Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1242-1243

# Ultra-Low-Power Superconducting Logic Devices using Adiabatic Quantum Flux Parametron

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## 1. Introduction

Energy-efficient logic devices are highly desirable for realizing high-performance computers that are capable of exascale performance. The most important metric when considering the efficiency of logic devices is the bit energy per switching event because the total energy required to solve a certain problem is determined by the total number of switching events of the computing system regardless of the computing time.

Rapid single flux quantum (RSFQ) logic [1] is a promising technology for reducing the energy consumptions of computing systems. Many successful high-speed demonstrations of RSFQ integrated circuits have been reported [2]. The intrinsic dynamic switching energy of an RSFQ gate is only $I_c\Phi_0$, where $I_c$ is the critical current of the Josephson junction and $\Phi_0$ is the single flux quantum (SFQ). However, currently more than 20 times the static energy is consumed at the resistor to supply the bias current; this reduces the efficiency of this technology when the cooling power of the system is taken into account. Recently, several new approaches for reducing or eliminating the static energy consumption in RSFQ circuits have been proposed, including LR load biasing [3], reciprocal quantum logic [4], and eSFQ logic [5]. In all approaches, the goal is to eliminate the static energy consumption, but the dynamic energy consumption per gate, $I_c\Phi_0$, still remains. An active method for reducing the dynamic energy consumption employs reversible superconducting circuits based on a negative-inductance superconducting quantum interference device (SQUID). This method has achieved a bit energy of the order of $k_BT$ per gate [6].

In this study, we propose a method for reducing the dynamic energy consumption of superconducting SFQ circuits. Our approach is based on adiabatic operation of quantum flux parametrons (QFPs) [7], [8], where the nonhysteretic QFP is operated adiabatically or very slowly.

## 2. Adiabatic Quantum Parametron

Figure 1 shows a circuit schematic of a QFP. The QFP is a two-junction SQUID composed of two Josephson junctions $J_1$ and $J_2$ and two inductors $L_1$ and $L_2$, which are shunted by a center inductor $L_q$ in the center node. To induce a magnetic flux in the SQUID, an exciting current $I_E$ is applied to inductors $L_{x1}$ and $L_{x2}$, which are magnetically coupled to $L_1$ and $L_2$ through mutual inductances $M_1$ and $M_2$, respectively. In operation, a low input current $I_S$ is initially applied to the QFP. The exciting current is then increased, which alters the QFP from having a single-well to a double-well potential energy. Consequently, the final state of the QFP is one of two states: the “0” state with an SFQ in the left loop or the “1” state with an SFQ in the right loop. A large output current, whose direction depends on the final state of the QFP, is generated in $L_q$.

For the symmetric QFP with $L_{x1} = L_{x2} = L_x$, $L_1 = L_2 = L$, $M_1 = M_2 = M$, and $J_1 = J_2 = I_0$, the normalized inductances $\beta_L = 2\pi LI_0/\Phi_0$ and $\beta_q = 2\pi L_qI_0/\Phi_0$ determine the hysteretic or nonhysteretic nature of the QFP when an exciting current is applied. Numerical analysis shows that the QFP operates in the hysteretic mode when $\beta_L$ x $\beta_q > 0.6$, where the sudden jump from the initial to the final state appears when the exciting current is increased. On the contrary, the QFP gradually changes the state, when $\beta_L$ x $\beta_q < 0.6$, which makes adiabatic operation of the QFP possible.

In adiabatic operation, if we assume a 2π phase transition at the Josephson junction occurs over a period of $T$, the junction voltage at the 2π phase transition will be of the order of $\Phi_0/T$. Therefore, the energy dissipation at the junction will be inversely proportional to $T$ and is given by $\Phi_0^2/(RT)$, where $R$ is the junction resistance. The dependences of the energy dissipation per switching event of the QFP gate on the rise and fall times of the exciting current were simulated using a circuit simulator. We assumed that the exciting current has a trapezoidal profile (see the inset of Fig. 2). The switching energy was evaluated by calculating the transient waveforms of the exciting current and voltage and integrating them over time. Figure 2 shows the calculation results. While the switching energy of the QFP gate in the nonadiabatic mode ($\beta_L$ = 1.0 and $\beta_q$ = 3.0) does not have a strong dependence on the rise and fall times, that of the QFP gate

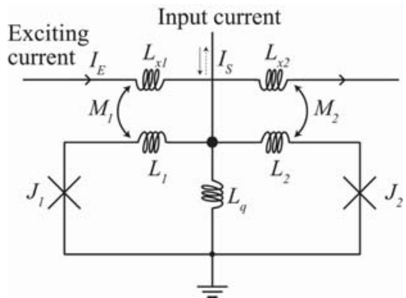



Fig. 1 Circuit schematic of a QFP.

