Research on Superconducting Qubit Manipulation Based on Arbitrary Waveform Generator

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Abstract. Quantum computing is an emerging technology which will influence the future. Quantum computing is currently limited by the scalability of qubits, especially the qubits manipulation of superconducting computing. In this paper, a superconducting qubits manipulation method based on AWG (Arbitrary Waveform Generator) is proposed. Based on the superconducting quantum computing system, the overall scheme of qubits manipulation is presented, including overall framework, multichannel coherent arbitrary waveform generation design, quantum state reading and acquisition design, multichannel synchronization design and quick feedback transceiver design. The simulation and experiment results show that the proposed method has good scalability, high synchronization index and good signal quality, which can meet the requirements of superconducting quantum computing for qubits manipulation.

1. Introduction

There are two bottlenecks in the practical application of quantum computer. One is the scalability of quantum computing. It is difficult to make a coherent control to a large number of qubits effectively. The other is the fault tolerance in quantum computing. It is urgent to reduce the error rate and improve the reliability of quantum computing.

The main implementation methods of quantum computing are to use: Quantum Dots, Superconducting Qubit Circuit, Ion Trap, Quantum Electrodynamics (QED), etc. And the method based on Superconducting Qubit Circuit is the most researched and potential. In this paper, qubit manipulation based on superconducting circuit is studied.

Superconducting qubit is the basic unit of superconducting quantum computing. The manipulation of qubits requires precise control of a variety of excitation signals. In a multi-bit superconducting quantum system, the coherence between excitation signals is highly required. How to generate excitation signal and receive readout signal at the same time, and maintain a high coherence between signals is the difficulty of superconducting qubit manipulation, and also a hot spot [1]. At present, Arbitrary Waveform Generator (AWG) is one of the core devices in most superconducting qubit manipulation instrument systems. And most of typical superconducting qubits computing manipulation instruments at home and aboard are implemented based on AWG.
2. Related works
In 2019, Google developed a quantum chip - Sycamore that can precisely manipulate 53 qubits with a 0.159% single bit error rate, which realized ‘Quantum Superiority’ or ‘Quantum Hegemony’ [2].

In March 2019, the IBM superconducting quantum computer - Q System One [3] can manipulate 20 qubits. In September 2019, IBM announced an increase in effective manipulation of the number of qubits to 53 with a 1% single bit error rate.

Intel and QuTech released the quantum chip – Horse Ridge [4], which can generate 2GHz to 20GHz qubit signals, support 128-bit qubits (Each of channel can control 32 bits and can integrate 4 RF channels into one chip) and work at 3K(-270℃).

Keysight Technologies launched the integrated arbitrary waveform generator, digitizer, IQ modem and other quantum engineering test suit – QET. And the waveform generation technical specifications are: sampling rate for 1GSa/s, bandwidth for 400MHz, 14bit; the quantum state acquisition and analysis specifications are: sampling rate for 500MSa/s, bandwidth for 200MHz, 14 bit; IQ modem specifications are: spectrum for 3GHz to 18GHz and good scalability. In 2019, Keysight Technologies acquired Labber Quantum Co of MIT, which accelerated the quantum testing process.

Zurich Instruments Co can manipulate up to 144 qubits through HDAWG multichannel arbitrary waveform generator and UHFQA quatum analyzer, and the waveform generation specification are: sampling rate for 2.4GSa/s, bandwidth for 750MHz, 16bit; the quantum state acquisition and analysis specifications are: sampling rate for 2.4GSa/s, bandwidth for 600MHz, 12bit; which can generate multi-channel correlation waveform by synchronous control.

BBN Technology’s qubit manipulation scheme can store 64000 waveform sequences and support 9-way synchronous waveform output. And the specifications are: sampling rate for 1.2GSa/s, 14bit and bandwidth for 400MHz.

3. Project Design
In this chapter, the relationship between qubit manipulation system and quantum entanglement unit, and detailed qubit manipulation scheme are given by introducing the superconducting quantum computing system.

3.1. Superconducting quantum computing system
The quantum computing system based on superconducting circuit which includes superconducting quantum computing unit, qubit manipulation unit, cable and microwave assembly, refrigerator etc. has a good scalability, which is a hot topic now. Based on Josephson Junction, the superconducting circuit realize quantum entanglement by applying week energy microwave signal to qubits, which is used in quantum computing.

![Superconducting quantum computing system](image-url)
3.2. Qubit manipulation design

![Diagram of Qubit Manipulation Platform](image)

Figure 2. Superconducting quantum computing system.

The qubit manipulation platform includes manipulating waveform generator, local oscillator, acquisition unit, up&down converter unit and quantum computing unit.

The manipulating waveform generator generates I/Q baseband signal which generates 4GHz to 8GHz microwave signal through the modulation unit and then enters the quantum computing chip in ultra-low temperature environment through cable, so as to manipulate qubit signal. One channel RF signal can manipulate one qubit. The acquisition unit reads the state of resonant cavity in superconducting quantum computing and gives real-time feedback to manipulating waveform generator. In addition, the pulse signal generated by manipulating waveform generator is used for dc input of the bias tee and manipulates Z component of qubit. It should be noted that the synchronization time of multi-channel arbitrary waveform generator and feedback time of acquisition unit are the difficulties in system design.

