Superconducting Digital Electronics for Controlling Quantum Computing Systems

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SUMMARY The recent rapid increase in the scale of superconducting quantum computing systems greatly increases the demand for qubit control by digital circuits operating at qubit temperatures. In this paper, superconducting digital circuits, such as single-flux quantum and adiabatic quantum flux parametron circuits are described, that are promising candidates for this purpose. After estimating their energy consumption and speed, a conceptual overview of the superconducting electronics for controlling a multiple-qubit system is provided, as well as some of its component circuits.

key words: qubit, quantum computing, single-flux quantum circuit, adiabatic quantum flux parametron circuit, superconducting integrated circuits

1. Introduction

Recently, superconducting qubits have attracted attention as devices capable of realizing scalable quantum computers using integrated circuit processes [1]–[3]. Even though the decoherence time of the firstly demonstrated superconducting qubit was about one ns [4], it reached several tens of microsecond in the recent superconducting qubits [5]. The gate fidelity exceeds 99 percent, which is larger than the fidelity threshold necessary for the quantum error correction using the surface code approach [6]. In light of the recent huge improvements in decoherence time, and with the help of the quantum error correction concept, the realization of a large-scale quantum computer system appears to be possible. For this reason, companies and national projects are actively pursuing quantum computing research and development, especially in Europe and the United States. It can be said that quantum computers have moved from the basic research to the applied research and development stage, where the full use of various peripheral technologies becomes important.

To realize a large-scale quantum computer system, one critical issue is how to externally control many qubits and read out their state to the outside world. Usually, control of the qubit state and the coupling between qubits is performed using external microwave pulses or current pulses. For example, to perform coherent control of qubits, it is necessary to apply accurate microwave pulses with uniformly synchronized phases into each qubit. Such pulses require that the frequency of the microwaves is on the order of several gigahertz with a small spectral linewidth. In addition, the rise time of the microwave pulse has to be less than several tens of picoseconds. For a small quantum computing system with several qubits, microwave pulses can be applied by room-temperature electronics. However, room-temperature control systems are challenging for large quantum computing systems with more than a few hundred qubits due to the huge number of microwave lines between cryogenic and room temperatures. Integration of a large number of qubits with microwave lines is not straightforward, and they induce a substantial heat load to the system.

To solve this problem, many studies aimed at manipulating and reading the qubit state using single-flux-quantum (SFQ) circuits [7] have been performed up to now [8]–[12]. Recently, the control of a superconducting transmon qubit by a train of SFQ pulsed was demonstrated with the fidelity of about 95 percent [13]. We also have been conducting research to realize a superconducting quantum computing system that combines superconducting qubits and superconducting digital electronics, as shown in Fig. 1. In this system, state control and readout of each qubit are performed using SFQ or adiabatic quantum flux parametron (AQFP) circuits [14], which make it possible to build a scalable quantum computing system with minimal external wiring. In addition to the high-speed manipulation and readout of the qubit state by SFQ circuits, AQFP circuits would provide another option to the interface circuits: extremely low-power and high-sensitive manipulation and readout of the qubit.

In this paper, superconducting circuits that are promising candidates for controlling the quantum computing system are described. After estimating their energy consumption and speed in Sect. 2, a conceptual overview of superconducting electronics for controlling a multiple-qubit system is provided in Sect. 3.

2. Superconducting Digital Electronics for Controlling a Quantum Computing System

To control a superconducting qubit, microwave pulses are mainly used to rotate the phase accurately. Square current pulses are also used to control the qubit state. To calibrate the parameters for qubit devices, DC biases have to be applied to each qubit. The requirements for the signals necessary to control qubits are as follows:

- The microwave pulses, whose typical frequency is...
several gigahertz, must have a rise/fall time of several tens of picoseconds and a controllable envelope amplitude on the order of several microamps [15]. The frequency and the envelope amplitude must be controllable for each qubit.

- The square current pulse must have a rise/fall time of several tens of picoseconds and an amplitude of several tens of microamps because the typical critical current of Josephson junction in superconducting qubits is ranging from 0.1 to 10 μA [16], [17]. The amplitude and width of the pulse must be controllable.
- A controllable DC bias with an amplitude of several tens of microamps is necessary for each qubit.

As for the detection of the qubit state, a small DC output current from the qubit must be detected. In recent circuit QED systems, the scattering parameters for microwave signals are measured to determine the qubit state. The requirements for detecting the qubit state are as follows:

- The DC current sensitivity must be less than several hundred nanoamps, assuming the typical critical current of Josephson junction is ranging from 0.1 to 10 μA.
- The microwave sensitivity must be less than the power ranging from −130 dBm to −120 dBm when the readout time of the qubit state is about 100 ns [18].

It is also important that the controlling electronics have a total energy consumption of less than 10 μW, which is the cooling power of the cold head of a typical 10 mK dilution refrigerator [19].

