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Sub-k_BT Bit-Energy Operation of Superconducting Logic Devices using Adiabatic Quantum Flux Parametron

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Abstract

Adiabatic quantum-flux-parametron (AQFP) logic is ultimately energy-efficient. In this study we investigated the bit energy of AQFP gates with under-damped (lossless) Josephson junctions. Simulation results showed that its bit energy reaches 12 yJ, which is only 20% of thermal energy at 4.2 K, with the rise/fall time of 2000 ps. An AQFP gate array was fabricated and its correct operation was confirmed.

1. Introduction

Superconducting digital devices are promising candidates to realize the future high-end computers due to their high energy-efficiency. Recently, many kinds of low-power superconducting devices have been studied, which include energy-efficient RSFQ (eSFQ) logic [1], reciprocal quantum logic (RQL) [2], low-voltage RSFQ (LV-RSFQ) logic [3], and the negative-inductance SQUID (nSQUID) logic [4]. Among them, adiabatic quantum-flux-parametron (AQFP) logic [5] is ultimately energy-efficient, whose bit energy could be below the thermal energy by changing its potential energy adiabatically.

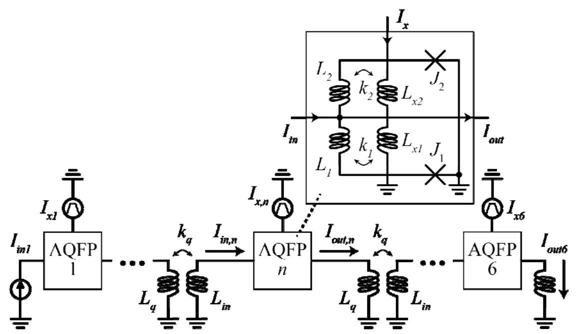
In our previous study, we investigated the circuit parameter condition of AQFP gates for the adiabatic operation mode and evaluated their energy dissipation by circuit simulation [5]. The energy dissipation of an AQFP gate was measured using a superconducting resonator-based method, by which the bit energy was estimated to be 10 zJ for 5 GHz operation [6]. This value is about five orders of magnitude smaller than that of state-of-the-art CMOS logic gates. We also designed and implemented a 1-bit AQFP full adder and showed by experiments that it has a wide current bias margin as large as about ±28% [7]. Throughout these studies, we used critically damped (or lossy) Josephson junctions with the McCumber parameter, β_c of ~ 1.

In this study, we investigate the bit energy of the AQFP gates with under-damped (or lossless) junctions. We will show that the AQFP gate with under-damped junctions can operate with the bit energy less than thermal energy k_BT with low bit-error rate (BER). Experiments on AQFP gates with under-damped junctions are also planned to verify their operation.

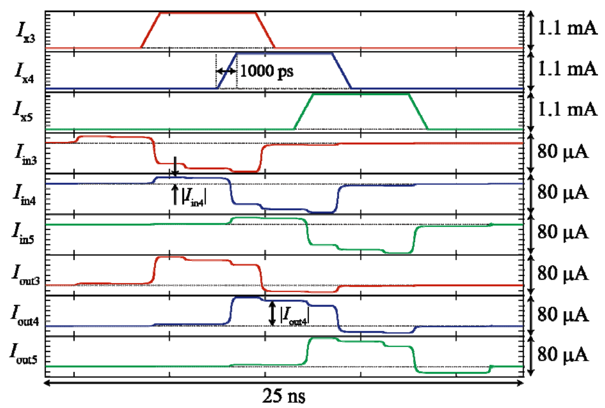
2. Bit Energy of AQFP Gates

As shown in the inset of Fig. 1(a), an AQFP gate is composed of two superconducting loops, which are composed of Josephson junctions J_1, J_2, and inductances L_1, L_2, L_q. We assume that the physical structures of the two loops are symmetry, then $J_1 = J_2 = I_c$ and $L_1 = L_2$. The operating principle of an AQFP gate is based on that of a quantum-flux-parametron (QFP) gate [8]. An AC excitation current, I_x applies excitation fluxes to the two superconducting loops, and one single-flux-quantum (SFQ) is stored in one loop dependently on the direction of the input current, I_{in}. Circuit parameters are normalized using the critical current, I_c; $\phi_x = 2\pi MI_x/\Phi_0$, $\beta_L = 2\pi LI_c/\Phi_0$, and $\beta_q = 2\pi L_qI_c/\Phi_0$, where Φ_0 is an SFQ and $M = k_1(L_1L_{x1})^{0.5} = k_2(L_2L_{x2})^{0.5}$. In the previous study [9], we optimized the parameters as $\phi_x/2\pi = 0.5$, $\beta_L = 0.2$, $\beta_q = 1.6$.

Fig. 1(a) is the schematic diagram for calculating the bit energy and BER of the AQFP gate, where six AQFP gates with the same circuit parameters are coupled in series with $I_{in1} = 0.1I_c$, $L_{in} = L_q$ and $k_q = 0.3$. We activated each excitation current in order and calculated the bit energy per switching event of each gate by integrating the product of the excitation current and voltage over time using the Jo-



(a)



(b)

Fig. 1. (a) Circuit schematic for calculating bit energy. $\phi_x/2\pi$ = 0.5, (β_L, β_q) = (0.2, 1.6), I_c = 50 μA, I_{in1} = 5 μA , $L_{in} = L_q$, k_q = 0.3. (b) Transient analysis of the third through fifth gates for a rise/fall time of 1000 ps.