1) Multichannel coherent arbitrary waveform generation

The number of manipulation signal channel is proportional to the number of entangled qubits. For example, for a 128-bit quantum system, at least 256 channels of synchronous IQ signal, 128 channels of synchronous local oscillator signal and IQ modulator, RF switch, multi-channel stable phase power supply are needed. Therefore, when multichannel manipulating signal generated, the design focus is how to improve the integration to effectively reduce complexity of the system.
Figure 3. Multichannel coherent arbitrary waveform generation

As shown in Figure 3, the multi-channel coherent arbitrary waveform generator (AWG) is used to generate IQ signal. 4 output channels are integrated into a single board card, and each channel uses a differential converter to amplify the output after filtering. AWG unit is mainly composed of high performance FPGA, DDR storage array, low phase noise clock unit and 4-channel DAC and so on. And the DAC sampling rate in this paper is 1.2GSa/s.

The IQ waveform can be stored in FPGA chip BlockRAM or plug-in DDR4 particles. BlockRAM generally has a small capacity and a playback time of about 5ms. Its advantage is that it is relatively fast, and its corresponding output time is only a few nanoseconds, which can be used for fast feedback output. The capacity of plug-in DDR4 particle is 4GB, and the playback time is 400ms. However, due to the timing refresh mechanism of DDR4, data can not be read during the refresh time, so the burst waveform response is slow, and a response delay of about 200ns may occur, which can be used for user programming output.

IQ signal output is controlled by synchronous trigger signal of the PXIe case, which enables all AWG modules in the case to output signals at the same time to achieve synchronous playback. In addition, the 10MHz time base signal distributed by PXIe case can guarantee the synchronization of all DAC sampling clocks in time.

2) Quantum state reading and acquisition

Figure 4. Quantum state reading and acquisition

The quantum state reading and acquisition unit realizes the synchronous reception of multichannel quantum readout signals and extraction of quantum information. In terms of the number of channels, there are generally fewer ways to read a signal than to manipulate it. The quantum state reading and
acquisition unit is shown in Figure 4. A single board card integrates 2 acquisition channels. After the quantum state signal is processed by the demodulation module, and IQ signal is generated, which is used as the input of quantum state reading and acquisition unit.

In this paper, ADC uses a single chip with 2 channels, 12 bit and a sampling rate of 1.2GSa/s. In the aspect of synchronous control, it is consistent with AWG unit, the acquisition synchronization is carried out by synchronization trigger signal, and the synchronic base mechanism is also adopted on the clock to achieve the purpose of time synchronization. The signal collected by ADC is input into FPGA for analysis and processing to complete the decision.

3.3. Synchronous design of multichannel qubit manipulate waveform

Figure 5. Multi-case synchronization

There are two main types of signal synchronization: synchronization of all modules within a single case and between cases. In this paper, the timing synchronization function of PXIe case is used to realize the high-precision synchronization. As shown in Figure 5, a timing synchronization board card is built into each PXIe case, and the card in main case controls all timing synchronization board card in sub cases. Then the card in each case realizes synchronization of all modules in them. A differential signal line and a time base signal line which are isometric are used to connect the main case and each sub case to realize clock and trigger synchronization.

Each case individually loads and manipulates waveform. After the waveform loading of all cases completed, the timing board card of main case generates a playback trigger signal, which is transmitted to all sun cases through cables. After receiving trigger signal, the signal in sub case is distributed to AWG module and acquisition module through the trigger bus of PXIe to realize synchronization of all modules. In order to compensate the isometric error of cables, the timing card can independently control the delay of all trigger signals, and the error rate can be reduced by calibration.

3.4. Fast feedback design for qubit manipulation

In the process of qubit manipulation, there is a design of quick transceiver feedback to realize rapid response from ‘Signal reception and information extraction’ to ‘Control signal generation’. At present, the typical feedback time of quantum computing needs to be less than 500ns.
In order to achieve rapid transceiver feedback, the cable and signal line running delay, digital processing delay of received signal and digital processing delay of transmitted signal need to be reduced, and the receiving and transmitting signal units can directly interact. In this paper, PXIe case local bus is used to realize the direct interaction between receiving and transmitting signal units. By means of FPGA-FPGA interaction, the transmitting digital unit can quickly recognize the message from receiving unit. The delay of each part of system transceiver feedback path is shown in Figure 6, and total feedback delay is about 420ns.

4. Simulation
Through the measurement of manipulating waveform generator unit discussed in this paper, the synchronization accuracy of multi-channel waveform can reach 25ps, and each channel supports 25ps stepper adjustment. The test figure is shown in Figure 7. IQ orthogonal modulation baseband output level and DC bias and phase can be adjusted. Output level fine tuning range is ±200mV. The phase adjustment resolution is about 0.04rad. The measured IQ waveform is shown in Figure 8. Typical spurious suppression (non-harmonics) is less than -80dBc, and the spurious measurement of output signal is shown in Figure 9.
Figure 8. IQ waveform measurement

Figure 9. Low frequency spurious measurement

5. Conclusion
In this paper, a superconducting qubit manipulation platform based on AWG is designed. And the implementation scheme and its characters and advantages of this scheme are analyzed in detail. Then the waveform signals generated by baseband unit of manipulation signal generation are measured. The test results show that the manipulation waveform has characters of high precision of multi-channel synchronization and low spurious free dynamic range, which can meet the requirements of synchronization, noise control and scalability of superconducting quantum computing, and has good application value in multi-bit superconducting quantum computing.

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