2.1 SFQ Circuits

Rapid SFQ (RSFQ) circuits are known as high-speed logic circuits operating at clock frequencies exceeding hundreds of gigahertz with low power consumption [7]. Recently, various types of energy-efficient versions have been invented and demonstrated, including low-voltage SFQ [20], efficient RSFQ [21], and energy-efficient SFQ [22] circuits, where static power consumption at the bias resistance was considerably reduced. Because of the low energy consumption of SFQ circuits, they are promising candidates for digital electronics for controlling a quantum computing system.

The bit energy (switching energy) $E_b$ of an SFQ circuit is determined by the dynamic energy consumption at the junction given by $E_b = I_c \Phi_0$, where $I_c$ is the critical current of the Josephson junction and $\Phi_0$ is a flux quantum. At any finite temperature, $E_b$ has to be much larger than the thermal energy $k_B T$ to reduce the bit error rate. In other words, $E_b \gg k_B T$, where $k_B$ is the Boltzmann constant and $T$ is the temperature. The switching time of the Josephson junction is given by the $L/R$ time constant:

$$\tau_{sw} = \frac{2 \pi L_j}{R} = \Phi_0 \frac{I_c}{I_c R} = \sqrt{\frac{2 \pi \Phi_0 C_s}{I_c}}.$$

where $L_j$ is the Josephson inductance given by $\Phi_0/2\pi I_c$, $C_s$ is the junction capacitance per unit area, $I_c$ is the critical current density for the Josephson junction, and $\beta_c$ is the McCumber parameter. The McCumber parameter is calculated by

$$\beta_c = 2 \pi R^2 C_s / \Phi_0,$$

where $R$ is the parallel resistance of the subgap resistance.
and the shunt resistance of the junction and \( C \) is the junction capacitance. In conventional SFQ circuits, \( \beta_c \) is chosen to be 1.

If we assume that the SFQ circuits are operating at a cryogenic temperature of several tens of millikelvins, we can reduce the value of \( I_c \) down to 10 \( \mu \)A, by accounting for both the error rate and the minimum size of the junction. If we assume that the junction size is 1 \( \mu \)m, which is a typical junction size with current fabrication technology, the critical current density for the Josephson junction has to be reduced to \( J_c = 1 \text{ kA/cm}^2 \), which corresponds to one-tenth of the present high-speed Josephson integrated process [23]. According to Eq. (1) and assuming the above values, the clock frequency of the SFQ circuit at a cryogenic temperature is deduced to be \( f_c = 10-15 \text{ GHz} \). The bit energy of the gate is estimated to be about 20 \( zJ \) per bit. The amplitude of the output current of the SFQ circuit is in the range of several microamps. When we integrate 1,000-gate SFQ circuits, the total power consumption is estimated to be about 2 \( \mu \)W at a 10-GHz clock frequency. This power is small enough for a dilution refrigerator with typical cooling power.

2.2 AQFP Circuits

An AQFP can realize a logic operation with extremely high energy efficiency by slowly and adiabatically operating a quantum flux circuit with a high intrinsic operating speed [14]. However, the operating frequency of the AQFP ranges from 2 to 5 GHz, which is still faster than CMOS circuits. The extremely low energy consumption of the AQFP circuit makes it a strong candidate for the control electronics of a quantum computing system.

The bit energy \( E_{\text{bit}} \) of the AQFP is represented by the ratio of two time constants [24], [25]:

\[
E_{\text{bit}} = 2I_c \Phi_0 \frac{\tau_m}{\tau_r},
\]

where \( \tau_r \) is the rise/fall time for the excitation current and \( \tau_{sw} \) is the intrinsic switching time for the Josephson junction given by Eq. (1). Because the shunt resistance can be removed from the junction to increase \( \beta_c \) in the AQFP circuit, the intrinsic switching time \( \tau_{sw} \) becomes quite small.
Fig. 3  Conceptual diagram of highly sensitive AQFP microwave detector. $I_{in}$ is a small signal from a qubit with a frequency of $\omega$ while $I_x$ is an excitation current with a frequency of $\omega_x$ applied to the AQFP gate. (a) When $\omega$ is equal to $\omega_x$, the output from the AQFP gate becomes “1” for every clock cycle. (b) When $\omega$ is not equal to $\omega_x$, the output signal exhibits both “1” and “0”.

Thus, the bit energy can be reduced significantly. In an AQFP circuit operating at a cryogenic temperature, we may even assume a critical current of $I_c = 50 \mu A$, which is similar to that for operation at 4.2 K because of the high energy efficiency of the AQFP circuit. Thus a similar critical current density can be used, which simplifies the testing of the circuits at 4.2 K. The amplitude of the output current of the AQFP is in the range of a few tens of microamps. If we assume a 5-GHz clock frequency, the switching energy of the AQFP gate per bit is estimated to be 0.5 zJ [25], which is six orders of magnitude better than that of semiconductor circuits and two orders of magnitude better than that of SFQ circuits. When we integrate 1,000,000-gate AQFP circuits, the total power consumption is estimated to be about 2.5 $\mu W$ at a 5-GHz clock frequency.

