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On-chip Microwave Generator for Manipulation of Superconductive Quantum Bits

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Abstract

A new on-chip microwave generator for manipulating superconductive quantum bits (qubits) have been proposed. To perform practical quantum computation, on-chip microwave generators, which can be controlled by single flux quantum (SFQ) circuits, are desirable because multiple qubits can be driven simultaneously with high accuracy by an SFQ control circuit and the number of wires between qubits and room-temperature electronics can be reduced. The proposed on-chip microwave generator is composed of an SFQ clock generator, which generates a periodic SFQ pulse train, and a band-pass filter. A sinusoidal microwave can be obtained by filtering an output of the SFQ clock generator. Simulation results indicate that the generated microwave has a sharp spectrum, which can be chopped by controlling the SFQ clock generator. Moreover, a phase of the generated microwave can be accurately controlled by adding a phase control circuit, which is composed of cascaded toggle flip-flops,

between the SFQ clock generator and the filter. The results indicate that we can perform fast and accurate quantum gate operations using the proposed on-chip microwave generator.

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Keywords: SFQ circuit, superconductive quantum bit, clock generator, microwave generator, superconducting circuit

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1. Introduction

A quantum computer has marvelous ability to solve several problems, which are never worked out by conventional computers, by using superpositions of the quantum states in a quantum bit (qubit). Among various physical systems proposed as a qubit, superconductive qubits composed of Josephson junctions are very promising because they use the attractive feature of superconductivity, macroscopic quantum effect, and can be easily fabricated using conventional LSI fabrication technologies. Up to now, several types of superconductive qubits have been experimentally demonstrated [1-3], and integration of multiple superconductive qubits was realized [4, 5].

To perform practical quantum algorithms, integration of at least several thousands of qubits is required. However, it is impossible to control such a large number of qubits using room temperature apparatuses directly. Furthermore, many wires between the low-temperature environment and room-temperature electronics are not desirable because they cause thermal loads, which may result in decoherence of the qubits. Therefore, a peripheral circuit, which is located at low-temperature environment and manipulates and controls the qubits, is indispensable to build a practical quantum computing system. A single flux quantum (SFQ) circuit [6] is thought to be very suitable for the peripheral circuit for superconductive qubits because the circuit can operate very fast at low temperatures with extremely low power consumption. Several groups are investigating the SFQ-qubit hybrid quantum computing system. [7, 8].

Quantum states of the qubit can be manipulated by irradiating microwaves with the frequencies corresponding to the energy spacing between two energy levels of the qubit [2, 3]. Arbitrary unitary transformations can be performed by irradiating multiple microwave pulses whose duration times are accurately controlled. In the phase qubit,

which is composed a current-biased Josephson junction, microwaves are also used to read out the states of the qubit [2]. The control of microwave irradiation is one of key technologies to perform precise quantum computation. Microwave frequencies typically used in the experiment of the superconducting qubits are ranging from 5 to 10 GHz at present [2, 3]. The main reason of this frequency limitation is due to the fact that the precise switching of the microwaves with the time resolution of about several tens of ps is necessary, which is difficult by using conventional microwave generators. Therefore if a microwave generator, which can produce microwaves of higher frequencies with higher time resolution, is realized, the energy spacing of the qubits can be increased, resulting in the high-speed and high-temperature operation of the quantum computing system.

In this study, we have proposed an on-chip microwave generator, which can be controlled by SFQ circuits, to manipulate the state of superconductive qubits and estimated the performance of the proposed circuit using circuit simulations.

2. On-chip microwave generator

Fig. 1 illustrates the principle of the proposed on-chip microwave generator. We can obtain a periodic SFQ pulse train using on-chip SFQ clock sources, which are, for example, a ring-type clock generator [6], a flux flow oscillator using a long Josephson junction [9], and so on. The spectrum of the SFQ pulse train contains many higher harmonics as shown in Fig. 1. A sinusoidal microwave, whose frequency is equals to the frequency of the SFQ pulse train, can be obtained by filtering the generated SFQ pulse train using a band pass filter (BPF). We propose an on-chip microwave generator using this method.