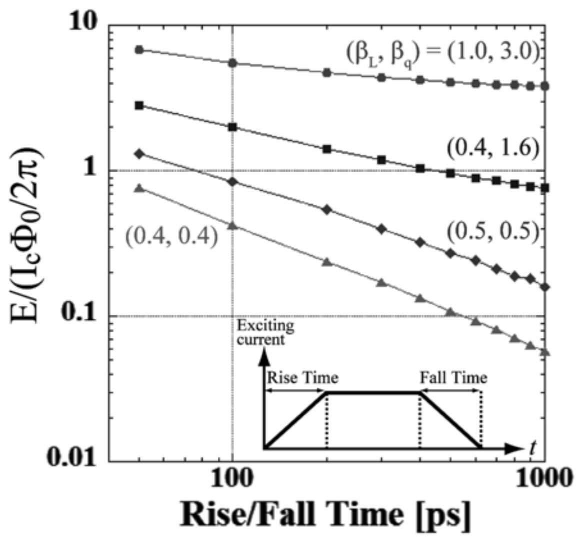


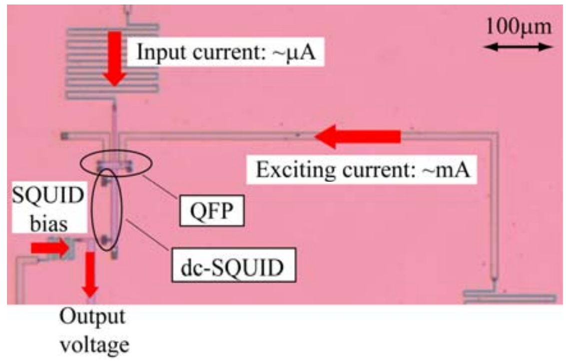

Fig. 2 Dependence of the energy dissipation per switching event of the QFP gate as a function of rise and fall times of the exciting current ($L_1$ = 3.0 pH, $I_0$ = 50 μA, $I_E$ = 1.0 mA, $I_S$ = 5.0 μA, $k = (M^2/LL_x)^{1/2}$ = 0.3).

in the adiabatic mode varies approximately inversely with the rise/fall time when $\beta_L$ and $\beta_q$ are low. The simulation results imply that an energy dissipation of much less than $I_0\Phi_0$ can be expected in the adiabatic QFP. They also confirm that the current gain of the QFP gate is larger than 1000 even when $\beta_L$ = 0.4 and $\beta_q$ = 0.4.

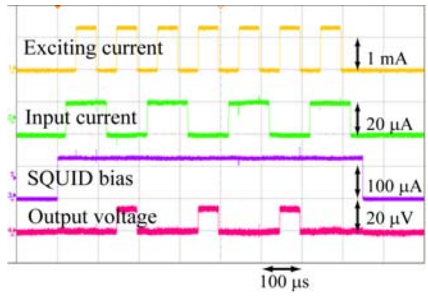
## 3. Experiment

A variety of adiabatic QFP gates with different circuit parameters, $\beta_L$ and $\beta_q$, were fabricated using a Nb Josephson process (ISTEC standard process, STP2 [9]) with a critical current density of 2.5 kA/cm$^2$ and their function was examined at low speed. Figure 3 (a) shows a micrograph of the fabricated QFP gate. A dc-SQUID that exhibits a voltage transition when the QFP gate is in the "0" state was used to detect the output current. Figure 3(b) shows a low-speed experimental result measured at 4.2 K of the QFP gate with the parameter ($\beta_L$, $\beta_q$) = (0.4, 1.6) when the input data (10101010) is applied. It shows that the correct output data (10101010) is observed when "Exciting current" is in the high state because the voltage transition of the output dc-SQUID corresponds to the "0" state of the QFP gate. We also verified the correct operation of QFP gates in the adiabatic operation mode with different circuit parameters: ($\beta_L$, $\beta_q$) = (0.4, 0.4), (0.6, 0.9) and (0.3, 2.0).

From the results in Fig. 2, we estimate the energy dissipation of the QFP gate with $\beta_L$ = 0.4 and $\beta_q$ = 0.4 to be 6% of $I_0\Phi_0$ (~ 0.006 aJ) when the rise/fall time is 100 ps; this corresponds to a dynamic energy dissipation of 140$k_BT$. Further energy reduction is possible if smaller $\beta_L$ and $\beta_q$ are used or junctions with higher Josephson current densities are used, which increases the intrinsic switching speed of the QFP gate. The minimum energy dissipation of the adiabatic QFP is still not known, but it is expected to be of the order of $k_BT$.




(a)




(b)

Fig. 3 (a) Micrograph of a fabricated adiabatic QFP gate. (b) Low-speed test results of the adiabatic QFP at 4.2 K when $I_0$ = 50 μA, $L$ = 2.64 pH, $L_q$ = 10.5 pH, $k$ = 0.3.

## 4. Conclusions

Adiabatic QFPs have been proposed that have energy consumptions per switch that potentially approach the minimum limit and are of the order of the thermal energy. We investigated the circuit parameter conditions of a QFP in adiabatic mode. The energy dissipation of the designed adiabatic QFP gate is estimated to be 6% of $I_c\Phi_0$ (~ 0.006 aJ) when the operation frequency is 4 GHz, which is six orders of magnitude smaller than that of the state-of-the-art CMOS logic device and can be further reduced by decreasing circuit inductances. Several adiabatic QFP gates were fabricated and their correct operation was confirmed.

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