3. Quantum Computing System Controlled by Superconducting Electronics

To realize a scalable quantum computing system, it is necessary to implement control and readout systems operating in the same temperature environment as the qubits, and to directly control and observe multiple qubits at cryogenic temperatures. This integration can not only significantly reduce the number of wires between the room-temperature and low-temperature environments but also enable high-speed repetitive and feedback calculations. In recent years, proposals have been made to reduce the number of control lines from room-temperature systems by mounting a semiconductor control circuit on a 4.2-K stage. However, this incurs a large cooling cost [26].
Figure 2 shows a conceptual diagram of the proposed qubit control system using superconducting digital electronics. An AQFP digital-to-analog converter (DAC) and demultiplexer (DEMUX) convert the digital signal from an AQFP controller to the analog signals, and provide it to the appropriate qubit. Microwave signals are also delivered to the appropriate qubit by DEMUX. The required number of the microwave lines per qubit depends on the method to control and readout the qubit. However, the total number of the microwave lines can be scalable with an increase of the...
number of qubits because the external microwave signals and DC signal are demultiplexed into each qubit, and signals readout from each qubit are multiplexed. AQFP sensors detect microwave or DC signal from qubit with high sensitivity. An AQFP multiplexer selects one of the qubit signals and sends it to the AQFP controller. An AQFP buffer chain provides DC calibration signals to each qubit. Some circuit blocks can be replaced with SFQ circuits if their speed is critical.

This system has the following features:

- By operating the controller and qubits in the same temperature environment, the number of control and reading connections between the room-temperature and cryogenic environments can be significantly reduced, and the scalability of the quantum computing system can be improved. It is possible to perform fast feedback operations with the qubits at the low-temperature stage, which opens new opportunities, such as a quantum-classical hybrid algorithm that repeats small-scale quantum computations.
- By using AQFP or SFQ circuits, variable DC pulse generators and microwave choppers with sub-nanosecond time resolution can be constructed. With the AQFP buffer array, it is possible to calibrate many qubits individually by applying a static bias current to each one. Because AQFP circuits have high current sensitivity without a transit to the voltage state, high-precision readout of the quantum state is possible. Also, they can have a high current sensitivity to the microwave input.

All these features make it attractive to use AQFP circuits as controlling and reading electronics for quantum computing systems.

Figure 3 shows a conceptual diagram of a highly sensitive microwave detector using AQFP circuits, where the amplitude of the microwave signal from a qubit with a frequency of ω is measured. In the figure, I is a small signal from a qubit while I is an excitation current with a frequency of ω applied to the AQFP gate. When the frequency ω of the input signal is equal to the frequency ω of the excitation current, the output from the AQFP gate becomes “1” for every clock cycle (see Fig. 3 (a)). When ω is not equal to ω, the output signal exhibits both “1” and “0” (see Fig. 3 (b)). Thus, the AQFP acts as a narrow line-width amplifier. By averaging the output signals from the AQFP with an analog or digital integrator, its sensitivity is expected to be considerably improved. The AQFP gate has a reported sensitivity of a few μA in the GHz operation frequency range at 4.2 K [27]. There is a possibility that the sensitivity is improved at a lower temperature.

Figure 4 (a) shows an example of an AQFP multiplexer for a hybrid quantum computing system. This multiplexer makes a parallel-to-serial conversion so that many qubit states can be read out from a single output port. The figure shows an example of a four-to-one multiplexer, where detected signals are input from D through D in parallel and the output signals are read out from D in serial. The circuit is clocked by two excitation currents: a low-speed clock with f = 1 GHz and a high-speed clock with f = 4 GHz. By using this readout scheme, the quantum states of multiple qubits can be read out in series. The circuit can also be used for the interface to decrease the number of wires between the room-temperature and cryogenic circuits. Figure 4 (b) shows the circuit simulation results for the four-to-one AQFP multiplexer. The simulation shows that the input data (D, D, D, D) = (0, 1, 0, 1) can be successfully read out from D in series.

4. Conclusions

The bit energy, operating frequency, and signal amplitude for SFQ and AQFP digital circuits applied to quantum computing systems have been evaluated. It was shown that these circuits are promising for the integration with and the control of qubits, as well as for improvement of the scalability of a quantum computing system. A concept of a quantum computing system controlled by superconducting electronics was also shown. Some component circuits were proposed and examined by circuit simulations.

References


Nobuyuki Yoshikawa received the B.E., M.E., and Ph.D. degrees in electrical and computer engineering from Yokohama National University, Japan, in 1984, 1986, and 1989, respectively. Since 1989, he has been with the Department of Electrical and Computer Engineering, Yokohama National University, where he is currently a Professor. His research interests include superconductive devices and their application in digital and analog circuits. He is also interested in single-electron-tunneling devices, quantum computing devices and cryo-CMOS devices. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan, the Japan Society of Applied Physics, the Institute of Electrical Engineering of Japan, and Cryogenics and Superconductivity Society of Japan.