Fig. 2 shows a block diagram of the on-chip microwave generator studied here. The proposed circuit is composed of a ring-type SFQ clock generator, transmission lines whose characteristic impedance is $2\ \Omega$, a 3rd-order constant K-type high-pass filter (HPF), and a 9th-order Chebychev low-pass filter (LPF) having a very sharp cutoff characteristic. If the impedance of the HPF is $2\ \Omega$, the capacitances of the filter become the order of 10 pF, which occupy the area of about several hundreds of μm^2 by using the present superconducting LSI technology and are difficult to implement on the chip. Therefore, we have increased the impedance of the HPF to $5\ \Omega$, though impedance mismatching takes place at the boundary of the transmission line and the HPF. The ring-type SFQ clock generator consists of Josephson transmission lines (JTLs), a confluence buffer, splitters, and a flip-flop with non-destructive read-out (NDRO) function, which switches on and off the circulation of an SFQ pulse in the ring corresponding to its internal states. Decision of cutoff frequency of filters is very important for designing the microwave generator because high-order filter has a ripple in the frequency domain, and the amplitude of output depends on the input frequency and the cutoff frequency of the filter. Moreover, the cutoff frequency of the LPF determines the rise time and the fall time of the generated microwave pulse. In our simulation, to obtain larger microwave amplitude and keep the generality, we have chosen the ratio of the cutoff frequencies f_{HPFCO} , f_{LPFCO} and microwave frequency f_{MW} as shown in Fig. 2.

3. Simulation results and discussion

Fig. 3 shows the simulated output waveform of the microwave generated by the on-chip microwave generator. In this simulation, the frequency of the SFQ clock

generator is set to be 32.7 GHz and the start signal and the stop signal for the clock generator are input at 1000 ps and at 2000 ps, respectively. The rise time and fall time of the microwave pulse are estimated to be less than 50 ps. The simulation results indicate that the irradiation time of the microwave can be controlled with accuracy of the order of tens of ps by controlling the SFQ clock generator. All these characteristics are better than those of the conventional technique, where microwaves are irradiated from microwave generators at the room temperature through highly filtered microwave cables. Fig. 4 shows the power density spectrum of the generated microwave calculated numerically. The spectrum shows the sharp peak at 32.7 GHz. The amplitude of the higher harmonic is attenuated by about 70 dB compared with that of the main peak of the generated microwave.

It should be noted that as the frequency of the generated microwave becomes lower, the amplitude of the microwave becomes smaller. Because the speed of quantum gate operation is proportional to the power of the irradiated microwave, we have calculated the dependences of the amplitude of the generated microwave on the microwave frequency. Though the amplitude of the microwaves is almost proportional to the frequency as shown in Fig. 5, we can obtain the microwave of 9 GHz, whose amplitude is above 20 μ V corresponding to the microwave power of 100 pW. Compared with the microwaves used in pervious experiments [2], this value is enough to drive the superconducting phase qubit.

We have shown that fast quantum gate operation can be performed using the on-chip microwave generator. It is known that 1-qubit operations can be performed very fast by shifting the phase of continuous microwave pulses adequately as illustrated in Fig. 6 [10]. We can perform the phase-shift of the microwaves by adding a phase control

circuit, which is composed cascaded toggle flip-flops, placed between the SFQ clock source and the filter. Fig. 7 shows an example of the phase control circuit. When the phase control circuit is composed of three toggle flip-flops as shown in Fig. 7, the phase control circuit decimates the input SFQ pulses by the factor of 8 in the initial condition. The phase of the SFQ pulse train can be shifted by $\pi/4$ rad. by applying an SFQ signal pulse to the first stage toggle flip-flop. In the same way, we can obtain the multiple microwave pulses whose phase was controlled in the accuracy of $\pi/4$ rad., as illustrated in Fig. 7.

4. Conclusion

We have proposed an on-chip microwave generator to manipulate superconductive qubits. Simulation results revealed that sinusoidal microwaves with a sharp spectrum, which can be controlled by SFQ circuits with high time resolution, can be obtained. It was shown that the proposed on-chip microwave generator is useful to perform fast and accurate quantum gate operation.

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Figure Captions

Fig. 1. Principle of the proposed on-chip microwave generator.

Fig. 2. A block diagram of simulated circuit. The ratio between the microwave frequency and cutoff frequencies are fixed in the simulation.

Fig. 3. The simulated output waveform of the microwave generator. The start and stop signals for the SFQ clock generator are input at 1000 ps and 2000 ps respectively.

Fig.4. Power density spectrum of the microwave generated by the on-chip microwave generator.

Fig. 5. Dependence of the amplitude of the generated microwave on the microwave frequency.

Fig. 6. Example of pulse sequence of the phase-shifted double-pulse method. $\Delta\phi$ denotes the phase shift between two microwave pulses. Arbitrary unitary transformations can be performed very fast by shifting the phase of continuous microwave pulses adequately.

Fig. 7. Example of the phase control circuit. TFF denotes an SFQ toggle flip-flop. The phase of an SFQ pulse train can be shifted by varying the condition of the phase control circuit by applying SFQ pulses to each TFF.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7