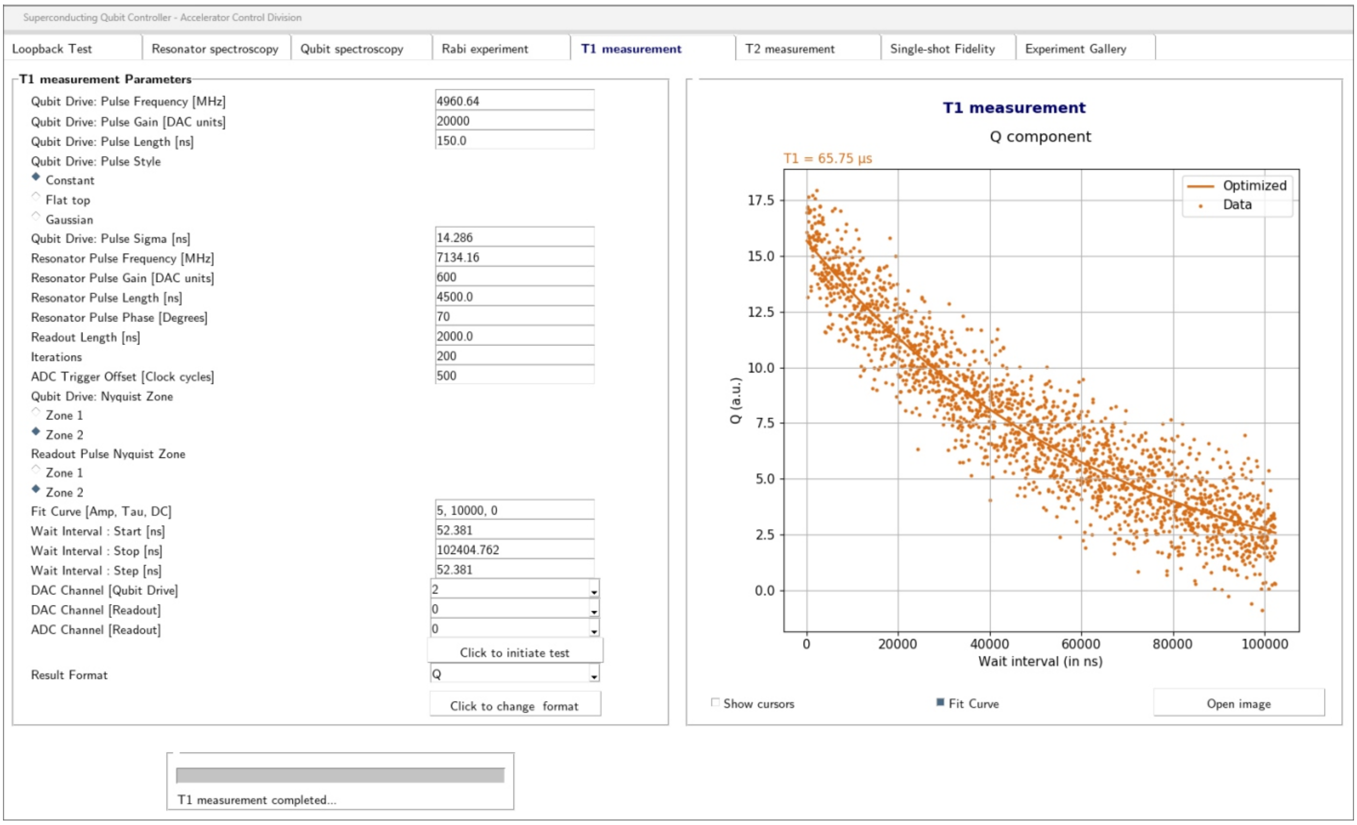
Experimental Results

Resonator spectroscopy

Resonator spectroscopy was performed to find out the resonant frequency of the readout resonator coupled to the qubit. A microwave signal with sweeping frequency was sent to the readout resonator, & the magnitude and phase responses of reflected signal were measured. At the point of resonance, two distinct features become evident: a reduction in signal magnitude and a sharp change in phase as depicted in Fig.4. The resonant frequency was measured to be 7.13416 GHz.