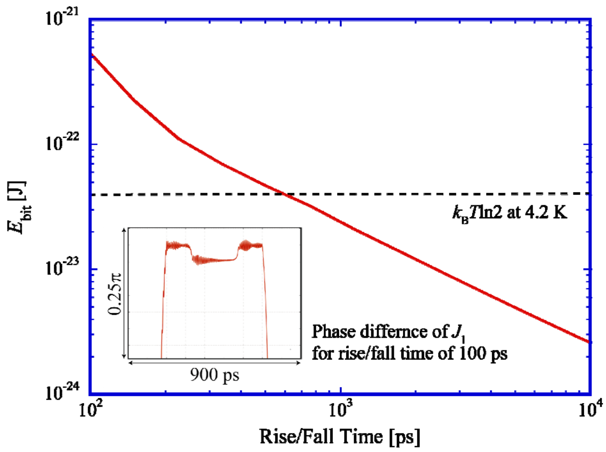


Fig. 2. Bit energy versus rise/fall time. $\phi_x/2\pi = 0.5$, $(\beta_L, \beta_q) = (0.2, 1.6)$, $I_c = 50$ μA, $I_{in1} = 5$ μA , $L_{in} = L_q$, $k_q = 0.3$, the junctions are unshunted with $\beta_c \sim 2600$.

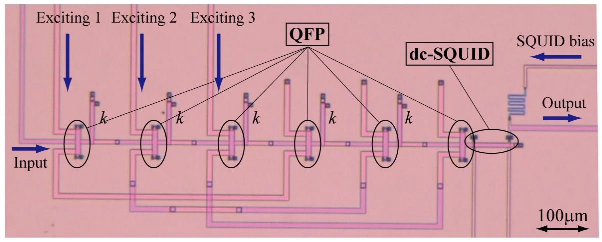
sephson-circuit simulator, JSIM. We assumed the use of the Nb Josephson process, the AIST standard process (STP2), where the density of the critical current is 2.5 kA/cm^2. We evaluated the fourth gate of the AQFP gate array. Fig. 1(b) shows the transient response of the AQFP gates. The upper three plots show the exciting currents for the third through fifth gates, respectively. The middle three plots and the lower three plots show the input currents and output currents for these three respective gates. The figure shows the correct operation, where each gate generates an output current after each excitation current is activated.

Fig. 2 shows the bit energy E_{bit} as a function of rise/fall time of the excitation currents for the AQFP gate with unshunted junctions ($\beta_c \sim 2600$). These simulation results show that the energy dissipation of AQFP gates decreases linearly with increase of the rise/fall time. Moreover, its bit energy goes below the thermal limit of $k_B T\ln 2 \sim 40$ yJ, which is well known as Landauer limit [10], where k_B is the Boltzmann constant and T is temperature. This means that there is no minimum energy dissipation for operating AQFP gates, unless there is a reduction in entropy in the system.

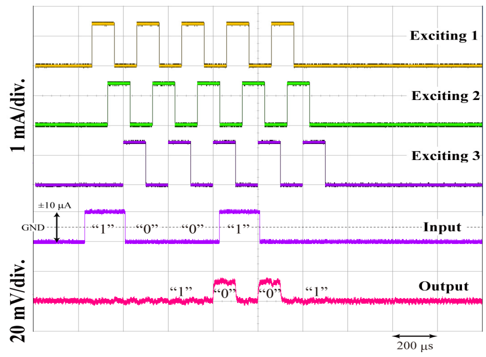
We also investigated BER of AQFP gates based on a Monte Carlo method. The simulation results show that BER is low enough even though the bit energy is below the thermal energy. The bias margin, where BER is smaller than 10^{-23}, is evaluated to be ±21.7%.

3. Experiment

Six stages of AQFP gates were fabricated using the STP2. Fig. 3(a) shows a micrograph of the fabricated QFP gate array. A dc-SQUID that exhibits a voltage transition when the QFP gate is in the "0" state was used to detect the output current. Fig. 3(b) shows a low-speed experimental result of the QFP gate array with the parameter $(\beta_L, \beta_q) = (0.2, 1.6)$ and $\beta_c = 1$ measured at 4.2 K when the input data (1001) is applied. We used three-phase exciting currents to drive the AQFP gate array. The figure shows that the correct output data (1001) is observed. Because the circuit uses the critically damped junction with $\beta_c = 1$ this time, the bit energy is expected to be about 50 times larger than that shown in Fig. 2. Measurement of AQFP gate arrays with under-damped junctions is under investigation.



(a)



(b)

Fig. 3 (a) Micrograph of 6 stages of adiabatic QFP gates. (b) Low-speed test results of 6 stages of adiabatic QFP gates at 4.2 K with $I_0 = 50$ μA, $(\beta_L, \beta_q) = (0.2, 1.6)$ and $k_q = 0.3$. β_c of the junctions is 1 in this sample.

4. Conclusions

We have calculated the bit energy of AQFP gates with under-dumped junctions. The bit energy reaches 12 yJ using unshunted 50 μA junctions and excitation currents with the rise/fall time of 2000 ps. These results indicate that the AQFP gates are practical for large computing systems with extremely small bit energy.

Acknowledgements

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