Qubit spectroscopy

Two-tone qubit spectroscopy experiment was performed to determine the qubit frequency. A low power, resonant signal was sent to the readout resonator, and the reflections were probed. Simultaneously, another tone with a sweeping frequency was sent to the resonator. When frequency of the second tone matches the qubit frequency, it excites the qubit



T1 measurement Parameters

Qubit Drive: Pulse Frequency [MHz]: 4960.64
Qubit Drive: Pulse Gain [DAC units]: 20000
Qubit Drive: Pulse Length [ns]: 150.0
Qubit Drive: Pulse Style
● Constant
○ Flat top
○ Gaussian
Qubit Drive: Pulse Sigma [ns]: 14.286
Resonator Pulse Frequency [MHz]: 7134.16
Resonator Pulse Gain [DAC units]: 600
Resonator Pulse Length [ns]: 4500.0
Resonator Pulse Phase [Degrees]: 70
Readout Length [ns]: 2000.0
Iterations: 200
ADC Trigger Offset [Clock cycles]: 500
Qubit Drive: Nyquist Zone
○ Zone 1
● Zone 2
Readout Pulse Nyquist Zone
○ Zone 1
● Zone 2
Fit Curve [Amp, Tau, DC]: 5, 10000, 0
Wait Interval : Start [ns]: 52.381
Wait Interval : Stop [ns]: 102404.762
Wait Interval : Step [ns]: 52.381
DAC Channel [Qubit Drive]: 2
DAC Channel [Readout]: 0
ADC Channel [Readout]: 0
Result Format: Q

T1 = 65.75 μs

T1 measurement completed...

Fig.3: A snapshot of application software of the prototype qubit control and measurement system.

from its ground state, and causes a shift in the resonator's resonant frequency. The frequency of the sweeping tone at which this shift occurs is the frequency of the qubit. Fig.5 (a) displays the result of the qubit spectroscopy experiment. The qubit frequency was measured to be 4.96064 GHz.

Rabi experiment

In this experiment, a qubit drive signal was applied to the qubit, immediately followed by a measurement of its state. The length of the qubit drive signal was systematically varied, and the state of the qubit was measured. The probability of qubit being in excited/ground state varies sinusoidally with the length of the qubit drive signal. The frequency of the Rabi oscillations depends on the power level of the qubit drive signal. The experiment was conducted with various power levels for the qubit drive. For one of these power levels, the π

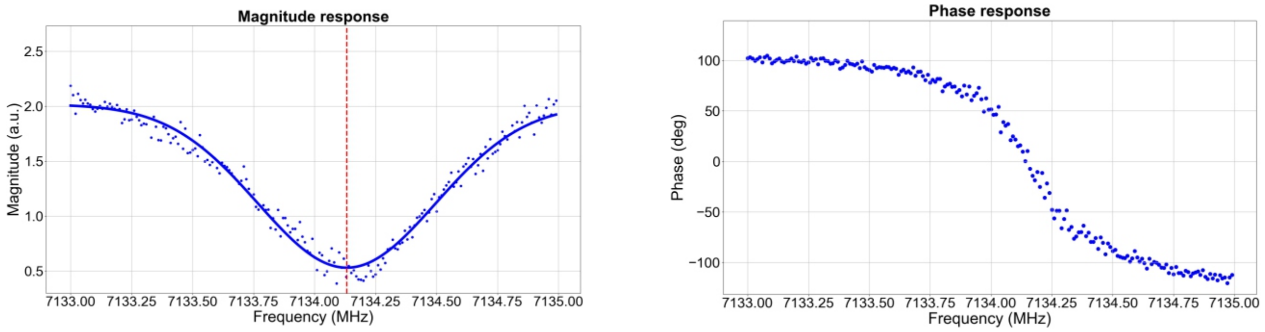
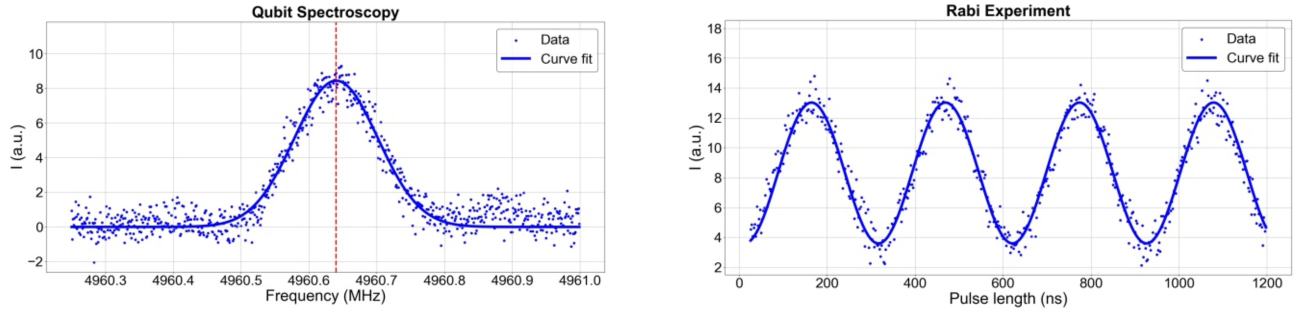
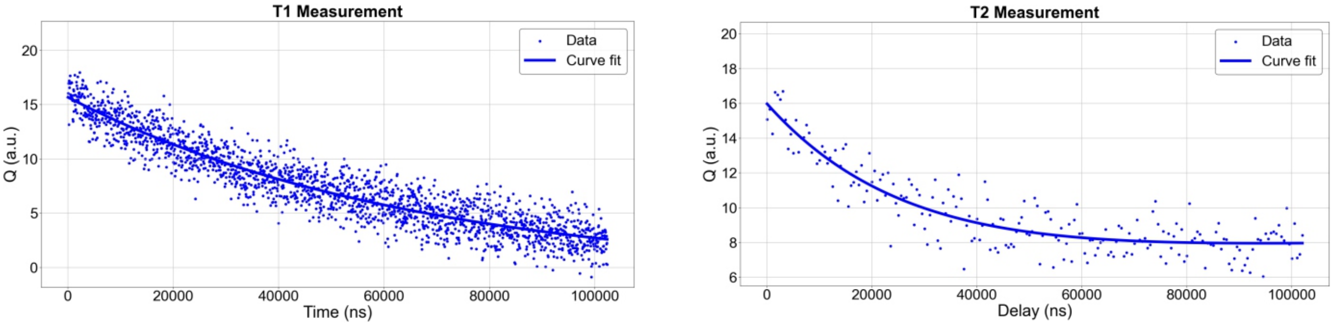


Fig.4: Resonator spectroscopy result.



(a) **(b)**

Fig.5: (a) Qubit spectroscopy result. (b) Rabi experiment result.



(a) **(b)**

Fig.6: (a) T1 measurement result. (b) T2 measurement result.

length duration was measured to be 152.34 ns, as shown in Fig.5 (b).

T1 measurement

To measure the qubit relaxation time, also known as T1 time, the qubit was first transferred from the ground state to the excited state by sending a Π pulse. Subsequently, the state of the qubit was measured at various time intervals to determine the rate of decay. The result of the T1 measurement is shown in Fig.6 (a). The T1 time was measured to be 65.75 μs.

Ramsey experiment

The Ramsey experiment is a fundamental technique used to determine the qubit dephasing time, often referred to as T2 time. In this experiment, the qubit was subjected to two Π/2 pulses with a variable time delay between the pulses. Subsequently, an immediate measurement was performed to assess the state of the qubit. The result of the T2 measurement is shown in Fig.6 (b). The T2 time was measured to be 37.14 μs.

Readout Fidelity

A quantum system is inherently sensitive to external disturbances. Therefore, an ideal control and measurement system should introduce minimal or no additional noise, ensuring that the predominant source of noise remains the intrinsic noise of qubit. Achieving this requires a low-noise driving source and readout signal processing chain. Additionally, low-jitter sampling clocks for the data-converters become essential to fulfil this objective.

Readout fidelity in quantum computing is a measure of how accurately a system can distinguish between different quantum states, such as the excited state and ground state of a qubit. Higher readout fidelity means the system can determine the state of the qubit more accurately.

The readout fidelity of the prototype controller was measured to be 75.85% with no parametric amplification. Fig.7 depicts the result of the readout fidelity measurements.

Conclusion

A high-quality classical control is needed for initialization, manipulation, and readout of quantum states. A room-temperature qubit control and readout system for superconducting qubits is being developed that can conduct qubit characterization experiments, and implement high fidelity quantum gates. The performance of the qubit controller was evaluated by characterizing a superconducting qubit. Our future work will focus on optimizing the controller's performance and expanding its capability to manage a greater number of qubits. This system is believed to offer itself as a cost-effective solution for rapidly prototyping control electronics for multi-qubit systems and executing quantum algorithms in a seamless and user-friendly manner.

Acknowledgment

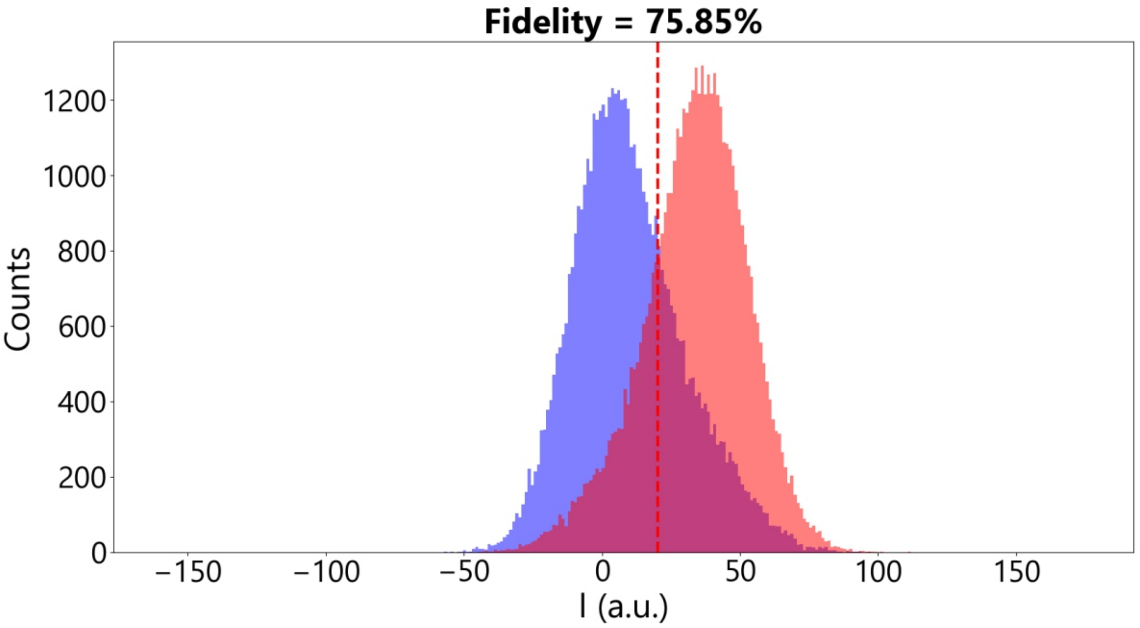


Fig.7: Single-shot readout values for the qubit in the ground state (blue) and excited state (red).

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